Dynamic behaviour of a railway viaduct with precast deck

Andreia Meixedo\(^1\), Diogo Ribeiro\(^2\), Rui Calçada\(^1\), Raimundo Delgado\(^1\)

\(^1\)Faculty of Engineering, University of Porto, R. Dr. Roberto Frias, 4200-465 Porto, Portugal
\(^2\)School of Engineering, Polytechnic of Porto, R. Dr. António Bernardino de Almeida, 4200-072 Porto, Portugal

email: ameixedo@fe.up.pt, drr@isep.ipp.pt, ruiabc@fe.up.pt, rdelgado@cloud.fe.up.pt

ABSTRACT: This paper describes the dynamic effects induced by traffic on a railway viaduct with a precast deck, located in the Portuguese railway network. For this purpose, numerical models of the viaduct and TGV Double high speed train were developed. The dynamic analyses allow evaluating the influence of different numerical methods for performing the train-bridge interaction, and the inclusion of track irregularities, in the dynamic response of the train-bridge system. Also the influence of the control point on different train vehicles and inside a vehicle, and the inclusion of the passenger-seat system in the dynamic response of the train subsystem, is analysed. The assessment of the train-bridge system dynamic responses is performed in terms of structural safety, track stability as well as passenger comfort according to EN1991-2 (2003).

KEYWORDS: railway viaduct; TGV Double; train-structure interaction, track irregularities, track stability, passengers comfort.

1 INTRODUCTION

In the last years, the adoption of economic and time efficient construction methods has revived the importance of prefabrication in railway bridges and made indispensable knowing in detail the dynamic behaviour of such type of structures.

The dynamic analyses of train-structure system are usually performed based on the finite element method, and involve an adequate modelling of the different subsystems, bridge, track, train, and their interfaces [1]. In order to obtain more realistic results, the application of methodologies considering the train-structure dynamic interaction is an important aspect, especially in situations requiring the evaluation of passenger comfort, to analyse the wheel-rail contact stability or evaluate the track irregularities effects. Several researchers concluded that not taking these effects into account may lead to very conservative estimates of the dynamic response of the train-structure system, particularly for resonant speeds [2,3].

This paper is centered on the evaluation of the dynamic effects induced by the passage of the TGV Double high speed train on Alverca railway viaduct. The dynamic interaction model of both subsystems, train and structure, was based on finite element method and the dynamic analyses were performed on TBI software developed in Matlab. The assessment of the dynamic behaviour of the train-bridge system involved evaluating the influence of the numerical method for performing the interaction between train and bridge subsystems, and the influence of track irregularities. Also the influence of the control point on different train vehicles and inside one vehicle of the train, and the inclusion of the passenger-seat system, on the train subsystem dynamic response is analysed. The evaluation of the dynamic responses considered aspects related to structural safety, track stability and passengers comfort, based on the most recent criteria established in EN1991-2 [4] and EN1990-AnnexA2 [5].

2 ALVERCA RAILWAY VIADUCT

2.1 Description

Alverca viaduct is a flyover structure located at the northern line of the Portuguese railway’s that establishes the connection between Lisbon and Porto. Its construction allowed separating the rail traffic flowing in the downstream and upstream directions of the line, maintaining the maximum speed of trains at 200 km/h. Figure 1 presents a perspective view of the North side of the viaduct and a cross section of the deck.

Figure 1. Alverca railway viaduct: a) cross view, b) perspective view
The viaduct has a total length of 1091 m divided in 47 successive simply supported spans, with lengths of 16.5 m, 17.5 m and 21.0 m. Each span supports one single railway track and consists in a single-cell box girder deck composed by a prefabricated U-shaped beam connected by an upper slab cast in situ. The deck is supported in the piers and in the abutments by elastomeric reinforced bearings, which are fixed in one extremity and longitudinally guided in the other extremity. The track is continuous between successive spans and is composed by 30 cm of ballast, monoblock sleepers and UIC60 rails.

2.2 Numerical model

The numerical model of the viaduct was carried out using a 3D finite-element model including the track developed in ANSYS software [6]. The model focused on the three simply supported spans adjacent to north abutment, one of them with 16.5 m (span 1) and the other two with 21.0 m (spans 2 and 3). Figure 2 presents an overview of the numerical model including a detail of the track.

The prefabricated beam, the upper slab and the ballast retaining walls were modelled using shell finite elements. The ballast layer, sleepers and rail pads were modelled by volume finite elements. The rails were modelled as beam elements, positioned at their centre of gravity. The track was modelled in an extension corresponding to the viaduct length and in a distance of 6 m from the north abutment, in order to simulate the support of the track on the adjacent embankment. Each support was regarded as a single point and modelled by a spring element. The non-structural elements (safeguards, edge beams, etc.) were considered as additional masses and applied to the nodes of the FE mesh according to their real location.

The compatibility of displacements and rotations between the nodes of the precast beam and the nodes of the upper slab and the compatibility of displacements between the nodes of the upper slab of the deck and the lower nodes of the ballast layer were accomplished by rigid finite elements.

The calibration of the numerical model was performed by means of an iterative procedure using a genetic algorithm and based on modal parameters, frequencies and modal configurations, identified from an ambient vibration test [7]. The calibration allowed obtaining optimal values for a large number of numerical parameters, significantly improving the agreement between numerical and experimental modal responses. A detailed explanation of the experimental model calibration is described in Malveiro et al. [7].

Figure 3 presents the main global vibration modes of the deck after calibration. Modes 1G, 2G and 5G are associated to simultaneous bending movements of spans 1 and 2. Mode 3G is associated to isolated bending movements of span 3 and mode 4G is a torsional mode.

The main geometrical and mechanical parameters of the numerical model of the viaduct based on the viaduct’s project information and on the optimum values obtained from the calibration process can be consulted in reference [7].

3 TGV DOUBLE TRAIN

3.1 Description

TGV double is an articulated train with two equal and symmetrical disposed compositions. Each composition is formed by 2 power cars, 2 transition cars and 6 passenger cars. The train has a total of 52 axles, a length of approximately 400 m and can reach a speed of 320 km/h. The axle loads varies between 163 kN and 170 kN.
Table 1. Geometrical and mechanical parameters of TGV Double train.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Parameter</th>
<th>Power car</th>
<th>Transition car</th>
<th>Passenger car</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>mass</td>
<td>$M_c$</td>
<td>$51500$</td>
<td>$35860$</td>
<td>$22525$ kg</td>
</tr>
<tr>
<td></td>
<td>rotational</td>
<td>$J_e$</td>
<td>$1.050 \times 10^6$</td>
<td>$1.658 \times 10^6$</td>
<td>$0.810 \times 10^6$ kg.m$^2$</td>
</tr>
<tr>
<td>Longitudinal damper</td>
<td>upper</td>
<td>$D_u$</td>
<td>-</td>
<td>$0.0495 \times 10^6$</td>
<td>N.s/m</td>
</tr>
<tr>
<td></td>
<td>lower</td>
<td>$D_l$</td>
<td>-</td>
<td>$0.0660 \times 10^6$</td>
<td>N.s/m</td>
</tr>
<tr>
<td>Passenger-seat system</td>
<td>mass</td>
<td>$M_s$</td>
<td>-</td>
<td>$80$</td>
<td>$80$ kg</td>
</tr>
<tr>
<td></td>
<td>stiffness</td>
<td>$k_s$</td>
<td>$58.4 \times 10^3$</td>
<td>$58.4 \times 10^3$</td>
<td>N/m</td>
</tr>
<tr>
<td></td>
<td>damping</td>
<td>$D_s$</td>
<td>-</td>
<td>$1658.6$</td>
<td>N.s/m</td>
</tr>
<tr>
<td>Structure</td>
<td>mass</td>
<td>$M_b$</td>
<td>$2200$</td>
<td>$2200$</td>
<td>$2900$ kg</td>
</tr>
<tr>
<td></td>
<td>rotational</td>
<td>$J_b$</td>
<td>$1900$</td>
<td>$1900$</td>
<td>$2508$ kg.m$^2$</td>
</tr>
<tr>
<td>Wheelset</td>
<td>mass</td>
<td>$M_r$</td>
<td>$1700$</td>
<td>$1900$</td>
<td>$1900$ kg</td>
</tr>
<tr>
<td>Primary suspension</td>
<td>stiffness</td>
<td>$k_p$</td>
<td>$2.60 \times 10^6$</td>
<td>$2.60 \times 10^6$</td>
<td>$2.00 \times 10^7$ N/m</td>
</tr>
<tr>
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<td>damper</td>
<td>$D_p$</td>
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<td>$1.20 \times 10^6$</td>
<td>$1.20 \times 10^7$ N.s/m</td>
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<tr>
<td>Secondary suspension</td>
<td>stiffness</td>
<td>$k_s$</td>
<td>$3.26 \times 10^6$</td>
<td>$0.90 \times 10^6$</td>
<td>$0.580 \times 10^7$ N/m</td>
</tr>
<tr>
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<td>damper</td>
<td>$D_s$</td>
<td>$0.90 \times 10^6$</td>
<td>$2.00 \times 10^4$</td>
<td>- N.s/m</td>
</tr>
<tr>
<td>Wheel-rail contact</td>
<td>stiffness</td>
<td>$k_r$</td>
<td>$1.53 \times 10^9$</td>
<td>$1.53 \times 10^9$</td>
<td>$1.53 \times 10^9$ N/m</td>
</tr>
</tbody>
</table>

Figure 4. TGV Double: a) train dimensions; b) dynamic model; c) numerical model; d) perspective view of the numerical model
3.2 Numerical model

The three-dimensional finite element model of the train was developed in ANSYS software. The carbody, bogies and axles of the vehicles were modelled by means of rigid beams connected by springs and dampers simulating the primary and secondary suspensions.

Table 1 shows the main mechanical and geometrical parameters of the numerical model of TGV Double. The damper properties of the articulated connection between cars (Du and Di) were based on values proposed by Lee and Kim [8]. The dynamic characteristics of the passenger-seat system were estimated based on the results of a dynamic test [9]. The remaining parameters’ values were defined according to ERRI D214/RP9 [10].

Figure 4 illustrates the dynamic and numerical models used for the power car, transition car and passenger car, including informations about the dimensions and the dynamic parameters’ designations.

The carbody and bogies were modelled by rigid beams with lumped masses, \( M_s \) and \( M_b \), and rotational inertia, \( J_s \) and \( J_b \), respectively. In the articulated section between vehicles, a release at the rigid beams’ ends was included, allowing the relative rotations between vehicles. The secondary and primary suspensions were modelled by spring-dashpot assemblies with stiffnesses, \( k_s \) and \( k_p \), and damping constants \( D_s \) and \( D_p \), respectively. The wheelset is defined by a lumped mass \( M_r \), while the wheel-rail contact stiffness was modelled by a Hertz-spring with stiffness \( k_c \). The upper and lower longitudinal dampers, positioned between the intermediate cars, were modelled by spring-dashpot assemblies with damping constants \( D_u \) and \( D_l \), respectively. Additionally the passenger-seat system was modelled, in a simplified manner, by a one-degree-of-freedom composed of a lumped mass, \( M_s \), over a spring-dashpot assembly with \( k_s \) and \( D_s \) as stiffness and damping constant, respectively.

3.3 Modal parameters

Figure 5 illustrates some of the modal configurations involving the intermediate vehicles of the train, in particular those related to the carbody (1C, 2C and 3C) and one bogie (1B, 2B and 3B). The modal configurations are represented only for the first composition of TGV-Double.

The carbody’s modal configurations involve global movements of all intermediate vehicles. In the carbody modes the movements of the bogie have very low amplitude. The same applies to the bogies modes where the carbody shows very limited movements.

The frequencies values are ranged between 0.75 Hz and 1.20 Hz, for the carbody’s vibration modes, and between 5.8 Hz and 6.5 Hz for bogies’ vibration modes. These values are in good agreement with the values presented in literature [11].

In case of passenger-seat system, the frequency values are approximately 4.3 Hz, which are similar to the values estimated by Wei and Griffin based on experimental campaigns performed on railway vehicles’ seats [12].

![Modal configurations](image)

Figure 5. Numerical modal parameters of TGV Double train.

4 Dynamic response of the train-structure system

The dynamic responses were derived from TBI software [13] developed in Matlab [14] which efficiently performed the dynamic analyses considering the train-structure interaction and including track irregularities. The software uses the modal superposition method for solving the dynamic equilibrium equations of the viaduct, and a direct integration method (Newmark method), for solving the dynamic equilibrium equations of the train.

The contribution of 33 vibration modes for the response of the viaduct, with frequencies between 6.73 Hz and 30 Hz, was considered. The time step of the analysis was equal to 0.001 s. The adopted values of the damping coefficients were equal to the average values of those obtained from an ambient vibration test [7]. A value of 1 % of damping coefficient was considered for the experimentally non-identified modes according to EN1991-2 [4].

4.1 Track irregularities

The track irregularities were obtained based on records provided by the track inspection vehicle EM 120 from REFER. Figure 6 illustrates the longitudinal levelling profiles of the left and right rails, in a track section between \( \text{km} +18.6765 \) and \( \text{km} +19.7735 \), which includes the entire Alverca viaduct. The track irregularities of the first three simply supported spans are outlined in the figure. These records consider the contributions related to wavelengths between 3 m and 70 m. The maximum amplitude of the irregularities is approximately 5.4 mm and occurs near the mid-section of span 2.
4.2 Dynamic response of the viaduct

Figure 7 shows the maximum values of displacement at the upper slab of the mid-span section of span 2 of the viaduct, for the passage of TGV train at different speeds, considering two different methods: moving loads and train-bridge interaction, with and without track irregularities.

The differences between both methods are relevant at the resonant peak, which occur for speeds between 420 km/h and 460 km/h, where an increase of approximately 10 % in the displacement values for moving loads method, in comparison with a train-structure interaction method, is registered. Also for resonant speeds, the displacements values obtained considering the track irregularities are approximately equal to those obtained without track irregularities.

Regarding the structural safety, the comparison between the maximum deck displacements’ values with the limit value obtained from the static application of the load model LM71 multiplied by the dynamic factor $\Phi_2$ (as presented in Figure 7), shows that this limit is exceeded for resonant speeds (from 440 km/h to 455 km/h) only when the moving loads method is used.

A comparison of the peak values of vertical accelerations of the deck with the regulamentar limit of 3.5 m/s² for ballasted tracks indicated in EN1990- Annex A2 [5], demonstrates that track stability criteria is accomplished for speeds up to 400 km/h.

4.3 Dynamic response of the train

4.3.1 Influence of track irregularities

Figure 9 presents the maximum accelerations values, as function of speed, measured at transition car R8 of the first composition, considering or not the track irregularities.

From the observation of the figure it can be noticed that up to speeds of 340 km/h the inclusion of track irregularities influence considerably the train’s dynamic response. As example for a speed of 190 km/h there is an increase of 700 % in the train’s dynamic response due to the inclusion of track irregularities. For resonant and near resonant speeds the influence of track irregularities is less pronounced because the influence of the movements of the bridge assume greater importance comparatively to the amplitude of track irregularities.
It should also be noted that the maximum acceleration values on car R8, equal to 0.6 m/s², is considerable lower than the limit of 1.0 m/s² defined in EN1990-Annex A2 [5] for a very good passenger comfort level.

4.3.2 Influence of vehicle

Figure 10 illustrates the maximum acceleration values, as a function of speed, at three distinct vehicles (R1, R5 and R8) considering a control point located at the carbody, near the front bogie, and with inclusion of track irregularities.

As expected, the maximum acceleration responses on vehicles R5 and R8 are considerably higher compared with those obtained at vehicle R1. The last vehicle of the train is more influenced by the movements of the bridge comparatively to the first vehicle, since the amplitude of vibration of the viaduct tend to considerably increase with the passage of the successive groups of axles of the train, especially in resonant speeds.

4.3.3 Influence of vehicle’s control point

Figure 11 shows the maximum acceleration values, as a function of speed, at three distinct points (C1, C2 and C3) of passenger car R5 and with inclusion of track irregularities. Control points C1 and C3 are located at the extremities of the carbody and control point C2 is located at the midspan of the carbody.

The results show that the maximum acceleration values registered at the ends of the carbody, in positions C1 and C3, are higher than those registered at position C2. The increased response amplitudes in the extreme positions are associated with the contribution of the longitudinal rotation modes of the carbody.

4.3.4 Influence of passenger-seat system

Figure 12 shows the maximum acceleration values, as a function of speed, at the seat base (C) and passenger (P), located at the extremity of passenger car R8 and considering the track irregularities.

The results show that the accelerations values measured at the passenger are slightly higher comparatively with accelerations at the seat base, demonstrating that the characteristics of the seat structure are important for evaluating the passenger’s dynamic response.

5 CONCLUSIONS

This paper was focused on the analysis of train-structure interaction effects on the dynamic response of Alverca railway viaduct under the passage of TGV Double high speed train. For this purpose, three-dimensional numerical models of the viaduct, including the track, and train were developed.

A sensitivity study of the viaduct and train dynamic responses, in terms of displacements and accelerations, considering a wide range of circulation speeds, including resonance, was carried out.
Regarding the viaduct’s response, the results from moving loads and train-structure interaction methods are almost identical with exception of resonant speeds, where the maximum response values are higher using the moving loads approach. The regulamentar track stability criterion was accomplished for circulation speeds up to 400 km/h.

For the train dynamic response, the inclusion of the track irregularities increased considerably the accelerations inside the vehicles of TGV train, especially in non-resonant speeds. The peak values of acceleration in the first vehicles of TGV train are considerably lower compared with those obtained for intermediate and end vehicles, due to the increasing amplitude of the viaduct movements with the passage of the successive groups of axles of the train. Also the maximum acceleration values registered at the carbody’s end positions are higher compared to those registered at an intermediate position, essentially due to the contribution of the longitudinal rotation modes of the carbody. The very good level of passenger comfort was achieved for all analyzed vehicles and positions inside the carbody. The inclusion of the passenger-seat system in the train’s numerical model allowed obtaining the dynamic response at the passengers, improving considerably the evaluation of passengers comfort.

As future developments, the authors intend to evaluate the performance of the train-bridge interaction model in the prediction of vibrations of the upper slab of the deck for the passage of Alfa Pendular tilting train, which currently operates over the viaduct at a speed near 220 km/h. The vibrations of the upper slab are significantly influenced by the contributions of local modes of vibration, with frequencies between 25 and 60 Hz, which are particularly influenced by the track irregularities.

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