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Validation of modeling and analysis methodology for train-bridge interaction in terms of displacements by a Python-Abaqus Framework

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Abstract. This paper proposes a framework for the dynamic analysis of railway bridges, which presents a challenge: to achieve accurate results from complex models while maintaining computational efficiency and low operational cost. In this framework, the structure is modeled, and modal analysis is performed, which is calibrated in terms of the fundamental natural frequency. After checking whether the natural frequency of the structure is adequate, integrate it with the forces coming from the vehicle. Wheel resultant forces are determined in a Python script, based on the properties and characteristics of the vehicle and the spectrum of track irregularities. Two examples of the application of the train-bridge interaction analysis methodology will be presented. First, a numerical example is performed. Second, an example using experimental data of real monitoring of a bridge subject to train action is run. The proximity of results demonstrates the ability to analyze and represent the physical phenomenon in terms of maximum displacements. The proposal of this Framework and its validation in numerical and experimental terms is important for the development of in-depth research in the area, for example, to generate a long dataset to allow the training of an artificial neural network or the improvement of analysis methods with considerations of more variables.

Keywords: Railway Bridges, Vehicle Model, Train-Bridged Dynamic Interaction, Structural Analysis.

1 Introduction

Railways are an important mode of transport, especially suitable for transporting large loads over long distances due to their low cost, as well as for transporting passengers, with improved quality and increased speed of vehicles. This mode of transport is by far more sustainable and environmentally friendly than its competitors [1]. Bridges are auxiliary structures for railways, generally made of reinforced concrete or steel, with different types. Reinforced concrete structures have been widely used for the construction of railway bridges [2]. Two main fields of study of railway bridges can be distinguished: one for the design of bridges to be built, the other for existing bridges that require durability monitoring or reinforcement.

Over the decades, models to represent the dynamic effect of trains have evolved, from simple moving loads to complex models of dynamic train-rail-bridge interaction. More complex models can represent the results more realistically, but they also require higher computational costs. The dynamic analysis of railway bridges challenges designers to obtain accurate results with a high degree of complexity combined with the efficiency and low computational cost of the model. Engineering researchers study the dynamic effect on bridges caused by moving vehicles using Vehicle–Structure Interaction (VSI) models. This technique describes the dynamic behavior of trains loaded over bridges. For Peng et al. [3], studying the multiple complex interactions between the different parts of the system is challenging.

Structures subjected to dynamic loads require a study of the dynamic effects generated to ensure that the behavior of the structure will be analyzed correctly. Understanding all the factors and parameters that affect the results and being able to model them is a challenge for designers [4].

Railway bridge and vehicle dynamic effects have been studied using finite element numerical models, considering the complexity and the influence of various relevant aspects. For example, speed, span length, train load, track irregularities, wheel-rail contact, ballast type, support elements, and other factors can influence the

responses of the structure and vehicle. These models present simplifications and considerations that can cause some errors, and to improve the simulation results the model calibration process is carried out. The accuracy of these models are strongly depends on the experimental validation of the numerical results [5].

Computational modeling strategies include considering the vehicle with a multibody formulation to represent the carbody, bogies and wheelsets, connected through flexible elements that simulate the primary and secondary suspensions, and modeling the bridge employing the finite element method.

Numerical models are validated by comparing numerical and experimental dynamic responses under traffic loads. Several authors also validate their models by comparing numerical responses with data obtained from instrument monitoring of those bridges under vehicle action. The validation stage is considered crucial to legitimize the accuracy of numerical results. Thus, this work aims to perform vehicle-bridge dynamic interaction computational modeling using a 31-degree-of-freedom vehicle model applied to a simple beam model, and validate this model ability to accurately represent the displacement behavior of the bridge.

2 31-degree-of-freedom vehicle model

This section describes the vehicle model employed in this work. The stiffness, damping and mass matrices used were presented by Antolin et al. [6], and the mathematical model with the forces of irregularities is developed. The equations of motion of a three-dimensional vehicle are formulated, describing the physical and geometric characteristics and its degrees of freedom.

The three-dimensional model of a railway vehicle is developed through the association of rigid bodies interconnected with suspension systems. These rigid bodies have homogeneous masses and mass moments of inertia. The model consists of a carbody, a front bogie, a rear bogie, primary suspensions, secondary suspensions and four wheelsets. Primary suspensions are stiffer than secondary suspensions and act between the axles and the bogies. Secondary suspensions act vertically between the bogies and the carbody. Each suspension system consists of a linear elastic spring and a linear viscous damper. Figure 1 shows the degrees of freedom of the vehicle.

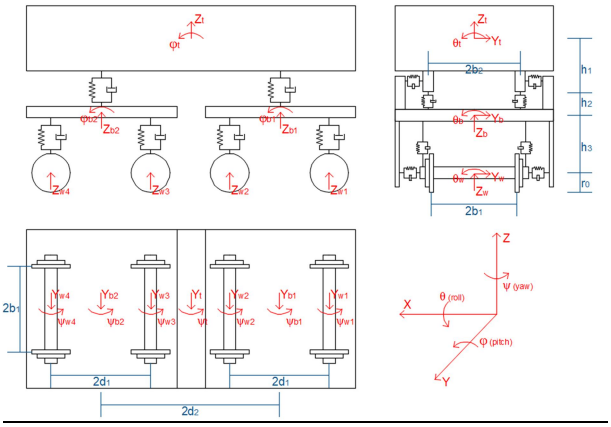


Figure 1. Degrees of freedom of the three-dimensional railway vehicle model

The carbody and bogies have three degrees of freedom, namely, rotation around the longitudinal and transverse axes, and vertical displacement. The wheelsets have four degrees of freedom, namely, rotation around the longitudinal and transverse axes, and vertical and transverse displacements.

3 Vehicle-bridge interaction computational modeling

The vehicle-bridge interaction system can be divided into vehicle subsystem and bridge subsystem, and interactions are obtained by contact points and their contact forces. An important component is the rail and track system, which represents an elastic support for the wheels and transmits forces to the bridge structure. Several authors developed and applied different methods to solve the vehicle-bridge interaction problem.

Each subsystem can be solved decoupled at each time step and updated until it reaches the convergence parameter. The equation of motion of the vehicle subsystem can be written, in generic form, as:

$$[M^v]\{\ddot{U^v}\} + [C^v]\{\dot{U^v}\} + [K^v]\{U^v\} = \{F^v\} \quad (1)$$

Where the matrices M^v, C^v and K^v are, respectively, mass, damping and stiffness for the vehicle subsystem. The vector U^v is the displacement and the external forces are described by the vector F^v.

The equation of motion of the bridge subsystem can be written, in generic form, as:

$$[M^b]\{\ddot{U^b}\} + [C^b]\{\dot{U^b}\} + [K^b]\{U^b\} = \{F^b\} \quad (2)$$

Where the matrices M^b, C^b and K^b are, respectively, mass, damping and stiffness for the bridge subsystem, and F^b is the nodal load vector generated by the wheel-rail interaction.

The solution of the general model can be performed by implicit or explicit integration methods, such as the Newmark Method [7], the Hilber-Hughes-Taylor Method – HHT [8], the Zhai Method [9], and the Wilson Method [10], which lead to the calculation of the responses at each time step.

The methodology proposed in this work is divided into two main stages: structural modeling, and resulting forces determination. First, the structure is modeled, and modal analysis is performed, which is calibrated in terms of the fundamental natural frequency. After checking whether the fundamental natural frequency of the structure is adequate, integrate it with the forces applied by the vehicle. Such forces are wheel forces which are determined in a Python script based on the properties and characteristics of the vehicle and the spectrum of track irregularities. Figure 2 shows this framework.

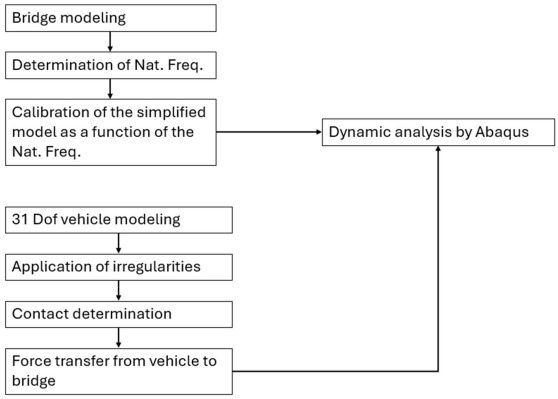


Figure 2. Framework of the methodology

According to Rigueiro [11], irregularities on the railway track are a source of discomfort and loss of vehicle stability due to the vibrations and noise generated, and they lead to the amplification of the dynamic effects that occur on the track and in the vehicle.

The components of irregularities can be divided into vertical (profile or cross-level) and horizontal (direction or gauge bias). The vertical profile irregularity refers to the uneven vertical height along the rails. The vertical cross-level irregularity refers to the elevation difference between the two rails in the same cross-section (superelevation). The direction horizontal irregularity refers to the longitudinal irregularity along the inside center of the rails, and the gauge bias irregularity refers to the bias between the shortest distance of the two rails compared to the standard rail. Bhardawaj et al. [12] and Javaid and Choi [13] present data according to the track class according to the Federal Railroad Administration (FRA) and Power Spectral Density (PSD) parameter data.

4 Numerical and experimental validation

In this section, two examples of application of the train-bridge interaction analysis methodology will be presented. First, a simple example proposed and solved by Yang and Yau [14], which demonstrates the numerical validation of the modeling strategy. This can be considered a classic example, used as a reference for several researchers. Second, an example using data from Malveiro et al. [15], of real monitoring of a bridge subject to train action, applying the 31 DOF vehicle model in the Abaqus software is considered. The proximity of results demonstrates the ability to analyze and represent the physical phenomenon in terms of maximum displacements. This represents a good capacity to analyze the train-bridge interaction combined with a low operational and computational cost methodology.

Example 1: Numerical validation of modeling

Validation example 1 is proposed by Yang and Yau [14] for a simply supported beam of length L=25 m subjected to a moving sprung mass, with the following properties: Young's modulus E=2.87 GPa, Poisson's ratio ν=0.2, moment of inertia I=2.90 m^4, mass per unit length m=2.303 t/m, suspended mass Mv=5.75 t, suspension stiffness kv=1,595 kN/m, and speed v=27.78 m/s.

The model was subjected to modal analysis to calibrate the first vibration mode, resulting in Fn = 4.78 Hz.

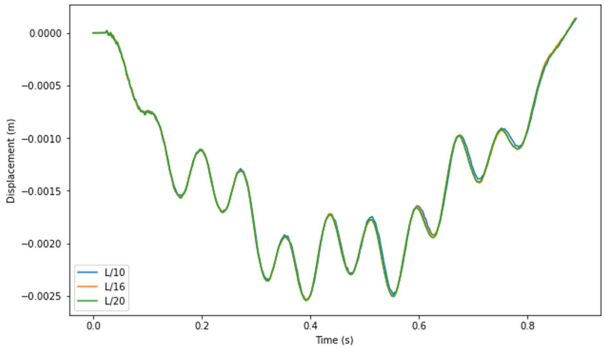


Figure 3. Mesh Convergence: mid-span displacement along time

Figure 3 shows the displacement over time graphs at the middle of the bridge span. The graphs were presented for 3 levels of mesh refinement: L/10; L/16; and L/20, where L is the bridge span. From the graphs in Figure 3 it is possible to see that there is high convergence between the responses and the finer mesh (L/20) is considered adequate.

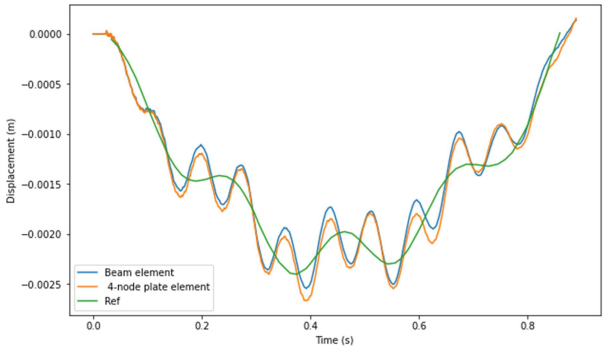


Figure 4. Comparison between beam and plate model

Figure 4 compares the results for the bridge modeled in FEM considering the beam model, plate model and the reference results (Yang and Yau [14]). The smooth nature of the reference curve results from neglecting the influence of higher-order vibration modes. Conversely, the detailed numerical responses exhibit rapid oscillations linked to high-frequency modes excited by the dynamic passage of the train across the bridge.

Example 2: Experimental validation of the model

In this section, one example of application of the train-bridge interaction analysis methodology will be presented, applying the 31 DOF vehicle model in the Abaqus software. The example uses data from Malveiro et al. [15] of real monitoring of a bridge subject to train action. The proximity of results demonstrates the ability to analyze and represent the phenomenon in terms of maximum displacements. This represents a good capacity to analyze the train-bridge interaction combined with a low operational and computational cost methodology.

This example analyzes a prefabricated and pre-stressed concrete bridge with a span of 21 meters of the Alverca Railway Viaduct that composes the Portuguese railways' Northern Line that connects Lisbon to Porto. The viaduct has a total length of 1,091m divided into parts of 16m, 17.5m or 21m of bridge span. The track consists of UIC60 rail with gauge of 1.688m, elastomeric rubber pads, prestressed concrete monoblock sleepers and a 25-cm ballast layer under sleepers.

Malveiro et al. [15] realized a dynamic test under railway traffic to obtain experimental responses, which

were used for validation of a numerical model. Based on the results of Malveiro et al. [15], the modeling and numerical model of 31 dof vehicle proposed in this work have been validated. The test was obtained for the passage of Alfa Pendular train at speed of 185 km/h. According to Ribeiro et al. [16], the Alfa Pendular train has a total length of 158.9m and can reach a speed of 220 km/h. The total weight, in normal load conditions, is 323.3 t. The wagon is 25m long, the distance between bogies is 19m, and the distance between axles is 2.7m.

The characterization of the main parameters of the numerical model of Alfa Pendular train is presented in Table 1, according to Gonçalves [17].

Table 1. Parameters of the numerical model of Alfa Pendular train

Parameter	**Value**	**Parameter**	**Value**
Car body mass	35,640 kg	Stiffness of the primary transversal suspension	30,948,200 N/m
Car body roll moment of inertia	55,120 kg m^2	Stiffness of the primary vertical suspension	1,652,820 N/m
Car body pitch moment of inertia	1,475,000 kg m^2	Damping of the primary vertical suspension	16,739 N s/m
Car body yaw moment of inertia	1,477,000 kg m^2	Stiffness of the secondary longitudinal suspension	4,905,000 N/m
Bogie mass	2,829 kg	Stiffness of the secondary transversal suspension	2,500,000 N/m
Bogie roll moment of inertia	2,700 kg m^2	Stiffness of the secondary vertical suspension	734,832 N/m
Bogie pitch moment of inertia	1,931.49 kg m^2	Damping of the secondary longitudinal suspension	400,000 N s/m
Bogie yaw moment of inertia	3,878.76 kg m^2	Damping of the secondary transversal suspension	17,500 N s/m
Wheelset mass	1,711 kg	Damping of the secondary vertical suspension	35,000 N s/m
Wheelset roll moment of inertia	733.4303 kg m^2	Longitudinal distance between bogies	19 m
Wheelset yaw moment of inertia	733.4303 kg m^2	Longitudinal distance between wheelsets	2.7 m
Stiffness of the primary longitudinal suspension	44,981,000 N/m	Gauge	1.688 m

The example is modeled with a previous support beam, the main beam under analysis, and a subsequent support beam. The stopped train is initially on the previous beam, travels on the main beam at a speed of 51.389 m/s and after completing the passage it rests on the subsequent beam. The reaction force on the train wheels is previously calculated using Python and applied to the Abaqus model. The model represents the wheel as a plate element. The beam is modeled as a bar element. The wheel-beam contact is assigned as "frictionless" in tangential behavior and as "hard contact" in normal behavior. The contact mechanical constraint formulation is the Penalty Method. For dynamic analysis, a time increment of $1.0e10^{-5}$ s is adopted. The model is subjected to modal analysis to calibrate the first vibration mode, resulting in Fn = 6.75 Hz.

This example is performed with three irregularity profiles. In the Irregularity Profile 1 (IP 1), it is adopted the wavelength from 1 to 3 m., while in the Irregularity Profile 2 (IP 2), it is adopted the wavelength from 3 to 20 m, and, finally, in the Irregularity Profile 3 (IP 3), it is adopted the wavelength from 20 to 30 m.

Figure 5 shows the graphs of vertical irregularities along the longitudinal track, with IP 1 on the left, IP 2 in the middle, and IP 3 on the right. This is an important parameter for calculating the forces transmitted by the vehicle to the rail, considered an external excitation that influences the contact force and the response of the structure.

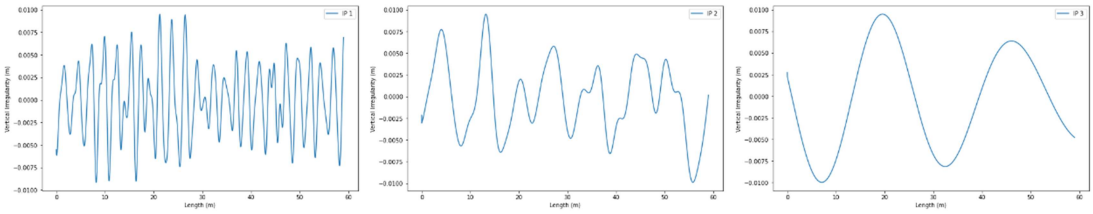


Figure 5. Irregularity Profile: IP 1 (left); IP 2 (middle); IP 3 (right).

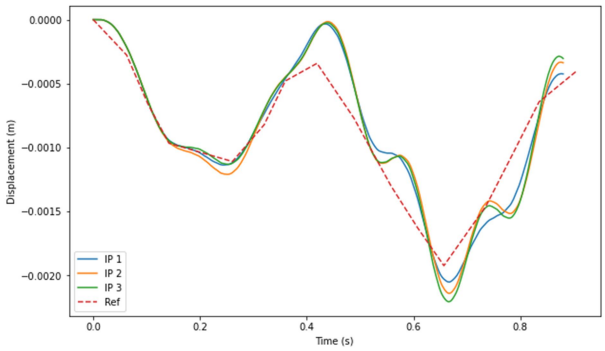


Figure 6. Modeling validation

Figure 6 compares the results for the bridge modeled in FEM considering the beam model and the reference results (Malveiro et al. [15]). Figure 6 shows the displacement-time graphs at the mid-span of the bridge. The results are similar to the reference results, with good correlation between the graphs with numerical solution and through the Python-Abaqus Framework.

5 Conclusions

This work proposed and validated a computational framework for analyzing train-bridge interaction in terms of displacements, using a methodology with Python scripting and Abaqus finite element modeling. The approach relies on a 31-degree-of-freedom multibody vehicle model and a finite element representation of the bridge structure. Forces arising from wheel-rail contact are computed externally in Python, based on track irregularities and vehicle parameters, and then integrated into the structural model.

Two case studies were conducted for validation purposes. The first demonstrated good agreement with classical literature results. The second, based on experimental monitoring data from the Alverca Railway Viaduct in Portugal, confirmed the method's capacity to reproduce maximum displacements under real train loading conditions. The correlation between numerical and experimental results validates the modeling approach in both simplified and complex configurations.

The main advantage of the proposed framework is its balance between accuracy and computational efficiency, making it suitable for large-scale parametric studies, calibration tasks, or the generation of datasets for machine learning applications.

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