The Sant Boi high-speed railroad bridge was designed in two segments, one that crosses a five-lane highway and a railway line and another that crosses a river. The 340 m long section that crosses the highway and railroad is a continuous composite structure with six spans, while the 530 m long section that passes over the Llobregat River is a continuous prestressed-concrete bridge with a maximum span of 50 m.
April 2008Civil Engineering

The designs of two recently completed high-speed rail bridges in Spain achieve cost-effective, aesthetically pleasing solutions through the optimal use of materials—including steel—and slender decks. By Juan A. Sobrino, D.Eng., M.ASCE

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town of Sant Boi de Llobregat. Although both structures were completed last year, the Llinars bridge is not yet in service because its associated rail line is not finished. The Sant Boi bridge, however, began operation this March.

Because they must support significant loads and meet strict technical criteria, the two HSR bridges employ structural elements that are much stiffer than what is normally required for automobile bridges. To achieve cost-effective solutions, the bridge designs relied on the optimal use of materials and the careful design of structural systems.

The owner of the bridges—the Administración de Infraestructuras Ferroviarias (ADIF), a public agency created to manage Spain’s railway infrastructure—retained the consulting engineering firm PEDELTA, S.L., of Barcelona, in 2002 and 2003 to design respectively the Sant Boi and Llinars bridges. The ADIF required that the designs conform to two codes developed by the public works ministry expressly for rail structures. Each bridge’s structural elements had to be designed in accordance with Spanish codes for concrete structures or recommendations by the public works ministry concerning the design of road bridges made of composite materials and steel.

The design of HSR bridges must account for certain factors not applicable to typical road bridges. For example, internal forces associated with railway traffic are 2 to 2.5 times greater than those induced by loads associated with roadway traffic. What is more, the dead load from the two ballasted tracks, including all bridge finishes, is approximately 120 kN/m. The design also must account for the fact that as much as 30 percent more ballast may be added during the life of the bridge. The table below gives typical values for loads associated with standard road and railway bridges having a mean span of 40 m and a width of 14 m.

In contrast to road bridges, railway traffic generates significantly larger horizontal loads, including loads associated with braking and traction forces, wind, centrifugal forces, and the interaction between track and structure. For example, a standard 300 m long HSR viaduct has a maximum braking and traction force of 7,000 kN. By contrast, a similar road bridge has an equivalent force of 850 kN. Loads induced by centrifugal forces in railway bridges can be 300 to 1,500 percent greater than those caused by the same force in road bridges.

In addition to accounting for the heavy loads, the designers of the HSR bridges had to ensure traffic safety and passenger comfort by doing the following:

- Verifying vibrations and limiting the deck’s maximum peak vertical acceleration induced by real trains;
- Verifying deck torsion and vertical deformations;
- Verifying the maximum vertical deflection, depending on the train speed and span length;
- Verifying the track, limiting stress to the rails from the combined response of the structure and track to variable actions, and limiting the longitudinal displacements induced by traction and braking.

The Llinars and Sant Boi bridges were designed to fulfill similar requirements stipulated by the ADIF. Furthermore, the bridges cross existing facets of infrastructure, including busy motorways, but road traffic could not be interrupted during the construction or operation of the bridges. Because the vertical clearance of both bridges with respect to the road below is no more than 5.5 m, the structural elements beneath the tracks had to be kept to a minimum. By reducing track elevations and embankment heights and limiting excavations along the rest of the rail line, these requirements helped to minimize the project’s untoward effects on the surrounding areas.

What is more, since the bridges are located at highly visible sites, they had to be carefully designed with aesthetics in mind so that they would fit in well with their surroundings and stand as symbols of creativity and innovation on the part of the ADIF.

To ensure compliance with the owner’s specifications, the design team analyzed a wide variety of alternatives for both bridges, including structures made of concrete, of steel, and of both materials, as well as such structural forms as box girders, I girders, and arches. Ultimately, the final design entailed a composite steel and concrete deck—with a maximum depth of 2.15 m below the track level and 1.45 m below the ballast—suspended from tied curved steel members. The main structure is above the deck level and consists of two planes of curved steel suspension members supported from vertical steel pylons.

In keeping with the owner’s requirements, the structures were designed to comply with the public works ministry’s codes pertaining to railway bridges and composite road bridges made of steel and concrete. And, as is required for all Spanish HSR bridges, the structures were designed in accordance with the European Commission’s EN 1991-2 (Eurocode 1: Actions on Structures—Part 2: Traffic Loads on Bridges) and EN 1990 (Eurocode: Basis of Structural Design). Although vertical train loads specified by the Eurocode are somewhat smaller than those specified by the Spanish code, loads for the dynamic analysis are clearly defined, as are track-deck

### Comparison of Standard Road and Railway Bridges

<table>
<thead>
<tr>
<th>Load (kN/m)</th>
<th>Road bridge</th>
<th>Railway bridge</th>
<th>Railway/road</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1—Self-weight</td>
<td>175</td>
<td>280</td>
<td>160%</td>
</tr>
<tr>
<td>D2—Dead load</td>
<td>45</td>
<td>180</td>
<td>400%</td>
</tr>
<tr>
<td>Q—Equivalent uniform live load</td>
<td>60</td>
<td>200</td>
<td>333%</td>
</tr>
<tr>
<td>Total D+Q</td>
<td>280</td>
<td>660</td>
<td>235%</td>
</tr>
</tbody>
</table>
interactions and other railway actions. *Eurocode 1* also clearly defines some serviceability limit states crucial to the design of HSR bridges, for example, accelerations, maximum vertical displacements from traffic loads, and maximum displacements and rotations at abutments.

In general, the serviceability limit states, particularly the control of deformations, govern the design of the steel elements. Because the bridges were constructed by means of incremental launching, the two vertical webs and the bottom flange of the longitudinal beams that support the deck were designed to resist loads that would occur during installation. The design of the connections between longitudinal and transverse beams was governed by the evaluation of the fatigue limit state.

The grade of steel used in both bridges is S355-J2G3, which according to *Eurocode 1* has a yield strength of 355 MPa. Depending on plate thickness or location, the steel had different classes of quality control or limitations on surface defects. For joints or plates that receive welded transverse plates, approximately 80 percent of the welds were examined by such means as ultrasonic or X-ray testing during the quality control process. The decks of both bridges were made of grade C-30 concrete, which has a compressive strength of 30 MPa when tested at 28 days using cylinder specimens.

Although with respect to geometry the two bridges somewhat resemble suspension bridges, they behave mostly as a continuous beam with variable depth. Different numerical models were developed for the design of both bridges. For example, a general linear elastic model combined the beam and shell elements of the concrete decks. To account for different loads or cracking in some areas, the stiffness of the shell elements was reduced to an effective value.

A general model was developed to evaluate the effects associated with launching the bridges during construction and to assess their dynamic behavior under real trains at different speeds. This model is an elastic model with beam elements. A complete dynamic analysis according to *Eurocode 1* was carried out to confirm each bridge’s behavior. Furthermore, models employing local finite-element methods were used to analyze the distribution of stresses in structural nodes or in areas that are strongly stiffened. The analysis was made using elastic shell members, and in some cases geometric imperfections were considered.

Following the specifications of *Eurocode 1*, the exhaustive dynamic analysis confirmed that the bridge designs provide excellent dynamic behavior, the maximum accelerations being lower than the admissible limit of 3.5 m/s² for ballasted tracks, even for speeds close to 400 km/h. The first flexural frequency

The 574 m long Llinars bridge comprises two parts: a 307 m long composite steel and concrete structure, above, which crosses a highway, and a continuous structure made of prestressed concrete that crosses a river. Each of the four segments of the highway crossing measured approximately 75 m in length, weighed roughly 700 metric tons, and took five weeks to assemble. Each segment was then pushed forward by a mobile unit that was connected to the underside of the structure.
is 1.28 Hz for the Llinars bridge and 1.33 Hz for the Sant Boi crossing, including all permanent loads.

The 574 m long Llinars bridge comprises two parts: a 307 m long composite steel and concrete structure crossing tollway 7 and a continuous structure made of prestressed concrete crossing the Mogent River with a maximum span of 48 m. The location of the piers was dictated by the highly skewed angle of the highway crossing and by the launching process used to erect the bridge. The final bridge features a composite steel and concrete deck suspended on structural steel tied members. An effort was made to develop an aesthetically pleasing solution that would be transparent and well suited to the site. To avoid interfering with the operation of Barcelona's critically important tollway 7, incremental launching construction methods were used for the composite steel and concrete section.

This section includes a deck that is a continuous structure with five spans measuring 45, 71, 75, 71, and 45 m. The 17.2 m wide bridge accommodates two ballasted tracks on its 14 m wide platform. The composite concrete and steel deck consists of parallel transverse I beams that are 1 m deep and spaced 3.55 m apart. The transverse beams are connected to the 1.6 m wide longitudinal box girders, which vary in depth from 3.5 to 6 m. The webs are longitudinally stiffened with two I beams either 150 or 250 mm tall and further stiffened with transverse stiffeners—typically T beams 300 mm in depth—spaced every 3.5 m or with diaphragms spaced every 7 m. In such areas as the center of the spans or below the pylons, the space between the transverse stiffeners is reduced to 1.75 m. These longitudinal beams are suspended from curved tied steel box members supported from 14.5 m high steel pylons. All the elements are made up of welded stiffened plates.

Because the piers can be located only at the highway shoulders and at the median strip, some are not beneath the deck. In fact, four piers are separated from the outer part of the deck by as much as 4 m. To address this situation, a transverse cantilever beam was designed so that the two pylons in the same vertical plane perpendicular to the deck axis would connect the longitudinal beam to the pier.

The suspension members have a typical box girder cross section with an average depth of 1.7 m. The flange width, 1.6 m, does not vary along the girder. For aesthetic reasons, the members have a radius of curvature of 48.6 m, limiting the large structure's vertical clearance over the highway and diminishing its visual obtrusiveness.

Pylons rising 14.5 m above the longitudinal beam’s top chord are subjected to significant internal forces, particularly the pylons that are supported by transverse cantilever beams. Each pylon’s cross section is a box girder with a depth varying from 2.1 to 2.7 m stiffened with standard I beams either 200 or 300 mm tall. The total weight of the structure’s steel components—not including the reinforcing steel used in the concrete elements—is 2,800 metric tons, which represents an average of 615 kg/m² along the 14 m wide platform.

The coating technique used to protect the steel members relied on a standard three-layer system for the exterior surfaces. After the steel was blast cleaned to a grade of Sa2.5 in accordance with RPI-95, the Spanish steel bridge code, or with the International Organization for Standardization’s standard 8501, a shop primer epoxy-polyamide pigmented with zinc phosphate was applied as a first layer to a depth of 25 μm, followed by an intermediate layer of epoxy-polyamide with a depth of 170 μm. A final layer of acrylic polyurethane was applied to a depth of 30 μm. For interior surfaces of the longitudinal girders, suspension members, and pylons, the coating system consisted of two layers—the shop primer plus an epoxy layer that has a depth of 200 μm. Because access to the pylons and suspension members for painting and inspection would have been difficult, they were completely sealed.
Construction of the Llinars bridge began in 2003. It was assembled in four segments, each approximately 75 m long and weighing roughly 700 metric tons. Each segment required roughly five weeks to assemble. After being assembled, the segment would be pushed forward by a mobile unit that was connected to the underside of the structure. Guided by a track, the unit employed jacks to generate the horizontal force needed to move the assembled segment forward, thereby permitting the assembly of the succeeding segment.

To reduce the internal forces associated with the construction process, a 30 m long launching nose was used. While at the assembly yard, the completed segments were mounted using temporary supports spaced approximately 10 m apart. After all the units that constituted a segment were welded together, the temporary supports were removed and the segment was supported by eight movable units having a maximum vertical capacity of 10,000 kN. Guided by a track anchored to the ground, the units were fixed to the structure’s upper part, but they slid on Teflon pads when the horizontal hydraulic jack, which had a capacity of approximately 60 metric tons, was applied. Above the piers, the bridge slid directly over a temporary launching bearing that was fixed to the pier. To ensure the proper distribution of the reaction on the box girder webs, launching bearings could rotate in all directions from a vertical axis.

Because some of the piers are not located directly beneath the longitudinal girders, temporary steel piers were erected to support the steel structure during launching. The maximum vertical displacement of the nose during launching was 360 mm. This displacement governed the bridge’s elevation during construction.

The 870 m long Sant Boi hsr bridge is similar to the Llinars bridge, although it is distinguished by a different geometry. At 340 m long, the bridge’s first section is a continuous composite structure with six spans measuring 44, 63, 63, 63, 63, and 44 m that crosses a five-lane highway and a railway line. The 530 m long second section, which passes over the Llobregat River, takes the form of a continuous prestressed-concrete bridge with a maximum span of 50 m. This second section was cast in place by using a traveling formwork apparatus.

The 17 m wide bridge accommodates two ballasted tracks on a 14 m wide platform. The composite concrete and steel deck consists of 1 m deep parallel transverse I beams spaced 3 m apart. The deck’s structural system is similar to that of the Llinars bridge. Longitudinal beams are suspended from curved tied steel box members supported from 11.5 m tall steel pylons.

The transverse beams are connected to the 1.4 m wide longitudinal box girders, which vary in depth from 3.5 to 5.5 m. The webs, which vary in thickness from 15 to 20 mm, are longitudinally stiffened with two or three 250 mm long steel I beams. The webs are stiffened transversely with welded plates to create a 200 mm high T-shaped cross section every 3.1 m or with diaphragms spaced every 6.2 m.
The cross section of the pylons is a box girder with a constant geometry of 2.4 by 1.5 m. The girder’s 25 mm thick plates are stiffened with 200 mm tall I beams of standard profile. The suspension members have a typical box girder cross section with a depth that varies smoothly between 1.2 and 1.8 m and a constant flange width of 1.4 m. For aesthetic reasons, the members were curved, the radius of curvature being 46.7 m. The final weight of the steel used in the bridge is approximately 2,637 metric tons, which amounts to 554 kg/m² along the 14 m wide platform. The coating system for the steel protection is similar to the one used for the Llinars bridge. A combination of green and gray was selected to emphasize the bridge’s slenderness.

The bridge’s sixth pier serves as a fixed support between the two sections of the structure. The pier is designed to accommodate a significant horizontal load with a magnitude of about 25,000 kN associated with braking, friction, traction from the trains, and the interaction between track and deck. According to the Eurocode, horizontal displacements at the deck level may not exceed 30 mm. This serviceability criterion governs the design of the pier, which is a reinforced-concrete structure founded on nine piles that are 2 m in diameter. The resulting structural configuration creates a very stiff element.

The superstructure is supported on concrete piers and abutments, and the substructure is founded on piles with a diameter of 2 m. Special attention was given to the aesthetic appearance of the piers. The tops of the reinforced-concrete piers employ curved surfaces and a large “window” to create a slender, transparent effect.

Construction of the bridge’s steel section began in January 2006 and concluded that May. The steel members were fabricated by different steel yards in Sevilla, Madrid, and Barcelona under the coordination of Talleres Torrejón, part of the conglomerate Acciona Infraestructuras, which is headquartered in Madrid. The bridge’s steel units were transported in lengths of approximately 15 to 20 m and assembled on-site on a platform behind the south abutment.

The bridge was assembled in three segments having lengths of approximately 125, 126, and 89 m. Each segment required roughly 12 weeks for assembly. Once assembled, a segment was pushed forward so that the next could be assembled. To reduce the internal forces associated with the construction process, a 25 m long launching nose was used.

The segments at the assembly yard were mounted using temporary steel supports spaced approximately 11 m apart. After all of the units that constitute a segment were welded together, half of the temporary piers were removed, and the segment was supported by the remaining temporary supports. To reduce friction during the launching, the steel structure slid on Teflon pads. Two vertical hydraulic jacks in each support ensured a uniform distribution of vertical loads in the two webs. These units also included a lateral guidance system that coincided with a longitudinal stiffener.

The steel structure was pulled from the abutment using two horizontal hydraulic jacks and high-strength steel bars connected to the bottom flange of the longitudinal beams. Above the piers, the structure was then slid directly over a temporary sliding unit supported on pot bearings, which
allowed rotation. The maximum movement of the launching nose during the launching was 270 mm.

Bridge construction represents a considerable portion of the overall total budget for an HSR network. Because of the magnitude of the vertical and horizontal loads, the design of these bridges required a judicious selection of structural configurations and erection procedures.

Steel and composite steel and concrete solutions may be competitive when compared with traditional decks made of prestressed concrete. Moreover, steel confers outstanding mechanical properties, facilitating the use of innovative forms and light, prefabricated elements that offer significant advantages during the erection process. In the projects outlined here, the selection of a composite deck suspended from curved steel members made it possible to design elegant bridges with strong personalities and to use an incrementally launched erection method that avoided interference with facets of operating infrastructure beneath the bridges.

Juan Sobrino, D.Eng., M.ASCE, is the president of PEDELTA, Inc., of Coral Gables, Florida. This article is based on the paper “Two Steel Bridges for the High Speed Railway Line Madrid–Barcelona–French Border,” presented by the author at the 2007 International Bridge Conference, which was sponsored by the Engineers’ Society of Western Pennsylvania and held last June in Pittsburgh.

**Project Credits**

**Llinars Bridge:**
Owner: Administración de Infraestructuras Ferroviarias
Conceptual and structural design: PEDELTA, S.L., Barcelona, Spain
Owner’s representative on site: SERCAT, Madrid, Spain
Contractor: Constructora Hispánica, Madrid, Spain
Steel erection: URSA Sociedad Cooperativa, Vitoria-Gasteiz, Spain
Bridge launching: ALE-Lastra, S.A., Madrid, Spain

**Sant Boi Bridge:**
Owner: Administración de Infraestructuras Ferroviarias
Project design and site supervision: GPO-PEDELTA, a joint venture of GPO Ingeniería, S.A., Barcelona, Spain, and PEDELTA, S.L., Barcelona, Spain
Conceptual and structural design: PEDELTA, S.L., Barcelona, Spain
Site supervision: GPO-PEDELTA
Contractor: Acciona Infraestructuras, Madrid, Spain
Steel fabrication: Talleres Torrejón, a division of Acciona Infraestructuras, Madrid, Spain

The section of the Sant Boi bridge that crosses the highway and railroad was assembled in three segments, each requiring 12 weeks, near a recently completed rail line. Once assembled, each segment was pushed forward so that work could begin on the next segment.