1

Introduction to High-Speed Railway Bridges

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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

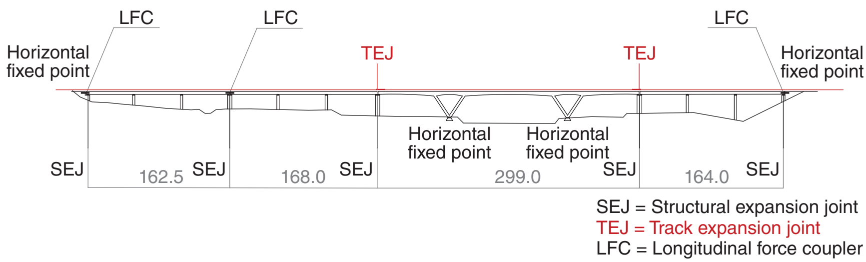

Figure 1.4 Structural scheme bridge over the river Main at Gemünden (1984).

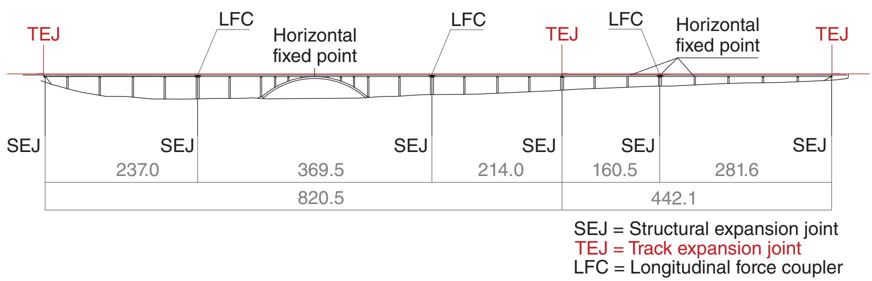

Figure 1.5 Structural scheme bridge over the river Main at Veitshöchheim (1987).

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].

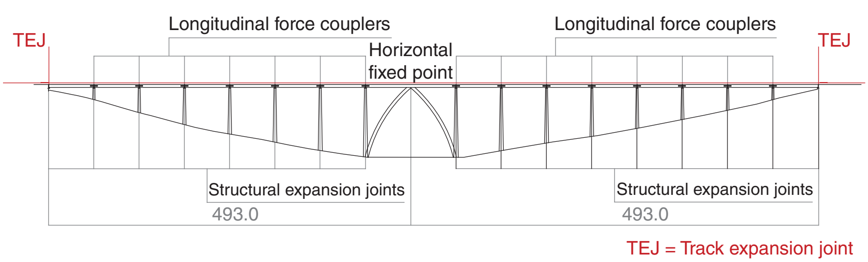

Figure 1.6 Structural scheme bridge over the Pfieffetal Viaduct (1989).

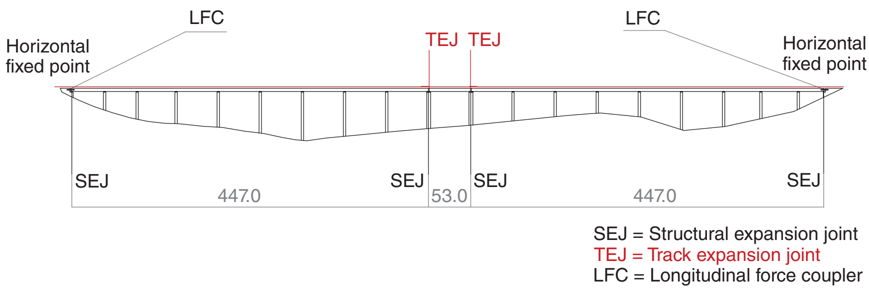

Figure 1.7 La Grenette Viaduct with 'inert' section and double expansion joints of structure and track.

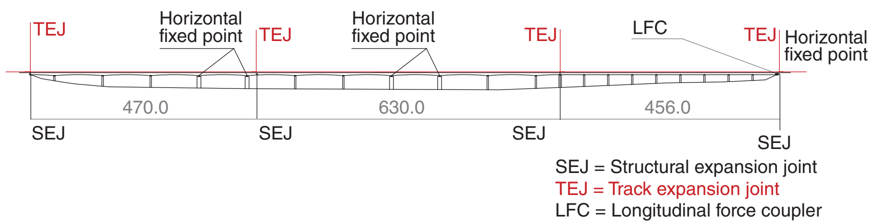

Figure 1.8 Avignon viaducts with intermediate expansion joint (1999).

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

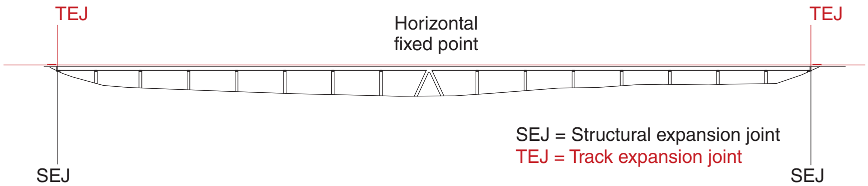

Figure 1.9 Example of a Spanish bridge with a continuous deck.

one or two intermediate fixed points in the form of A-shaped piers that transmit the braking loads to the ground (Figure 1.9).

On the other hand, Spain's rugged orography has given rise to a series of long-span bridges in which structural rigour has been combined with the aesthetic and landscape aspects of the works, as described below [7].

1.4.2 Recent High-Speed Bridges

1.4.2.1 Recent French Bridges

The bridges on the most modern TGV (Train à Grande Vitesse) lines have generally maintained the design criterion of long bridges with an inert central span.

A singular bridge in the French high-speed lines is the Savoureuse Viaduct (Figure 1.10). This viaduct is a succession of short sections with special piers that have structural expansion joints between them and allow the rail to be continuous and therefore there is no track expansion joint [8].

1.4.2.2 Second-Generation German Bridges

The bridges already built in Germany in the second decade of the 21st century have been developed according to the indications of the DB Netz Design Guide for Railway Bridges in 2008 [2]. With the implementation of this guide, the condition that the decks should be quickly replaceable has been eliminated and semi-integral bridges have been designed, generally without track expansion joints and structure joints every 100–120 m or so. Examples of bridges designed along these lines are the Unstruttal Bridge and the Gänsebachtal Viaduct.

The Unstruttal Bridge has a height of about 40 m above the valley, the arch spans have a span of 108 m, and the standard spans have a span of 58 m (Figure 1.11). There are structural and track expansion joints every 580 m [3].

The Gänsebachtal Viaduct (Figure 1.12) with a deck height of about 18 m, has shorter spans (24.50 m) and structural expansion joints every 112 m and does not need track expansion joints [3].

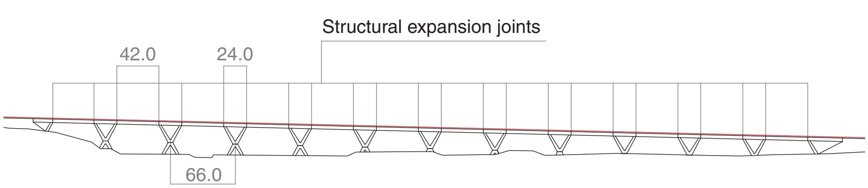

Figure 1.10 La Savoureuse Viaduct (2011).

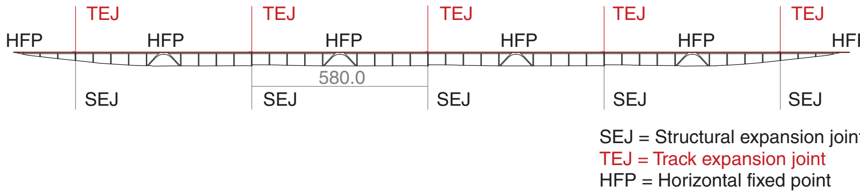

Figure 1.11 Unstruttal Bridge (2012).

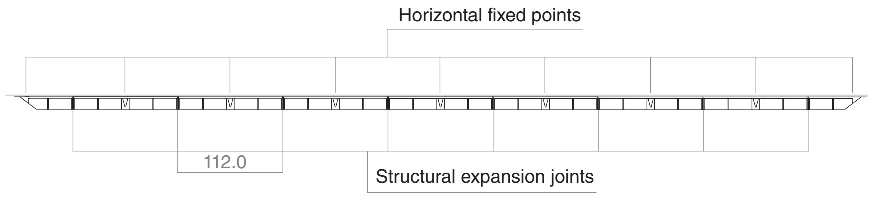

Figure 1.12 Gänsebachtal Viaduct (2012).

1.4.2.3 Recent Spanish HSRB

On the other hand, Spain's rugged orography has given rise to a series of long-span bridges in which structural rigour has been combined with the aesthetic and landscape aspects of the works, as described in [7] including:

1. Precast decks with constant depth with spans up to 45 m
2. Precast decks with variable depth with spans up to 60 m
3. Prestressed concrete box-section bridges built with movable scaffolding system (MSS) with spans of up to 75 m
4. Steel–concrete composite deck up to 66 m of span
5. Extradosed steel bridges with spans up to 75 m
6. Bow-string arches with spans in the range of 125–130 m
7. Concrete box deck built by cantilevering up to 150 m of span
8. Steel truss decks with 240 m of span
9. Concrete arches with a maximum span of 384 m

For the above-mentioned bridges see Appendix B.

1.4.2.4 Bridges for High-Speed Railway Lines in China

The structures that have been and are currently being built in China are grouped into two characteristic types. On the one hand, there are the long multi-span viaducts and on the other hand, special bridges with one or more main spans with long spans.

The long viaducts currently being built in China are isostatic spans that are prefabricated completely and assembled directly from previously built spans (Figure 1.13).

On the other hand, the orography of mountainous areas and the width of riverbeds have led to the construction of long-span bridges. The construction of arch bridges, cable-stayed bridges, and even the first suspension bridge are undoubtedly a sign of China's determination to build a high-speed network that does not stop at any technical challenge.

For bridges mentioned above see also Appendix B and Table 1.1.

Figure 1.13 Isostatic multi span bridge, China (Courtesy of China Railways).

Table 1.1 List of the major high-speed railway bridges (HSRB).

Name of the Bridge	Main Span (m)	Typology	Year of Completion	Design Operation (km/h)	Function*	Country
Wufengshan Yangtze River	1092	Suspension	2020	250	4R+8H	China
Hutong Yangtze River	1092	Cable stayed	2020	250	4R+6H	China
Tongling Road-Rail	630	Cable stayed	2015	250	4R+6H	China
Anqing Yangtze River	580	Cable stayed	2015	250	4R	China
Huanggang Yangtze River	567	Cable stayed	2014	250	2R+4H	China
Tianxingzhou	504	Cable stayed	2008	250	4R+6H	China
Zhaoqing Xi River	450	Steel box arch	2014	250	2R	China
Beipan River	445	Concrete arch	2016	300	2R	China
Wuhu Yangtze River	588	Cable stayed	2019	250	4R+6H	China
Yachi River	436	Steel truss arch	2019	250	2R	China
New Baishatuo Yangtze River	432	Cable stayed	2019	250	6R	China
Almonte River	384	Concrete arch	2016	330	2R	Spain
Dashengguan Yangtze River	336	Truss arch	2011	300	6R	China
Yibin Jinsha River	336	Bow-string arch	2018	250	4R+6H	China
Alcántara	324	Concrete arch	2019	330	2R	Spain
Grümpen	270	Concrete arch	2011	300	2R	Germany
Contreras	261	Concrete arch	2009	350	2R	Spain
Dongping Channel	242	Truss arch	2009	NA	NA	China
Ulla Estuary	240	Truss beam	2015	250	2R	Spain

*R = number of railway tracks.
H = number of highway lines.

Figure 1.14 Colne Valley Viaduct of HS2, England, UK (Courtesy of Knight Architects).

Figure 1.15 Fresno Viaduct in California, USA (Source: California High-Speed Rail Authority).

1.4.2.5 British High-Speed Bridges

The HS2 line between London and Birmingham is currently under construction. This line runs on flat terrain and the viaducts to be built have a very low gradient. The solutions being used in general are prefabricated multi-girder decks with continuity lintels constructed on site.

The Colne Valley Viaduct (Figure 1.14), which crosses one of the most scenic areas of the line, stands out as a singular bridge within the section. It is a continuous viaduct with maximum spans of 105 m that has a very careful design and will undoubtedly be the most emblematic bridge on the line.

1.4.2.6 High-Speed Railway Bridges in the USA

The high-speed rail line from San Francisco and Sacramento to Los Angeles is currently under construction. The structures being built are generally continuous viaducts with concrete box section or prefabricated girders. One of the most important works on the line is the Fresno River Viaduct (Figure 1.15).

The other line in the project phase is the line from Dallas to Houston, which is also planned with solutions using concrete box-section decks and precast concrete elements.

1.4.3 Conclusions

In order to establish an analysis of trends in the design and construction of high-speed bridges, it is first necessary to make a clear distinction between viaducts of more or less length on the one hand, and bridges requiring a long main span on the other hand.

1.4.3.1 Viaducts

There are currently three types of solutions for viaducts with moderate spans and shorter or shorter lengths.

In Europe, with the exception of Germany, continuous bridges are generally built with a minimum number of structural expansion joints and corresponding track expansion joints. The deck is supported by two devices per pier and per abutment. The bridges on the US lines also generally follow these design criteria.

In China, on the other hand, isostatic solutions are being built with a complete prefabrication in one piece of the deck of each span and therefore with an expansion joint on each pier, but without track expansion joints.

As seen in Germany, semi-integral bridges are being designed and built, i.e. without pier bearings, but with structural expansion joints, and in some cases without track expansion joints.

1.4.3.2 Long-Span Bridges

The typologies being used to date are similar to road bridges. Deck trusses with variable edge have been used up to 250 m span. For longer spans (up to 450 m), arch bridges have been successfully built. For longer spans, cable-stayed bridges are the usual solution. In these cases, the decks are trussed to give greater rigidity to the system and often have two levels: the lower one for rail traffic and the upper one for road traffic.

Table 1.1 summarises the bridges for high-speed lines with the longest spans built to date.

1.5 The Landscape and the Design of High-Speed Railway Bridges

1.5.1 The Traveller's Experience

The 21st century society, at least in the West, is governed by feelings [9]. The quality of any service is measured by the user experience [10]. High-speed rail is no exception to this premise.

Traditionally, when the designer analysed the engineering work and its relationship with the landscape, they did so taking into account only the view of the observer of the bridge from the surrounding environment. In this way, it is common to analyse from the different points from which the bridge or viaduct can be observed what modification it will introduce into the pre-existing landscape. The height and configuration of the abutments, the cadence of the deck spans, the relative dimensions of the deck and its spatial relationship with the morphology of the site are the aspects on which the bridge designer concerned with the landscape reflects.

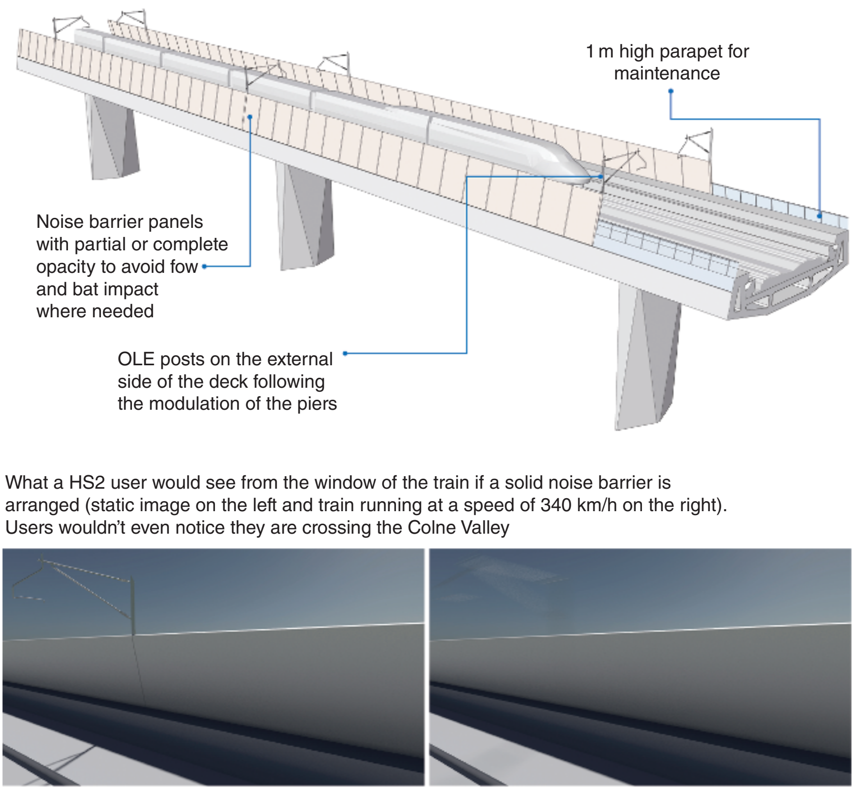

Figure 1.16 Example of a standard anti-noise panel on the bridge (Courtesy of Knight Architects).

However, it is clear that this is no longer enough. The 21st century bridge designer must also consider the landscape that the traveller will be able to contemplate when the train travels over the bridge being designed [11].

When this aspect is analysed, it is discovered that the structure itself rarely obstructs the view from the train in any way. However, it is common that parts of the bridge equipment, especially the anti-noise or wind barriers (when these are opaque), disturb or limit the view of the landscape from the train (Figure 1.16).

If the bridge is short, the loss of vision caused by such panels would only be for a few seconds. However, when the tracks run continuously through urban or peri-urban areas, the tunnel effect can be annoying or uncomfortable for the user. The same applies when the railway line passes through a point of outstanding scenic beauty, such as a major river crossing, if the passenger's view of the outside is limited by some element of the bridge.

In such cases, it will be important for the viaduct designer to be aware of whether the structure requires any type of panelling that will at least partially obstruct the vision of the traveller. Whether it is necessary to install panels or whether it is the structure itself that is disturbing, for example if the resistant section of

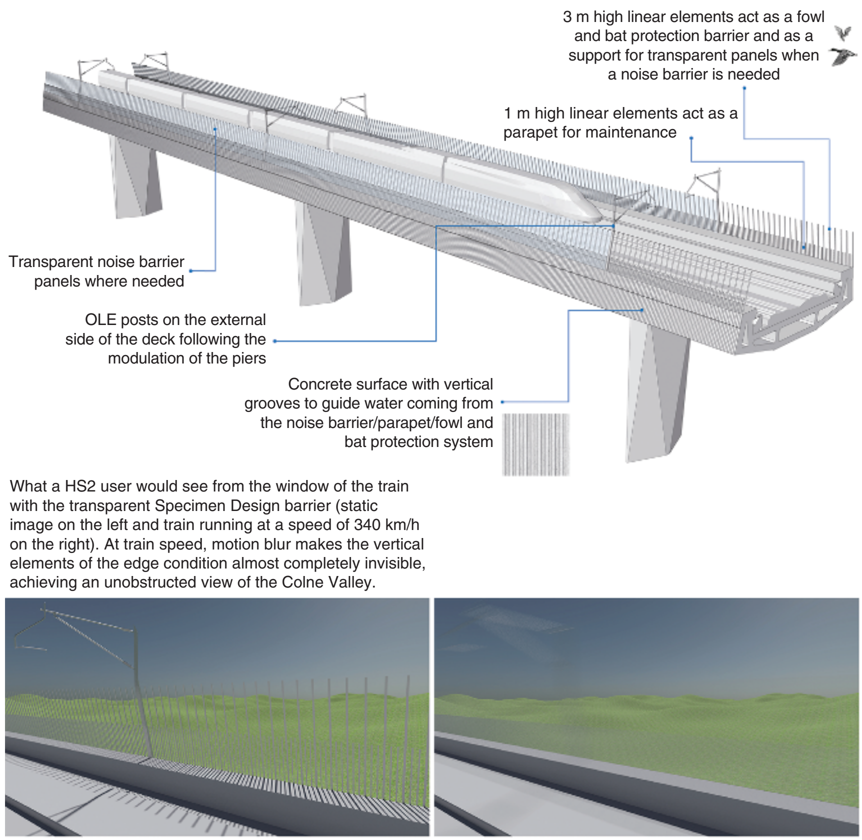

Figure 1.17 Study of the view from the train as it passes over the Colne Valley Viaduct, England, UK (Courtesy of Knight Architects).

the deck is U-shaped, the project team must analyse whether it is possible to reconcile functional requirements (noise emission control, wind safety, etc.) with the possibility of the traveller being able to enjoy the landscape at least for a fleeting glimpse (Figure 1.17).

1.5.2 The Bridge in the Landscape

The railway layouts of the 19th century and those built later for moderate traffic speeds allowed for the adaptation of the railway line to the orography, except in mountainous areas. However, compared to roads, railways have always needed more bridges and viaducts to overcome the natural obstacles they have encountered, as the layout conditions have been and still are more rigorous in the case of railways compared to the design requirements of roads.

The railway has transformed and continues to transform the landscape through which it passes. High-speed lines with their very wide radii of curvature in plan of about 8000 m minimum for 350 km/h lines require the construction of a large number of viaducts and tunnels as soon as the terrain has some movement. Even in flat terrain, it is common for modern high-speed lines to be built in structure in order to maintain transverse territorial permeability under bridges. It is very important in these cases to decide correctly on the level of the railway grade on the ground because of its implications for the design of the viaducts.

The participation of bridge specialists in the early stages of the project is important for the definition of the basic geometry of the line and to avoid starting the project with initial conditioning factors that could damage the overall quality of the solution, for example: the transverse permeability, the landscape implications of the design, the technical quality, or the construction cost of the work.

Sections 1.5.2.1 and 1.5.2.2 analyse the landscape aspects of bridges and viaducts on high-speed lines in different scenarios.

1.5.2.1 Long Viaducts with Low Vertical Level

If the level is relatively low in relation to the ground (less than 8 m), the spans have to be short in order to leave a sufficient clearance between the bottom of the deck and the natural ground. If it is also necessary to install noise barriers, the height of the noise barrier must be added to the actual height of the deck under the track, which will make the bridge visually very heavy. One way to solve this problem is to use 'U' sections, with the structure itself acting as a noise barrier so that the clear span is as large as possible (Figure 1.18).

However, whenever possible, it is better to raise the level somewhat to avoid the aforementioned problems. From the point of view of the cost of the bridge, an increase in the height of the piers from 8 to 12 m has little influence on the final cost of the structure, since there will only be a slight variation in the foundations and a higher cost of the pier shafts (which in any case is a small cost in relation to the total cost of the bridge) and this increase in height will not condition the construction process of the deck. In any case, and whenever it is necessary to build either noise barriers or U-shaped structural sections, it is essential to study the shapes and finishes in order to break up the massiveness of the faces.

1.5.2.2 Long Viaducts with Medium or High Level

As explained above, when viaducts are long, it is necessary to fix the deck to the infrastructure. If the bridge is also very high, the connecting element(s) will play a special role in the formal appreciation of the bridge in the landscape.

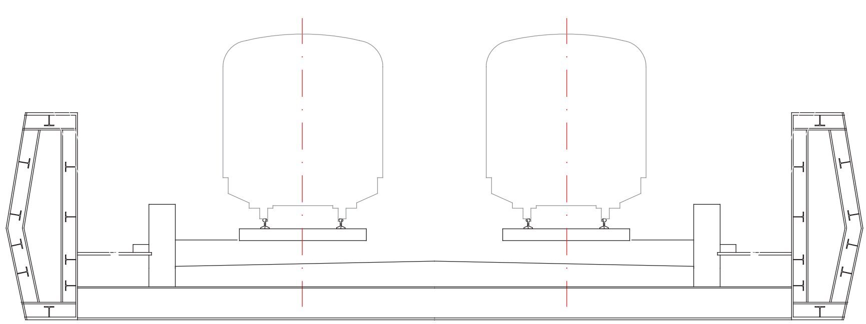

Figure 1.18 Semi-through deck structure (Source: FHECOR).

Figure 1.19 Isostatic deck, China (Courtesy of China Railways).

Figure 1.20 La Savoureuse Viaduct (2011), France (Courtesy of Wilkinson Eyre).

Isostatic Bridges When the viaduct is made up of a succession of isostatic spans, it is common for both the deck itself and the piers to be particularly robust. As the decks are isostatic, they are less efficient than continuous decks and require a greater depth (see Chapter 3). The piers also have to individually withstand the corresponding braking load and therefore require larger dimensions than in the case of continuous structures (Figure 1.19).

The La Savoureuse Viaduct (Figure 1.20) has recently been built, breaking with the French tradition of continuous bridges. In this viaduct, the piers are formed by a tetrapod-shaped structure supported at one of its vertices, which on the one hand breaks the massiveness of the piers of isostatic bridges and on the other hand reduces the span of the isostatic spans. The result is a unique structure that works well in the surrounding views.

Continuous Bridges Continuous bridges have the advantage of reducing the number of expansion joints in the structure. When these bridges are long, they require one or more points to fix the deck longitudinally.

The first example of this way of solving the central connection by means of a single element is the Pfieffetal Viaduct in Germany, 1989 (Figure 1.21). This bridge is actually an isostatic span bridge, but because of its height the piers cannot carry the braking load, which is transferred to a portal pier with two inclined piers. The shape of the V-shaped valley makes the role of this central pier very clear.

Figure 1.21 Pfieffetal Viaduct (1989), Germany (Courtesy of Wolfgang Pehlemann).

Figure 1.22 Bridge over the river Main at Gemünden (1984), Germany (Courtesy of Deutsche Bahn AG).

Another type of situation occurs when a long viaduct is required which can be resolved with modest spans, but which presents a singular span due to having to cross a major obstacle locally. This type of solution perhaps begins with the Gemünden Bridge (Figure 1.22) , which serves as the cover of the most widely read book on bridge aesthetics [12].

However, to return to very long viaducts that require a single span, the revolution brought about in Germany by the Deutsche Bahn Guide [2] is worth mentioning. It stipulates that long bridges for the Deutsche Bahn should generally be semi-integral and as far as possible without a track expansion joint.

The first long bridges designed according to these guidelines are the Unstruttal (Figure 1.23) and Gänsebachtal (Figure 1.24) viaducts [3]. Both bridges are superb in terms of design, structural efficiency, maintenance of both bridge and track, as well as structural innovation, with an obvious reading on the landscape to the trained eye.

Singular Bridges Another classic design situation occurs when the obstacle to be overcome is significant and it is necessary to build at least one large span. This is a situation that occurs when crossing deep valleys or when passing over very wide and fast-flowing rivers or streams.

When crossing deep valleys, it is common for the bridge to be a short interval between tunnels. This is the case, for example, with the colossal Beipanjiang Bridge (Figure 1.25) on the high-speed line from Shanghai to Kunming in the Chinese

Figure 1.23 Unstruttal Bridge (2012), Germany (Courtesy of Deutsche Bahn AG).

Figure 1.24 Gänsebachtal Viaduct (2012), Germany (Courtesy of Störfix).

Figure 1.25 Beipanjiang Viaduct (2016), China (Courtesy of China Railways).

Figure 1.26 Alcántara Bridge (2019), Spain (Courtesy of Carlos Fernández Casado CFC & ADIF).

Figure 1.27 Almonte Viaduct (2016), Spain (Courtesy of Arenas Asociados & ADIF).

province of Guizhou, which with its 445 m main span fits perfectly into the narrowing of the gorge flanked by two tunnels [13].

In areas with a hilly but not necessarily mountainous topography, it may be necessary to build a large main span accompanied by two long access viaducts. This is the case, for example, of two Spanish bridges, the Alcántara viaduct (Figure 1.26) with a span of 324 m [14] and the Almonte viaduct (Figure 1.27) with 384 m main span [15].

In both cases, the continuity of the deck and the careful design not only of the main span but also of the access viaducts stand out, making these works excellent examples of the concern for the visual aspect typical of Spanish engineering.

The above three are good examples of how well rigid arches fit into a rugged landscape when there is a major obstacle.

It should be pointed out here that, although at first sight the arch is a typology which is not very suitable for use on the railway as it has to support significant variable loads, in long-span bridges, the weight of the structure itself is the dominant gravity load compared to the railway overload and it is sufficient for the arch to be sufficiently rigid for it to function correctly.

Another special design situation for high-speed line bridges is the crossing of large rivers or estuaries. Especially when the crossing depths or navigation demands require long spans.

The solutions in these cases are usually trusses, either with straight girders (for moderate spans) or bow-string or cable-stayed bridges for large spans.

The Nantenbach Bridge (Figure 1.28) in Germany [16] and the Ulla Bridge (Figure 1.29) in Spain [17] are good examples of the application of the variable-edge straight-deck typology at river or estuary crossings. In both cases they are bridges for two high-speed railways tracks.

When it is a question of covering very long spans and with many railway tracks, the solution is usually a double-level cable-stayed bridge deck. This is the case, for example, with the Hutong Bridge over the Yangtze River (Figure 1.30). The bridge

Figure 1.28 Nantenbach Bridge (1993), Germany (Courtesy of Deutsche Bahn AG).

Figure 1.29 Ulla Estuary Viaduct (2015), Spain (Courtesy of ADIF).

Figure 1.30 Hutong Yangtze River Bridge, China (Courtesy of China Railways).

Figure 1.31 Proposal Terceira Travessia do Tejo, Lisbon, Portugal (Source: ADF-FHECOR-IDEAM).

has a colossal main span (1092 m) in which the upper part of the deck serves a motorway while the lower part accommodates the high-speed railway.

In both cases the piers are bottle-shaped. An alternative to these piers is the one proposed for the Third Tagus River Crossing in Lisbon (Figure 1.31), also designed with a two-level deck. In this case, the pylon has A-shaped outer shafts, which give the pylon a very clean form despite its robustness.

1.6 Railway Bridges as Landmarks or Icons of a Line

Fortunately, the requirements for bridges on high-speed lines are so stringent that only relatively short-span bridges have been built to date, and only very rarely, with designs that go against the logic of strength or function. Formal speculation is therefore far removed from long spans but sometimes manifests itself in long viaducts with short spans where the structural challenge is not so relevant.

Undoubtedly, at least in Europe, there is a particular attention to aesthetics. Aesthetics not as a branch of philosophy that studies the essence of beauty and the perception of beauty in art, but aesthetics as the image of any object.

This ‘aesthetisation’ of the world, as Lipovetsky reminds us [18], strives to make the formal expression of any object novel or unique. Bridges are no strangers to this drive, and their design has been influenced in some way, in these first decades of the 21st century, by this trend in which the most important thing is the appearance of form.

Fortunately, in the case of long-span or long bridges, the site and the functional requirements they have to meet make each bridge a unique and unrepeatable example. This should at least calm the desire for novelty [19].

This does not mean that designers should abandon the care for the formal aspects of their bridges. On the contrary, they should strive to combine appearance and substance. An effort that should be directed not only towards achieving excellence in singular works, but also towards seeking beauty, following Yanagi's ideas [20], in normal bridges, those that are seen every day.

The expert eye and perhaps also the non-specialist will appreciate the effort made in many high-speed bridges to wisely reconcile these in no way contradictory aspects of design. These exemplary works will surely become part of the collective heritage and culture of the technical community and society in general.

1.7 Railway Bridge's Legacy

Since its beginnings, the railway has marked the evolution of bridges. The conditions required by the 19th century railway marked the development of structural engineering, both in terms of materials and in the typology of the bridges themselves (Figure 1.32).

It is the epic era of engineering marked by successes but also by great failures. The dynamic loads due to the railway, the fatigue of the materials gave rise to resounding accidents that served as a lesson to move towards safer structures.

The magnitude of the challenges and the integrity of the engineers had a strong impact on the society of that time. The material and human development that was achieved thanks to this new means of transport revolutionised the society of that time.

Society as a whole and art did nothing but focus on the railway and its works. Bridges appear in paintings first and then in photography creating a whole imaginary regarding the progress created by the engineers.

Figure 1.32 Maria Pia Bridge (Ponte de Dona Maria Pia, 1878) Porto, Portugal (Source: Seyring [21], photo: José Olgon).

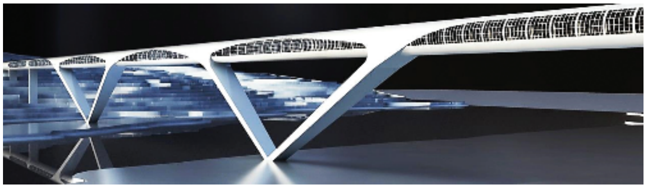

Figure 1.33 Proposal for the Ulla Bridge, Spain (Source: FHECOR).

Perhaps the railway bridges where the first works in which society could admire the plastic and formal value of the engineers' work. The visual strength of these structures undoubtedly had a favourable impact on a society that admired the value of the technique with fascination [22].

1.8 Building for the 21st Century

High-speed rail routes have very high radii of curvature in plan. This requires the construction of long tunnels and viaducts when the terrain is hilly. Unlike railways laid out in the 19th and 20th centuries, bridges and viaducts are no longer the main defining elements of the route. The bridges are subordinated to the route and this means that they are very long constructions which undoubtedly shape a modelled landscape.

These bridges are therefore an excellent opportunity to showcase the advances in structural engineering of the 21st century. In addition to the technical challenges of this type of construction, there are also the demands of a mature society that is logically concerned about the environment and the sustainability of any project.

Structural engineering has to rise to these great challenges. In this way, both the design of the bridges, and therefore their formal expression, and their construction and setting in the terrain must be respectful of their landscape and environment [23].

These designs, especially when it comes to singular works, must be a sample of engineering concerned with the maintenance and durability of their structures, creating bridges that can be the legacy of the engineers of the first decades of the 21st century (Figure 1.33).

1.9 Conclusions

HSRB are the best example of how a technology, the railway, is developed to reach land speeds only previously imagined by man. The speed and the necessary safety of the lines require highly demanding structures that have to meet strict design criteria. The structural engineering of the moment has very powerful design and calculation tools that allow the design of these bridges that were unthinkable a few decades ago.

However, in order to continue achieving challenges, collaboration between railway engineers and bridge designers is essential. The following text is a good example of this joint knowledge that is offered to the reader here.

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