Salto del Carnero Railway Bridge, Saragossa, Spain

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Introduction

Delicias Station at Saragossa is an infrastructure of prime importance on the new Madrid-Barcelona high speed railway [1]. Station construction entailed re-organization of the railway tracks leading into the city and construction of an overpass spanning eight tracks in very close proximity. Many key aspects of the bridge project were governed by construction site-related and geometric, functional, constructional and economic constraints.

But demanding boundary conditions often spur careful and indeed even innovative structural design. Since the successful translation of numerous constraints into a reliable, functional, cost-effective and aesthetically attractive structure is primarily a question of consistent conceptual design, the importance of this step in the design process as a whole cannot be overstated. The ideas underlying the conceptual design for the Salto del Carnero railway bridge, in particular with respect to the specific boundary conditions involved, are explained in the article, along with the actual layout and a few comments on the design of structural details.

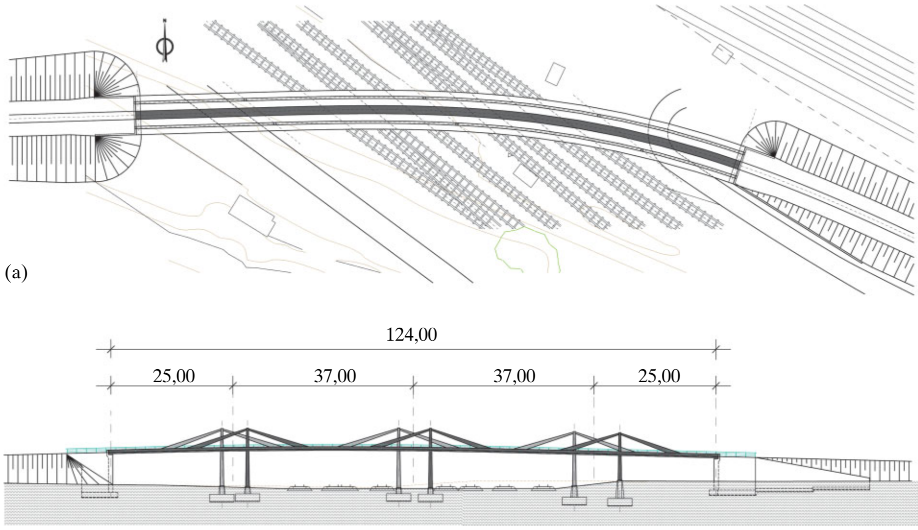

Fig. 1: Salto del Carnero railway bridge a) Plan view b) Elevation

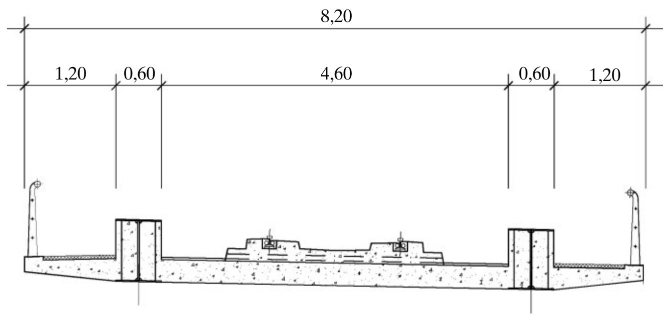

Fig. 2: Cross-section of bridge deck

Boundary Conditions

Situated only one hundred metres from Delicias Station, the overpass spans eight railway tracks, including the Madrid-Barcelona high-speed railway as well as regional and commuter train tracks. In plan view, the bridge track alignment is curved with a radius of only 200 m at its sharpest (*Fig. 1a*). It is, moreover, substantially skewed with respect to the railway tracks it crosses. The elevation alignment is not flat either, but has a maximum slope of 2,5% (*Fig. 1b*). The single track carried by the bridge, exclusively for shunting purposes (*Fig. 2*), is subject to a 4,6 m horizontal clearance requirement. There are, in addition, two 1,2-m wide maintenance gangways located on either side of the track.

In most public works, economic constraints are a decisive factor in the adoption of a given structural design from amongst various feasible options. In the present case, economic criteria were particularly important, for it is the owner's intention to dismantle the bridge after a relatively short service period as a result of alignment changes planned for the railway it carries. In the absence of any further information about the estimated service period at the design stage, however, it was felt that structural analysis and design should be undertaken to conservative criteria, assuming the normal notional service life for railway bridges (100 years).

With respect to bridge aesthetics, in light of the increasing demand in many communities for more than just utilitarian structures, and the Salto del Carnero location in the immediate vicinity of the new station, this overpass definitely had to meet high aesthetic standards. The challenge was therefore to design a sound solution based on modern structural concepts, in which elegance was to go hand-in-hand with the efficient use of materials.

Conceptual Design

Layout

The basic ideas underpinning the conceptual design for the Salto del Carnero railway bridge followed directly from the aforementioned conditions. The bridge was designed to the form-following-function principle, according to which structural form stems from functional requirements and site constraints.

The composite steel and concrete deck (*Fig. 2*) comprises two partially embedded steel plated I girders spaced at 5,2 m (from centre points) and a reinforced concrete slab that connects the lower part of the two girders and cantilevers 1,5 m on both sides of the deck, bringing its total width to 8,2 m. The railway track runs between the two girders, whereas the gangways are situated on the cantilevered edges. The girders project upward from the slab, forming a physical barrier that separates maintenance staff that use the gangways from railway traffic.

The total bridge length of 124 m is divided into two outer spans, each 25 m long, and two inner spans measuring 37 m each (*Fig. 1*). The two girders rest on three intermediate piers whose shafts are aligned with the girder they support. Since in a plan view piers are aligned parallel to the railway tracks spanned by the overpass, each set of piers is significantly skewed with respect to the bridge deck.

The pier shafts continue through the bridge deck to a height of 4,4 m above slab level. Two rigid stays connect the top of each shaft to the respective main girder at a distance of approximately 12 m from the shaft-girder intersection. With this structural layout, in addition to the rigid support provided by the pier shafts and abutments, the longitudinal girders have intermediate elastic supports, namely the stays, spaced very roughly to divide the central spans into thirds. The skewed bridge layout along with the arrangement of the three pairs of piers and their respective stays make for a very attractive design (*Figs. 1b* and *3*).

Members

The bridge deck consists of two longitudinal composite girders and a connecting reinforced concrete slab. The total height of the partially encased steel plated I girders is 800 mm, while the top and bottom flanges are each 600 mm wide. The flanges are widened at the pier-girder intersection to accommodate the flow of forces around pier shafts (*Fig. 4*). Standard web thickness is 15 mm, while flange thickness varies from 30 to 60 mm. The concrete slab is a constant 0,3 m thick between the longitudinal girders, tapering to 0,2 m at the outer edge of the cantilevered portion. Structural member and detail sensitivity to train axle loads and dynamic effects is minimal, for the solution adopted requires no transverse beams (*Fig. 4*).

The diameter of the circular pier shafts ranges from a minimum of 400 mm at the top to 800 mm at the bottom, near the foundations. The shafts are concrete-filled steel tubes. The rigid stays consist of welded steel box sections with a constant width of 200 mm and a height ranging from 300 mm at the top of the pier to 800 mm where they abut with the main girders. The reduction of the height of the cross-section towards the top of the pier contributes to reducing the bending moments in these members.

The abutment at the west end of the bridge is a conventional, open structure with a shallow foundation and reinforced concrete walls. The abutment at the east end is designed as a cellular concrete box filled with gravel to transmit starting and braking forces from the deck to the soil. Geotechnical parameters are such that shallow foundations suffice in all abutments and piers.

Transverse Stability

Because of the small, 200 m radius of the sharpest curve, the 2,5% slope of the bridge and the specific use of its railway track for shunting, a very slow nominal maximum train speed was established for the design, i.e., only 40 km/h. Consequently, the small centrifugal forces involved allowed for a very simple conceptual approach. Indeed, by connecting the bridge deck to the pier shafts, the combination of each pair of piers and the deck constitutes a portal frame (*Fig. 5*). The three resulting frames, along with the horizontal bearings at the abutments, provide sufficient strength for the transmission of horizontal forces, including the centrifugal forces induced by the trains, from the bridge deck to the foundations. This solution also ensures suitable stiffness for good service performance. Moreover, under the conceptual design described, no additional transverse members are needed for the frames, thereby enhancing bridge aesthetics.

Structural Design

Overall Design

System reliability is highly dependent upon whether behaviour is ductile or brittle, the reliability of the latter type of systems being much lower than in the former. The importance of failure mode is even greater considering that the behaviour of brittle structures may be very sensitive to the uncertain effects of actions such as creep, shrinkage, temperature, differential settlements or earthquakes and that therefore collapse may occur suddenly, without prior warning. The recommendations [2] to which the bridge was designed

Fig. 3: Top view of the finished bridge

Fig. 4: Under view of bridge deck and intersection with pier

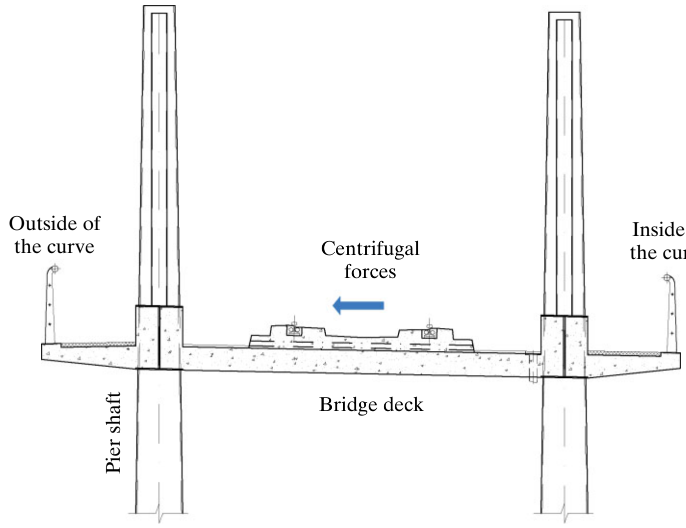

Fig. 5: Frame constituted by the shafts of two piers and the bridge deck

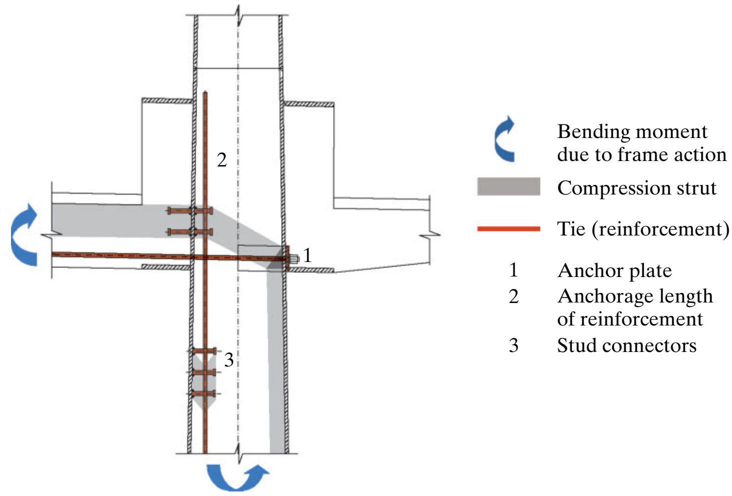

Fig. 6: Stress field at corner joint with compression on the outside

include a strain-oriented method with which the behaviour of composite cross-sections can be established on the basis of their moment-curvature diagrams. Such diagrams can be used not only to determine section ultimate strength but also to evaluate its ductility with a sufficient degree of accuracy to design structures exhibiting ductile behaviour.

Structural Detail Design

The methods for concrete structural design currently available do not enable engineers to map forces through a structure. This drawback is particularly troublesome when designing structural discontinuities such as joints and corners. Great strides have been made in reinforced concrete design in recent years in the wake of the introduction of the stress field method [3], with which consistent design models can be developed on the basis of the lower bound theorem of the theory of plasticity. In the present case, the theorem was reformulated for use in composite structure detailing. The following practical procedure can be followed in joint design (adapted from [3]):

- Computation of internal forces and moments in adjacent members pursuant to conventional structural theory.
- Analysis of the distribution of internal forces on the basis of the resultants.
- Determination of the concrete, structural steel and reinforcement cross-sections required. The forces to be considered in this regard usually result from the forces affecting adjacent members.
- Stress field analysis of joint details.
- Reinforcement and connection device layout.
- Iteration as necessary.

Take, for example, the corner joint on the inside of the curve of the transverse frame shown in *Fig. 5*, subjected to compression forces on the outside of the corner. The compression forces must be doubly deviated to achieve the frame action required (*Fig. 6*). This calls for horizontal and vertical tension members on the inside of the corner. According to [3], any such deviation on the compression strut must be carried to the very surface of the concrete, an effect that can only be attained if the horizontal and vertical reinforcements are fully active on the outside of the respective nodal regions. Anchor plates are therefore used in the horizontal reinforcement on the outside of the pier shaft. By contrast, as the available anchorage length of the vertical reinforcement positioned inside the pier shaft is adequate, no external anchorage plates are required. Forces are transmitted from the vertical reinforcement to the pier shaft via stud connectors welded to the inner side of the steel tube. As this steel component constitutes a discontinuity between the horizontal strut and the nodal region, stud connectors are also used to transmit forces between the horizontal strut, the nodal region and the diagonal strut.

Construction

The general contractor introduced a few changes in the original bridge design. Specifically, higher centrifugal and braking forces than initially established for the design were proposed. This decision was possibly based on the recommendation in [4] to increase the line speed assumed to cover potential changes in future infrastructure or rolling stock. Nonetheless, given the track alignment (*Fig. 1*) and the planned use of the bridge for shunting, adopting nominal maximum train speeds of over 40 km/h seems highly conservative at best. The outcome of increasing the nominal maximum speed was that the substantially greater centrifugal forces involved could no longer be transmitted to the ground by the frame effect provided by bridge deck and piers. Accommodating contractor preference and assumptions therefore led to the need for a transverse beam connecting the piers underneath the deck. This change unfortunately came at the expense of the aesthetic quality of the structure as originally designed.

The Salto del Carnero Bridge is a clear example of the importance of conceptual design. When the conceptual approach is well thought out, the design will undergo only minor changes in subsequent stages. The success of a structural design depends on fluent communication between the structural engineer and the owner or its representatives throughout all the design stages. Both, such communication and close cooperation with the contractor are of crucial importance during construction, to ensure structures are built to design. Changes made during execution stage are usually more a reflection of contractor preference or other circumstantial demands than of actual technical or practical needs. The interaction between design, execution and technical and aesthetic quality of a bridge clearly calls for the designer to take an active role in construction.

References

[1] TANNER, P.; BELLOD, J. L.; and CALVO, J. M. "Roof structure for the new Zaragoza Delicias station. Concept and design", *In: Structures for High-Speed Railway Transportation*, IABSE Report Vol. 87, 2003, ISBN 3-85748-109-9.

[2] RPX-95, "Recommendations for the design of composite bridges", Ministry of public works, Madrid, 1996, (available in Spanish and English), ISBN 84-498-0223-8 (Spanish version).

[3] MUTTONI, A.; SCHWARTZ, J.; THÜRLIMANN, B. "Design of concrete structures with stress fields", Birkhäuser Basel, Boston, Berlin, 1997, ISBN 3-7643-5491-7.

[4] EN 1991-2, "Actions on structures. Part 2: Traffic loads on bridges", European Committee for Standardisation, Brussels, 2003.

SEI Data Block

Owner:
Gestor de Infraestructuras Ferroviarias

Structural engineers:
P. Tanner and J. L. Bellod, Cesma Ingenieros, Madrid;
Oficina Técnica FCC

General contractor:
Joint Venture
Ferrovial Agromán – FCC

Structural steel [t]:	190
In situ concrete (bridge deck) [m^3]:	400
Estimated total cost [EUR millions]:	0,67
Service date:	2003