Vernègues Viaduct – From the architectural design to the construction

Bertrand LENOIR
Co-gérant
SECOA
Nanterre, France

Edgard CLEMENT
Directeur méthodes
DODIN
Toulouse, France

Alain CHAUVIN
Directeur
STRUCTURES
Chatillon, France

Gunter DIEBLER
Ingenieur en chef
INGEROP
Courbevoie, France

Summary

The Vernègues viaduct is one of the main structures on the new "TGV méditerranée" line: it crosses the quiet Cazan valley, near the village of Vernègues.

The special and innovative aspect of the architectural design lies in the pre-stressed concrete deck. It is a multi-boxed girder with semi-cylindrical shaped sections of constant height in the central part of the structure, the height decreasing at each end in order to maintain a visual balance in relation to the distances from the ground.

Three main construction methods were adopted for building the bridge: launching, casting on scaffolding, and balanced cantilevering by means of sections cast in place on removable formworks.

Keywords: High speed railways; pre-stressed concrete; innovative architectural design; construction methods; paraseismic design.

1. Introduction

The Vernègues viaduct carries the "TGV Méditerranée" line across the Cazan valley, near the village of Vernègues between Avignon and Marseilles.

The Cazan valley forms an obstacle to the TGV 1200 m long and 40 m deep. It is mostly open: the flat valley floor is planted with vines and the gently sloping valley sides are covered by scattered shrubs, typical of the Provencal *garrigue*.

This very peaceful site requires a very specific architectural approach, whose aim is to soften the visual and phonic impact of the TGV and to integrate the structure into the environment.

2. The architectural design

The architectural design has been developed by the Amedeo-Padlewski practice, in close consultation with the engineering staff of the SNCF (IGON), the objective throughout being to reach the best compromise between the architectural imperatives and the technical constraints.

For an observer in the valley or on the neighbouring hills, the structure shows the following principal characteristics:

Along the central section, above the flat bottom of the valley, the deck is a half-cylinder 16m in diameter, open towards the top, carrying the permanent way on its upper horizontal surface, and whose lower, rounded part presents very regular, smooth concrete surfaces.

On top of the viaduct, the permanent way is hidden by 3 m high lateral reinforced concrete screens that reduce the acoustic impact of the trains. Their curve and external faces are in perfect continuity with the semi-cylindrical deck.

Thus, out of a total height of 8 m, the lateral screens represent 3 m, while the height of the structural part of the deck represents 5 m.

This deck is built on piers 80m apart, which present the same rounded shape, with no edges or irregularities but of smaller dimensions: the width of the piers corresponds to 75% of the visible height of the deck, i.e. 6m.

The monolithic, simple aspect of the whole structure contributes to the impression that the TGV trains run in a tube.

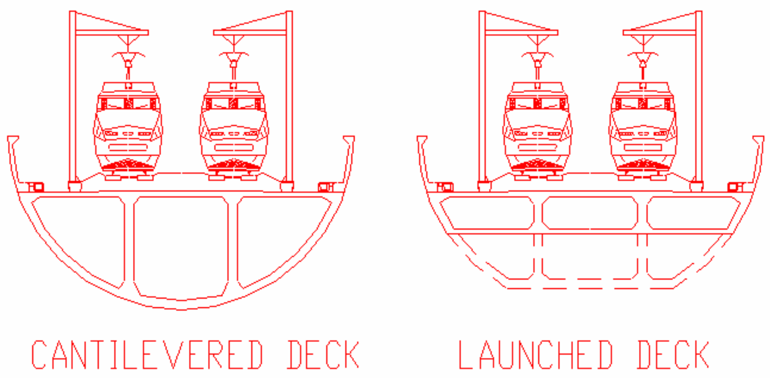

Fig. 1 Typical cross section

Above the sloping hillsides of the valley, i.e. a distance of 315m over the north side and 395m over the south side, the structure's proportions have been arranged to ensure visual harmony in relation to the height of the viaduct above the ground:

The length of the spans reduces gradually from 80m in the central zone to 15m on the north side and 20m on the south side. For the 1208m crossing, 26 spans have been planned, their length varying from 15m to 80m which corresponds to a mean length of 46.5m.

The deck height is progressively reduced in proportion to the spans:

A slightly inclined plane measured up to the longitudinal axis of the viaduct intercepts its lower part and delimits a very attenuated ellipse which constitutes the underside of the deck. The total height of the deck thus decreases by 3.5m, passing from 8m in the central zone across the valley floor, to 4.5m at the abutments, whereas the width of the horizontal underside of intrados varies according to the elliptical form up to 13.23m over the abutments.

The piers also vary: their total width decreases in the same ratio as one approaches the ends of the viaduct. Their transverse dimension, perpendicular to the axis of the TGV, increases in such a way that their lateral vertical faces remain in harmony with the elliptical line of the deck's intrados, but their shafts are divided into two, forming, with the superior cross beam, a frame that supports the deck in a structure that allows the landscape to be seen through the supports.

This artistic shaping of the exterior of the structure, worthy of a sculptor, creates an image that reflects the power of this project and while respecting the gentle aspect of the natural landscape.

The construction of the viaduct required the designers to overcome multiple technical difficulties related to three characteristics of the structure: the **innovative architectural design**, the special features of high-speed **railway bridges** and the need to consider the **seismic risk**.

3. The technical design

3.1. Special features of high speed railway bridges

Railways, with their continuously welded rails, are compatible, by means of expansion devices, with the discontinuities encountered in big structures. However, they require great horizontal rigidity of the supports that are the fixed points of the structure. Moreover, the thermal and rheological effects acting on the deck mean that expansion joints are required. These joints must be arranged in such a way that the expanded length from the middle point of expansion in no way exceeds 450m.

Moreover, the deck requires great vertical rigidity if its dynamic behaviour is to be satisfactory during the passage of high-speed trains.

These specific characteristics have contributed to the development of competing and innovative designs:

By the end of the 1970s, the Paris-Lyon TGV line saw the development of pre-stressed concrete decks made of a two-web box girder (one web under each line), constructed in accordance with the launched bridges technique with spans of about 50m.

The success of such a design can be attributed to an optimal concordance between, on the one hand, the longitudinal and transversal design of the box girder, and, on the other hand, the rigidity required for construction by the launching method and for a satisfactory behaviour under the live load of a high speed train.

By the end of the 1980s, the Paris-Lille/Calais TGV line showed the advantages of decks in double steel girder with concrete upper slabs, placed by launching or by crane over spans of 50m. The success of such a design results from the improved competitiveness of double steel girders with concrete slabs.

The required rigidity of high speed railway bridges constitutes an additional constraint for the designers in the case of a seismic zone, because rigid structures do not behave optimally under earthquake conditions.

The need for paraseismic protection of this structure led to several studies being undertaken and to the use of specific devices such as steel tenons to provide the link between the piers and the deck, and high capacity dampers.

Due to the “plastic hinges” theory, which is generally used for paraseismic design, the reinforcement of the double shafted and framed piers was very difficult to calculate.

3.2. The solutions chosen for the Vernègues viaduct

The unusual architectural design of the structure imposed the choice of concrete as the material but could not be implemented by a classical design such as a two-web box girder of pre-stressed concrete or a double steel girder with concrete slabs.

Fig. 2 Cazan valley transformed into a working site

The analysis of the **transversal behaviour** of the deck showed that it was necessary and rational to have the main beams - the webs - under the running lines and this determined the choice of a pre-stressed concrete box girder for the main longitudinal framework of the deck. Thus, the question was whether the rounded side shells would be able to contribute to the longitudinal resistance of the deck or whether they were to be considered, like the lateral screens next to the rails, as purely decorative elements with a passive function in the structure.

The desire to achieve a structure whose function is coherent with its architecture, led to the choice of a multi-box girder with four webs: two vertical interior webs placed in an optimal position under the running lines and two curved, external webs participating in the resistance of the deck.

The design of the longitudinal structure of the deck is closely linked to the construction process. Construction using the launching method, very well adapted to TGV bridges, is not economically viable for the central part of the structure. This is for two principal reasons: the 80m spans are significantly beyond the normal limits where this process is valid and also the circular shape of the intrados of the deck does not offer the horizontal supporting ledges required for launching. On the other hand, this process is suitable for the end zones of the deck where the intrados is flat between the central webs. The variable length of the spans (15m to 60m) means that full advantage cannot be taken of the process, but it is still well adapted.

For the central part, construction with scaffolding to a height of 40m would have been possible but very costly: the designers preferred the method of construction by balanced cantilever from the piers using removable formwork~~s~~.

The unavoidable presence of an expansion joint, breaking the longitudinal continuity of the deck, made the organisation of the task somewhat complicated. This joint had been logically planned at the meeting point between a section erected by the launching method and a section erected by the incremental balanced cantilever method. However, in order to fit in with the variable length of the spans, it was necessary to place the joint over a pier, which determined a zone 35m long that could be erected neither by the launching method nor by the incremental balanced cantilever method from the piers. This part of the structure was cast on scaffolding.

This analysis leads to the choice of the various types of construction detailed below:

North side: a deck 845m long, whose central piers provide the fixed point for the horizontal movements, was built using three construction processes:

Over a zone 220m long from the north abutment, the deck, whose height and span length vary progressively, was erected by the launching method.

Over the central zone, 590m long, the deck was erected by the incremental balanced cantilever method from the piers and is joined directly to the launched part of the deck described above.

Over a zone 35m long, included between the part erected by the incremental balanced cantilever method and the southern launched part, the deck was cast on scaffolding.

South side: Over a zone 363m long, whose height and span length vary progressively, the deck was launched from the south abutment.

4. The construction of the viaduct

4.1. The foundations and the supports

The north deck is fixed longitudinally over three central piers and set on the other piers by means of sliding bearings on both sides.

The south deck is fixed in the longitudinal direction, by means of six 27T15 cables, over the fixed intermediate pier~~s~~ (P17) directly above the joint between the two decks and set on the other piers by means of sliding bearings.

The piers are extended into the deck by means of steel tenons that offer a cross thrust bearing in case of earthquake.

The geology of the site consists of two limestone outcrops on either side of the valley: between these two outcrops the central part consists of marls covered by recent silts saturated with water.

The slab foundations of the piers and abutments were constructed inside steel sheet pile cofferdams in the central part.

The foundations of the fixed piers are anchored in the rock by means of micro-piles that guarantee their stability in case of earthquake; the pier shafts are very strongly reinforced: 200 high adherence bars of 40mm diameter for each shaft; the continuity between the bars and the reinforcement of the footings is guaranteed by screwed connecting bolts.

4.2. The deck erected by the incremental balanced cantilever method

Over the 8 central piers, which are the highest, the first 8m long voussoir is set on ~~a~~ temporary concrete wedges and is fixed into the upper part of the pier by means of 4 19T15 cables and 4 12T15 cables.

The removable sets of formwork, assembled on the ground on either side of the pier, are pulled up and then joined and anchored over the first voussoir. After concreting the first pair of segments and prestressing the cables, the formwork is moved along on both sides, allowing subsequent symmetrical segments to be constructed at an average rate of 3m per week.

Eleven pairs of segments are constructed for each balanced cantilever before the two deck halves are joined together.

Two sets of formwork~~s~~ are used to construct the 8 balanced cantilevers.

The semi cylindrical cross-sectional form of the deck requires particular precautions to be taken; indeed, the shuttering was made monolithic in order to ensure absolute regularity of the concrete surfaces, thus, any vertical or horizontal movement at any point causes a systematic movement of the other parts of the shuttering. The need to rigorously respect the geometry led to the use of a combination of cambers and adjustments.

4.3. The launched deck at the south end

The structure being launched over its elliptical lower face (which is slightly curved in elevation in order to conform to the general longitudinal profile of the high-speed line), the trackbed itself is used to form the pre-production area.

The spans being of variable length from 20m to 60m, concreting sections 15m long were adopted for the construction.

The deck is equipped with a steel nose 40m long and weighing 1000 KN. Its dimensions were chosen to enable the last span of 60m to be crossed and it is thus over-dimensioned for all the remaining spans.

The pre-production area, 32m long, is set out 100m behind the abutment.

The structure slides over reinforced concrete ground sills, constructed between this area and the abutment.

This allows the whole of the first span to be constructed and the prestressing to be applied before it functions as a cantilever.

The launching operations, executed by means of high power pushing jacks acting on the back of the deck and resting on reinforced concrete blocks anchored to the bed rock, follow the concreting operations of the sections in lengths of 15m.

In the pre-production area, the plywood formwork of the structure slides on a steel sheet greased for this purpose.

On the ground sills and on each successive pier, the structure slides on elastomer pads covered in PTFE over stainless steel sheets.

Since the friction coefficients are less then 2% and the slope is greater than 3% for the first launchings, the structure slips very quickly just after leaving its pre-production area. A braking device was therefore set up using retaining bars anchored to the supports of the pushing jacks.

The entire weight (130 MN of concrete) of this viaduct has been anchored to the tenon of the transition pier by 6 27T15 cables. Between two launchings, the deck is held on the abutment by two high-capacity jacks which produce an adequate vertical force. However, these devices did not totally eliminate a regular creeping of several centimetres per week, due to daily thermal variations.

The continuously variable cross-sectional geometry is shuttered using a system that can be adapted to any shape.

The bottom of each section has a trapezoidal shape; each larger base of the preceding section being the smaller of the succeeding one. Thus, the bottom of the formwork moves out from the axis of the structure as construction goes on.

The top slab, of constant width, comes closer to the ground as the cross-sectional height varies from 4.5m at the beginning to 1.5m at the abutment.

Fig. 3 Formworks on preproduction area

The lateral formwork, used over a total width of 6m at the beginning, while being strongly inclined, moves progressively towards the vertical in order to maintain a constant angle with the upper slab. The inner formwork undergoes the same variation.

To the geometrical variation of the cross sections must be added the continuous variation of the whole structure. Indeed, because of the disparity in the length of the spans, the struts are never in the same position for any two sections, thus requiring the modification of the entire interior structure of the formwork for each section.

4.4. The launched deck at the north end

The geometrical variation of the north part of the structure is the same – in principle – as that described for the southern part, however, it does not have the same parameters.

The spans are shorter and vary between 15 and 40 m. The same type of nose is, however, used.

The launching area has an upward slope of 0.5%.

The successive launchings are achieved in cycles of 15m using two 1500 KN jacks, equipped with manometers; those jacks rest against a toothed rack anchored into the foundation, thus allowing progression by steps of 25 cm at a rate of 7 m/h.

The toothed rack positioned at the back of the pre-production area becomes inadequate at the end of each launch operation, so the launch is ended by using prestressing cables anchored to the abutment. Those cables are “swallowed” by two jacks positioned behind the deck.

After docking onto the last pier and having the nose removed, the launched deck is joined to and made continuous with the last cantilever of the deck built by the balanced cantilever method.

5. Conclusion

The design of this exceptional structure meets the architectural challenge of reconciling the power of the TGV with the respect for a peaceful environment.

The success of the project results from a close and constructive collaboration between architects and engineers right from the initial concept phase.

A great deal of ingenuity has been necessary, not only to choose the method best adapted to each situation – launching, cantilevering, casting – but also to devise new pieces of equipment such as moveable, monolithic formwork systems, continuously variable formwork systems to allow the construction of a variable-height deck on flat launching areas and the systems for launching and restraining the enormous masses of pre-stressed concrete.

There is every reason to believe that the concept of trains passing over an environmentally sensitive valley in a "tube" will be used in other situations. It is our hope that the difficulties overcome and the innovations created for this project – particularly the fact of including the paraseismic design right from the start of the preliminary studies – will be recognised and adopted by others, in order to achieve that crucial harmony between the rational organisation of a structure and a pleasing architectural design.

The bridge was built by a joint-venture set up by DODIN and SOGEA. The construction design was undertaken by a joint-venture company from three engineering firms: SECOA as main contractor and deck designer, INGEROP for the supports and STRUCTURES for the paraseismic calculations.