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Two FE models to analyse the dynamic response of short span simply-supported oblique high-speed railway bridges: Comparison and experimental validation

P. Galvín[a,*], A. Romero[a], E. Moliner[b], M.D. Martínez-Rodrigo[b]

[a] Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain
[b] Universitat Jaume I, Department of Mechanical Engineering and Construction, Avda. Sos Baynat s/n, 12071 Castellón, Spain

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ABSTRACT

In this paper the dynamic response of a particular type of high-speed railway bridge common in the Spanish railway system is analysed with the aim of evaluating the levels of vertical vibrations experienced at the platform. To this end, Bracea I bridge which belongs to the Madrid-Sevilla High Speed railway line is selected. The bridge is composed by two identical short simply supported spans. The pre-stressed concrete girders deck dimensions and level of obliquity make this structure prone to (i) experience important vertical accelerations under railway traffic and (ii) present a dynamic response with a high participation of modes different from the longitudinal bending one. Therefore the structure is not expected to behave as a beam-type structure. The results of an experimental campaign recently performed at the site are presented with the objective of characterising the soil dynamic properties and the structure response under ambient vibration conditions and under railway traffic. The experimental response of the bridge is then compared in the time and frequency domains to numerical predictions given by two Finite Element models which adopt common assumptions in engineering practice. The study provides interesting conclusions regarding the structure experimental response under resonant and not resonant conditions. Additionally, conclusions regarding the adequacy of the numerical models for predicting the bridge response and assessing the Serviceability Limit State of vertical acceleration in ballasted railways are presented.

1. Introduction

The evaluation of the dynamic effects caused by modern railway transportation systems on railway infrastructures is a key factor to guarantee structural integrity and travelling comfort. At circulating speeds above 200 km/h, resonance effects caused by the regular nature of the train axle loads may entail harmful consequences on railway bridges, such as ballast destabilization, passenger discomfort or a raise in the maintenance costs of the line. Especially critical in this regard are short-to-medium span simply-supported (S-S) bridges with usually low associated structural damping and mass, which may experience considerably high vertical accelerations at the deck level [1,2]. In these structures the Serviceability Limit State of vertical acceleration is one of the most demanding specifications for their design or upgrading. These facts point out the importance of developing accurate numerical models, able to realistically predict the vibration levels on the bridge with reasonable computational costs.

Several research works on this topic have been presented in recent years. Liu et al. [3] and Doménech et al. [4] investigated the conditions under which train-bridge interaction should be considered for the dynamic analysis of a bridge under railway traffic. The authors identified key ratios between structural and vehicle properties that maximized the influence of the vehicle suspension systems on the bridge response. Ülker-Kaustell and Karoumi [5] studied the influence of variations in the bridge natural frequency and modal damping with the vibration amplitudes under resonance. The results indicated that these variations may considerably reduce the resonant amplitudes and the critical train speeds. Lu et al. [6] investigated the frequency contents in the bridge response as well as in the train excitation. They concluded that for short bridges, well-distributed frequency peaks occur at a number of dominant frequencies, whereas for longer bridges the main frequency peak tends to concentrate towards the lowest dominant frequency. Rocha et al. [7] used a probabilistic approach to analyse the sensitivity of the dynamic response of a short span bridge due to the variability of the main structural parameters. The Canelas Railway Bridge was used as case study. The procedure showed that the bridge deck sectional and

* Corresponding author.
E-mail address: pedrogalvin@us.es (P. Galvín).

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mechanical properties, the mass of the ballast layer and the vertical stiffness of the supporting bearings were the parameters that most affected the bridge response. Ülker-Kaustell et al. [8] analysed the influence of soil-structure interaction (SSI) on the dynamic properties of a portal frame railway bridge by means of dynamic stiffness functions describing the stiffness and damping of the foundation-soil interface. Romero et al. [9] also studied the dynamic soil-bridge interaction in High-Speed (HS) railway lines. The authors concluded that SSI affects the structure dynamic behaviour, and showed how the fundamental period and damping ratio of the structure substantially increased when SSI was considered. Gu [10] presented a vehicle-bridge numerical model including the coaches suspension systems for traffic analysis under realistic conditions. This model revealed that TGV trains operating in France, Korea and in the UK on long-span bridges were highly vulnerable to resonance. Moreover, the author mentioned that the design codes are not yet available for designing long-span railway bridges with low natural frequencies. Cantero and Karoumi [11] numerically investigated the consequences of assuming that the maximum load effect in S-S railway bridges happens at mid-span, with particular attention to resonant situations. The authors found that significant errors appear when the relative energy content of the higher modes of vibration is high, for example, when one of the bridge higher natural frequencies matches a loading frequency. Doménech et al. [12] developed a numerical investigation analysing the effects of SSI on the free vibration response of simply-supported beams in a wide range of travelling velocities. This study justified how resonant amplitudes of the bridge under the circulation of railway convoys may be affected by the soil properties, leading to substantially amplified responses or to almost imperceptible ones, from the conditions of maximum free vibration and cancellation of the deck response. Bebiano et al. [13] applied a semi-analytical formulation for the dynamic analysis of a real 46 m span thin-walled HS railway bridge. From this study the authors concluded that local deformation modes have influence on the dynamic response of thin-walled decks.

In order to realistically predict the response of a bridge under railway traffic the calibration of numerical models with in situ dynamic testing becomes crucial. With this purpose a number of researchers have performed experimental campaigns on railway bridges in the past. Xia et al. [14] presented the results of dynamic experiments on the Antoing Bridge located on the HS railway line between Paris and Brussels. Modal parameters, strains and vertical and lateral accelerations were identified from measurements. Marefat et al. [15] carried out dynamic and static load tests to evaluate the remaining strength of a plain concrete arch bridge. The bridge showed a relatively large energy absorption capacity and did not experience any resonance effects. Rebelo et al. [16] presented the results of experimental measurements on a number of existing small to medium length single span ballasted railway bridges in Austria. From the tests, the authors concluded that the damping due to friction between the ballast particles and at the supports considerably affects the maximum acceleration. Also, the fundamental frequencies of the bridges vary with the amplitude of the vibration, that is, increasing vibration amplitudes lead to a decrease in the first natural frequency in a consistent way for all investigated bridges. Flener and Karoumi [17] experimentally studied the dynamic response of an 11 m span corrugated steel culvert railway bridge. The tests showed that the train speed had an important influence on the bridge response. Dynamic amplifications higher than the values specified in bridge design codes were measured, even though this type of bridge structure seems less sensitive to resonance effects due to its inherent high damping. Liu et al. [18] presented in situ dynamic measurements and an experimental validation of the numerical model of the Sesia composite viaduct for the prediction of HS train-induced vibrations. This study provided a better understanding of the structural behaviour of composite railway bridges under the excitation of High-Speed trains (HST). Kim et al. [19] proposed a methodology for estimating modal parameters from the free vibration response immediately after the train passage. The technique was successfully validated in a two-span steel composite girder bridge. Wallin et al. [20] studied the Söderström steel Bridge, located in the city of Stockholm. A 3D finite element (FE) model was implemented and verified with measurements. The strengthening methods considerably improved the fatigue life of the bridge. A change in the structural system drastically modified the dynamic behaviour of the bridge and the deck acceleration levels. Vega et al. [21] presented a complete study of a culvert from the HS line between Segovia and Valladolid, in Spain, including on-site measurements and numerical modelling. Ribeiro et al. [22] presented the calibration of the numerical model of a bowstring-arch railway bridge based on modal parameters. Johansson et al. [23] examined three railway lines in the southern part of Sweden since the government was considering increasing the design speed from 200 km/h to 250 km/h. The simplified numerical study covered 1000 bridges. A high number of these bridges, mainly with spans shorter than 12 m, did not fulfill the code requirements. Malveiro et al. [24] carried out the calibration and experimental validation of the dynamic model of a railway viaduct with a precast deck. Costa et al. [25] calibrated a numerical model of a stone masonry arch railway bridge using dynamic modal parameters identified from ambient vibration tests. The authors used a genetic algorithm which allowed estimating the elastic properties of the materials. Park et al. [26] proposed an experimental method to measure the viscoelastic properties of the railway track under flexural vibrations using the wave propagation approach.

In the previous experimental studies the attention mainly focusses on the dynamic response of the bridge deck under ambient or train induced vibrations. However, as indicated in the cited literature, the dynamic response of short-to-medium span S-S railway bridges is difficult to predict during the design or upgrading stages, since the influence of environmental parameters and super-structure components (rails, ballast) can be significant and it is considerably uncertain. Additionally, in double track bridges, modes different from the longitudinal bending one (i.e. first torsion and transverse bending modes with close natural frequencies) may affect significantly the maximum response of the bridge. This is related to usual structural typologies in the range of lengths under consideration and to the ratio between the span length and the width of the deck. Despite the high vibration levels that such structures may experience, the number of reported experimental campaigns is scarce. Finally, even though some studies reveal that SSI may significantly affect the bridge dynamic response under certain conditions [8,9,12], especially in the case of short S-S structures, the properties of the soil are seldom measured during the tests nor included in the numerical FE models. Only when the interaction between the super-structure and the soil is more evident due to the bridge typology, as it is the case of portal frames or soil-steel composite railway bridges [8,27], SSI is taken into account.

In this work the results and conclusions from an experimental campaign performed on a short S-S bridge belonging to a HS railway line in Spain are included. This bridge is particularly interesting as (i) the structure presents a skew angle of 45° and a span length similar to the deck width. For these reasons its dynamic response substantially differs from that of a beam-type structure; and (ii) in a preliminary numerical evaluation of the bridge [28], performed assuming the main simplifications adopted by practitioners in accordance with the European Standards [29,30], an important transverse vibration response was predicted at the deck level. In the work presented herein, the tests performed aim to identify the soil properties at the site, the bridge modal parameters and the structural transverse response under different trains circulating at speeds comprised between 200 and 300 km/h, approximately. First, the effect of SSI is disregarded in a first approach based on the measurements. Then, two different FE numerical models, typical for this particular bridge typology, are implemented and calibrated from experimental results. Conclusions are finally extracted regarding: (i) the structure performance under resonant and not resonant conditions, and (ii) the adequacy of the numerical models