Human-induced vibration analysis and human comfort assessment of pedestrian footbridges

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Abstract. The design of pedestrian footbridges has always been challenging. Essentially, this type of structure presents long spans and, due to more resistant materials, the structural elements slenderness has been considerably increased. Consequently, the excessive vibration problems become more evident and may cause discomfort to the pedestrians or even structural risk. Therefore, aiming to predict the dynamic structural response of footbridges induced by human walking, two mathematical models were used: single force model and biodynamic models. Based on the use of the two loading models, an extensive parametric study was carried out considering the pedestrian step frequencies, the pedestrian-footbridge mass ratios and the structural damping rate. The results obtained along this investigation shows that the influence of the human walking depends on the relationship between the mass of the pedestrians and the footbridge, and the pedestrian-footbridge dynamic interaction effect can be irrelevant for small mass ratios. On the other hand, the human walking can, without any doubt, provoke higher dynamic structural responses, especially when the footbridge fundamental frequency is close to the pedestrian step frequencies' range. In this situation, the structural system can reach high vibration levels that can compromise the footbridge user's comfort.

Keywords: Pedestrian footbridges, Biodynamic models, Dynamic structural analysis.

1 Introduction

The significant technological advance in civil construction, over the past few years, has allowed the use of more resistant, lighter materials and, thus, the architecture of pedestrian footbridge has become increasingly bold. In other words, these facts have contributed to the design of very slender pedestrian footbridges, sensitive to dynamic excitation, and, consequently, changed serviceability and ultimate limit states related to their design. A direct consequence of this design trend is a considerable increase in excessive vibration problems [1–4].

Therefore, considering the increasing number of reported excessive vibration problems in footbridges [1], this research work aims to investigate the dynamic structural behaviour and assess the human comfort of pedestrian footbridges, when subjected to pedestrian walking, based on experimental tests and model adjustment in finite elements. Besides that, it also aims to evaluate the effect of pedestrian-structure interaction on the dynamic structural response of the structure, through the influence of different step frequencies, the mass ratio, and the damping ratio. This way, the test structure is related to a real pedestrian footbridge, located, next to the new Maracanã Stadium, in the city of Rio de Janeiro/RJ, Brazil.

2 Investigated pedestrian footbridge

The analysed structural model is related to a real design, located on the Osvaldo Aranha Street, route of great importance and very heavy traffic of vehicles along the day, next to the new Maracanã Stadium, in the city of Rio de Janeiro/RJ, Brazil [1]. The footbridge is made of a composite steel-concrete structural system and presents two spans with length equal to 29.5m and 24m, respectively, and a total length of 53.5m, see Fig. 1. The investigated span is located next to the Social Security Building and presents a total length equal to 29.5m. This span was reinforced with steel profiles, welded to the lower bottom of the original longitudinal steel beams of the footbridge, see Fig. 1.

The footbridge design was provided by the General Project Coordination (CGP) of the Rio de Janeiro City Council [1]. It must be emphasized that there was a concrete column that divided the studied span (L=29.5m), see Fig. 1 (a-b). It is worth mentioning that the real reason for the non-existence of this concrete column after the project completion was not confirmed by CGP. This way, in the author's opinion the structural reinforcement has been a consequence of this fact [1], see Fig. 1. Subsequently, the structural details of the cross-section typical of the footbridge and the reinforcement steel beams are presented in Fig. 1 (c-d).

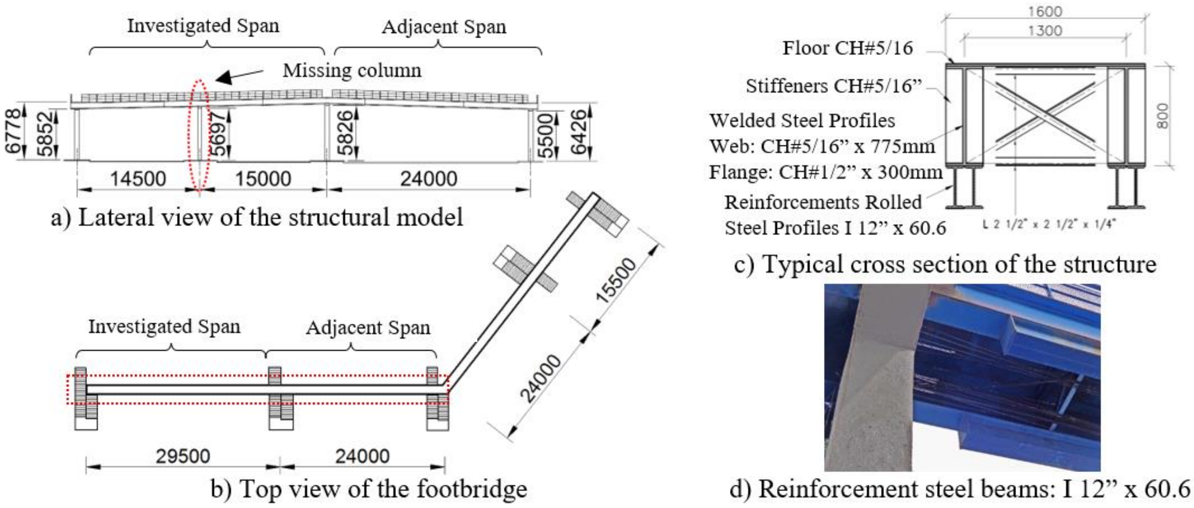

Figure 1. Structural design and details of the pedestrian footbridge [Dimensions in mm]

3 Finite element model

Having in mind the development of a numerical model in order to the calibration of the experimental results, a finite element model representative of the footbridge was developed, based on the use of the usual discretization techniques, utilising the ANSYS computational program [7], see Fig. 2. It must be emphasized that the longitudinal steel beams, reinforcement steel beams and the floor of the structures were modelled, based on the use of shell finite elements (SHELL63 [7]). On the other hand, the bracing system was represented by three-dimensional beam finite elements (BEAM44 [7]), see Fig. 2.

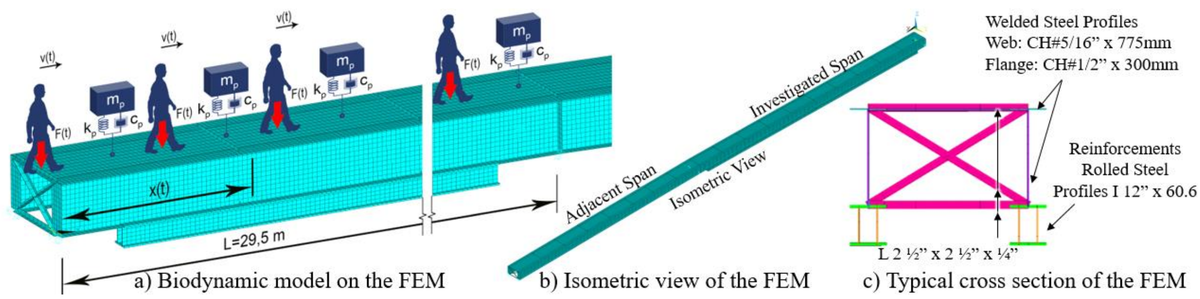

Figure 2. Finite element model including the biodynamic model, jointly with the force model, representative of human walking on the footbridge

With regard to the models representing the pedestrian action, the only force model (FM) applied was considered as moving harmonic precise loads traveling across the structure at a speed proportional to the respective pedestrian step frequency. The expressions defining the time-varying vertical force applied by each pedestrian, based on dynamic load factors (DLF) and the number of contributing harmonics are shown in Silva [1]. With regard to the DLFs, the ones adopted were proposed by Bachmann and Amman [5] and Kerr [6], B&A and K respectively in this work. The vertical force can be divided into static and dynamic components. The static component corresponds to the pedestrian weight, and the dynamic component is the sum of harmonic functions with frequencies that are integer multiples of the step frequency.

In the numerical simulations, the force model is used individually or jointly with the biodynamic model (BM) to represent the effects of pedestrians walking on the structure and the dynamic effects of the body vibrations. The BMs were evenly distributed along the investigated span of the footbridge, according to the number of individuals who are simultaneously on the structure, and modelled as a fixed spring-mass-damper (SMD) system with one degree of freedom (SDOF), based on the use of finite elements (COMBIN40 [7]) resulting from the combination of a spring and damper in parallel, associated to a nodal mass. The parameters of the biodynamic systems were considered according to Toso et al. [8] who proposed three empirical equations for human walking based on experimental tests on a rigid surface for pedestrian mass, damping and stiffness.

4 Modal analysis

The operational modal analysis (OMA) was performed (free vibration tests), based on the dynamic experimental monitoring, considering a single pedestrian jumping at the central section of the footbridge span [1]. At this point, the vertical accelerations were recorded in time domain for a time sufficient for all the energy of the jumping to be dissipated. This way, the experimental results, obtained in the frequency domain, aiming to identify the natural frequencies that produce the main energy transfer peaks of the footbridge dynamic structural response. Comparatively, the natural frequencies (eigenvalues) and the vibration modes (eigenvectors) were calculated based on a traditional numerical modal analysis, based on the use of the ANSYS program [7]. Subsequently, Tab. 1 shows the frequency values, associated with the mode shapes [1].

Table 1. Natural frequencies of the footbridge: numerical analysis (FEM)

Vibration Mode	Frequency (Hz)	Physical Phenomenon	Maximum Amplitude
1st	1.99	Torsion	Span 1 (29.5m)
2nd	3.70	Torsion	Span 2 (24m)
3rd	3.83	Bending	Span 1 (29.5m)
4th	6.04	Bending	Span 2 (24m)

Based on the results of Silva [1], the frequency domain acceleration obtained by fast Fourier transform (FFT), it can be observed that the largest contribution of energy transfers to the structural model (highest peak) corresponds to the vertical bending vibration mode with a frequency value of 3.83 Hz ($f_{03OMA} = f_{03FEM}$ = 3.83 Hz, see Tab. 1) related to the investigated span (L = 29.5 m). The peak with the second-largest contribution is referred to the frequency of 5.94 Hz corresponding to the vertical bending (f_{04OMA} = 5.94 Hz and f_{04FEM}= 6.04Hz: differences equal to 1,65%; see Tab. 1), associated to the adjacent span (L = 24 m). It is also possible to observe another energy transfer peak contribution related to the footbridge dynamic response, corresponding to the torsion vibration mode, which corresponds to the third-largest contribution with frequency value of 1.99 Hz (f_{01OMA} = 2.03 Hz and f_{01FEM} = 1.99 Hz; differences equal to 2,01%; see Tab. 1), related to the investigated span (L = 29.5 m). Comparing the footbridge natural frequency values obtained based on the experimental dynamic monitoring and numerical modelling, an excellent agreement between these results (numerical and experimental) can be verified. This fact has indicated an adequate finite element modelling of the investigated structural model and the refined FE model has produced numerical values very close to the experimental results. This way, it was necessary no calibration of the developed footbridge FE model, but only the validation of the results in relation to the experimental ones.

5 Dynamic analysis

Initially, aiming to obtain results at the central section of the footbridge span, a sensitivity analysis was carried out, using the modal superposition method, to verify the number of vibration modes most appropriate for representing the dynamic structural response of the footbridge. This approach considerably reduces the mathematical complexity involved in the dynamic forced vibration analysis. Therefore, the focus was on the first 10 modes of vibration of the structure and, with this, it was possible to observe a convergence in the response from the use of the 5 superimposed vibration modes (modal superposition), in the numerical simulation of each of the walking tests with a single pedestrian, considering the biodynamic models BM-B&A and BM-K as loading (Fig. 2).

The investigated pedestrian footbridge was subjected to four walking tests [1], according to the step frequency (f_p), with a single pedestrian present on the path: slow (f_p = 1,6 Hz), in resonance (f_p = 1,9 Hz), normal (f_p = 2,0 Hz) and fast (f_p = 2,45 Hz). The results of the vertical acceleration peaks of the numerical models, obtained using the computer program ANSYS [7], associated with the walking of pedestrians, according to the BM-B&A and BM-K models are presented in Tab. 2 in comparison with the values of these accelerations obtained through experimental tests (ET) performed on the pedestrian footbridge, in the time and frequency domains. It is important to emphasize that resonance walking aims to force a resonant movement of the second harmonic (2x 1.90 Hz = 3.80 Hz) of the pedestrian walking with the first vertical vibration mode (f_{03} = 3.83 Hz, see Tab. 1).

Table 2. Comparison between peak vertical accelerations of the numerical model and experimental tests

Step frequency (Hz)	Value	Peak acceleration (m/s²)			Difference (%) Numerical x Experimental	
		ET	Numerical model			
			BM-B&A	BM-K	BM-B&A	BM-K
1.60	max	0.096	0.113	0.092	17.4	4.0
	min	0.104	0.110	0.119	6.1	14.5
1.90	max	0.228	0.255	0.262	12.0	14.7
	min	0.246	0.287	0.252	16.5	2.6
2.00	max	0.161	0.153	0.146	3.9	0.7
	min	0.147	0.154	0.150	4.6	6.6
2.45	max	0.212	0.186	0.199	12.2	6.0
	min	0.178	0.202	0.159	13.5	10.6

Comparing the values of peak accelerations, it can be seen that the dynamic characteristics of the model under study are well represented numerically by the computational model developed, via the finite element method (ANSYS [7]) because the existing error between the numerical and experimental values are very small. The difference in the values between the numerical models and the experimental tests, for the maximum and minimum peaks, were: 4.0% and 14.5% for the slow walking (f_p= 1.60 Hz); 2.6% and 14.7% for resonance walking (f_p = 1.90 Hz); 2.5% and 14.7% for normal walking (f_p = 2.00 Hz); and 6.0% and 10.6% for fast walking (f_p = 2.45 Hz).

Silva [1] presents the graphical comparison of the results obtained by the experimental tests (TE) with the dynamic responses of the computational numerical model developed, using the finite element method (ANSYS [7]), using the models as loading BM-B&A and BM-K. It can be seen that the experimental and the numerical results had the same time-varying behaviour, with very well defined acceleration peaks. According to the results obtained from the experimental monitoring, it is possible to notice that the experimental walking tests were well represented by the finite element models (FEM), except for some difference, due to the pedestrian's intravariability - difficulty in synchronizing the step frequency and maintaining the same step length - throughout the walking on the footbridge.

6 Parametric studies

The footbridge vibration induced by human walking is mainly influenced by step frequency, footbridge damping ratio. In addition, the effect of pedestrian-structure interaction depends on the mass ratio between pedestrians and the structure. Thus, from the finite element model, considering the biodynamic models, described in section 3 (Fig. 2), the influences of step frequency, mass ratio and damping rate were evaluated. For this purpose, the results were analysed and compared due to the use of the biodynamic jointly together with the force model (BM-B&A and BM-K) and the only force models (FM-B&A and FM-K).

6.1 Step frequency

Considering a normal walking on a horizontal surface, the step frequency range was found between 1.5 and 2.5 Hz [5]. It has long been known that the step frequency dominates the resulting dynamic load [5]. In general, the peak of the force of a single-footfall increases with the step frequency [9]. Thus, for relatively higher step frequency, a larger dynamic response may be induced [1], mainly if the natural frequencies of footbridges coincide with one multiple of the step frequency. In this case, resonance response will occur, and the magnitude may be greater than that of the higher step frequency. Figures 3 show the results obtained.

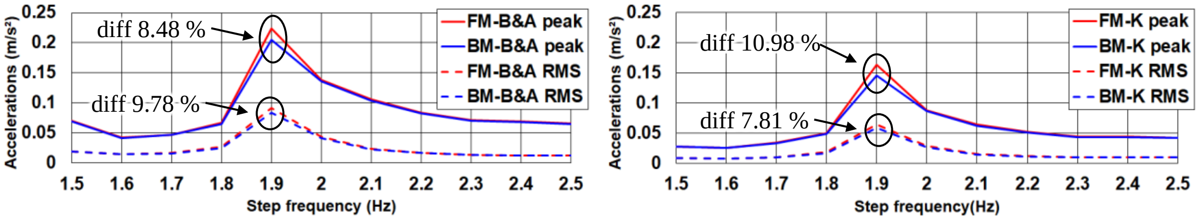

Figure 3. The influence of step frequency on the dynamic response of the footbridge: comparison of peak and RMS accelerations values. FM- B&A x BM-B&A (left) and FM-K x BM-K (right)

The peak and RMS values of each acceleration history, according to Fig. 3 for loading models used, showed an upward trend with the increase in the step frequency. However, significant gains can be seen in the step frequency of 1.9 Hz, due to its multiples, which were compatible with the fundamental frequency of the footbridge (that is, 3.83 Hz, as shown in Tab. 1), and as a result, the occurrence of resonance at this frequency of 2 to 4 times the initial value, depending on the loading model employed.

6.2 Mass ratio

As previously mentioned, the pedestrian-structure effect is significant if the human mass is comparable to that of the structure, but it is negligible when it is relatively small in comparison to it. The relationship between the pedestrian-structure effect and the mass ratio was assessed using masses adopted according to the number of occupants on the footbridge, 1 to 10 pedestrians (mass ratio from 0.32% to 3.16%). The peak and RMS values of the acceleration histories were obtained from the biodynamic loading models BM-B&A and BM-K and only force model FM-B&A and FM-K, as illustrated by Fig. 4.

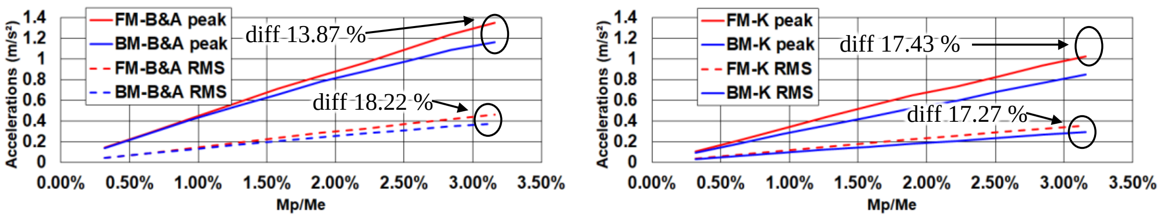

Figure 4. The influence of mass ratio on the dynamic response of the footbridge: comparison of peak and RMS accelerations values. FM- B&A x BM-B&A (left) and FM-K x BM-K (right)

It can be seen that the differences between the results obtained between the only force models and the force models combined with biodynamic models increase along with the increase in the mass of the individuals present. With a mass ratio of 3.16%, BM-B&A showed a reduction of 17.4% in relation to FM-B&A, both for peak accelerations and RMS. In addition, the BM-K model, for the same mass ratio, provided 13.9% and 18.3% lower responses, respectively, for peak accelerations and RMS. This indicates that the influence of the pedestrian-structure effect becomes more significant with the increase in the proportions of mass of the human occupants in relation to the footbridge.

6.3 Damping ratio

The influence of the footbridge damping ratio was investigated in the range of 0.2% to 2% and the step frequency was assumed to be 2 Hz with a step length of 0.75 m. The peak and RMS values obtained from the biodynamic loading models BM-B&A and BM-K and only force models MFD B&A and MFD-K applied to the three-dimensional model in finite elements using the ANSYS software [7], are shown in Fig. 5.

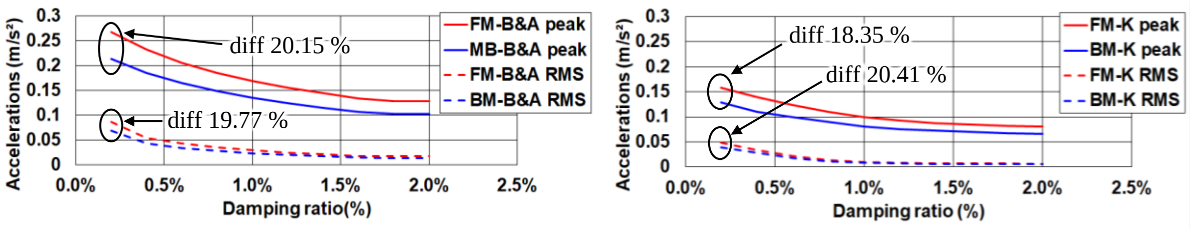

Figure 5. The influence of damping ratio on the dynamic response of the footbridge: comparison of peak and RMS accelerations values. FM- B&A x BM-B&A (left) and FM-K x BM-K (right)

It can be noted, from observations made in Fig. 5, that the accelerations, both peak and RMS values, obtained in the only force model decreased more quickly with the increase in the damping ratio in the range of 0.2% to 1.0%. The reductions were considerable, a drop of about 50% for peak accelerations and 80% for RMS accelerations. Thus, it can be concluded that the footbridge damping ratio, in the present case, plays an important role in the vibration of the structure, highlighting the importance of the pedestrian-structure effect. It should also be noted that the damping associated with human beings introduces significant damping in the structures.

7 Human comfort assessment

This section aims to investigate the dynamic behaviour of the footbridge in terms of human comfort through actions of human walking. For this purpose, the maximum vertical accelerations of the structure obtained by the experimental tests [1], slow, normal, in resonance, fast and random walking, were analysed. Additionally, numerical walking simulations were carried out aiming to represent situations closer to the reality of the footbridge in terms of pedestrian traffic and the densities recommended by the technical guides SÉTRA [10] and HIVOSS [11], using 22 pedestrians in a single line equivalent to 0.5 pedestrian/m² (Class III/SÉTRA [10] or TC3/HIVOSS [11]). Table 3 presents the human comfort level for each walking test performed.

Table 3. Human comfort level by walking test (experimental and numerical)

<table>
<tr><th rowspan="2">Test</th><th rowspan="2">Walking</th><th rowspan="2">Number of pedestrians</th><th rowspan="2">Step frequency (Hz)</th><th rowspan="2">Peak vertical acceleration (m/s²)</th><th colspan="2">Human comfort level</th></tr>
<tr><th>SÉTRA</th><th>HIVOSS</th></tr>
<tr><td>Experimental</td><td>Slow</td><td>1</td><td>1.6</td><td>0.10</td><td colspan="2">Maximum</td></tr>
<tr><td>Numerical</td><td>Slow</td><td>22</td><td>1.6</td><td>0.61</td><td colspan="2">Medium</td></tr>
<tr><td>Experimental</td><td>Resonance</td><td>1</td><td>1.9</td><td>0.25</td><td colspan="2">Maximum</td></tr>
<tr><td>Numerical</td><td>Resonance</td><td>22</td><td>1.9</td><td>1.09</td><td colspan="2">Minimum</td></tr>
<tr><td>Experimental</td><td>Normal</td><td>1</td><td>2.0</td><td>0.16</td><td colspan="2">Maximum</td></tr>
<tr><td>Numerical</td><td>Normal</td><td>22</td><td>2.0</td><td>1.03</td><td colspan="2">Minimum</td></tr>
<tr><td>Experimental</td><td>Fast</td><td>1</td><td>2.45</td><td>0.21</td><td colspan="2">Maximum</td></tr>
<tr><td>Experimental</td><td>Random</td><td>8</td><td>–</td><td>0.39</td><td colspan="2">Maximum</td></tr>
</table>

Thus, the values of maximum accelerations, both experimental and numerical, were analysed in comparison with the limits of the guides previously mentioned in order to identify the possibility of occurrence of undesirable and uncomfortable vibration levels for pedestrians. The point of the analysed structure corresponds to the intersection of the middle of the span of the footbridge with its longitudinal axis.

From the results listed in Tab. 3, it can be noted that the experimental and numerical vertical acceleration peak values are within the limits of 0.0 to 2.5 m/s² proposed by the SÉTRA [10] and HIVOSS [11] guides, corresponding to the range of human comfort between the maximum and minimum levels. It is worth mentioning that the walking simulations with 22 pedestrians (0.5 pedestrians/m²) led the footbridge to medium and minimum comfort levels, with the highest vertical acceleration peak value, equal to 1.09 m/s², recorded in the in resonance walking (f_p = 1.9 Hz), indicating the possibility of excessive vibrations from this footbridge in the presence of larger groups of pedestrians.

8 Conclusions

Considering the pedestrian-structure effect, two different loading methods (FM and BM) were developed in this investigation to predict the dynamic structural response of footbridges due to human walking. The influence of the step frequencies, mass and damping ratios on the footbridge dynamic response caused by human walking was studied. Some conclusions from this study are described as follows:

1. The experimental walking tests had the same time-varying behaviour, with very well defined acceleration peaks, and were well represented by FEM, except for some difference due to intravariability (real pedestrian) throughout the walking on the investigated footbridge.
2. In addition, the influence of the pedestrian-structure dynamic interaction, due to the mass ratio of occupants to the structure, significantly modified the dynamic response of the investigated footbridge numerical model with reductions of up to 18% (RMS acceleration). Besides that, considerable reductions were identified in proportion to the increase in the damping ratio of the assessed structure (maximum 80% for RMS acceleration). In addition, considerably higher responses were stimulated for the structure evaluated by fundamental frequency close to the multiple of the step frequency (4 times the initial value in resonance case).
3. Experimental walking tests (1 and 8 pedestrians) resulted in maximum comfort levels for the investigated footbridge. However, numerical simulations based on the use of 22 pedestrians have reached medium to minimum comfort levels, indicating susceptibility to excessive vibration problems for groups with higher numbers of people walking on the footbridge.

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