Numerical analysis of a reinforced concrete railway bridge considering soil-structure interaction

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Abstract. The integrity and performance of bridges are crucial for railway infrastructure. Consequently, evaluating their condition and dynamic response remains a top priority for infrastructure operators. This paper delves into the study of dynamic structural responses of bridges in the presence of railway-type trains. We focus on the soil-structure interaction process, considering local soil characteristics and foundation types. A six-span reinforced concrete bridge served as our case study. We developed a computational finite element model employing finite shell elements, augmented with calibrated springs to represent the foundations, temporary steel supports, and neoprene bearing supports. The study sheds light on the natural frequencies of vibration, accelerations, and velocities within the railway bridge components. These results were juxtaposed with monitoring data to gauge the bridge's structural response to dynamic loads. The numerical findings closely aligned with the monitoring data, reinforcing the validity of our modeling approach. This model stands as a robust tool to appraise structural conditions and predict bridge behavior throughout its lifespan. Furthermore, it has potential applications in forecasting failures, bolstering monitoring efforts, guiding inspection campaigns, and even merging into a digital twin framework for comprehensive bridge integrity management.

Keywords: finite element method, railway bridges, soil-structure interaction, dynamic analysis.

1 Introduction

Railway bridges are fundamental infrastructure assets for sustaining a country's economy, whether used to transport people or commodities. Throughout their lifecycle, these structures experience deterioration processes that lead to their performance reduction and an increased risk of hazards. Therefore, assessing the structural condition of these assets is crucial to ensure secure operational integrity. In this sense, this paper proposes a computational modeling strategy for the dynamic analysis of railway infrastructure employing a soil-structure interaction (SSI) approach. For this, a properly calibrated Winkler spring model was used to portray the combined effects of the structure-foundation-soil system and its material properties [1].

In this context, research frequently focuses on proposing various methods to depict the interaction between soil confinement and foundations, especially considering its influence on the natural frequency of vibration modes. [2]. König, Salcher and Adam [3] also demonstrated that the damping provided by the soil-structure interaction significantly influences the structural behavior in resonance conditions when using vehicle-bridge interaction models. Thus, a more efficient methodology is sought to represent the effects of the soil and foundation interaction on the asset dynamic behavior to achieve computational responses that closely approximate the actual structure behavior when subjected to vehicle loads.

In the case of soil-structure interaction models applied to bridge foundation elements, most of the published papers use independent linear springs [4]. Other works present SSI techniques based on soil degradation and its plastic behavior for certain load levels. Raheem [5] mentions a strategy for considering soil physical nonlinearity using springs and dampers in deep foundations. The basic concept aims to attribute a nonlinear behavior to the soil due to hysteresis cycles, penalizing the shear modulus according to the level of demand on account of stiffness losses caused by plastic deformations.

Advanced techniques employing two-dimensional finite elements [6] and three-dimensional finite elements [4] have demonstrated encouraging results in modeling soil masses. While the two-dimensional models present challenges in predicting dynamic behaviors related to the asset's torsional processes, the three-dimensional approach comes with its own drawbacks. Notably, the increased degrees of freedom in the finite element mesh can lead to significant escalations in computational processing time and demands.Thus, such practices may be limited to smaller bridges or for analyzing specific and isolated railway infrastructure elements. Previous literature experiences, such as Zhao, Dong and Wang [7], have also displayed that the use of springs to represent the soil confinement effect in deep foundations of bridge abutments produced noteworthy results for the prediction of force-displacement equilibrium curves according to the type of soil in terms of compactness.

This paper presents dynamic results of a railway bridge employing soil-structure interaction techniques through Winkler springs. The numerical model was calibrated and validated according to experimental responses obtained from a monitoring campaign. Thus, the influence of using SSI models was investigated by comparing the computational results concerning natural frequencies, vibration modes, accelerations, and velocities with experimental data, assessing the bridge structural response when subjected to dynamic loads.

2 Railway bridge geometric model

For this paper, a six-span reinforced concrete railway bridge with 180 meters in total length, built in the 80s and rehabilitated in 2017, was employed as a case study. The asset is in the northern region of Brazil. The bridge comprises two continuous sections: the first includes two 25-meter spans, and the second has four 25-meter spans. Each section ends with abutments, and a five-centimeter expansion was introduced between the two continuous segments at the intermediate support. The bridge superstructure consists of two longitudinal beams with rectangular cross-sections, transverse beams, and a concrete deck with variable cross-sections. The superstructure is supported on the pile caps by neoprene bridge bearings. The infrastructure comprises pile caps and caissons supported by a rock layer (Fig. 1).

Figure 1. Reinforced concrete railway bridge employed as a case study

A parameterized geometric model of the reinforced concrete bridge was developed using the environment Rhino 7/Grasshopper. Data about design, construction, and “as is” information obtained from previous in-situ activities were employed to create the geometric model. Grasshopper is a visual programming language that works with Rhino, allowing more efficient computer-aided design applications and enabling parametric modeling. Among the advantages of this technique, the possibility of generating parts of the asset or changing geometric proportions quickly and efficiently stands out. Fig. 2 displays the parametric Grasshopper code of one of the bridge piers.

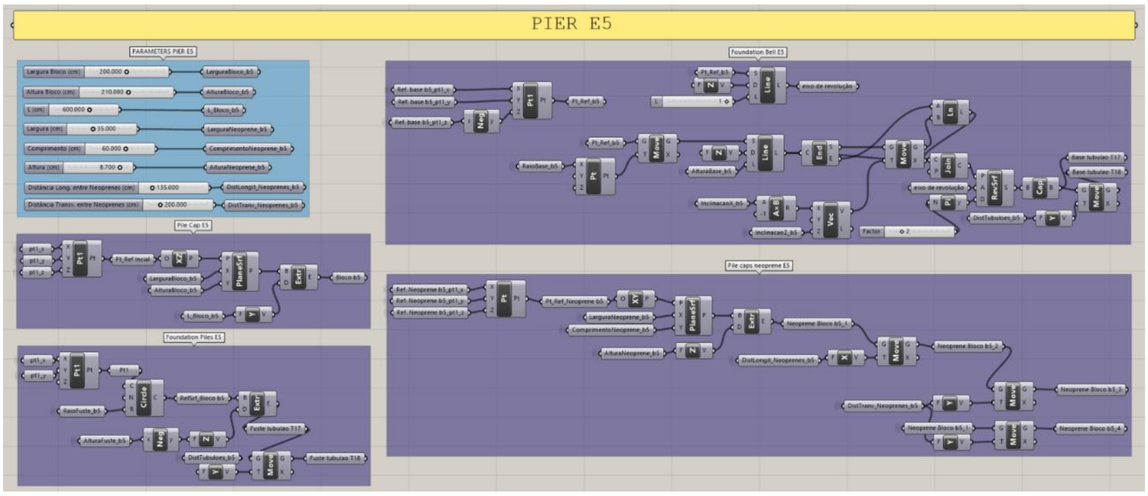


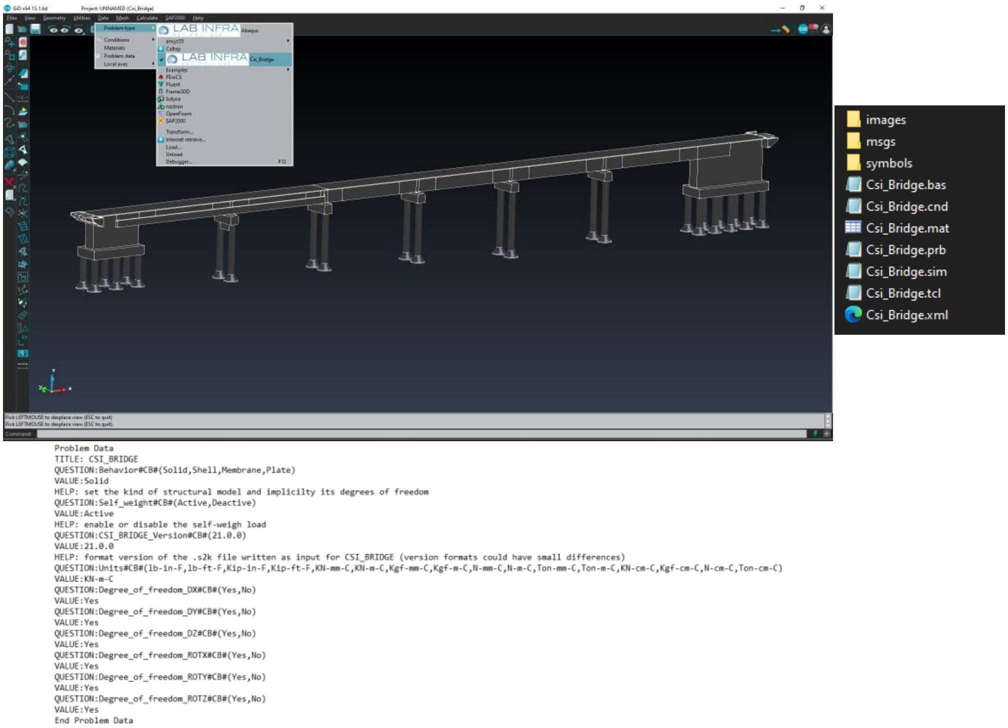
Figure 2. Parametric Grasshopper code of the bridge pier E5

From the parametric code, the geometry of specific bridge components or the entire bridge can be rapidly generated (Fig. 3). Additionally, the geometry parts can be organized by layers representing the asset structural arrangement, supporting numerical model development and metadata inclusion into the geometry components.

Figure 3. Complete parameterized geometric model of the reinforced concrete railway bridge

3 Pre-processing procedure for FEM integration

The pre-processing step of the computational model was generated in the GiD version 15.1.6 program interface (Fig. 4). Thus, customized programming routines were developed to create data files to feed different packages of FEM solvers, automating and scaling the numerical modeling process. This paper will focus on the plugins produced for the CSi Bridge v.21 software. In simple terms, the geometric model is imported into the GiD interface using the native *".3dm"* file extension of Rhino. Subsequently, an unstructured mesh composed of shell elements is generated. From the programming routine created for the input interface of CSiBridge, a *".b2k"* file containing essential information for numerical analysis (mesh data, material properties, and boundary conditions) can be exported and imported into CSiBridge to develop the proposed dynamic evaluations for the bridge.



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Problem Data
TITLE: CSI_BRIDGE
QUESTION:Behavior#CB#(Solid,Shell,Membrane,Plate)
VALUE:Solid
HELP: set the kind of structural model and implicilty its degrees of freedom
QUESTION:Self_weight#CB#(Active,Deactive)
VALUE:Active
HELP: enable or disable the self-weigh load
QUESTION:CSI_BRIDGE_Version#CB#(21.0.0)
VALUE:21.0.0
HELP: format version of the .s2k file written as input for CSI_BRIDGE (version formats could have small differences)
QUESTION:Units#CB#(lb-in-F,lb-ft-F,Kip-in-F,Kip-ft-F,KN-mm-C,KN-m-C,Kgf-mm-C,Kgf-m-C,N-mm-C,N-m-C,Ton-mm-C,Ton-m-C,KN-cm-C,Kgf-cm-C,N-cm-C,Ton-cm-C)
VALUE:KN-m-C
QUESTION:Degree_of_freedom_DX#CB#(Yes,No)
VALUE:Yes
QUESTION:Degree_of_freedom_DY#CB#(Yes,No)
VALUE:Yes
QUESTION:Degree_of_freedom_DZ#CB#(Yes,No)
VALUE:Yes
QUESTION:Degree_of_freedom_ROTX#CB#(Yes,No)
VALUE:Yes
QUESTION:Degree_of_freedom_ROTY#CB#(Yes,No)
VALUE:Yes
QUESTION:Degree_of_freedom_ROTZ#CB#(Yes,No)
VALUE:Yes
End Problem Data
```

Figure 4. GiD interface, problem type files, and segment of the data file that feeds the FEM software

4 Dynamic analysis

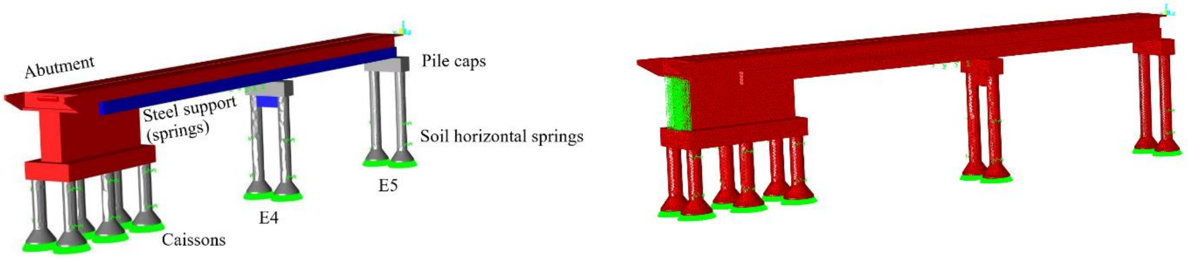
A Fast Nonlinear Analysis (FNA), also known as nonlinear modal time-history analysis, was employed for the system dynamic evaluation. FNA is a modal analysis method useful for static or dynamic assessment of linear and nonlinear structural systems. Due to its computationally efficient formulation, FNA generally provides more accurate and efficient results than the direct-integration time-history analysis. A basic formulation of FNA is given by Li, Peng and Irwin [8]. According to the authors, the method results in a fast recursive algorithm that produces stability in dynamic computational analysis.

An influence-based enveloping analysis was utilized to simulate the load case of a railway vehicle, considering the lane width as the bridge track gauge. Then, a modal time-history analysis with a solution based on natural modes and frequencies was employed for a damping coefficient of 3.6% (experimentally measured) for all vibration modes. The dynamic evaluation was conducted using a time step of 0.1 seconds for 200 steps, leading to a simulation time of 20 s in total. The vehicle speed was 60 km/h with an actuation time of 20 seconds, discretized at intervals of 0.05 seconds. Table 1 presents the properties adopted for the numerical model, representing the material parameters, the thickness of the shell elements, and the stiffness reduction employed to calibrate the proposed model according to the data obtained in the field by a monitoring campaign.

Table 1. Material and cross-section properties adopted for the computational model

Bridge region	Material properties	Shell section properties
Superstructure	E = 24 GPa; ν = 0.2; f_c = 18 MPa	Shell thick; e = 25 cm; $k_{12,\ membrane}$ = 0.65
Infrastructure	E = 21.8 GPa; ν = 0.2; f_c = 15 MPa	Shell thick; e = 17.5 cm; $k_{12,\ membrane}$ = 0.80
Strengthening	E = 29 GPa; ν = 0.2; f_c = 75 MPa	Shell thick; e = 17.5 cm; $k_{12,\ membrane}$ = 0.80

Due to an act of vandalism, the continuous segment with two spans of the bridge had to be recovered and reinforced in 2017. This paper focused on numerically analyzing only this section of the bridge, given its importance and the amount of monitoring data available. Fig. 5 illustrates the computational model developed in CSiBridge composed of three-node shell elements representing the railway bridge after its rehabilitation. The numerical model has about 52,000 nodes and 110,000 finite elements. The railway bridge foundations were assumed as fixed supports at the bedrock region. The reinforcement was modeled according to design features using shell elements.



(a) **(b)**

Figure 5. Bridge computational model: (a) components description after rehabilitation, (b) FEM mesh and springs position

The stiffness adopted for the soil and elastic supports resulted from applying Morrison [9] and Guerreiro [10] models. Table 2 summarizes the spring stiffness values incorporated into the numerical model (foundation, pile caps and abutment). The spring stiffness values used were calculated based on the geometric and material characteristics of the elements.

Table 2. Springs stiffness adopted for the computational model

Asset part	Kx (tf/m)	Ky (tf/m)	Kz (tf/m)	Rx (tf.m/rad)
Abutment	130.0	130.0	---	---
Steel support	---	---	170	---
E4 (pile caps)	7.8	---	8131.0	55.7
E5 (pile caps)	3.3	---	2120.0	10.5
Caisson (h=1.40 m)	8134.0	8134.0	---	---
Caisson (h=3.50m)	10780.0	10780.0	---	---

5 Computational results

The computational model was evaluated and calibrated according to the four vibration modes of the bridge. Fig. 6 and Tab. 3 compare the natural frequency results obtained from the numerical models and the monitoring campaign for each vibration mode. Fig. 7 illustrates the railway bridge vibration modes.

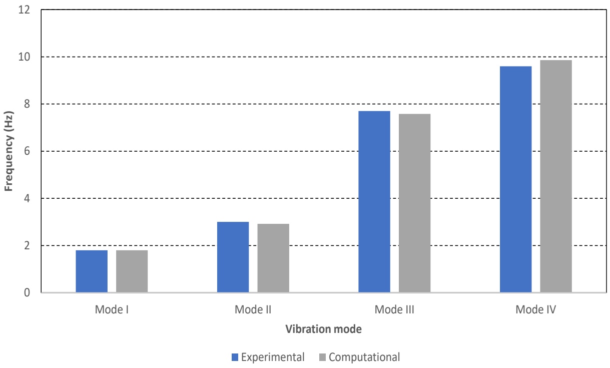


Figure 6. Comparison of the numerical and experimental natural frequency results

Table 3. Natural frequency results and vibration modes

Vibration mode	Experimental	Computational	Variation (%)
Mode I: horizontal flexure	1.8	1.8	0.0
Mode II: horizontal flexure	3.0	2.9	2.7
Mode III: vertical flexure	7.7	7.6	1.6
Mode IV: torsion	9.6	9.9	2.7

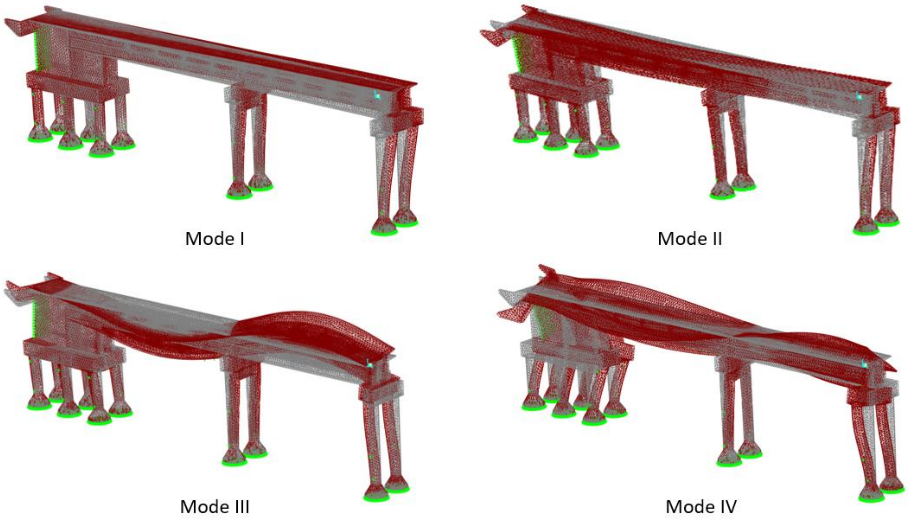


Figure 7. Railway bridge vibration modes

The computational results obtained are close to those measured during the monitoring. The dynamic analysis results were also evaluated using the FNA technique for velocities and accelerations measured in the foundation block on axis E5 (Fig. 5), as displayed in Fig. 8 and Tab. 4. The maximum average velocity obtained from the time-history analysis was less than 40 mm/s (Fig. 8). According to DIN 4150-3 [11], speeds below 40 mm/s do not cause structural problems in concrete structures.

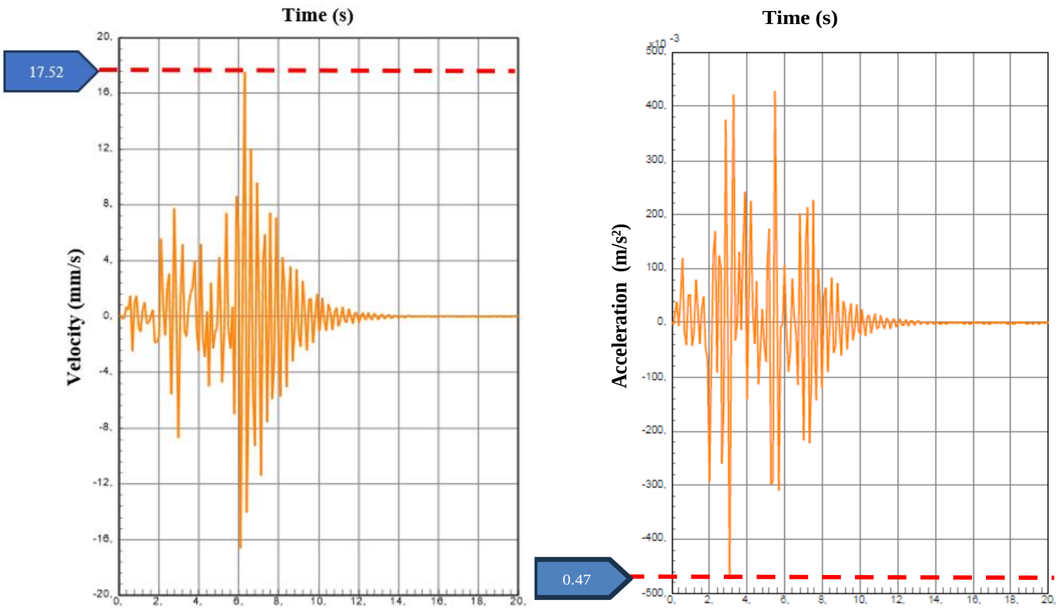


Figure 8. Velocity and acceleration results for the time-history analysis of the foundation block in the E5 axis

Table 4. Dynamic analysis responses for foundation block in E5 axis

Dynamic result	Experimental	Computational	Variation (%)
Longitudinal acceleration (m/s²)	0.50	0.47	6.38
Longitudinal velocity (mm/s)	19.35	17.52	10.44

6 Conclusions

From the results derived from the proposed computational model, the following conclusion can be drawn:

a) Computational responses, encompassing natural frequencies and vibration modes, closely approximate the experimental results obtained by the monitoring campaign, exhibiting a maximum variance of less than 3% in the identified frequencies.

b) The selected models for soil-structure interaction and the representation of elastic supports by Winkler springs satisfactorily represented the railway bridge dynamic behavior.

c) The dynamic analysis results for the foundation block on the E5 axis revealed a velocity of approximately 17.52 mm/s, well below the critical threshold of 40 mm/s, which is associated with potential infrastructure damage.

d) The calibrated numerical model can now be used for several analyses to assess the bridge structural condition and support further experimental investigations.

References

[1] A. L. Gamino, M. A. Amaral, R. R. Santos, G. V. Menezes, T. N. Bittencourt and M. M. Futai. “Soil-structure interaction approach of a timber-concrete composite pedestrian bridge”. *Pract. Period. Struct. Des. Constr.*, vol. 28, n. 3, pp. 04023018, 2023.
[2] K. A. Shaik and G. P. Chandradhara, “Soil structure interaction studies on Krishnaraja Sagara Bridge, Mysuru”. *Materials Today*, vol. 52, n. 3, pp. 549–555, 2022.
[3] P. König, P. Salcher and C. Adam, “An efficient model for the dynamic vehicle-track-bridge-soil interaction System”. *Engineering Structures*, vol. 253, n. 1, pp 1-15, 2022.
[4] M. Shamsi, M. Zakerinejad and A. H. Vakili, “Seismic analysis of soil-pile-bridge-train interaction for isolated monorail and railway bridges under coupled lateral-vertical ground motions”. *Engineering Structures*, vol. 248, n. 1, pp. 1–21, 2021.
[5] S. E. A. Raheem. *Soil–structure interaction for seismic analysis and design of bridges. Innovative Bridge Design Handbook: Construction, Rehabilitation and Maintenance 2nd Edition*. Butterworth-Heinemann, 2022.
[6] A. A. Faizan and O. Kirtel, “Non-linear soil-structure interaction analysis of railway bridge subjected to earthquake ground motions considering different types of soil”. *Arabian Journal of Geosciences*, vol. 14, n. 1, pp. 1–11, 2021.
[7] Q. Zhao, S. Dong and Q. Wang, “Seismic Response of Skewed Integral Abutment Bridges under Near-Fault Ground Motions, Including Soil–Structure Interaction”. *Applied Sciences*, vol. 11, n. 7, pp. 1–24, 2021.
[8] K. Li, J.X. Peng and G.W. Irwin, “A Fast Nonlinear Model Identification Method”. *IEEE Trans. Autom. Control*, 50, 1211-1216 (2005).
[9] N. Morrison. *Interacción suelo-estructuras: semi-espaço de winkler*. MSc. Dissertation. Barcelona: Universidad Politécnica de Cataluña, 1993.
[10] L. Guerreiro. *A borracha na concepção anti-sísmica.* Faculdade de Engenharia da Universidadedo Porto. Porto: FEUP, 2003.
[11] DIN 4150-3. *Structural vibration part 3: effects of vibration on structures.* 1-11 (1999).