ASSESSMENT OF HUMAN COMFORT IN A FOOTBRIDGE SUBJECT TO DYNAMIC LOADS

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Abstract. Footbridges are structures susceptible to excessive vibrations. To avoid this type of problem, it is necessary to study these, especially the modal characteristics. Thus, the present study aims to perform a numerical dynamic analysis in finite elements and experimental of a pedestrian footbridge, located in the city of Natal. For this, a computational model of the structure was developed using the ANSYS 2019 – R3 software, from which a modal analysis was performed to numerically determine the natural modes and frequencies of footbridge vibration. Finally, an experimental modal analysis was performed, using the smartphone application iDynamics, in order to compare the results of the two analyses. The horizontal and vertical numerical frequencies are similar to the experimental ones and are in the range of 2 Hz for the frequency that characterizes the first lateral vibration mode and 4 Hz for that corresponding to the first vertical mode. The results achieved are analyzed in light of current national and international standards and indicate that the structure is in the critical range, which may lead to resonance problems. They also indicate that a smartphone can be used to perform early and fast measurements of the natural frequencies of mixed footbridges.

Keywords: Vibration, Dynamic Analysis, Ansys.

1 Introduction

The loads produced by the movement of people occur at low frequencies, which can approach, or even coincide with, the natural frequencies of the structures on which they are affecting, especially if they are light and flexible, such as footbridges. It is likely that, in these cases, problems of excessive vibrations occur, making possible the phenomenon known as resonance. Therefore, to avoid this type of problem, it is essential to know the excitation frequency imposed by the users and the dynamic characteristics of the structure. These conditions, determined after a dynamic analysis, will give the designer support to characterize the structure as to an adequate behavior or not, in face of the action produced by pedestrians, Pereira and Doz [1], Braido and Pravia [2], Barbosa et al. [3] and Silva [4]. Bearing in mind that the standards recommend that footbridges be designed so that their natural frequencies are not within a certain critical range.

An estimation of the level of maximum accelerations in an already built structure can be done in a simple way through smartphones. Current smartphones are equipped with MEMS (Micro-Electro-Mechanical Systems) accelerometers, and due to the low costs associated with them, their use for measuring accelerations in civil structures has intensified, as well as research on specific applications for recording. of accelerations, such as iDynamics, Feldbusch et al. [5], for example. The records of the structure's accelerations vibrating freely make it possible to obtain the natural frequencies.

Based on the above, this work presents the modal analysis of a footbridge in the city of Natal, located in the state of Rio Grande do Norte. The work is developed in numerical form and the accelerations generated in a free vibration test are obtained through a smartphone, thus allowing an estimate of the first frequencies that characterize the structure. Results are compared with recommended regulatory limits.

2 Theoretical Reference

2.1 Characterization of the loading produced by pedestrians

Although this work does not present a dynamic analysis of the footbridge under study, it is important to understand how the dynamic loading generated by pedestrians in the structure is usually considered, in order to conduct an adequate analysis of the modal parameters obtained.

According to Wheeler [6], it is possible to characterize the loading due to the movement of people through a function of time that incorporates parameters such as the average step frequency (f_p), the step speed (v_p) and the step length. of step (l_p).

The step frequency can be defined as the number of steps taken in a time interval of one second and is considered the main parameter for the characterization of pedestrian action and is usually expressed in Hertz (Hz).

Authors such as Bachmann and Ammann [7] consider a dominant step frequency of 2.0 Hz for the vertical walking action of pedestrians, while other authors such as Wheeler [6] assume a range of 1.4 to 2.4 Hz.

According to Santos [8] the function that expresses the action of walking towards the vertical direction is the sum of the fixed portion, which corresponds to the pedestrian's weight, and the periodic portion, representative of a combination of harmonics associated with excitation. dynamics. For the horizontal direction, the function is represented only by the dynamic load. The eq. (1) mathematically represents the dynamic action in the vertical direction and eq. (2) in the horizontal direction.

$$F_v(t) = G_0 + \sum_{i=1}^{n} G_0 \,.\, \alpha_{i,v} \,.\, sen\,(2\,.\,\pi\,.\,i\,.\,f_p\,.\,t + \varphi_{i,v}) \tag{1}$$

$$F_h(t) = \sum_{i=1/2}^{n} G_0 \,.\, \alpha_{i,h} \,.\, sen\,(2\,.\,\pi\,.\,i\,.\,f_p\,.\,t + \varphi_{i,h}) \tag{2}$$

Where:
G_0: static force (vertical component for the pedestrian's weight, usually adopted as 700 N);
$\alpha_{i,}$: fourier coefficient, or dynamic load factor (FDC) of the i-th harmonic;
α_i: walking frequency;
t: time in seconds;
φ_i: phase angle of the i-th harmonic in relation to the first;
n: number of harmonics considered.

2.2 Simple acceleration measurements

Current smartphones are incorporated with MEMS accelerometers, which are sensors that generally detect accelerations using inertial force, Braido and Pravia [2].

One of the applications using the MEMS principle is “iDynamics”, which was developed at the University of Kaiserslautern, Germany. It utilizes the potential and sensitivity of smartphone's built-in sensors for the purposes of simple vibration analysis, system identification and structural monitoring.Limites Normativos.

2.3 NBR 8800: 2008 – Design of steel structures and mixed steel and concrete structures of buildings

A NBR 8800: 2008 [9] states that the use of floor structures with large spans and reduced damping can generate vibrations that cause discomfort during common human activities or cause damage to the operation of equipment. It is determined that in no case shall the fundamental frequency (Hz) of the floor of the structure be less than 3.0 Hz.

2.4 NBR 6118: 2014 – Design of concrete structures - Procedure

The NBR 6118:2014 [10] does not establish any criteria related to the comfort of footbridge users. But it suggests moving the structure's own frequency (f_0) away from the excitation frequency ($f_{crít}$) as much as possible. The condition to be satisfied is given by eq. (3):

$$f_0 \geq 1.2 \,.\, f_{crít} \tag{3}$$

In the absence of experimentally defined values, the standard suggests adopting the value of 4.5 Hz for $f_{crít}$ in footbridges.

2.5 EUROCODE 1: 2003 – Actions on structures – Part 2: Traffic loads on bridges

The code EUROCODE 1:2003 [11] makes some observations as to whether or not dynamic analysis is necessary, given the natural frequencies of the structure. So that no further verification is required, the horizontal ($f_{0,h}$) and vertical ($f_{0,v}$) fundamental frequency of the platform must be:

$$f_{0,h} > 2.5\ Hz$$

$$f_{0,v} > 5\ Hz$$

2.6 BS5400-2 (2006)

According to the British standard BS5400-2 [12], are exempted from checking for dynamic effects, generated by the action of pedestrians, footbridges whose natural frequency is greater than 5Hz for vertical vibration modes, and greater than 1.5Hz for horizontal vibration modes.

3 Developed analysis

3.1 Structural model

The structure to be analyzed is a mixed footbridge, with two metal trusses on the sides, located on BR 110, in the urban perimeter of the city of Natal in the state of Rio Grande do Norte, as illustrated in Fig. 1. The place is characterized by the high agglomeration of pedestrians, due to the bus stops and companies that are on the sides of the highway.

Figure 1 - Footbridge in Natal (Google TM, 2022) Google Earth

The footbridge is divided into access and crossing ramps. The structural system is a mixed truss, where the steel structure works together with the concrete floor and roof slabs. The interface between the elements is made through connectors welded to the metallic structure.

For the study of the dynamic behavior of this footbridge, only the horizontal span of 60 m in length will be considered in a simplified way. For steel parts, a modulus of elasticity of 205 GPa was considered. The concrete slabs have a characteristic compressive strength of 25 MPa and a modulus of elasticity of 20 GPa.

The slabs have an average thickness of 8 cm. The crossing has a total width of 220 cm. The horizontal span is also formed by upper and lower beams and chords and by diagonals. The chords, diagonals and crossbars are formed by rectangular tubes of 160 × 100 x 6.3 mm, 100 × 100 x 4.75 mm and 100 × 100 x 4.75 mm sections respectively. The footbridge also has a guardrail in metal structure with a height of 1.20 meters and protection in metal mesh with a total height of 2.05 m. Fig. 2 shows the schematic drawing of the footbridge cross section.

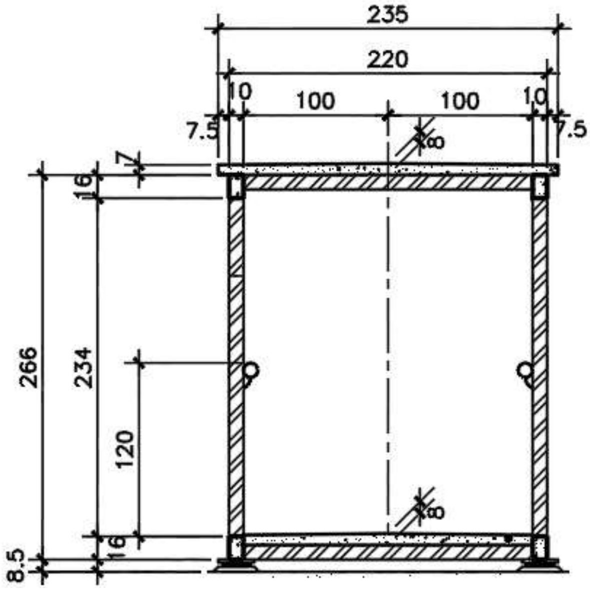

Figure 2 - Cross-section of the footbridge (cm)

3.2 Numerical-computational modelin

Numerical-computational modeling via the finite element method was performed using the Ansys 2019 R3 program [13]. Only the central span of the walkway was modeled, considering that it is supported at three points with restricted translational movements. The elements of the truss and the metallic beams were represented by the BEAM188 element. The board was modeled by SHELL181 elements. The discretized model has 13094 nodes and 4679 elements. Fig.3 shows the idealized model.

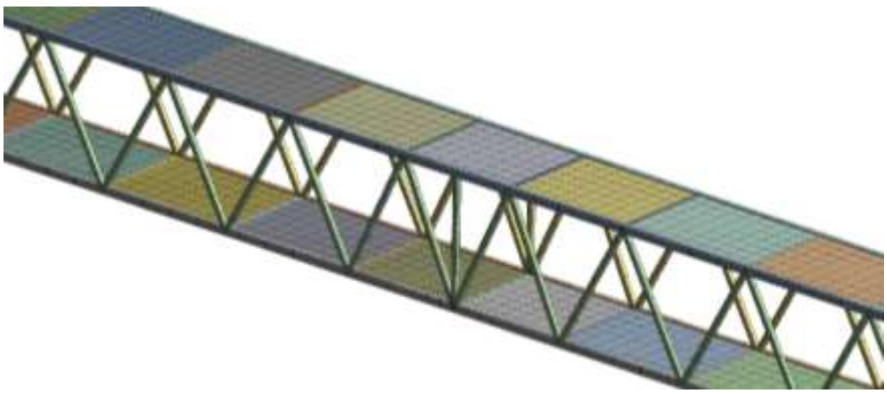

Figure 3 - Discretization of part of the lattice structure, through the beam element BEAM188 and roof and floor plates, with the shell element SHELL181

3.3 Modal analysis

From the model created in the program Ansys 2019 R3 [11], modal analysis was performed to determine the natural frequencies of the idealized structure. The first five modes and their respective frequencies are shown in Tab. 1.

Table 1 - Frequencies and vibration modes of the footbridge horizontal span

Vibration Mode	Natural Frequency [Hz]	Features of the Vibration Mode
1	1.63	1st horizontal bending mode
2	3.90	1st twist mode
3	4.11	2nd twist mode
4	4.22	1st vertical bending mode
5	5.81	2nd vertical bending mode

The footbridge natural frequencies related to the first vertical and horizontal bending modes lie in the critical ranges of the second harmonic associated with the dynamic loads produced by people walking or running on the footbridge. The graphical results obtained for the 1st horizontal flexion mode and 1st vertical flexion mode can be seen in Fig. 4 and Fig. 5, respectively.

Figure 4 - First horizontal bending vibration mode – 1.63 Hz

Figure 5 - First vertical bending vibration mode – 4.22 Hz

It can be seen that mode 1 (1.63 Hz) presents transverse bending, with frequencies close to the second harmonic (around 2 Hz for the transverse direction). The mode 4 (4.22 Hz) shows bending in the vertical direction, with frequencies close to the second harmonic.

3.4 Experimental analysis

In order to identify the dynamic properties of the footbridge, the experimental analysis was performed in free vibration, with no load applied to the span, in order to find the natural frequencies of the structure for the first mode of vibration.

To find the fundamental frequency experimentally and validate the numerical model developed, the iDynamics application was used, which uses the MEMS accelerometer. The smartphone assembly was performed using double-sided tape to fix the smartphone to the structure to avoid local vibration during the measurement. His position corresponds to 1/4 of the footbridge length.

The measurement of the natural frequency for the first vibration mode by the app was performed for 20 seconds. This was initiated by recording the data that was later displayed on the acceleration-time diagram. The frequency spectrum produced by the fast Fourier transform is also displayed parallel to the time signal. Vibration amplitudes as well as natural frequency are displayed during measurement for both vertical and horizontal direction.

From the results obtained it was found that the natural frequency for the first vertical vibration mode obtained experimentally is equal to 4.00 Hz and for the horizontal direction it is equal to 1.85 Hz.

3.5 Analysis of results

Following the study, a comparison was made between the value of the fundamental frequency of the model under study, obtained experimentally, with that resulting from the numerical-computational modeling, via the finite element method, through the use of the Ansys program, as shown in Tab. 2.

Table 2 - Footbridge horizontal span vibration frequencies and modes

Vibration mode	Natural frequency (Hz)		
	Numeric	Experimental	Difference (%)
Horizontal	1.63	1.85	11.9
Vertical	4.22	4.00	5.5

According to the results presented in Table 2, it was observed that the values of the natural frequencies, calculated numerically, presented differences in relation to the results provided by the experimental method using the proposed iDynamics smartphone application, and these quantitative differences are in the order of 11.9% for the horizontal direction and 5.5% for the vertical direction, respectively. The difference found between the experimental and numerical results, especially in relation to the horizontal mode, of around 10%, leads to the questioning of the numerical model and the instruments used. However, when studying footbridges of the same type, results similar to those found numerically in this work can be seen. For example, the footbridge studied by Barbosa et al [3] presented a first frequency corresponding to vertical flexion of the order of 3.5 Hz, which leads us to consider that the model developed here is correct and the differences observed may be due to the lack of precision of the instruments used. However, the use of a smartphone seems to be a good alternative for a first estimation of the modal parameters of the structure.

Finally, the natural frequencies corresponding to vertical bending found numerically and experimentally were compared with the current normative limits of national standards NBR 8800:2008 [9] and NBR 6118:2014 [10], and international standards such as: EUROCODE 1 [11] and BS5400-2 [12] to assess the risk of resonance, respectively in Figs. 6 and Fig. 7.

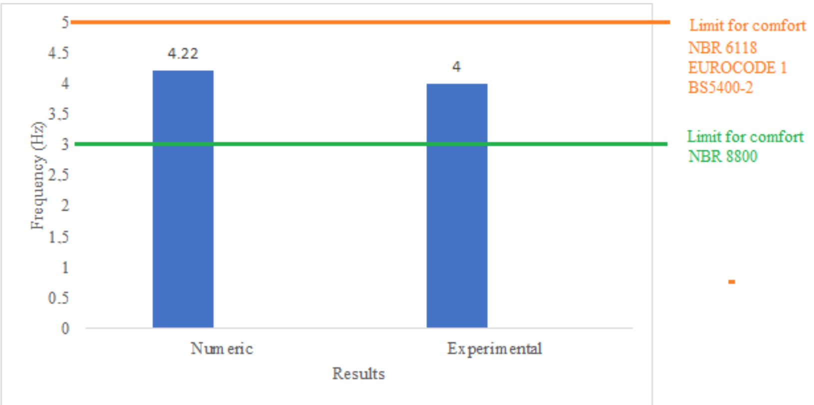

Figure 6 – Comparison between service limits and natural frequencies of vertical excitation of the structure.

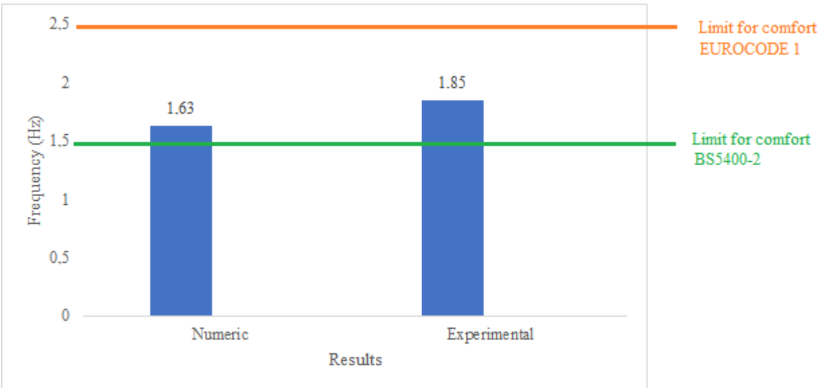

Figure 7 – Comparison between service limits and natural frequencies of horizontal excitation of the structure.

Regarding the modal analysis stage, the results obtained showed that for the vertical direction, the footbridge presented a frequency in the first vibration mode of 4.22 Hz numerically and 4.00 Hz experimentally. Comparing with the current standards, it appears that the results are higher than the minimum established by NBR 8800:2008 [9], however, they did not meet the normative limits for NBR 6118:2014 [10], EUROCODE 1 [11] and the BS5400-2 [12].

For the horizontal footbridge direction, the frequency in the first vibration mode was 1.63 Hz numerically and 1.85 Hz experimentally. Comparing with the standards, it is observed that it does not meet the criteria for the minimum natural frequency in the horizontal direction for EUROCODE 1 [11], but meets BS5400-2 [12].

4 Conclusions

The footbridge model located in Natal developed in the Ansys software proved to be very representative and realistic, approaching the values of natural frequencies and numerical vibration modes (extracted from the program) to those obtained experimentally with the iDynamics application. These results indicate that a smartphone can be used to perform early and fast measurements of the natural frequencies of mixed footbridges. It is also verified that the results achieved were analyzed in the light of current national and international standards and indicated that the structure is in the critical range, which may lead to resonance problems. Therefore, a more detailed dynamic analysis is recommended.

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