XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Steel-concrete composite floors dynamic assessment when subjected to human walking loads

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Abstract. This work aims to evaluate the people-structure dynamic interaction effect on the floor's structural behaviour, considering the development of experimental tests and also numerical modelling. This way, the investigated structural model is related to a steel-concrete composite floor building which is composed of a hot-rolled framing system, with a total area equal to 1300 m². The floor system is used for normal school occupancy and is supported by steel-concrete composite columns with a ceiling height of 3.40 m. In this investigation, the biodynamic models associated with "spring-mass-damper" systems with one degree of freedom (SDOF) were adopted aiming to represent the people's walking on the investigated floor. The proposed numerical model, developed for the steel-concrete composite floor building dynamic analysis, adopted the usual mesh refinement techniques present in finite element method (FEM) simulations implemented in the ANSYS computational program. Considering the experimental results calibration, the investigated floor dynamic response was evaluated based on a parametric study, to study the influence of the people's step frequencies, number of people walking and stationary on the floor, structural damping, and also different trajectories of people walking on the structure. The composite floor dynamic response was determined based on the displacement and acceleration values, and the results were compared with those calculated utilising the traditional dynamic loading mathematical models ("only-force models"); and with recommended limits for excessive vibrations related to the design codes, aiming to assess the floor human comfort.

Keywords: experimental tests, finite element modelling, buildings floors.

1 Introduction

In the last years, based on the use of slighter and more resistant materials, and having in mind the significant progress of the construction processes, the increase in the building floors structural project's slenderness has been significant. However, these floors are designed as light weight structures with low frequencies and low damping. These facts have generated slender building floors, sensitive to human dynamic excitation, and consequently changed the serviceability and ultimate limit states associated to their design. These facts validate that the structural systems of building floors have low values for vibration natural frequencies. In addition, the design of structural systems with low levels of structural damping is observed, related to the kind of materials used, category of construction, non-structural elements presence, age and construction quality [1,2].

Another important point concerns the multifunctionality that the business market has demanded from current engineering designs, based on the buildings intended use for residential common use spaces, offices and gyms [1], which has contributed to these buildings' floors be more susceptible to excessive vibrations arising, mainly, from human activities, such as: walking, jumping, dancing, rhythmic gymnastics and others, generating disturbances to the user with regard to human comfort [1,2]. This can be explained for the reason that these human activities present excitation frequencies harmonics close to natural frequencies values of most structures, in the range of 4 to 8 Hz [3,4].

In this research work, the main objective is to evaluate the effect of the dynamic individual-structure interaction, qualitatively and quantitatively, on the structural behaviour of building floors, through the development of experimental tests and numerical modelling. Therefore, this investigation has as its central objective numerical modelling and performance of experimental tests to study the mixed floors (steel-concrete) modal parameters, used for school occupation, with total area of around 1300 m², being supported by mixed pillars with 3.40m of ceiling height. In addition, a human comfort analysis of the structural model was carried out according to procedures established in design and standard guides.

Free vibration experimental tests were made in order to calibrate the results obtained in the numerical modal analysis with the experimental analysis results. Furthermore, forced vibration numerical and experimental tests were performed with person’s walking in order to face assess human comfort based on the limits established in design guides compared to numerical results. The biodynamic model was used in numerical modelling.

2 Investigated Structural Model

The investigated structural system associated to a steel-concrete composite floor, used for school occupation, with a total area of approximately 1300 m² (see Fig. 1), corresponds to a typical example referring to the 8th floor of a mixed building (steel-concrete), with sixteen stories, including engine room, keg, water tank bottom and water tank cover. The design is from a real and existing building, which is under construction. The investigated building was designed to be a teaching hospital for a private university in Belo Horizonte/MG, Brazil.

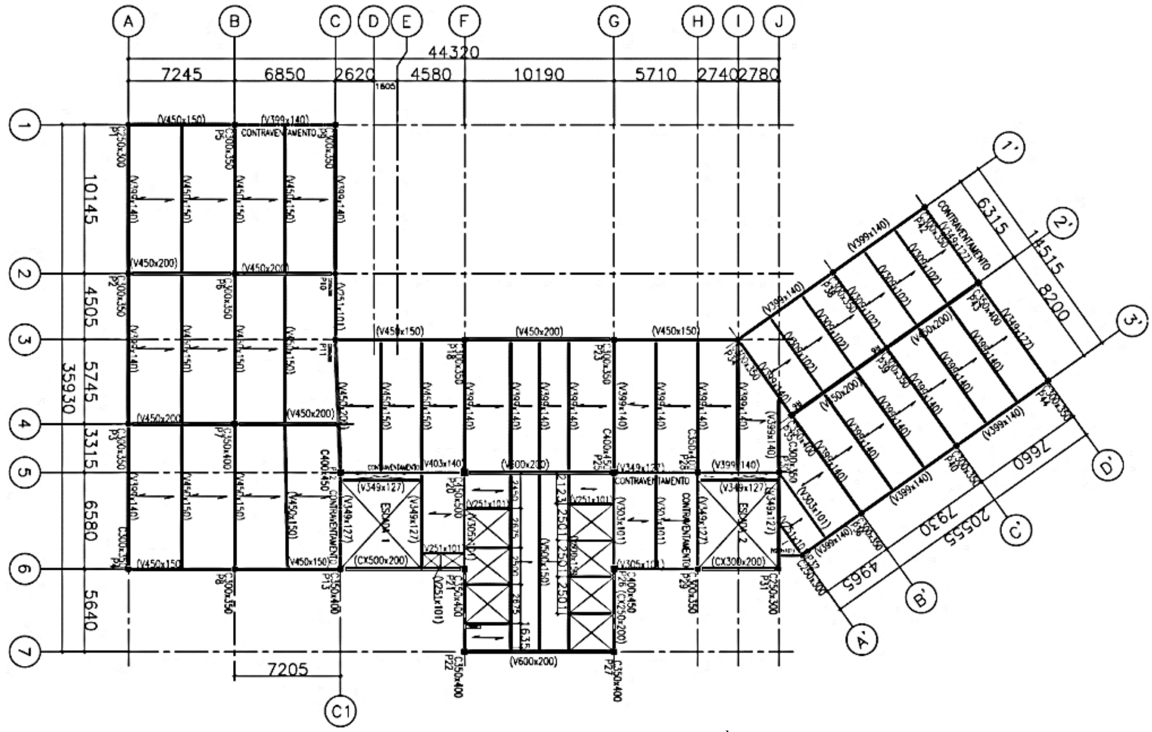


Figure 1. Investigated steel-concrete composite floor: 8th floor (dimensions in mm)

The building has a standard height between occupable floors of 3.40 meters. The building pillars and framework structures consists of welded profiles, with geometric dimensions and properties according to design provided by the construction company executing, emphasizing that the pillars are made of welded profiles in the form of a coffin filled with concrete. The slabs are steel deck type with a total thickness of 15 cm, including the MF75 type shape (7.5 cm high) and the shape thickness which, in this design, can assume values of 0.85 or 0.95 mm. It was considered masonry 1.5 meters high around the entire floor, stairwells and elevator boxes, aiming to simulate in a more realistic way the conditions found in the construction at the experimental tests time. It is a structural masonry, built with a 14x19x29 cm structural ceramic block and filled with grout and steel bars, there is also a concrete top beam.

Regarding the materials used physical characteristics, concrete has a characteristic compressive strength (f_{ck}) equal to 29,43 MPa, an elastic modulus (E_c) of 25800.00 MPa, Poisson's ratio (ν_c) equal to 0.2 and specific weight (γ_c) of 2500.00 kgf/m³; and steel has characteristic yield strength (f_y) of 258 MPa, modulus of elasticity (E_s) of 208000 MPa, Poisson's ratio (ν_s) equal to 0.3 and specific weight (γ_s) of 7849.05 kgf/m^3. For structural masonry, a longitudinal elasticity module (E_a) of 12000 MPa was adopted, Poisson's ratio (ν_a) equal to 0.15 and specific weight (γ_a) of 1250.00 kgf/m³, according to criteria established by ABNT NBR 15812-1: 2010 - Structural Masonry - Ceramic blocks Part 1 [5], in the absence of tests or precise information about block characteristics.

3 Finite Element Modelling

The structural model was analysed using the ANSYS software [6], by the usual discretization techniques associated with the Finite Element Method (FEM). Thus, in the system numerical modelling of steel beams and columns were represented by three-dimensional finite elements BEAM44 [6], where the bending and torsion effects are considered. Steel deck slabs were simulated using finite shell elements. For this simulation the finite shell element SHELL63 [6] was used, which is based on the Thin Plate Theory. The biodynamic components were simulated by a damped single-degree-of-freedom (SDOF) oscillator (i.e., a classic mass-spring-damper), using the element COMBIN40 [6], and the individual biodynamic characteristics used were extracted from studies based on experimental tests by Silva et al. [7].

The complete interaction between the steel deck slabs and the steel beams was considered in the study (i.e., nodes are coupled in order to prevent the occurrence of landslides). The steel and concrete are considered having elastic linear and isotropic behaviour, and all sections of the structural model remain flat in the deformed state. The boundary conditions considered restrict as a third-gen support the base and top nodes of the pillars that are half standard height above and below the analysed pavement. The numerical model presents an appropriate refinement degree mesh, in order to allow a good representation of the floor dynamic structural behaviour, as illustrated in Fig. 2. It is noteworthy that the beams, columns and slabs have a discretion of 0.25 meters. The SDOF mass-spring-damper model and the floor chosen for experimental tests are presented in Fig. 3.

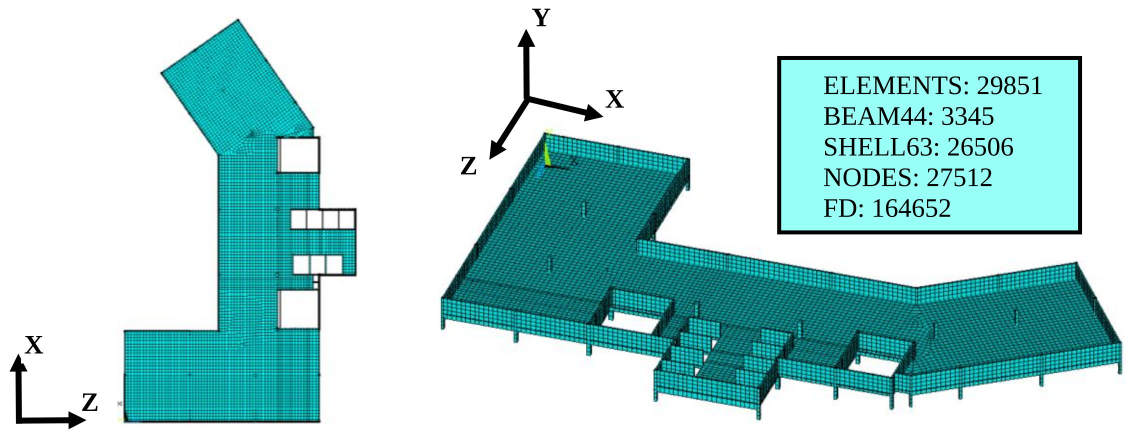


Figure 2. Finite element model of the investigated steel-concrete composite floor

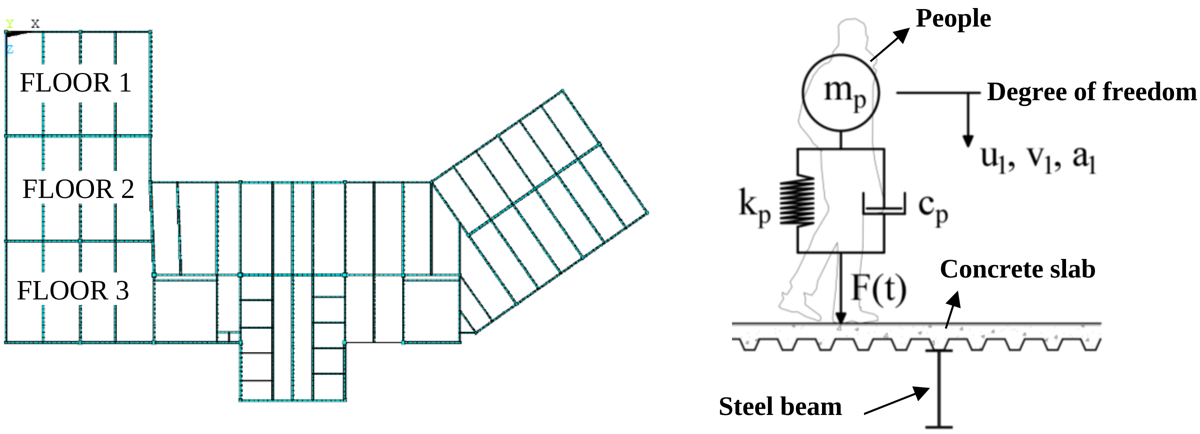


Figure 3. Floors chosen for experimental analysis and the SDOF mass-spring-damper (biodynamic system)

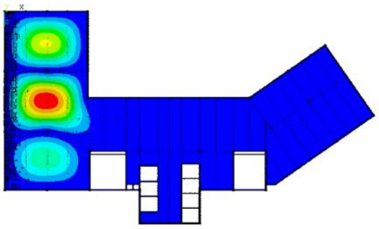
4 Modal analysis: numeric and experimental free vibration

The structural system dynamic behaviour (free vibration) is investigated based on the floor natural frequencies values and vibration modes, considering the experimental tests and numerical analysis. The modal analysis (free vibration) was performed using the ANSYS software [6], where the natural frequencies (eigenvalues) and their respective vibration modes (eigenvectors) were calculated. Fig. 4 illustrates the first four slab bending vibration modes and Table 1 presents the natural frequencies values.

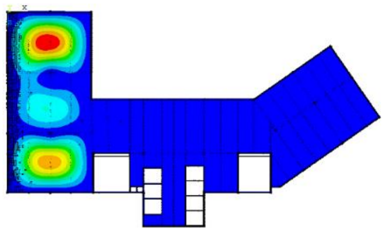
Table 1. Natural frequencies of the investigated structural model

Vibration mode	Frequency (Hz)	Physics Characteristics
1st	5.73	Slab Bending
2nd	6.51	Slab Bending
3rd	6.88	Slab Bending
4th	7.35	Slab Bending
5th	7.40	Slab Bending
6th	7.87	Slab Bending

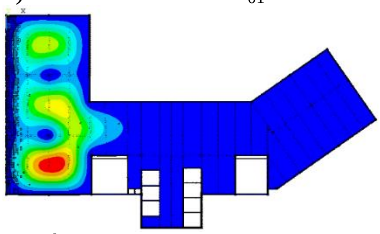
It is worth mentioning that these natural frequencies correspond to vibration modes with maximum modal amplitude on strategic slab panels of the structure (Fig. 3), aiming at comparing the natural frequencies values obtained through finite element modelling and by experimental modal analysis according to criteria established by AISC [8] for human comfort.



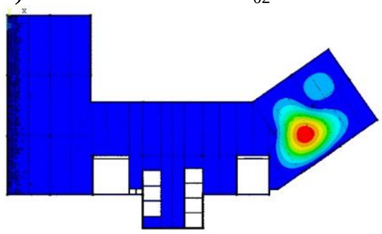
a) 1st vibration mode: f_{01} = 5.73 Hz



b) 2nd vibration mode: f_{02} = 6.29 Hz



c) 3rd vibration mode: f_{03} = 6.88 Hz



d) 4th vibration mode: f_{04} = 7.35 Hz

Figure 4. First four bending vibration modes of the studied floor

The experimental modal analysis was performed through dynamic experimental monitoring, through the seismic accelerometers installation of the brand PCB Piezotronics, model 393B04, connected to a data acquisition system (brand Bruel and Kjaer, model 3050-A -060), which was connected to a portable computer, responsible for assess the structure response in the time or frequency domain. The free vibration test was performed considering that floors 1, 2 and 3 (Fig. 5) were excited by a 102.6 kg person impact, wearing boots with flexible plastic soles, jumping in their respective floor's centres, at a height of 0.48 m. The method used in this test was single input and multiple output data (SIMO).

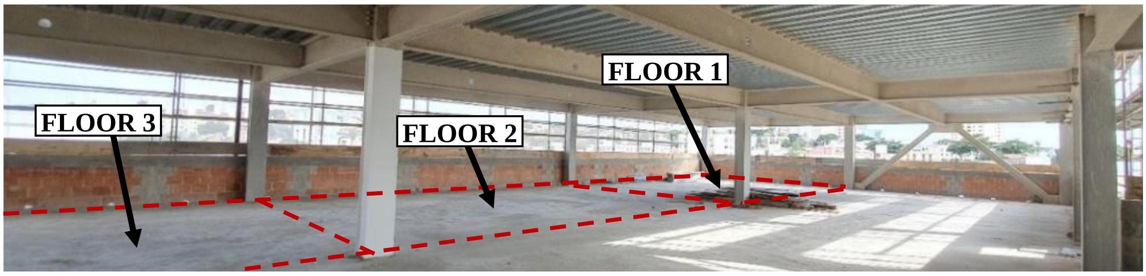


Figure 5. Floors chosen to carry out the experimental tests

In sequence, Fig. 6 presents the floor frequency domain response, associated to the experimental tests performed on the concrete slabs (free vibration), aiming to identify the floor natural frequencies that present the most relevant peaks of energy transfer when the dynamic response is investigated. The floor natural frequencies are determined through the FFT (Fast Fourier Transform) of the investigated floor structural sections dynamic response.

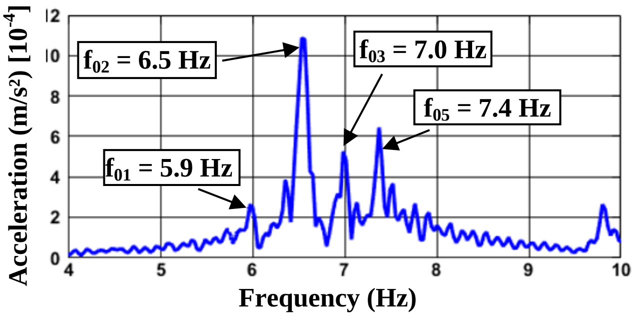


Figure 6. Floor 1 frequency domain response determined by experimental tests

The structure modal damping coefficients for the first six bending modes were obtained based on the use of the logarithm decrement method, and are equal to 1,26% (1st mode), 1,03% (2nd mode) and 1,19% (3rd mode), respectively. Analysing the Fig. 6 results, it appears that it is possible to identify the main frequencies peaks corresponding to the five structure vertical vibration modes, for the three performed tests. It is observed that the 4th and 6th vibration modes do not manifest themselves in the obtained floors test responses, due to the fact that these modes present low oscillations on the structural system, being difficult to be identified, see Fig. 6.

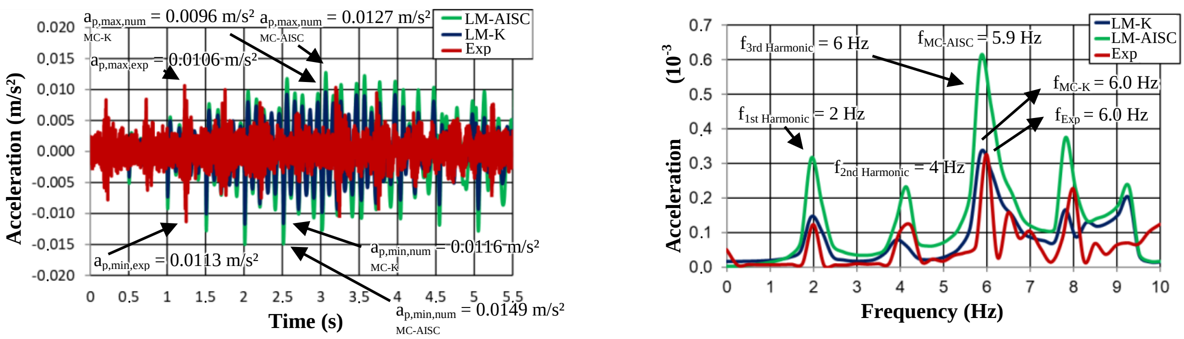
Based on the presented values in Table 2, it is noted that the experimental results obtained for the three floors have a good agreement with each other, as well as when compared to the numerical results which presents a difference from the numerical result, in relation to experimental response of all floors, above 3 %.

Table 2. Comparison of the natural frequencies values: experimental tests and numerical modelling

Mode (See Fig. 4)	Natural Frequencies (Hz)				Difference (%)		
	Numeric Modelling	Experimental test					
		Floor 1	Floor 2	Floor 3	Floor 1	Floor 2	Floor 3
1st	5.73	5.9	5.9	5.9	2.97%	2.97%	2.97%
2nd	6.51	6.5	6.5	6.5	0.15%	0.15%	0.15%
3rd	6.88	7.0	6.9	7.0	1.74%	0.29%	1.74%
5th	7.40	7.4	7.4	7.3	0.00%	0.00%	-1,35%

5 Dynamic analysis: calibration and parametric study

Based on the calibration tests considering two mathematical models LM-K model and LM-AISC model, it can be concluded that the steel-concrete composite floor dynamic properties were well represented, when the LM-K model (combination between Kerr Loading Model [9] and the SDOF mass-spring-damper) was considered in the analysis. It must be emphasized that when the LM-K model was studied based on one person walking on the Floor 1 (see Fig. 7), considering eighteen dynamic responses, eleven were calculated with differences smaller than 10 % (maximum and minimum peaks).

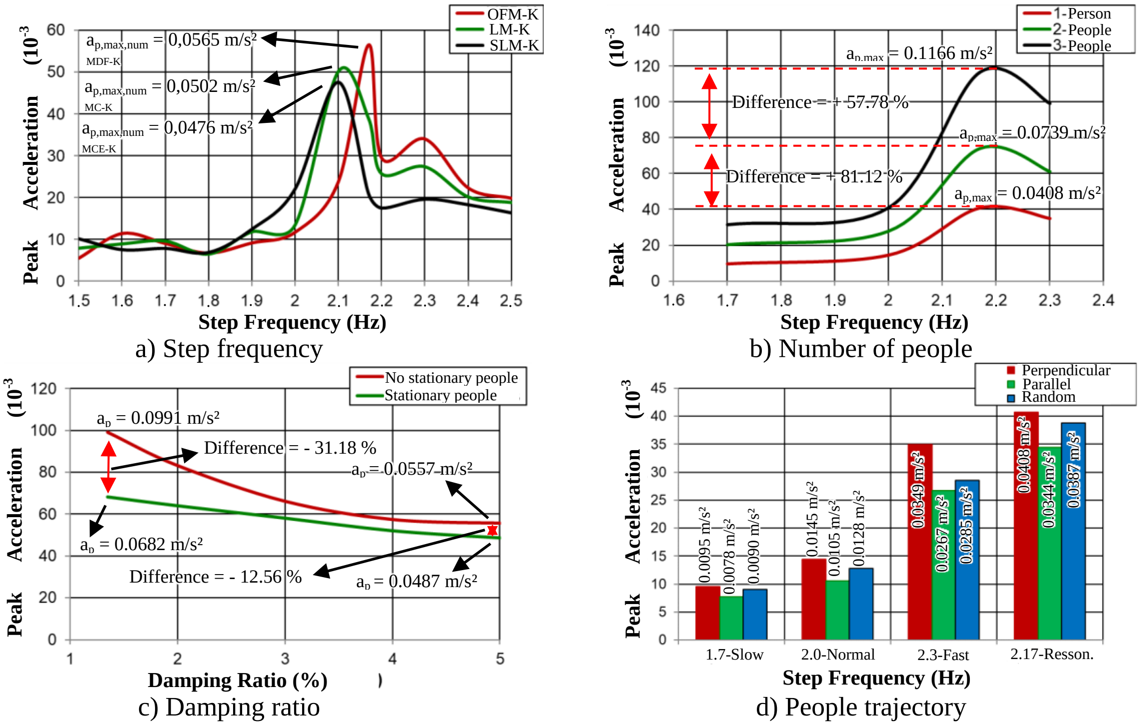


a) Peak Acceleration b) Frequency domain (FFT)

Figure 7. Calibration tests: accelerations in time and frequency domain

After the calibration tests, a parametric study was developed in order to investigate the influence of the people's step frequencies, number of people walking and stationary on the floor, structural damping, and also different trajectories of people walking on the structure. The step frequency range was changed between 1.5 Hz and 2.5 Hz. The floor peak accelerations were calculated using as reference the expressions of Kerr [9], and the biodynamic models were used in this analysis based on the use of two modelling strategies: moving damped-oscillator and moving and stationary damped-oscillators, as presented in Fig. 8.

In Fig. 8-a it can be observed that dynamic response increases significantly when the 3rd harmonic of step frequency is approximately the natural frequency of Floor 1 (f_{03} = 6,5 Hz). The biodynamic models (only a person walking and stationary people added, LM-K and SLM-K, respectively) have a reduced dynamic response in approximately 15% when compared to only force loading (OFL-K). This reduction may be related to additional damping coupled to floor associated to natural frequencies reduction due considering the human-structure interaction (HSI). In Fig. 8-b it can be observed that dynamic response increases proportionally when number of walking people also increases.



a) Step frequency b) Number of people

c) Damping ratio d) People trajectory

Figure 8. Investigated floor dynamic response: parametric study

Based on the results presented in Fig. 8-c, it is seen that the differences obtained from model with and without stationary people decrease rapidly while increase of the damping ratio in the range between until 1 % and 5 %. It can be seen that the peak accelerations values, both for the case without and with stationary, they decreased approximately 44 and 29 %, respectively, with the variation of the damping ratio. In Fig. 8-d it is observed that dynamic response is changed according to person trajectory and the trajectory perpendicular to secondary girders obtained the larger dynamic response, while the parallel trajectory perpendicular obtained the smaller dynamic response.

6 Human comfort assessment

The dynamic structural response of the steel-concrete composite floor was investigated through a parametric study, when subjected to human walking; having in mind possible discomfort related to excessive vibrations. Additionally, human comfort was also verified for all numerical walking simulations that were performed aiming to represent situations proposed in the parametric study. Therefore, the dynamic responses found in the parametric study for Floor 1 were compared with the threshold values proposed by the technical literature of AISC [8] and ISO 2631-2 [10].

This way, the peak and RMS acceleration values calculated in the dynamic analysis were compared with the corresponded limits proposed by AISC (a_{lim} = 0.05 m/s² [8]) and ISO-10137 [10] (a_{lim} = 0.005 m/s), respectively. Based on the parametric study results, it can be verified that the investigated floor (Floor 1) is considered comfortable to occupation for normal walking, see Table 3. The maximum peak and RMS acceleration determined in experimental tests considering a person walking on the Floor 1 were equal to 0,03 m/s² and 0,004 m/s², respectively. Therefore, according to criteria AISC guide and ISO-10137, the comfort human for excessive vibrations was attended for this case study.

Table 3. Human comfort assessment (Floor 1: normal walking)

Rhythmic	NP	PS	a_p (m/s²)	HC-AISC	a_{RMS} (m/s²)	HC-ISO
Normal	1	NO	0.0145	Satisfy	0.0014	Satisfy
		WITH	0.0134	Satisfy	0.0013	Satisfy
	2	NO	0.0279	Satisfy	0.0027	Satisfy
		WITH	0.0262	Satisfy	0.0025	Satisfy
	3	NO	0.0408	Satisfy	0.0039	Satisfy
		WITH	0.0386	Satisfy	0.0037	Satisfy

NP: number of people walking on the floor concrete slab; PS: number of people stationary on the floor; HC-AISC: human comfort according to AISC [8], based on the peak accelerations; HC-ISO: human comfort according to ISO 2631-2 [11], based on RMS accelerations; a_p: peak acceleration; a_{RMS}: RMS accelerations.

7 Conclusions

This research work investigated the dynamic structural response of a steel-concrete composite floor subjected to human walking, based on the use of traditional only force models and biodynamic models, having in mind the assessment of the people-structure dynamic interaction effect and the human comfort. Thus, the main conclusions of this paper are:

1. Considering the floor natural frequencies, the finite element model proved to be calibrated in relation to the obtained experimental results (free vibration). The differences observed between the numerical model and experimental monitoring results were mostly below 3 %.
2. Considering the peak accelerations, when the experimental results were compared to the numerical model results the differences were below 10 %, presenting a good relationship for the dynamic response calibration.
3. When the biodynamic models were considered in the dynamic analysis, the human-structure interaction (HSI) has induced lower dynamic structural responses due to the people's damping added to the floor.
4. Having in mind the parametric study results, the human comfort assessment of the investigated steel-concrete composite floor indicated that the structure attended the recommended design limits.

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

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