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Safety assessment of a short span railway bridge for high-speed traffic using simulation techniques

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ABSTRACT

The dynamic behaviour of railway bridges in high-speed lines has been the subject of several studies in recent years. Nevertheless, most of the work was developed assuming a deterministic perspective. In this paper a probabilistic approach is used to analyse the sensitivity of the dynamic response of a small span bridge due to the variability of the main structural parameters. A filler beam railway bridge was selected as case study and random variables were identified. A variable screening procedure was performed in order to determine which variables had a higher influence on the dynamic response of the bridge. Simulation techniques were applied to analyse the variability of the dynamic response of the bridge, as these methods allow an accurate consideration of the randomness of the main structural parameters. Based on the simulation results, a traffic safety assessment of the bridge was performed. As conclusion, the safety assessment results are discussed, with special focus on the comparison between the results obtained when adopting the European standards approach and when considering a probabilistic approach.

1. Introduction

The dynamic behaviour of railway bridges has been the research subject for many engineers in the last decades since the dynamic effect caused by trains crossing a bridge is one of the most relevant aspects to take into account during the design stage [1–4]. With the generalisation of high-speed railway lines in the last decade, the interest in this theme has grown. Recent research has shown that excessive vibrations have a higher tendency to occur for speeds above 200 km/h as a consequence of the resonance phenomena [5,6]. This can lead to several problems, namely the instability of the ballast layer, the loss of contact between the wheel and the rail, the increase of fatigue-related damage or even the comfort of the passengers. The current European standards reflect the concern for excessive vibrations by imposing the application of a dynamic analysis in almost every case where the maximum line speed exceeds 200 km/h [6].

Furthermore, it is observed that the resonance phenomenon occurs more often in short span bridges [5,7]. In French high-speed lines many problems were reported in early stages, especially on short span structures, due to the excessive vibration caused by resonance phenomena, which led to ballast instability causing a rapid deterioration of track quality [8]. It is also important to remind that in short span bridges the dynamic behaviour is not only influenced by the structural properties of the bridge but it is also strongly affected by the dynamic characteristics of the track, namely the ballast and the rail, as well as the dynamic properties of the vehicle. These aspects result in particularly difficult predictions of the dynamic response during the design stage for this type of structure [9]. During this stage it is common that some aspects are not entirely known, leaving the designers to face some major uncertainties. Unfortunately, these uncertainties may be responsible for unexpected dynamic response of railway bridges, which can result in higher acceleration values than those considered admissible in the European standards [6].

Recent studies tried to evaluate the influence of ballast on the dynamic response of small to medium span bridges, namely to understand the contribution of the ballast layer to the global bending stiffness and the correspondent first eigenfrequency of the bridge, which is known to have a high correlation with resonance effects [10]. In Ref. [11] the use of fluid viscous dampers was suggested in order to control the vibrations in short span bridges. Another study focused its attention on the properties of the vehicles. Instead of modifying the properties of the bridge, the use of size-adjusted vehicles was proposed. Since the resonance phenomenon is caused by cyclic excitation of the bridge due to load repetition, this work proposed the introduction of size-adjusted vehicles in the train arrangement so that the vibration would become "out of phase" and, consequently, suppressing resonant effects [12].

From the literature it can be noticed that most of the work done in this research field was performed through deterministic analysis. This reveals that not much attention has been given to the variability of the parameters that are known to influence the dynamic

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response of the bridge or to the identification of the parameters that have a significant effect in the structural response. The concern about the variability of the parameters can be seen in Ref. [13]. In that paper some properties of both the bridge and vehicle were considered to be random, and a reliability analysis based on response surface methods was performed, in order to assess how variations in the parameters affect the dynamic response. A prestressed concrete box girder bridge was used as case study and the reliability analysis showed that bridge-related uncertainties have greater influence in the reliability indexes than train-related uncertainties.

The present paper intends to introduce a different perspective on this subject keeping in mind the variability of the bridge parameters and to understand how this variability affects the dynamic behaviour of a short span bridge. Since the limit state functions are extremely complex when a large number of variables are considered, simulation techniques were applied in this paper. Simulations techniques allow a large number of experiments to be performed, taking into account the real variability of the structural parameters of the bridge. In this paper the Monte Carlo method, which is the most common simulation method, was used [14].

A bridge with six simply supported spans of 12 m each was selected as case study. The displacements and accelerations at several points of the span were analysed for several hypothetical scenarios. The Monte Carlo method will allow the evaluation of how the dynamic response of the bridge is affected by changes in its properties and which variables play the most important role in the dynamic behaviour. Besides determining which variables are the most important for the dynamic response, a safety assessment of the bridge, based on the simulation results, was also performed in order to establish train speed limits on the bridge.

2. Case study – Canelas Railway Bridge

The present case study is the Canelas Bridge, located in the Northern line of the Portuguese railway. The bridge has six simply supported spans of 12 m each, resulting in a total length of 72 m.

The bridge deck is a composite structure consisting of two half concrete slab decks with nine embedded rolled steel profiles HEB 500. This kind of structural system is called filler beam and is a very common structural solution for small span bridges in the European high-speed railway lines, especially in France and Germany [11,15]. A general view of the bridge used as case study is shown in Fig. 1, as well as the typical cross section of the bridge deck.

As can be seen in Fig. 1, the bridge has two separate and independent decks, each one supporting a single track. However, the ballast layer is continuous over both decks, which can originate some connection between the decks. This fact was not considered in the current work, though recent investigations studied the interaction effects between independent decks due to the continuous ballast layer [10]. The columns and the abutments are also unique, hence supporting both decks. Each cross section of the deck has a total width of 6.2 m, where 4.5 m correspond to the width of the concrete slab with a height of 0.7 m and 1.7 m is the width of the cantilever with a variable height from 0.3 to 0.5 m. Embedded on the concrete slab with a spacing of 0.475 m are the referred nine rolled steel profiles HEB 500. Cement plates were placed underneath the concrete slab, between the steel profiles, to be used as formwork during the concreting of the slab. Under each steel profile a laminated neoprene elastomeric bearing is placed, for a total of nine bearings for each deck. It should also be pointed out that each deck has a small ballast retaining wall placed on the top of the slab and right before the beginning of the cantilever, corresponding to a beam with 0.6 m of height and 0.3 m of width.

3. Numerical model

3.1. Numerical model of the bridge

The bridge was modelled with 2D beam elements in the FEMIX program [16]. The numerical model was defined according to the design drawings and in situ measurements. Along with the deck, the model included the ballast, the rail and the bearings. The deck and the rail were modelled as beams, positioned at the corresponding centre of gravity, whereas the bearings were modelled as springs. The connection to the bearings is positioned at the corresponding centre of rotation. The laminated neoprene elastomeric bearings are placed under each rolled steel profile HEB 500. Due to the existence of steel plates between each neoprene layer, each layer acts as an individual spring so the bearing, as a whole, works as a system of series-connected layers. The bearing stiffness was calculated according to [17]:

$$K_v = \frac{1}{\sum_{i=1}^{n} \frac{1}{k_i} \cdot t_i} \tag{1}$$

$$k_i = \frac{E \cdot a \cdot b}{t} \tag{2}$$

$$E = 3 \cdot G \cdot \left(\frac{a}{t}\right)^2 \cdot \gamma \cdot R \tag{3}$$

$$K_h = \frac{a \cdot b \cdot G}{\sum t_i} \tag{4}$$

where G is the shear modulus of the neoprene, a is the largest dimension of the bearing, b is the smallest dimension of the bearing, t is the thickness of the neoprene layers, γ is a coefficient that depends on the relation between the dimensions of the bearings and R is a coefficient that takes into account the effects of dynamic loads.

The ballast behaviour predicted in Ref. [5], due to frictional effects, follows a bi-linear relationship. The ballast has a linear elastic range until a relative horizontal displacement, u_0, of 0.002 m is reached, followed by a plastic phase. In this work a shear resistance, k, of 20 kN/m, corresponding to an unloaded track, was considered. Since the relative displacements are smaller than the u_0 limit, the ballast stiffness was computed in accordance with the elastic range. Horizontal springs were used to reproduce the frictional behaviour of the ballast. The connection between the track elements and the deck elements, and the connection between the deck elements and the bearings was accomplished by means of rigid beams. A longitudinal scheme of the Canelas Railway Bridge can be seen in Fig. 2.

The structural system of the bridge consists of simply supported beams. However, the rail is continuous and this continuity affects the dynamic response of the bridge. This is included in the numerical model by extending the rail 10.5 m in both directions over the length of the bridge. Experimental campaigns on the bridge also confirmed that all the spans have similar dynamic response and for this reason there is no need to include all the spans in the finite element model, which allows for the consideration of a lighter numerical model. A schematic view of the bridge model used can be seen in Fig. 3.

3.2. Random variables

Taking into account the properties of the bridge, several variables that might have relevant nondeterministic properties, which variation might lead to a relevant variability on the structural response were selected at an early stage of the work. These variables may