STEEL AND COMPOSITE BRIDGES FOR HIGH SPEED RAIL: ADVANCED SOLUTIONS FOR CHALLENGING DESIGNS

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BIOGRAPHY

Prof. Dr. Javier Manterola is a Spanish civil engineer and emeritus professor at the ETSICCP Madrid (Madrid Civil and Structural Engineering University). For more than 40 years, he has developed a prolific career mainly in the engineering firm Carlos Fernández Casado (CFCSL), devoted to the design and construction of many types of singular structures, but specially focused on bridges. In 1964 he cofounded CFCSL Company, where he has been the lead designer of some world record works like the Barrios de Luna cable stayed bridge (1984) or the Alcantara Arch Bridge (2012). His prestigious activity has been recognized with several distinctions, as the Gold Medal of the Féderation International de la Précontrainte (FIP-1996) or the International Award of Merit of the International Association for Bridge and Structural Engineers (IABSE-2006).

Manuel Escamilla is a Senior Bridge and Structural Engineer, who obtained his Civil Engineering Master Degree in the University of Granada (Spain). Since 2001 he has been working in the design and construction of singular bridges. In 2007, he joined CFCSL to lead the construction of the New Cadiz Bay Bridge, and in 2011 he started collaborating with CALTROP Corporation and CALTROP-CFC in the Forth Replacement Project (Scotland) and the Gerald Desmond Bridge Replacement Project. He has professional memberships in many associations, such as the Working Commission 2 “Steel, Timber and Composite Structures” of IABSE, the Spanish Mirror Group of the Horizontal Group-Bridges, depending on AEN/CTN Committee 140 “Structural Eurocodes”, or the Working Commission 3 “Execution” of ACHE (Scientific and Technical Association for Structural Concrete).

SUMMARY

From the perspective given by 20 years of experience with HSR bridges, including some current records, CALTROP and CFCSL wish to present with this paper the latest evolutions in the design and construction of the steel elements used within this typology of structures: latest structural layouts, use of special materials, new constructive procedures, special execution requirements and future foreseen development of standards and codes. Additionally, a review on the Quality Control and Quality Assurance aspects governing the execution of the steel members of this kind of bridges will also be presented, given that the robustness of these structures strongly relies in the quality of construction, due to the importance of fatigue phenomena and the dynamic actions to be faced. As practical examples, some representative case-studies will be described.

We intend to show our contribution to a topic of international relevance, which we think can attract the attention of design professionals and construction engineers.

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Introduction: Worldwide Development of HSR

High Speed Rail networks have been developed in many countries as a modern, sustainable, efficient, punctual, functional and comfortable mean of transportation. Since 1964, when Japan unveiled the Tokyo-Osaka HSR, more than 12,000 miles of HS railway have been constructed and are nowadays in service. The stringent requirements for the design, construction and operation of this kind of railway lines (with gentle slopes and low curvatures) have theireffect on the multiple structures needed to be constructed to materialize the railway. Specific technology, standards and codes have been developed worldwide in order to determine the special criteria to be taken into account when designing structures for HSR: rail-deck interaction, dynamic impact of live loads, fatigue-resistance design, aerodynamic effect of HS trains, derailment, collisions, etc.

Fig. 1: Current European HSR.

Europe is decidedly supporting and financing not only national HSR, but also international HSR links between its more relevant countries since 1994, when the first Eurostar HS trains linked London, Paris and Brussels (Belgium). Spain, France and Germany have extensive and consolidated HSR networks, which implementation has been possible thanks to the development of new train, electric, communication, traffic-control and structural technologies. The Spanish HSR development is particularly remarkable, since it has been done in only 2 decades (since 1992), becoming the largest in the World in 2010. Nowadays China has taken the lead, with a huge investment plan to link its main western urban areas by 2020.

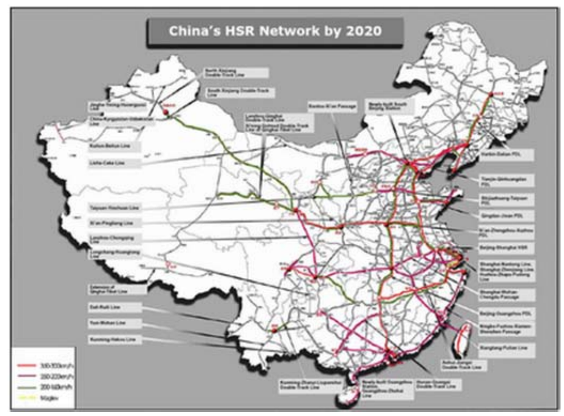

Fig. 2: Planned China's HSR Network by 2020.

Surprisingly, this exceptional development of the so called lead mean of modern mass transportation has not made impact in North America so far. Differential aspects as the strong reliance on more traditional transportation networks, less petrol-dependent economies and longer average travel distances can in some way explain this fact, but it seems something is changing, and the first comprehensive plans to design, build and operate HSR in North America are now being developed. In 2009, President Obama made a statement unveiling his vision for HSR in USA and in some States like California, the implementation of a HS network is currently under way.

Fig. 3: USA HSR Map unveiled by President Obama.

The Challenging Design of HSR Bridges

The design and calculus of HSR bridges presents many particularities when compared with the designs of highway or conventional railway bridges: as in the latters, the relative weight of the live loads, related to dead loads, is considerable higher than the traffic loads of a highway bridge, but furthermore the high velocity of these live loads reflects on the emergence of larger longitudinal actions due to braking, stringent provisions regarding travelers' comfort and very significant dynamics effects.

The dynamic effects of moving loads were originally analyzed by several eminent scientists like Stokes (1), Willis (2), Inglis (3) and Timoshenko (4), later followed (from the nineteen fifties onwards) by research commissions of the International Union of Railways (UIC) or the European Rail Research Institute (ERRI). Since the deflections caused by a dynamic load in simply supported bridges were identified to be larger than the ones corresponding to the same load acting statically (see figure 4), the first approach to this phenomenon was to use an impact coefficient that multiplies the static deformations and forces (which, in normal conditions, remain proportional to each other) in order to cover the dynamics effects.

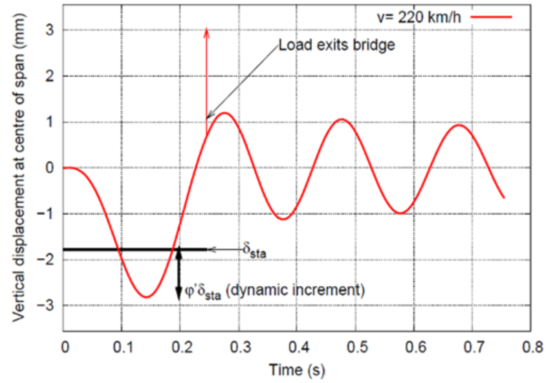

Fig. 4: Midspan vertical deflections due to a moving load on a simply supported bridge, compared with the static deformation (δsta). Note that the deck continues moving after the load has gone out.

But the simple consideration of a proportional increment of the corresponding static behavior by an impact coefficient does not give answer to the whole phenomenon. Indeed, a high speed train convoy can dynamically excite the deformations of the bridge deck, with the result of a resonant growth of the deflections. The susceptibility of appearance of resonance in a determined bridge deck depends thus not only on the value of the train loads, but also on their spatial distribution, the train speed, the rigidity of the convoy, the irregularities of the rail and the natural modal frequencies of the deck itself (determined by it mass, stiffness, span length and support conditions).

Therefore, nowadays complex modelling not only of the bridge, but also of the train convoys is used in order to properly analyze their dynamic interaction (see figure 5)

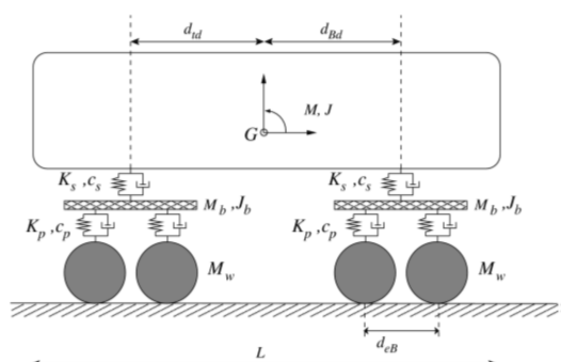

Fig. 5: Complete model of a train wagon used for dynamic analysis. Mass spatial

distribution, bogies rigidity and damping capacities are to be taken into account.

Finally, the design of HSR bridges has also to deal with safety, operational and users' comfort aspects, reflected in stringent limitations not only on the values of deformations, but also in the acceleration with which the deck deflects or in the maximum allowable horizontal displacements (not to overstress the rail and compatible with the capacity of rail expansion joints). The influence of all the aforementioned aspects reflects on the bridge layout and on in its detailed design, leading to the development of new bridge typologies.

Bridge Dynamics: Parametric Analysis

When dealing with bridge dynamics, it is very important to know not only the parameters to be taken into account, but also their relative weight into the dynamic behavior of the system and the way in which they can be tuned to obtain an optimal design (feasible, reliable, economic, effective). It is necessary to point out that since the dynamic behavior of the bridge depends on the characteristics of the train convoys, design needs to consider a wide range of actual and fictitious train configurations, in order to make sure the structure is able to deal with any possible load arrangement during its lifespan. To illustrate this, the influence of the span length in the dynamic behavior of the bridge for a particular HS train is represented on figure 6.

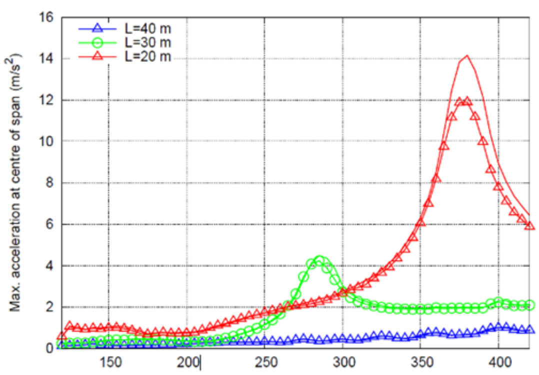

Fig. 6: Midspan vertical accelerations due to a given moving load train configuration on a simply supported bridge, for different span lengths and different train speeds. Note that maximum admissible values are usually between 2 and 4 m/s^2. From Goicolea (5).

The influence of the mass of the bridge is also very significant. For a given structural configuration, increasing the mass of the bridge elicits a reduction of the critical resonant speed (which is adverse) but also of the maximum vertical acceleration (which is positive). Incrementing bridge stiffness (while ideally maintaining all other parameters unchanged) raises the critical resonance speed, but does not have effect on the maximum vertical accelerations nor on the maximum deflections. Finally, a simultaneous increment on the mass and the stiffness of the bridge will produce a reduction of the maximum deflections and accelerations, without affecting the critical resonant speed.

Concrete vs. Steel in HSR Bridges

It has been only recently that all know-how corpus and the calculus resources to obtain representative and reliable data to explain HSR bridge dynamics on a reasonable time-consuming process have been developed. This can justify the traditional prevalence of continuous post-tensioned box-section concrete deck bridges as solutions for conventional HSR bridges, given their optimal combination of stiffness and mass, together with the relatively industrialized construction procedures for short and medium spans and the well-developed engineering knowledge. Post-tensioned concrete solutions even began to be used in HSR bridge typologies long-established as exclusive for steel application, such as continuous lattice beams with the railway inside the deck cross section. That is the case of the Ebro HSR Bridge in Spain (see figure 7).

Fig. 7: River Ebro HSR Bridge, designed by CFCSL (2000). The deck is configured as a Vieerendel continuous bridge, built up completely with post-tensioned concrete.

Early noteworthy attempts to use steel in HSR bridges lacked structural intelligibility due to the incomplete development of the necessary technology. The natural inclination to use traditional bridge typologies did not give correct solutions to HSR requirements, or at least not as it did with concrete alternatives. The complexity of the dynamic phenomena affected also to the robustness of steel joints, due to the origination of cyclic loading that derived into fatigue damages.

Fig. 8: Garde Adhemar HSR Viaduct in France, designed by Marc Mimram. One of the earliest singular designs using steel for HSR bridges (1995-1999). Note the unusual link connecting the two bowstring arches, necessary to withstand dynamic loading.

But the evolution of HSR bridges has to face increasingly demanding challenges, where composite steel-concrete solutions have proven to be optimal answers. Indeed, there are a lot of situations in which reducing the mass of the bridge becomes mandatory: High-piles viaducts, where normal lifting equipment is overpassed, incrementally launched decks, bridges in areas with low geotechnical capacity and HSR in seismic areas are good examples. In these cases, the conjunction of the lightness of the steel with the robustness of concrete in composite designs can reduce up to 2 or 2.5 times the total weight of the deck compared with alternative concrete designs, proportioning at the same time the necessary stiffness.

The path to achieve composite designs complying with the stringent technical requirements for HSR bridges has resulted in a re-invention of traditional designs, expanding the composite action of connected steel-concrete sections to face not only positive bending moments, but also negative ones and even torsional forces (see (6)), while at the same time adhering the limitations of accelerations and horizontal displacements, even for large continuous viaducts (up to 3.15 km – approximately 2 miles), see figure 9.

Fig. 9: Archidona Viaduct, designed by IDEAM (2011). 2-mile long composite weathering steel and concrete continuous deck bridge without intermediate expansion joints, designed to extend the composite action to give torsional stiffness to the cross-section in a seismic area (HSR Cordoba-Granada, Spain. See (6)).

For all the aforementioned reasons, the re-invention of composite steel-concrete bridge designs is enabling them to gain access into the HSR bridge arena, demonstrating their competitiveness and reliability.

In order to give an accurate idea of the adaptation of the main structural characteristics of composite bridges to the requirements of HSR lines, a description of the design process of a real composite bridge will be described. A significantly skewed crossing above an existing and operating HSR was needed for a new HSR, conducting to an 86 m-282 ft. long main span, combined with stringent requirements affecting the vertical clearance above the existing railway. Conventional concrete box sections were not able to cover the above mentioned restrictions, so a bow-string arch was early selected as the proper typology by the Design team (A. C. L. Structures – University of Granada, see (7) for further details). The longitudinal tension stresses the arch transmits to the lower deck lead to steel as the adequate material for main longitudinal beams. Placing the railway between two symmetrical arches, the loads have to be transferred to these main structural elements by means of transversal beams linked to the longitudinal ones. Composite steel-concrete beams were selected for the transversal beams, whereas the construction boundary conditions, requiring no affection to the existing HSR, tipped the balance in favor of also using steel for the arches, given the substantial subsequent reduction of weight that made feasible the completion of the steel part of the bowstring out of the operation area of the existing HSR, and its collocation in place in only a few hours by lateral skidding.

The design process began by pre-dimensioning the main structural members, based on a static analysis of a frame model (see figure 10) affected by impact coefficients to broadly take into account dynamic effects. Once this static dimensioning was complete, dynamics began to be analyzed and the outputs obtained substantively transformed the initial design -a classical conception of a bow-string arch with vertical hangers- into an adapted evolution of this well-known typology to the HSR requirements, as will be shown. Early dynamic approaches indicated that it was necessary to increase vertical rigidity of the arches in order to restrain the acceleration due to live loading to the admissible value of 3.5 m/s^2. In this sense, the first measure adopted was to confer continuity to the deck along the lateral spans (avoiding expansion joints in the arch ends).

Fig. 10: 3D Frame-member structural model used for static pre-dimensioning.

Once a detailed finite element model was developed, large vertical accelerations were found (up to 3 times the maximum admissible values) and further measures were needed. The adopted strategy consisted of pursuing a decrease of the vertical deflections and accelerations by means of a simultaneous increment in the mass and stiffness of the bridge, together with a more detailed modelling of the structure, to take into account shear-lag effects and the real allocation of masses, aspects that were found to be of key relevance to properly represent the dynamic behavior. The main decisions adopted were the following:

- Proportionate variable depth to the main longitudinal and transversal beams (maximum at midspan, minimum at both ends).
- Provide a rigid connection between transversal steel beams and the upper concrete slab by using stud connectors.
- Increase steel plate and concrete slab thicknesses.
- Raise the number of vertical cable hangers.

Once these modifications were implemented, a new dynamic analysis showed a significant but not sufficient reduction of vertical accelerations, which continued surpassing admissible values by a ratio of 1.6. A comprehensive study of the contribution of each mode of vibration to the vertical accelerations indicated that the global main asymmetric mode was critical, so reducing its influence became the main goal.

Finally, the substitution of traditional vertical hangers by tubular diagonal members (see figure 11) enabled the virtual cancellation of the contribution of the asymmetrical mode, and the accelerations became finally admissible.

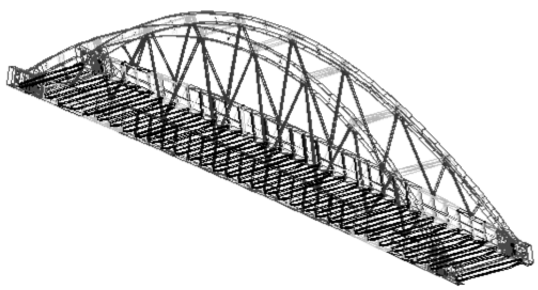

Fig. 11: 3D view of the final design, with tubular diagonal members.

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