XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGENEERING

Vibration analysis and human comfort assessment of pedestrian footbridges when subjected to dynamic vandalism loads

Amanda Borges Oliveira[1], Paula de Oliveira Bezerra Diniz[1], Gilvan Lunz Debona[2], José Guilherme Santos da Silva[1]

[1]Civil Engineering Postgraduate Programme (PGECIV). State University of Rio de Janeiro (UERJ).
São Francisco Xavier St., No 524, Maracanã, 20550-900, Rio de Janeiro/RJ, Brazil.
engcivil.amandab@gmail.com, engpaula.uerj@gmail.com, jgss@uerj.br
[2]Department of Architecture and Urbanism (DAU). Rural Federal University of Rio de Janeiro (UFRRJ).
BR-465, Km 7, Seropédica, 23.897-000, Rio de Janeiro/RJ, Brazil.
gilvanld@ufrrj.br

Abstract. This research work aims to investigate the dynamic structural behaviour of pedestrian footbridges, when subjected to dynamic actions associated with vandalism (rhythmic human loads), based on the development of experimental tests and numerical modelling. The investigated pedestrian footbridge is associated to a simply supported concrete structure with span of 24.4 m, currently used for pedestrian crossing and located at the Faculty of Engineering (FEN) of the Rio de Janeiro State University (UERJ). Initially, an experimental modal analysis was performed on the investigated footbridge, in order to identify and assess the global dynamic behaviour of the system. After that, several loading scenarios were idealized to carry out experimental forced vibration tests on the structure, with the participation of up to 20 people, aiming to simulate dynamic excitations associated with vandalism loads. Subsequently, a finite element model was developed and calibrated based on experimental results, considering traditional mathematical functions, corresponding to only-force models, in order to represent human-induced dynamic loads related to vandalism. Based on the forced vibration experimental tests and the dynamic analysis, the footbridge dynamic structural response was investigated. The results of this study indicated that excessive vibrations and human discomfort can occur from fifteen people jumping on the analysed pedestrian footbridge.

Keywords: Pedestrian Footbridges; Dynamic Structural Behaviour; Human Comfort Assessment.

1 Introduction

Actually, the modernity of civil construction projects has led to more and more lightweight and slender footbridges, often characterized by low damping levels, contributing to the susceptibility of vibrations, facilitating the excitation of resonance in certain structures, generating problems of human discomfort and even collapse associated to design extreme situations. Thus, considering the relevance and timeliness of the research topic under study, plenty of scientific research has been conducted.

Šána et al. [1] developed a model of people swinging on a footbridge, representing the action of vandals aiming to achieve excessive vibration levels due to their periodic swing on knees while keeping the contact between the footbridge and their feet. The research presents DLF coefficient as a continuos function for frequencies ranging from 1 Hz to 3 Hz, based on measurements of 15 random people and comparisons with experimental data.

Čáp et al. [2] conducted an experimental dynamic analysis of a footbridge located on the Jizera River in Mladá Boleslav – Czech Republic. The experimental dynamic analysis was conducted on the footbridge to assess the efficacy of the installed TMDs considering the random pedestrian crossings with flow densities pedestrian similar to normal usage conditions, torsional, flexural and lateral excitation: two pedestrians stepping

synchronously with the same feet (resonance condition), besides pedestrian running and vandals swinging synchronized and controlled fot metronome. The experiment was divided into two stages: the first without TMDs, and the second with TMDs installed and activated.

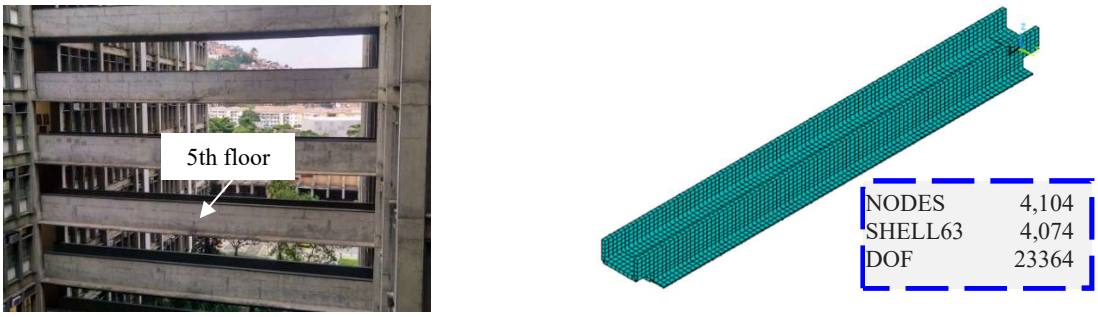
Okur et al. [3] presented a modified Fourier model to simulate with precision the stochastic dynamic jumping force induced by an individual during the jumping motion on a rigid floor. The contact ratio, the frequency of rhythm and the amplification factor are the critical parameters in modelling the force, being these parameters considered random variables. The average, standard deviation and variation interval were based on force-time experimental recordings individual jumps. Thus, the authors simulated the vandal loading by modeling jumps on a steel floor in the finite element model. The numerical and experimental responses were compared, demonstrating that the jumping force model is simple and can be utilized for assessing of vibration serviceability capacity of structures.

Thus, this research work aims to investigate the dynamic structural behaviour of pedestrian footbridge, located at the Faculty of Engineering (FEN) of the State University of Rio de Janeiro (UERJ), when subjected to dynamic actions associated with vandalism (rhythmic human loads), based on the development of experimental tests and numerical modelling.

2 Investigated pedestrian footbridge and finite element modelling

The investigated structure is related to an existing pedestrian footbridge located on the campus of the State University of Rio de Janeiro (UERJ), Rio de Janeiro/RJ, Brazil. The structural system is based on an internal simply supported footbridge, made of reinforced concrete and with a span of 24.4 m, formed by concrete beams and slabs, and being currently used for people crossing (Fig. 1a). The concrete presents a 14 MPa specified compression strength and a 1.78 x 10^{10} N/m² Young's Modulus. The material properties of the concrete were obtained in the original drawings of the footbridge structural project. It's important to mention that this pedestrian footbridge was constructed at the end of the 1970's and the material properties are in fact real and were widely used in the design practice in Rio de Janeiro/RJ, Brazil, at that time. The total mass of the investigated structure is equal to 66,200 kg (Figure 1b).

The developed finite element model adopted the usual mesh refinement techniques present in finite element method simulations, based on the ANSYS computational program, as illustrated in Figure 1b.

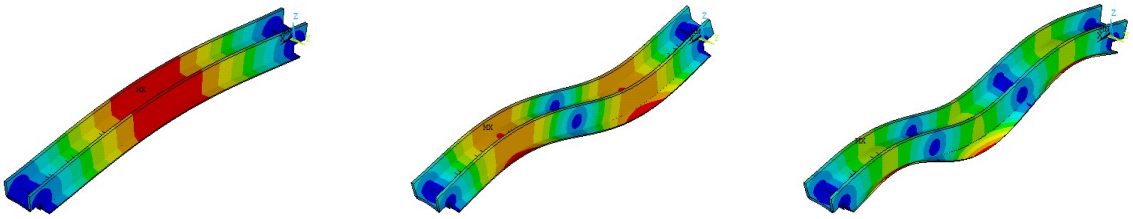


(a) Investigated footbridge (b) Finite element model

Figure 1. Investigated reinforced concrete pedestrian footbridge

3 Numerical modal analysis

The natural frequencies (eigenvalues) and the vibration modes (eigenvectors) of the investigated pedestrian footbridge were calculated based on a traditional numerical modal analysis, based on the use of the ANSYS program. This way, Fig. 2 illustrates the first three modal shapes associated with the footbridge, which correspond to the first three natural frequencies of the structure.



(a) 1st vibration mode (f_{01} = 4.85Hz) (b) 2nd vibration mode (f_{02}=15.77Hz) (c) 3rd vibration mode (f_{03}=31.84Hz)

Figure 2. Vertical vibration modes of the analysed pedestrian footbridge

According to Fig. 2a, the first vibration mode exhibits a predominance of the first vertical vibration mode of the footbridge, with greater intensity located at the center of the span, in the z-axis direction. In the second mode (Fig. 2b), there is a predominance of the second vertical vibration mode of the footbridge, with greater intensity in 1/4 and 3/4 of the beams' span, in the z-axis direction. Finally, the third vibration mode (Fig. 2c) presents a predominance of the third vertical vibration mode of the footbridge's deck, with greater intensity in 1/6, 1/2 and 5/6 of the span, in the z-axis direction.

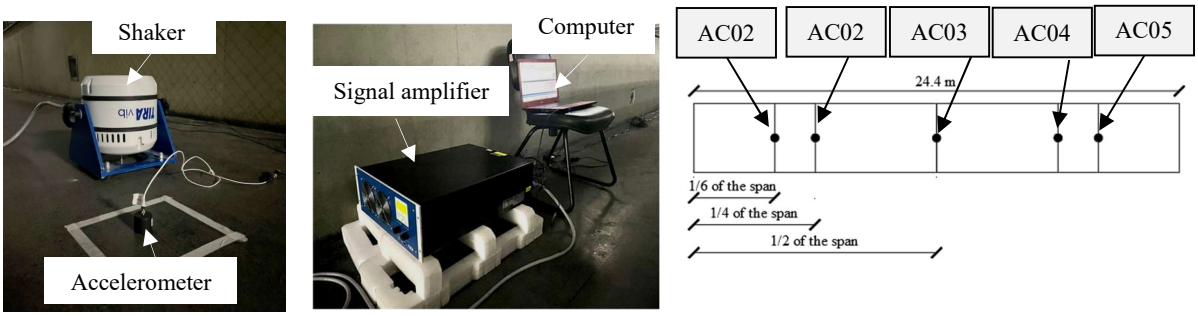
Thus, the modal analysis revealed that the first vibration mode is the most significant for the dynamic behavior of the footbridge, particularly under human-induced loading. This mode presents the lowest natural frequency and, consequently, is more easily excited by pedestrian activities, which typically occur within the low-frequency range.

4 Experimental modal analysis

Several free vibration tests were conducted using the Shaker S 51140-M (Fig. 3a), aiming to obtain the natural frequencies and mode shapes corresponding to the first, second, and third vibration modes of the structure. In the tests, five accelerometers were strategically positioned at distinct points on the deck, namely: 1/6, 1/4, 1/2, 3/4, and 5/6 of the footbridge span (symmetrically), as indicated in Fig. 3c.

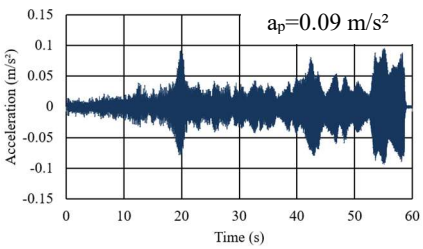
The test was conducted to excite the structure using a Shaker, powered by an external amplifier (Fig. 3b), and positioned at the center of the footbridge span. Since the fundamental natural frequency (first vibration mode) is the most critical for a dynamic analysis – representing the lowest excitation frequency required to induce resonance and, consequently, the highest vibration amplitude - it was chosen to position the shaker exclusively in the larger amplitude region in this mode.

The response spectra of the structure vibrations at 1/4 of de span is presented through Fast Fourier Transforms (FFT), corresponding to the outputs associated with the five Dytran accelerometers used in the experimental modal analysis of the footbridge. These responses can be visualized in Fig. 4, extracted from the AqDAnalysis software of the Data Acquisition System ADS 2500.

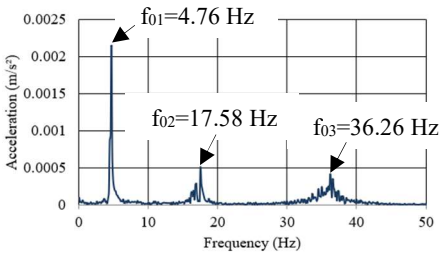


(a) Shaker at the central structural section (b) Signal generator and power amplifier (c) position of accelerometers in plan

Figure 3. Free vibration tests



(a) Acceleration in the time domain

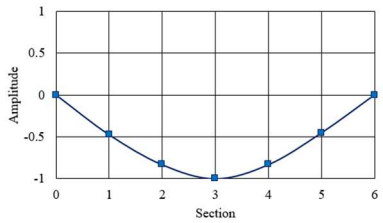


(b) Acceleration in the frequency domain

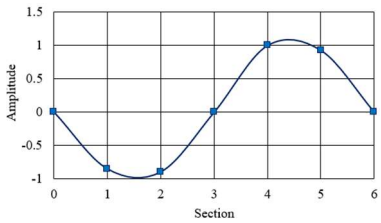
Figure 4. Investigated structural section: 1/4 of the span. Excitation frequency: 1 to 50 Hz. Position of dynamic excitation: 1/2 of the span

Analysing the results presented in Fig. 4, it becomes evident that three frequency peaks are identified, corresponding to three vertical vibration modes associated with bending (f_{01} = 4.76 Hz; f_{02} = 17.58 Hz; f_{03} = 36.26 Hz).

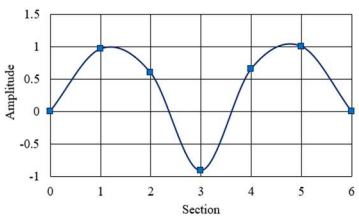
Next, the first three experimental vibration modes are presented, generated by correlating the amplitudes obtained in the previously presented frequency domain graphs, representative of each accelerometer used on the footbridge. As indicated in Fig. 5, sections 0 and 6 correspond to the supports of the footbridge, while sections 1, 2, 3, 4, and 5 are associated, respectively, with accelerometers in positions 1/6, 1/4, 1/2, 3/4, and 5/6, respectively.



(a) 1st experimental mode vibration (ξ=1.70%)



(b) 2nd experimental vibration mode (ξ=1.15%)



(c) 3rd experimental mode vibration mode (ξ=1.02%)

Figure 5. Experimental vibration modes

The modal damping coefficients of the structure, referring to the first three vibration modes with an emphasis on the effects of bending, were determined using the logarithmic decrement method. The values obtained were 1.70% for the first mode, 1.15% for the second mode, and 1.02% for the third mode, respectively. Next, The numerical results were compared with the obtained experimental results, according to Tab. 1.

Table 1. Comparison between the natural frequency values

Natural frequencies (Hz)				Differences (%)
Experimental tests		Numerical modelling		
f_{01}	4.76	f_{01}	4.85	1.89
f_{02}	17.58	f_{02}	15.77	11.47
f_{03}	36.26	f_{03}	31.84	13.88

Comparing the values of the natural frequencies of the footbridge, it can be observed that the structural model under study is well numerically represented by the computational model developed via the finite element method (ANSYS). The dynamic characteristics of the system, regarding the natural frequencies (mass and stiffness), are well represented, as the difference between the numerical and experimental values is small, with maximum values of around 1.89%, 11.47%, and 13.88% for the first, second, and third vertical vibration modes of the structure, respectively.

5 Forced vibration analysis

The dynamic excitation acting on the footbridge was done through the simulation of two groups of people jumping on the structure at a time (Fig. 6 and Fig. 7). The first test was performed utilising a group of fifteen individuals jumping near resonance (f_p = 2.20 Hz), and the second test was performed using twenty people jumping in resonance e near resonance (f_p = 2.40 Hz and f_p = 2.20 Hz, respectively).

Besides, the results obtained from the experimental tests were recorded AqDados software through a data acquisition system ADS 2500, connected to two strategically positioned PCB Piezotronics accelerometers in the center of the footbridge span (Fig.8). Also, two accelerometers were used to calibrate the results during the test.



Figure 6. Fifteen people jumping



Figure 7. Twenty people jumping

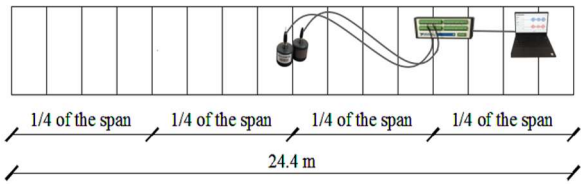


Figure 8. Point of structural analysis

Regarding to the numerical analysis, the research is based on two traditional mathematical functions, corresponding to only-force models, which represent human-induced dynamic loads related to vandalism. Below, eq. (1) to eq. (3) represent the numerical models numerical of Hanning [4] and eq. (4) to eq. (6) represent Semi-sinusoidal [5].

$$F(t) = CD\left\{k_p P\left[0.5 - 0.5\cos\left(\frac{2\pi}{T_c}t\right)\right]\right\} \rightarrow t \leq T_c \tag{1}$$

$$F(t) = 0 \rightarrow T_c < t \leq T \tag{2}$$

$$k_p = \frac{2T}{T_c} \tag{3}$$

Where,
F(t): Dynamic load induced by human action (vandalism)
CD: Lag coefficient
k_p: Contact coefficient
P: Individual weight
T_c: Contact time between the feet and the ground
T: Activity period

$$F(t) = k_p G \operatorname{sen}\left(\frac{\pi}{t_p}t\right) \rightarrow t \leq t_p \tag{4}$$

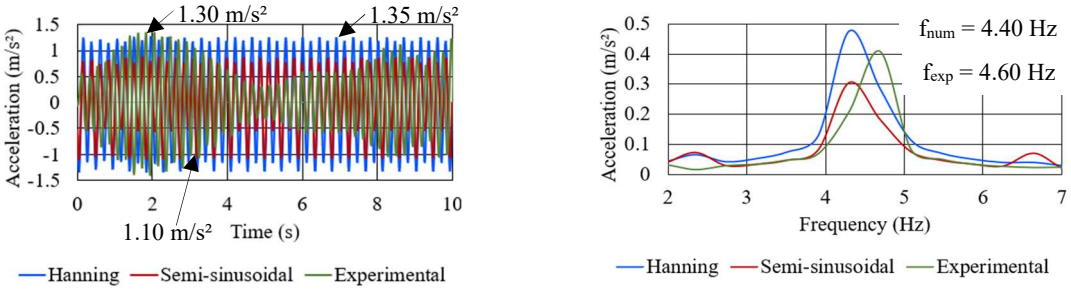
$$F(t) = 0 \rightarrow t_p < t \leq T_p \tag{5}$$

$$k_p = \frac{\pi}{2\alpha};\ \alpha = \frac{t_p}{T_p} \tag{6}$$

Where,
F(t): Dynamic load induced by human action (vandalism)
k_p: Contact coefficient
G: Individual weight
t_p: Contact time between the feet and the ground
T_p: Activity period

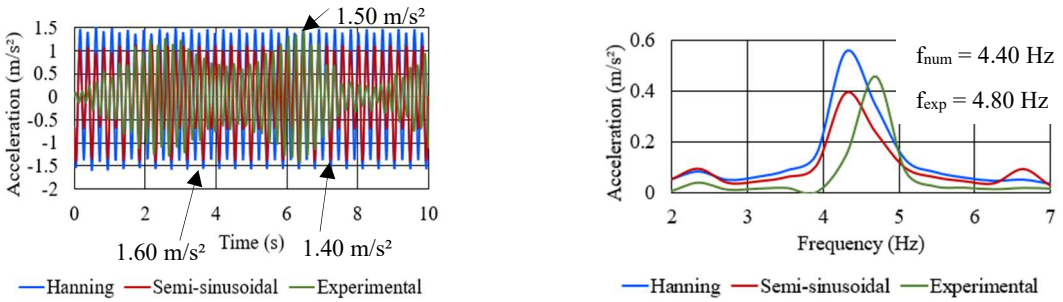
5.1 Analysis and discussion results

In this section, Fig. 9 to Fig. 11 show the dynamic responses concerning by experimental and numerical accelerations of the pedestrian footbridge in time and frequency domain, when fifteen jump in near resonance (f_p = 2.20 Hz) and when twenty people jump in near resonance and resonance (f_p = 2.20 Hz and f_p = 2.40 Hz).



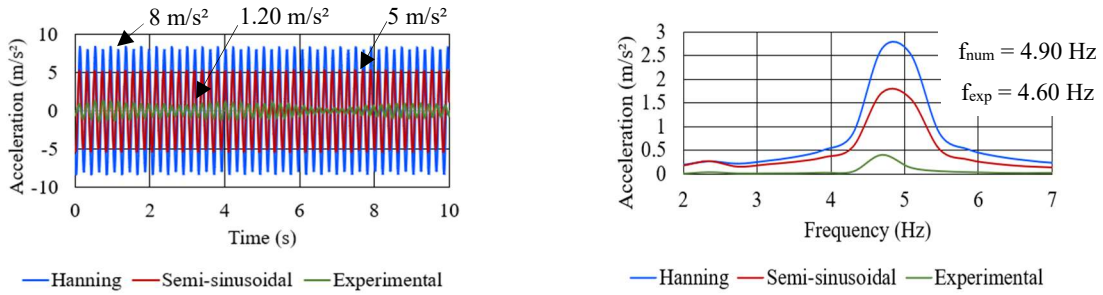
(a) Acceleration in the time domain (b) Acceleration in the frequency domain

Figure 9. Numerical and experimental vertical acceleration. 15 people jumping near resonance (f_p = 2.20 Hz)



(a) Acceleration in the time domain (b) Acceleration in the frequency domain

Figure 10. Numerical and experimental vertical acceleration. 20 people jumping near resonance (f_p = 2.20 Hz)



(a) Acceleration in the time domain (b) Acceleration in the frequency domain

Figure 11. Numerical and experimental vertical acceleration. 20 people jumping resonance (f_p = 2.40 Hz)

From the graphs of experimental test results and numerical model responses presented in this section (Fig. 9 to Fig. 11), it can be observed that for fifteen and twenty people jumping near resonance (f_p = 2.20 Hz), the results exhibited excellent behavior over time and frequency, with very well-defined acceleration peaks. Regarding to the acceleration values related to the fifteen jumping near resonance, the responses are 1.30 m/s² (experimental), 1.35 m/s² (Hanning) and 1.10 m/s² (semi-sinusoidal). In relation to the twenty people jumping near resonance (f_p = 2.20 Hz), the results are 1.50 m/s² (experimental), 1.60 m/s² (Hanning) and 1.40 m/s² (semi-sinusoidal).

However, a discrepancy was noted when twenty people jumped at resonance, with numerically simulated acceleration values of 8 m/s² (Hanning) and 5 m/s² (semi-sinusoidal), because only-force models do not take into account the effect of dynamic individual-structure interaction. Consequently, the peak acceleration values calculated via the Finite Element Method (FEM) using these mathematical models—especially under resonance conditions—are excessively high, as shown in Figure 11, and do not align with practical project realities.

Finally, comparing the results with the human comfort criteria specified in Eurocode [6] and BS 5400 [7] (0.7 m/s² and 1.10 m/s², respectively), the maximum accelerations from all mathematical and experimental models, for both fifteen and twenty people exciting the footbridge near resonance (f_p = 2.20 Hz), exceed the human comfort limits established by these standards [6,7].

6 Conclusion

The following conclusions can be drawn from the results presented in this investigation:

1. The results of the numerical and experimental modal analysis showed good convergence, considering that the value of the first natural frequency of the investigated footbridge, equal to 4.85 Hz (numerical model), presented a percentage difference of around 1.89%, with reference to the value of the experimentally determined frequency, equal to 4.76 Hz.

2. Regarding the forced vibration analysis, the results were satisfactory considering the excitation frequency scenario close to resonance (f_p = 2.20 Hz). However, in the resonance case (f_p = 2.40 Hz), the numerical results presented values that disagreed with the design reality, since the only-force models employed do not consider the effect of the pedestrian-structure dynamic interaction. Thus, it becomes necessary to develop biodynamic mathematical models through experimental testing and numerical modeling, aiming to incorporate into structural analysis the effect of the pedestrian-structure dynamic interaction.

Acknowledgements. The authors gratefully acknowledge the financial support for this research work provided by the Brazilian Science Foundation's CNPq, CAPES and FAPERJ.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Šána, Vladimír; Plachý, Tomáš; Polák, Michal; Boháčová, Magdaléna. "Study of the ground reaction force induced by swaying or bobbing people and its dynamic effect on loaded structures". *WSEAS Transactions on Applied and Theoretical Mechanics*, vol. 18, 2023.

[2] Čáp, Miroslav; Šána, Vladimír; Polák, Michal; Plachý, Tomáš. "Experimental dynamic analysis of the footbridge across Jizera River in Mladá Boleslav". *Acta Polytechnica CTU Proceedings*, vol. 49, pp.1 - 7, 2024.

[3] Okur, Fatih Yesevi; Altunişik, Ahmet Can; Okur, Ebru Kalkan. "Development and validation of new methodology for automated operational modal analysis using modal domain range". *Structural Control and Health Monitoring*, v. 2025, pp.11, 2025.

[4] Faisca, R. G. Characterization of dynamic loads generated by human activities. Doctoral thesis, Federal University of Rio de Janeiro, 2003.

[5] Bachmann, H. e Ammann, W. "Vibrations in structures induced by man and machines". *International Association for Bridges and Structural Engineering*, 1987.

[6] European Standard, "Eurocode 5: Design of timber structures, Part 1-2," European Standard, 1993.

[7] British Standards Institution. "BS5400: Steel, concrete and composite bridges: specification for loads: Part 2", British Standards Institution, 1978.