High-Speed Railway Bridges

Conceptual Design Guide

José Romo
Alejandro Pérez-Caldentey
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Foreword

At the request of the authors, I have been given the honour of writing the foreword to this book, which is devoted to railway bridges. It develops the aspects referring to their structural conception, taking into account the characteristics of railway traffic: actions, limit states, speeds, etc., and includes a detailed analysis of the superstructure of the track with its different components and singular elements (for example, expansion devices) that allow the correct behaviour of the track.

In the following chapters, the knowledge and experience of the authors is passed on. In this respect, I remember a technical conference that took place in the 1970s at the Eduardo Torroja Institute, dedicated to bridges; at that time, the undersigned engineer was assigned to the Renfe Bridge Division and attended it. Ramón del Cuvillo, professor of Concrete at the School of Civil Engineering in Madrid, presented a paper in which he focused on the defects and mistakes in design and execution in projects and works in which he had been involved. His presentation was the most applauded of the day's and, personally, the one from which I learned the most. I hope that reading this book will be useful to avoid the repetition of problems that can be avoided, without having to wait for experience after the execution of the works.

As the reader will appreciate, special emphasis is placed on the interactions between the structure and the track, subjected to railway and environmental actions, taking into account the requirements of their stability in different situations; solutions are also proposed and considered in relation to the transitions between the bridge and the adjacent infrastructure (and track).

Special attention is paid to the dynamic nature of railway actions, studying the dynamic response of the structure and its influence on the behaviour, also dynamic, of the track and its components, with the repercussions that this may have on safety, traffic flow quality, and maintenance needs.

To conclude, I would like to transmit here some ideas that the Emeritus Professor of Structural Engineering of the University of Berkeley, Edward L. Wilson, sets out in his book *Static and Dynamic Analysis of Structures*. In a section of Personal Remarks, he relates that his first-year physics professor warned his students 'not to use an equation they could not prove'; he also advises, with respect to modern structural engineering, ‘not to use a structural analysis program unless you fully understand the theory and approximations contained in the program’. I fully agree with these considerations; I therefore share them with the reader, in the hope that they will be useful to them.

Madrid, June 2023

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About the Authors

José Romo is Chief Executive Officer and partner of FHECOR, and also a bridge engineer fully specialised in large-span bridges with more than 40 years of experience in bridge design, 35 of them working in FHECOR. He has vast technical knowledge based on his design background complemented with his activity as professor of concrete and steel structures at Madrid University, and his active participation in national and international associations of bridge designers and concrete and steel materials. He is a member of many scientific committees such as Eurocodes, IABSE, and ACHE where he became president in 2014 and was awarded with the honour's medal in 2008. He is a fellow of the Institution of Civil Engineers of UK. He has always worked as a bridge designer participating in innumerable bridge projects in Spain and worldwide, and also in the construction engineering for many of them. He has a great aesthetic vision that he applies to all the designs, while having great concern for sustainability and the use of new materials and construction techniques.

Alejandro Pérez-Caldentey is full Associate Professor at the Department of Mechanics of Continuous Media and Theory of Structures for the Civil Engineering School at the Polytechnic University of Madrid. He joined FHECOR in 1989 after graduating from UPM where he also obtained his PhD in Civil Engineering in 1996. During his more than 34 years of experience, Alejandro has developed structural bridge projects in countries such as Spain, Chile, Italy, and the USA. He is experienced in managing multidisciplinary structural teams, developing designs, and planning and defining the scope of works. He also has extensive experience in managing and developing Research and Development projects, in Standardisation (member of the Project Team for EN 1992-1-1:2023), and in Education (Professor at UPM). He holds Engineering licenses for Spain, Chile, Virginia, Texas, Florida, North Carolina, Québec, Ontario, and British Columbia. He is also a partner and member of the Board of FHECOR Consulting Engineers.

Manuel Cuadrado holds an MSc in Civil engineering from the Polytechnic University of Madrid. He is currently Associate Professor at the Carlos III University of Madrid and a member of the Technological Committee of the Spanish Railway Research Foundation (SRRF). Manuel Cuadrado has been working for 34 years, mainly in the railway industry, for Spanish and French Engineering companies, as an independent Consultant, and from 2005 to 2017 for the SRRF. He has participated both in key Spanish High-Speed projects and in International High-Speed Lines (Portugal, Turkey, California), and has been involved in many R & D projects mainly related to the mechanical behaviour of railway infrastructures. As a result of his R & D activity, he has produced many monographs, published several papers in national and international journals, and presented many papers in national and international congresses, including WCRR 1999-Tokyo, WCRR 2001-Köln, WCRR 2006-Montreal, WCRR 2008-Seoul, and WCRR 2016-Milan, and UIC High Speed Congresses 2010-Beijing and 2015-Tokio. He was also invited to participate as a specialist in the drafting of railway standards, as a member of Spanish, European, and international technical committees. Finally, from December 2017, he has been participating as Infrastructure Assessor and Lead Assessor in several Rail Safety & Interoperability assessments, as Infrastructure expert and as Slab-track expert.

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1

Introduction to High-Speed Railway Bridges

José Romo

1.1 Book's Content

One of the particularities of this book is that it includes not only the aspects related to the design and behaviour of these types of bridges, but also those questions linked to the railway technology of the track itself. It is clear that the knowledge of both fields and the interaction between these two technologies, structural and railway, is fundamental for the complete design of these bridges.

The first chapter of the book is dedicated to explain the particularities of high-speed railway bridges (HSRB), in comparison with structures for conventional railways. The typological particularities of this type of bridge are also explained, as well as the importance of these works as a legacy for future generations.

Chapter 2 is devoted entirely to explaining the technology of the track and the particularities of the high-speed infrastructure. This chapter explains the special constraints in terms of rail traffic safety and passenger comfort. It also deals with critical elements in the design of these structures, such as rail joints and other special track elements.

Chapter 3 reviews the main concepts which affect the design and includes the main typologies used in structures for high-speed railway lines. The dimensions and characteristic weights of the different solutions are also included. This chapter also describes the special structural elements of these structures, such as abutments and fixed points. Finally, the particulars of the design of HSRB located in seismic areas are included. This chapter also has a worked example corresponding to a railway viaduct, which starts with the general definition of the bridge in a specific valley and the geometric definition of the different structural elements that make up the structure.

Chapter 4 is dedicated to the Design Basis of bridges of the railways high-speed lines. In this section, the typical loads and design criteria are indicated, as well as its application to the worked example defined in Chapter 3.

Chapter 5 is devoted entirely to analysing the dynamic phenomena associated with HSR bridges. In this section the different methods of analysis, the trains that

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must be analysed to calculate the dynamic response, as well as the way to consider other aspects of the response, such as the irregularity of the track and the vehicle or the interaction between the vehicle and the structure, are presented. The chapter is completed with several practical examples and an appendix which includes the theoretical aspects of general dynamics and their application to the analysis of HSRB.

Chapter 6 is dedicated to the interaction between the track and the structure. This section analyses this phenomenon and how to take into account the thermal effects, traction and braking forces, vertical loads and rheological effects, in the case of concrete decks. In addition to the analysis models, the checks to be carried out to calculate stresses in rails and relative displacements are analysed. This chapter also deals with the criteria for the placement of track joints, as well as the practical application of the worked example.

Chapter 7 deals specifically with aspects linked to the conceptual design with maintenance of bridges for high-speed rail lines in mind.

In addition to Chapters 1–7, the book includes two appendices. One is devoted to a review of the general concepts of dynamics that the reader of Chapter 5 on the dynamic behaviour of these bridges should be familiar with. The second appendix includes a ‘register’ of high-speed railway bridges built in different parts of the world.

1.2 What is Special About a High-Speed Rail Bridge?

It is often asked what is so special about a railway bridge for a high-speed line and particularly, what makes a railway bridge for a high-speed line different from a conventional railway bridge. The corresponding Sections 1.2.1–1.2.4 that follow in this chapter describe the causes or aspects that make HSRB so special.

1.2.1 Dynamic Amplification and Resonance

On railway bridges, there are a number of factors that lead to a dynamic response of the structure under traffic loads.

On the one hand, the loads are fast so there is an impact effect. On the other hand, the trains are composed of a more or less long succession of vehicles which means that the loads are repeated, so the dynamic effect is amplified. Finally, the imperfections of both the track and the vehicles create disturbances in the value and the way of applying the loads, which leads to an increase in the response of the structure.

Therefore, the actual forces and deformations of a bridge due to rail traffic are of a dynamic nature and their values can be considerably higher than those due to static actions. In order to take this amplification into account in the calculations, an impact or dynamic magnification coefficient is applied to the static loads, a coefficient established in the design standards on the basis of statistical studies carried out on bridges in service.

But all these causes are increased when the speed of trains is increased, and as will be seen throughout the book, the critical range of speeds for the phenomenon of resonance on a bridge occurs when trains run over 220 km/h.

Resonance of a structure occurs when the frequencies of the dynamic excitatory actions coincide with the eigenfrequency of vibration of the structure f_0 (a whole fraction of it). In the case of railway bridges, resonance can be produced by the passage of trains with regularly spaced axle loads or groups of axles (d_k metres) running at a certain critical speed (v in m/s).

$$v/d_k = f_0/i \qquad \text{with } ; i = 1,2,3 \ldots \tag{1.1}$$

Thus for a 30 m span bridge with a typical eigenfrequency of 3.5 Hz, on which high-speed trains with 18 m coaches are running, the critical speed of passage is $3.5 \cdot 18 \cdot 3.6 = 227$ m/s.

The coefficients of dynamic load magnification do not cover the risk of the effects of the resonance of the structure.

The amplification of stresses and accelerations due to the proximity to the resonance frequency means that special problems typical of HSRB can occur. These problems can affect the functionality of the structure as they can lead on the one hand to safety problems for rail traffic and on the other hand to a loss of comfort for train users.

Therefore, it must be verified that the vibrations of the deck do not reduce the lateral support of the track or reduce the contact pressure between the wheel and the rail, which could cause the wheel to come off the track and the convoy to derail.

1.2.2 Rail Traffic Security

One of the effects that can jeopardise the safety of rail traffic as a result of the high speed of the train is the high vertical acceleration of the deck produced as a dynamic effect of the excitation of the structure if the frequency of the loads is close to the vertical frequency of the structure. In these cases, track instability can occur as a result of the loss of ballast support or the loss of geometric quality of the track.

Other effects, such as the danger of derailment by deck twist or by the deformation of the deck or rotations in supports, or by the transverse deformation of the deck, or by the relative displacement of the deck, increase considerably as the speed of passage of train increases.

All this obliges the establishment of much more rigorous limits for the highest speeds and even, as will be seen later, to create fixed longitudinal connection points between the deck and the infrastructure to avoid its relative movement.

1.2.3 Passenger's Comfort

Also, as a consequence of the vertical accelerations suffered by the structure, there may be a loss of comfort for train users. For this reason, the design of the structure must seek to distance the vibration frequencies of the structure from the frequency of passage of the bogies and therefore the loads, in order to reduce this problem so that the acceleration experienced by the passengers and therefore their loss of comfort is within manageable limits. To analyse that a dynamic analysis used different types of trains has to be carried out.

1.2.4 Track–Structure Interaction

On all railway bridges there is an interaction between the track and the structure. The track is laid on the structure and therefore there is a joint response to the loads. For example, the difference in temperature between the rails and the structure, the transmission of traction and braking loads make it necessary to control the stresses on the rails to prevent them from breaking. The complexity of the mechanics of the connection between the rails and the deck and between the deck and the substructure (including the foundations) means that in any bridge project for a high-speed line it is necessary to analyse the interaction between the rails and the structure by means of a non-linear analysis. This type of complex analysis allows calculating the value of the stresses in the rails as well as the distribution of loads to the different part of the structure.

1.3 General Ideas on High-Speed Railway Bridges

Here again it might be asked what the differences are between a conventional railway bridge and a high-speed one. Firstly, it should be noted that the deformation and acceleration limits that must be met in this type of bridge are much more demanding, due to the stricter demands on the regularity of the track to achieve high-throughput speeds, and consequently the decks are slightly more robust than in the case of a conventional railway bridge.

But perhaps what most differentiates an HSRB from other bridges is the need to rigidly fix the deck to a fixed point in the infrastructure, in the common case of continuous decks. This means that on the one hand the longitudinal typology of these bridges is different and on the other hand the connection details between superstructure and substructure are special as will be explained below [1]. There is also another factor that conditions the longitudinal typology. The stroke of the track expansion devices homologated for high-speed. For a time the maximum stroke was 600 m and then in the last decades it went up to 1200 mm.

The need to fix the deck longitudinally to one point of the infrastructure, in bridges with a continuous deck, means that on the one hand the longitudinal behaviour of this type of bridge is radically different from that of other bridges. Firstly, the resistance to longitudinal action is concentrated at one point, which means that the deck will be subject to significant traction and this influences the design of the deck. On the other hand, when the deck is fixed at one point, it is often necessary to have rail expansion joints in one of the abutments when the structure exceeds a length of approximately 90 m in order to reduce the over-stress on the rails.

In all cases where the deck is continuous, at least one element of the infrastructure must be designed with high longitudinal rigidity (Figure 1.1). As will be seen later, in the case of long viaducts, and due to the limitation of maximum movements of commercial expansion joint devices, it may be necessary to have a fixed point in the middle of the bridge.

An alternative to the previous design is to make isostatic bridges in which each pier takes the corresponding part of the longitudinal load, especially the traction and

Figure 1.1 Sar Viaduct (FHECOR), Spain (Source: FHECOR).

Figure 1.2 Span by span isostatic solution: China, China Railways (Courtesy of China Railways).

braking force. This allows the elimination of joints in the rails but on the contrary, there are structural expansion joints in all sections of the deck coinciding with the piles. This solution, which might seem better from the point of view of track maintenance, has the disadvantage of higher maintenance of the structure and in the case of bridges in seismic areas, the lack of robustness in combination, which could cause relative movements between adjacent decks during the seismic actions. This type of design is being used very often in China because it is highly industrialisable and because it allows for very flexible construction (Figure 1.2).

There are some intermediate alternatives that involve the construction of a series of continuous sections having intermediate joints every certain number of spans. This solution has recently been used in Germany [2] and [3], shown in Figure 1.3.

Figure 1.3 Gänsebachtal Viaduct (schlaich bergermann partner sbp), Germany, DB Netz AG (Source: Störfix).

In summary, and from a typological point of view, high-speed bridges have some specific aspects which make them, at least from a longitudinal perspective, different from other bridges, as will be seen in Sections 1.4 and 1.5.

1.4 Evolution and Trends in High-Speed Bridge Design

1.4.1 First High-Speed Bridges

The first high-speed railway lines were built in the 1960s and 1970s in Japan and later in Europe in Germany, France, and Spain. The first viaducts for high-speed railway lines were built in Japan. The population density throughout Japan has meant that most of the lines have been built on viaducts. The typologies of bridges for the Shinkansen are varied, although the most singular are the extradosed bridges, a typology that originated in Japan itself.

In Europe, the first high-speed railway lines were built between one and two decades later than the Japanese lines. On these lines, large sections of embankment or cuttings alternate with a few viaducts and tunnels at specific points along the route.

1.4.1.1 First-Generation German Bridges

The German bridges for first-generation high-speed lines were designed according to the principle of rapid replacement of the decks in case of failure of one of them. Thus, except in exceptional cases, the bridges were built with isostatic spans, with maximum spans of 55 m. These bridges were obviously heavier than the continuous bridges and required four bearings and expansion joints in all the pier supports, which is obviously a problem for the maintenance of the structures. However, this typology allowed the track to be continuous and therefore without rail joints, with the great advantage that this entailed for track maintenance.

On these early lines, when the size of the obstacle made it impossible to use isostatic spans, Deutsche Bahn allowed the use of continuous bridges but with a length

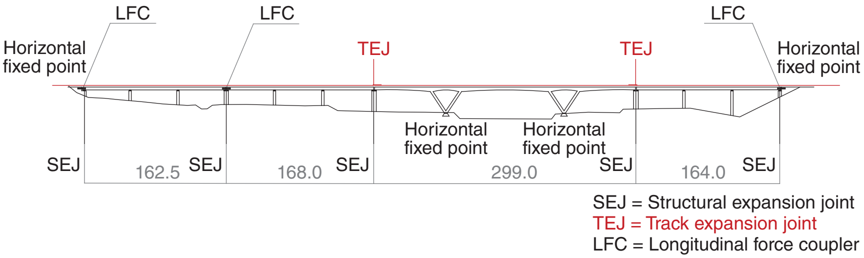


Figure 1.4 Structural scheme bridge over the river Main at Gemünden (1984).

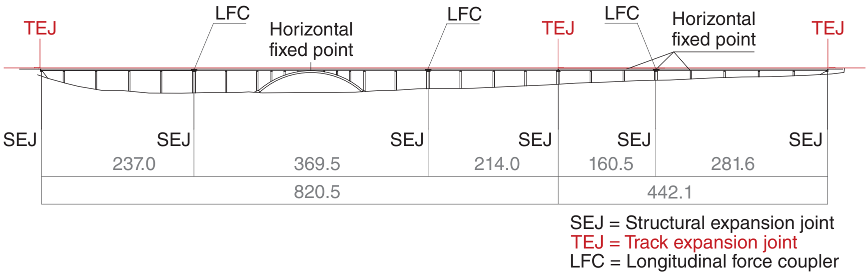


Figure 1.5 Structural scheme bridge over the river Main at Veitshöchheim (1987).

limited to 400 m so that this section could be replaced, at least theoretically, in a single operation.

The bridges over the river Main in Gemünden (Figure 1.4) and Veitshöchheim (Figure 1.5) built in 1984 and 1987, respectively, are structures with continuous spans and therefore with rail expansion joints between the individual deck subsections [4].

The Pfieffetal Viaduct, built in 1989 (Figure 1.6), was the first bridge in which, while maintaining the isostatic replaceable span solution, a central point was designed to collect the braking loads there. The isostatic decks were connected to each other longitudinally by means of a prestressing system centred on the deck, which allows the braking loads to be transferred to this central point. In this case, the track has two expansion joints coinciding with the abutments [4].

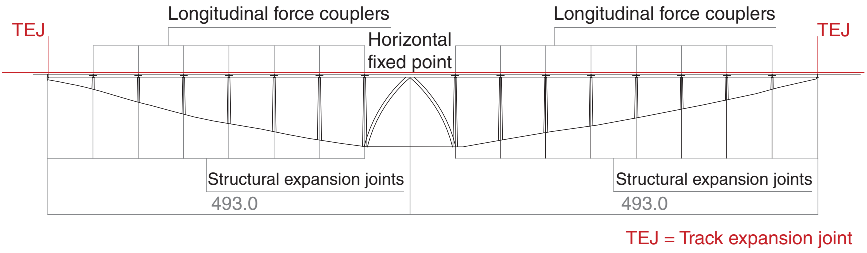
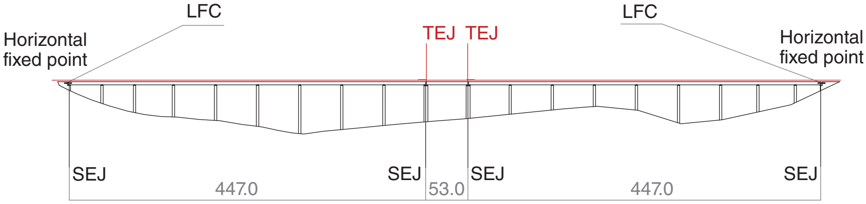
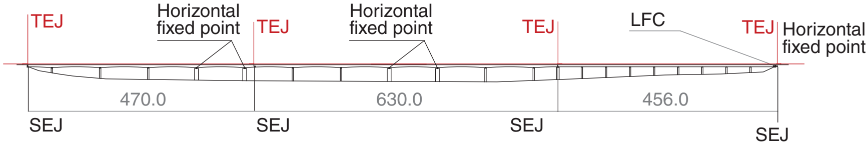


Figure 1.6 Structural scheme bridge over the Pfieffetal Viaduct (1989).



SEJ = Structural expansion joint
TEJ = Track expansion joint
LFC = Longitudinal force coupler

Figure 1.7 La Grenette Viaduct with 'inert' section and double expansion joints of structure and track.



SEJ = Structural expansion joint
TEJ = Track expansion joint
LFC = Longitudinal force coupler

Figure 1.8 Avignon viaducts with intermediate expansion joint (1999).

1.4.1.2 First-Generation French Bridges

In contrast to the first-generation German bridges, the first French high-speed bridges were built with continuous decks. This implies that for long bridges it is necessary to provide track expansion joints.

Usually, long decks are divided into three parts. The two lateral sections are long and are connected longitudinally to their respective abutments. Between these two spans is an isostatic central span called the neutral or inertial span, which allows the effective expansion length of the bridge to be divided by two (Figure 1.7). These bridges have two rail joints coinciding with the two expansion joints of the neutral portal frame structure [5].

In some cases, the provision of a central expansion joint coinciding with an intermediate point of a span has been tested in order to provide one single track expansion joint in one intermediate point of and intermediate span instead of the two necessary in the case of solutions with an inert span (Figure 1.8) [6].

Unlike in other countries, special bridges on French high-speed lines have always been designed in collaboration with architects and engineers. This has perhaps meant that all the designs have been special and have somehow departed from purely structural solutions.

1.4.1.3 First-Generation Spanish Bridges

Spanish bridges built from 1987 are characterised by the use of continuous solutions with a fixed point, usually at one abutment, and a structural and track expansion joint at the opposite abutment. In the case of very long bridges, it is common to have