Experimental analysis of walking induced vibrations in composite floor and performance evaluation considering human confort

Análise experimental de vibrações induzidas pelo caminhar em sistemas compostos de pisos e avaliação do desempenho considerando o conforto humano

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Abstract

NBR 8800 was updated in the year of 2008. Acceptance criteria of vibrations on floor performance considering human comfort were simplified and only minimum values of fundamental frequency are considered for performance evaluation. The objective of this article is to evaluate a methodology of experimental analysis of footfall-induced vibrations in steel and composite system floors and footbridges in order to check the human comfort conditions. The methodology was established according to international standard recommendations and international design guides. In order to present its applicability, it was applied to four case studies. The spectrum processing provided the values of natural frequency, damping ratio and peak acceleration. All the floors presented values of fundamental frequency greater than the minimum values recommended by NBR 8800. However, the obtained peak acceleration for some cases presented values greater than the maximum value recommended by international criteria. Therefore, the simplified acceptance criteria proposed by NBR 8800 were insufficient for performance assessment of some system floors and footbridges.

Keywords: Experimental vibration analysis. Heel-drop tests. Walking tests. Induced vibrations. Human comfort.

Resumo

A NBR8800 foi atualizada no ano de 2008. Os critérios de aceitação de desempenho de sistemas de piso e passarelas considerando conforto humano às vibrações foram simplificados e apenas valores mínimos de frequência fundamental são considerados para avaliação de desempenho. O objetivo deste artigo é avaliar uma metodologia de análise experimental de vibrações induzidas pelo caminhar em sistemas compostos de pisos e passarelas, para verificar as condições de conforto humano. A metodologia foi estabelecida de acordo com recomendações de normas e guias. Para verificar sua aplicabilidade, ela foi aplicada a quatro estudos de caso. O processamento do espectro forneceu os valores de frequência natural, amortecimento e aceleração. Todos os sistemas de pisos apresentaram valores de frequência fundamental superiores aos mínimos recomendados pela NBR 8800. No entanto, a aceleração de pico obtida para alguns casos apresentou valores superiores ao valores máximos recomendados por critérios internacionais. Portanto, os critérios de aceitação simplificados propostos pela NBR 8800 foram insuficientes para a avaliação de desempenho de alguns sistemas de piso e passarelas.

Palavras-chave: *Análise experimental de vibrações. Ensaio de impacto. Ensaio de caminhada. Vibrações induzidas. Conforto humano.*

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Introduction

The production of strength materials was possible due to the technological progress during the last few decades and, consequently, construction of lighter and displaceable structures became possible. In structural engineering, this fact is evidenced by metallic structures because steel is a material with high mechanical strength. Structural systems greatly affected by the stiffness variation are the steel and composite floors. The checking of the serviceability limit state is very important in deflection and vibration control, since the lower the floor system stiffness, the greater its deformability. A careful assessment of these aspects is essential to avoid structure malfunctions and user discomfort due to induced vibrations by human activities.

Vibration analysis of steel and composite floor systems and footbridges has become increasingly important, whereas recent structural solutions allow the construction of thinner and less stiff structures. Moreover, daring architectural designs lead to the need of a meticulous evaluation of footfall-induced vibration of these floors, even to the cases where major concerns did not exist. In the past, the structures were harder and the vibration problems rarely happened. Millennium Bridge is an emblematic history case of a structure where the footfall-induced vibrations caused human discomfort. The footbridge is located in the city of London, it is 325 meters long and was opened on June 10, 2000. The rhythmic walking of the crowd that crossed it caused excessive horizontal and torsional vibrations, leading to discomfort and nausea in the users (ALFRED, 2009; COSTA, 2012).

According to Holmlund and Lundström (1998), the human response to vibrations can be divided into five categories. The categories are perception, degraded comfort, interference with activities, impaired health and occurrence of motion sickness. In case of multi-story buildings constructed with steel and composite materials, the vibrations cause degraded comfort. Varela (2004) states that the human sensitivity to vibrations is a complex topic, which involves physical and psychological aspects. The main aspects that influence the human sensitivity to vibration are: position (standing or lying down), spine orientation in relation to the vibration direction, nature of activity performed by the individual, frequency of occurrence, individual age, among others.

Experimental studies show that people react adversely to frequencies between 5 and 8 Hz (HANES, 1970). According to Bachmann *et al*. (1995), the perception and discomfort generated by vibrations are proportional to acceleration when the vibration frequency has value in a range of 1 to 10 Hz. This variation can be explained by the fact that each part of the human body has a specific fundamental frequency. Besides, each individual presents a higher or lower vibration sensitivity depending on extrinsic factors.

Performance of dynamical tests is an efficient way to evaluate the structure behavior, considering vibration problems. The main objectives of dynamical tests are determining the natural frequencies associated to the vibration modes of the structures, estimate the damping rates and determine the amplitude of displacements. Heel-drop tests and walking tests are usually used to evaluate the induced vibrations by human activities in composite floor systems and footbridges. Hicks, Lawson and King (2000), Varela (2004), Homem (2007), Battista *et al*. (2012), Chen, Xu and Zhang (2014), Liu and Davis (2015), Brownjohn, Racic and Chen (2016), Chen, Li and Racic (2016), Mohammed, Pavic and Radic (2018) and Huang, Gao and Chang (2020) evaluate the floor performance using these tests.

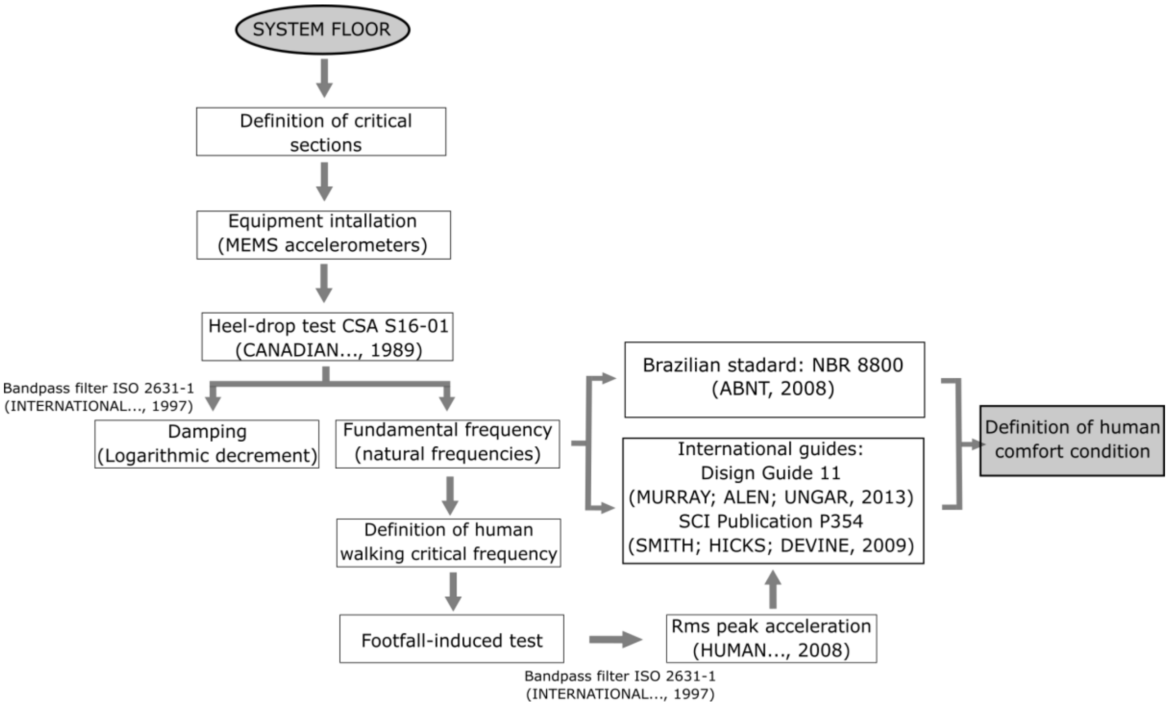
NBR 8800 - Design of steel and composite structures for buildings was lastly updated in the year of 2008 (ABNT, 2008). The acceptance criteria of floor systems performance considering human comfort of this standard were simplified and only minimum values of fundamental frequency are considered for performance evaluation. According to the standard, the designer defines the need for an accurate evaluation of the floor system performance considering other parameters, such as the amplitude of acceleration, natural frequencies and damping. The standard is currently being updated (ASSOCIAÇÃO…, 2021).

This article presents a methodological assessment of experimental analysis of footfall-induced vibrations in steel and composite system floors and footbridges. The methodology is based on international standards and guides, whereas the Brazilian standard does not establish these criteria in a normative way. The goal of this research is to verify the efficiency of the NBR 8800 (ABNT, 2008) to evaluate floors more susceptible to footfall-induced vibrations. The methodology was applied to composite floor systems and footbridges of four case studies from buildings of Universidade Federal de Viçosa, Brazil.

Materials and methods

The methodology of the research is presented in the flowchart on Figure 1.

Figure 1 – **Methodology flowchart of the research**



The first step consisted of determining the fundamental frequency of the analyzed floors (1st natural frequency). Fundamental frequency is the easiest excitation frequency. Human walking has a low frequency and low excitation energy and it will be the frequency that human walking will be able to excite. Then, tests were carried out in floor systems of the structure with less stiffness, great deflections and, consequently, high levels of vibration. The floor sections where the fundamental frequency excitation was obtained were denominated critical sections. In these sections, critical points were defined (points with greatest displacements). At these points, MEMS accelerometers were installed using a magnetic base. After installing the device, a heel drop test was performed.

As a result of the test, besides the fundamental frequency, the damping of the floor was also obtained. The damping was calculated through the time domain signal and the logarithmic decrement, after the application of the bandpass filter in the signal. Fundamental frequency was obtained by the result analysis of the frequency spectra, using fast Fourier transform.

Critical frequency of the human walking was calculated based on the fundamental frequency previously obtained, according to the recommended frequency intervals (BACHMANN *et al*., 1995). The footfall-induced test was performed through the structure using the obtained critical frequency of human walking. As result, the peak acceleration of root mean square value (rms) was obtained.

Brazilian and international standards and guides, values of fundamental frequency and rms. Peak acceleration obtained through the tests allows evaluating the induced vibration level and, consequently, the human comfort conditions. In case of the Brazilian standard, only the fundamental frequency is used and in the international criteria also is considered the peak acceleration of rms. The obtained results enabled an assessment of the currently Brazilian standard applicability in steel and composite floor systems and footbridges.

Equipment

MEMS (Micro-electro-mechanical systems) accelerometers, GP2L x USB model from SENSR were used in this research. GP2Lx USB is a triaxial data acquisition system specific for dynamic structure monitoring. It has a frequency response amplitude in the range of 0 to 200 Hz with a sampling rating equal to 400 Hz. Its high sensitivity accelerometer can be programmed in four ranges of 1.5 to 6.0 gravity (g).

The great advantage of using the GP2L x USB model is the easy handling of the equipment. The equipment has small size and the sensors, and the signal conditioner and data acquisition center are coupled in a single device. The data acquisition center connects to a USB port of a computer and a magnetic base is fixed to the acquisition center, which allows easy attachment of the equipment to the steel beams of a floor system (Figure 2).

Testing procedure

The first step of the testing procedure is defining a test script of the studied structure. In this stage, the critical sections of the structural system most susceptible to vibrations are defined. In each critical section, the accelerometer installation location is defined with the goal of obtaining representative values of response for the heel-drop test (impact test) and the maximum value of root mean square (rms) acceleration obtained by the footfall-induced test (walking test).

The dynamic tests were carried out according to ISO 2631-1 (INTERNATIONAL…, 1997) and ISO 2631-2 (INTERNATIONAL…, 1989) standards. These standards define practices of measurement and evaluation of periodic, random and transient vibrations. The signal records generated by dynamic tests were carried out without any type of filter according to recommendations of ISO 2631-2 (INTERNATIONAL…, 1989).

Impact test

The test consists of causing structure excitation by impact. It is used to identify a critical floor section (where the largest amplitudes of dynamic displacements are obtained) and the modal characteristics (vibration modes, natural frequencies and damping). According to Murray, Alen and Ungar (2003) the structure can be excited through heels. The heel drop test must be carried out by a person with medium weight (69.4 kg to 80.0 kg) using soft soled shoes (CANADIAN…, 1989). This person must stand on tiptoe and drop onto his heels near the place where the accelerometer was installed. The test was carried out five times in each section of the studied structure to ensure its statistical reliability.

Walking test

Using the values of fundamental frequency obtained through the impact tests, it is possible to determine the critical frequency of human walking for each section of the floor. The critical frequency of the human walking has a harmonic equal or similar to the fundamental frequency of the studied floor. According to Bachmann *et al*. (1995), the human walking frequency has a range of 1.7 to 2.3 Hz. When the frequency or harmonic of the human walking coincides with the floor system frequency, higher accelerations are generated in the structure and this phenomenon can cause human discomfort.

The walking test and impact test must be carried out by the same person. The test consists of three cycles of walking throughout the entire structure. During the tests, the walking frequency must be constant and monitored by a metrometer.

Figure 2 – **GP2Lx USB accelerometer assembled over to a magnetic base**

Signal processing

SensView from SENSR and MatLab *software* were used in the collection and processing of the signs obtained through the dynamic tests. SensView were used in the acquisition of the floor system fundamental frequency with the goal of critical frequency evaluation of human walking for each section of the structure, without using any type of filter. Matlab was used to process the signs collected through SensView. Signal filters recommended by ISO 2631-1 (INTERNATIONAL..., 1997) were applied to the collected signs. The results obtained after the application of the signal filters were compared with the limit values proposed by international standard recommendations and international design guides.

The response spectra of the accelerations in the time domain obtained for vibration assessment of floor is not always clean. This occurs because besides the accelerations induced by the vibrations, there are additional vibrations induced by external factors, such as the wind and vehicle traffic.

The external factors cause vibrations with higher frequencies than the fundamental frequency of the floor. These frequencies make the selection of the acceleration peak difficult for the implementation of the logarithmic decrement method and estimation of the modal damping. A bandpass filter is used with the goal of eliminating the frequencies caused by the external factors and generating a clean and homogeneous signal.

The Butterworth bandpass filter from Matlab was applied to the signals obtained through the heel-drop test and footfall-induced test, using recommendations of ISO 2631-1 (INTERNATIONAL..., 1997). A filter of 1/3 octave frequency and a filter in a range of 0.4 to 100 Hz were used for both tests, respectively.

In the case of the walking test, the rms accelerations were calculated using an equation proposed by HIVOSS design guide (HUMAN..., 2008) after application of the filter in the signal spectra.

Experimental assessment of modal damping

Damping is one of the most sensitive properties of materials and structures in macroscopic and microscopic scales (LAZAN, 1968). It is the phenomenon in which the mechanical energy of a system is dissipated (SILVA, 2007). It is also the mechanism that delimits the vibration amplitude of a resonating element and the residence time of the vibration after the shutdown of the exciting source.

The knowledge of the physical phenomenon and the mechanism, which causes damping is not clear. This fact leads to the difficulty of the mathematical calculus or the determinations of the individual contributions from the various energy dissipation mechanisms in a building. Then, the obtaining of a structural damping occurs by impact tests (PAVIC; REYNOLDS, 2002).

The logarithmic decrement method is based on the rate at which the amplitude of a free damped vibration decreases. In this method, the energy is transferred to other system parts or is absorbed by the system. The greater the damping, the greater the rate of decrease. The method has proved to be convenient to determine the quantitative variable of a structural system damping. According to Pereira *et al*. (2012), this method is the most adequate for measuring elements with medium and low damping, such as steel and composite floor systems. The decrement is measured using the experimental curve of displacement versus time and the selection of the consecutive peaks.

According to Cossolino and Pereira (2010), the logarithmic decrement (δ) is calculated through Equation 1.

$$\delta = \frac{1}{n} ln\, ln \left(\frac{A}{A_n}\right) \quad \text{Eq. 1}$$

Where:

n is the number of acceleration peaks from A to An;

A is the first acceleration peak; and

An is the last acceleration analyzed peak.

The damping rate (ξ) is calculated through Equation 2.

$$\xi = \frac{1}{\sqrt{1+(2\pi/\delta)^2}} \quad \text{Eq. 2}$$

The logarithmic decrement is widely used for estimating the modal damping in the response processing of dynamic tests on composite floor systems and footbridges considering human comfort. Santos (2009), Peralta *et al*. (2010), Varela and Battista (2011), Baldoni Junior and Pinheiro (2012), Marcos (2015), Albuquerque (2016) and others authors used the decrement logarithm for determining the damping ratio.

Actual researches point out that this method is limited compared to recent methods. However, the use of this method in assessment of walking induced vibration in composite system floors and footbridges is justified because it is easy-to-use and the damping ratio is not be directly used in the performance evaluation considering human comfort. It is used to correlate the acceleration peaks with the damping ratios and numeric model implementation.

Design criteria for vibration evaluation considering human comfort

Although human sensibility to vibration is subjective, national and international standards for vibration evaluation were proposed based on human comfort studies carried out over several years.

NBR 8800 (ABNT, 2008)

NBR 8800 (ABNT, 2008) presents a simplified manner of vibration assessment of floor based on its fundamental frequency. In any case, the fundamental frequency must not be less than 3 Hz. In places such as offices and homes, where people regularly walk, a simplified assessment can be performed and the fundamental frequency must be limited to 4 Hz. In floors where people develop rhythmic activities, like gyms, dance halls, gymnasiums and sports stadiums, the fundamental frequency must not be less than 6 Hz and it must be increased to 8 Hz when the activity is repetitive.

These presented limit values consist of a simplified assessment of floor vibrations caused by human activities and it cannot represent an adequate solution for the problem. In the case of a careful assessment, the designer must carry out dynamic analyses and the standard does not present criteria to perform these types of analyses. They must take into account the nature of the dynamic excitations resulting from human walking and rhythmic activities, acceptance criteria for human comfort, natural frequency of the floor, modal damping and effective weight of the floor.

Design Guide 11 – AISC

The Design Guide 11 from the American Institute of Steel Construction – AISC presents practices and tools for floor systems and footbridge assessments exposed to human activities. The acceptance criteria for human comfort proposed by this guide is based on dynamic responses, and can be used to evaluate structural systems (offices, shopping malls, footbridges, and similar occupancies) (MURRAY; ALLEN; UNGAR, 2003). The design guide presents a graph of peak acceleration (% g) versus the fundamental frequency (Hz). The graph contains limit curves for different occupancies of the floor considering the baseline curve proposed by ISO 2631-2 (INTERNATIONAL..., 1989).

The acceleration limits for the different occupancies are defined using a multiplying factor applied to the values of the ISO baseline curve. The multipliers for the proposed criterion, which is expressed in terms of peak acceleration, are 10 for offices and residences, 30 for shopping malls and indoor footbridges, and 100 for rhythmic activities and outdoor footbridges. For design purposes, the limits can be assumed to range between 0.8 and 1.5 times the recommended values depending on the duration of vibration and the frequency of vibration events.

SCI Publication P354

The publication proposes that this vibration response be compared with the criteria defined in the BS 6472 (BRITISH…, 1992) and ISO 10137 (INTERNATIONAL..., 2007) standards for general structures, and with the specific NHS performance standard for hospitals from Health Technical Memorandum 08-01 (THE STATIONERY…, 2008). Different occupancies of floor systems are considered in this guide, such: as rhythmic activities, hospitals, offices, parking, housing, footbridges, among others. Strategies for numerical analysis of structures using finite element methods are also presented in Publication P354.

Similarly to Design Guide 11, the acceptance criteria for human comfort of this guide are based on acceleration curves defined by the application of multiplying factors on a baseline curve. These factors depend on floor occupancy, occurrence time and vibration type. The curves are presented in BS 6472 (BRITISH…, 1992) and ISO 10137 (INTERNATIONAL…, 2007). The obtained rms acceleration for a determined floor system must be compared with the limit of acceleration that corresponds to the occupancy type. Tables 1 and 2 present the multiplying factors according to occupancy.

Table 1 – **Recommended multiplying factors based on single person excitation (SMITH; HICKS; DEVINE, 2009)**

Place	Multiplying factor for exposure to continuous vibration
Office	8
Shopping mall	4
Dealing floor	4
Stairs - light use (e.g., offices)	32
Stairs - heavy use (e.g., public buildings, stadia)	24

Table 2 – **Recommended multiplying factors given in HTM 08-01 (THE STATIONERY..., 2008)**

Room type	Multiplying factor for exposure to continuous vibration
Operating theaters, precision laboratories, audiometric testing booth	1
Wards	2
General laboratories, treatment areas	4
Offices, consulting rooms	8

Results and discussion

In order to achieve the objective of this research, which was to verify the efficiency of the simplified methodology proposed by NBR8800 (ABNT, 2008), four case studies with different characteristics were selected to evaluate human comfort, considering induced vibrations in civil structures. The case studies are presented bellow:

(a) accessibility footbridge of a sports building;

(b) accessibility footbridge of a multi-story building;

(c) observation walkway of Laticínio FUNARBE building; and

(d) multi-story building.

For all case studies, their critical section (those more susceptible to vibrations caused by human walking) were analyzed. This chapter presents the results for the most critical section of each case study. This strategy was taken with the aim of evaluating the sections with greatest sensitivity to vibrations induced by human walking, verifying the experimental methodology proposed in this article and evaluating the efficiency of NBR 8800 (ABNT, 2008).

System floors and footbridges description

Geometrical characteristics, profiles and materials of studied floors and the critical sections and position of accelerometers are presented in this section. Figure 3 presents the studied system floors and footbridges. Figures 3(a), 3(b), 3(c) and 3(d) correspond to case studies 1, 2, 3 and 4, respectively. The GP2Lx USB accelerometers were installed in the points (P01, P02 and P03) demonstrated in Figure 4.

Case study 1: accessibility footbridge of a sports building

Figure 3(a) presents the accessibility footbridge of a sports building from Universidade Federal de Viçosa, Brazil. The ramp is composed of four inclined parts and four landings and it was built using steel pillars and a composite system floor.

The edge beams are composite beams formed by laminated profiles type W 410x60 with distance equal to 1950 mm between axes. These beams are supported on cantilever beams through screw connections. The cantilever beams are formed by laminated profiles type W 530x72 and W 520x82 and they are connected to the columns through a welded connection. The cantilever beams have a corbel at the bottom, in order to increase the system strength. The in-situ concrete slabs are solid, with 2103 mm of width and 125 mm of thickness. The interaction between the slab and the beams is done through stud bolts.

The accelerometers were installed on P01, P02 and P03 points of footbridge edge beams, see Figure 4(a). The devices were fixed in the center of the longitudinal section of these beams, since they are simply supported elements.

Figure 3 – **Case studies**

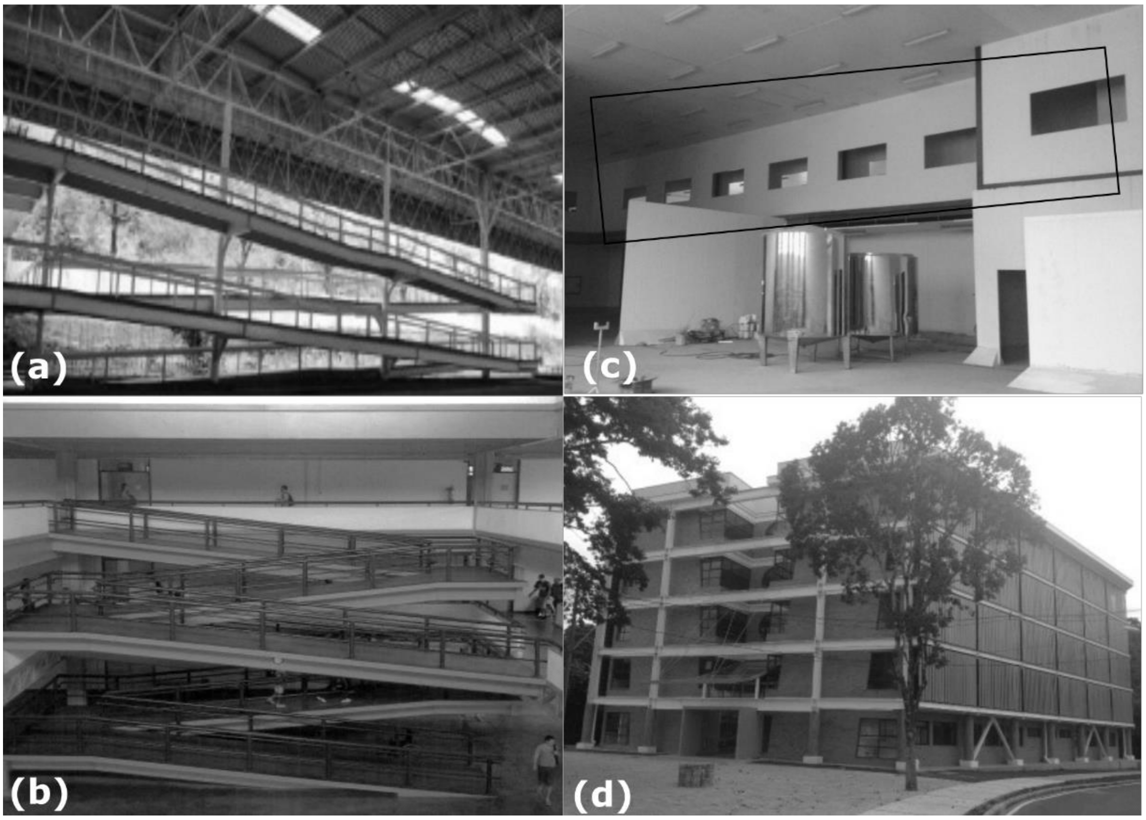
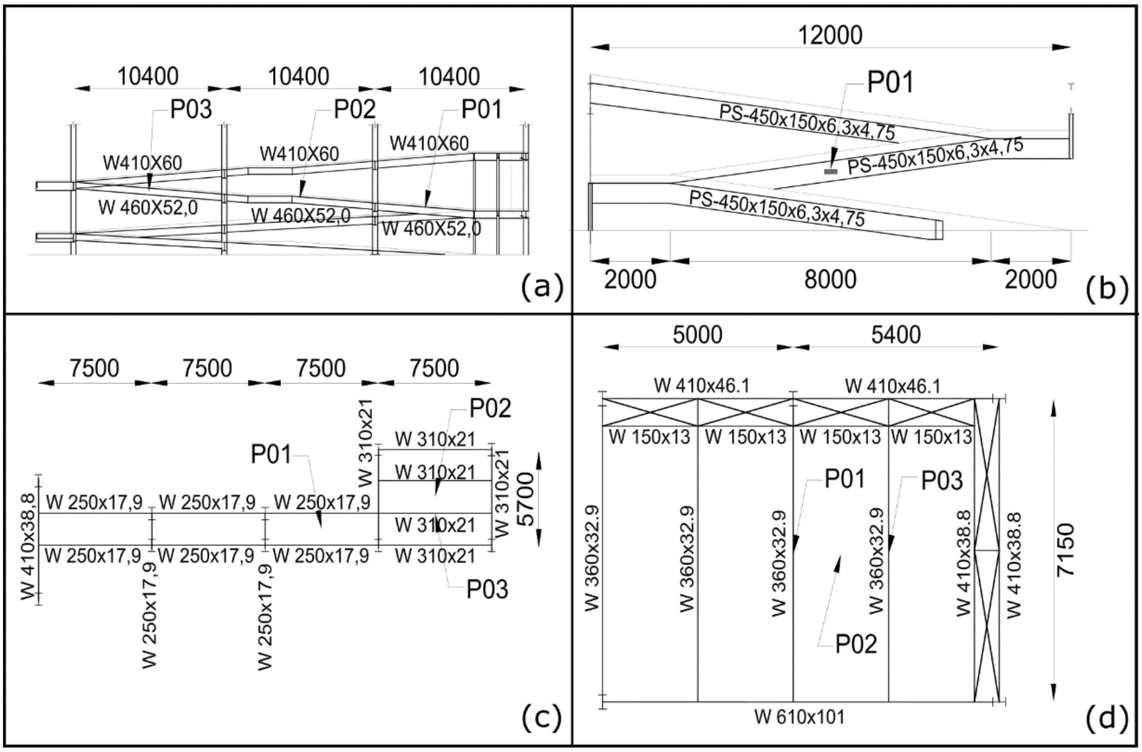


Figure 4 – **Design of case studies and installation position of accelerometers**



Case study 2: accessibility footbridge of a multi-story building

Figure 3(b) presents the accessibility footbridge of a multi-story building from Universidade Federal de Viçosa, Brazil. The ramp is composed of five inclined parts and four landings andt was built using steel pillars and a composite system floor.

The composite beams are formed by welded profiles type PS 450x150x6.3x4.75 with a distance equal to 1000 mm between axes. These beams are supported on intermediate landings formed by welded profile type PS 450x150x6.3x4.75 or adjacent floors through screw connections. The landings are connected to the top and bottom adjacent floors through pillars formed by profiles type PS 250x150x6.3x4.75 welded connected. The in-situ concrete slabs have 2000 mm of width and 150 mm of thickness and they are formed by a steel deck with 75 mm of height. The interaction between the slab and the beams is done through stud bolts.

The accelerometer was installed on P01 point of a footbridge part, see Figure 4(b). The device was fixed in the center of the longitudinal section of this beam, being a a simply supported element. Other points of the ramp were not tested because the three superior inclined parts of the ramp present the same characteristics of the tested ramp part (P01 point). The inferior inclined part of the ramp was not also tested because it has a smaller span than the other parts. The small span of this footbridge part had higher stiffness and, consequently, higher fundamental frequency when compared with the other ramp parts.

Case study 3: observation walkway of Laticínio FUNARBE building

Figure 3(c) presents the observation walkway of the Laticínio FUNARBE building from Universidade Federal de Viçosa, Brazil. The walkway is located in the upper floor of an industrial building where dairy is produced and it has the goal of the production line observation. The walkway is composed of steel pillars and a composite system floor.

The composite beams are formed by laminated profiles type W 250x17.9 and W 310x21. These beams are supported on pillars formed by laminated profile type W 200x26.6 through screw connections. The in-situ concrete slabs have 2100 mm of width and 150 mm of thickness and they are formed by a steel deck with 75 mm of height. The interaction between the slab and the beams is done through stud bolts.

The accelerometers were installed on P01, P02 and P03 points of the walkway system floor, see Figure 4(c). The devices were fixed in the center of two slabs (P01 and P02) and in the center of the longitudinal section of a beam (P03). The test was carried out in the walkway without cover and a wall of insulated panels.

Case study 4: multi-story building

Figure 3(d) presents a multi-story building from Universidade Federal de Viçosa, Brazil. The building contains classrooms, an auditorium, professor rooms and laboratories. It is composed of five floors, steel pillars, composite system floors, a slab formed by a steel deck and perforated bricks.

The composite beams of the critical section are located on second floor and they are formed by laminated profiles type W410x46.1, W610x101, W 360x32.9 and W410x38.8. These beams are supported on pillars formed by laminated profile type HP 310x79 through screw connections. The in-situ concrete slabs have 150 mm of thickness and they are formed by a steel deck with 75 mm of height. The interaction between the slab and the beams is done through stud bolts.

The accelerometers were installed on P01, P02 and P03 points of the system floor, see Figure 4(d). The devices were fixed in the center of one slab (P02) and in the center of the longitudinal section of two beams (P01 and P03).

Fundamental frequency

Fundamental frequency of the studied cases was obtained through impact tests. Table 3 presents the results of the case studies.

Table 3 - **Fundamental frequencies of studied floors**

Case	Frequency (Hz)
1	6.64
2	6.35
3	7.81
4	11.20

NBR 8800 standard (ABNT 2008) recommends a fundamental frequency with a value greater than 4 Hz for system floors where people regularly walk, such as offices and homes, and a fundamental frequency with a value greater than 6 Hz for system floors where people develop rhythmic activities, like gyms, dance halls, gymnasiums and sports stadiums. All the case studies presented a fundamental frequency greater than the acceptable minimum limit recommended by NBR 8800.

Besides, the studied cases of 1, 2 and 3 case studies presented a fundamental frequency in a range from 5 to 8 Hz. According to experimental research of Hanes (1970), this range of frequency causes more discomfort to the users. The obtained results show the need of an accurate evaluation for performance assessment considering human comfort for walking induced vibration.

Modal damping

Results of modal damping were obtained by the logarithmic decrement method with a fifth-order Butterworth band pass filter. Table 4 shows the calculated damping ratios of critical points of the floors, which presented the lower natural frequency (fundamental frequency).

The obtained damping of the cases (see Table IV) presented a ratio in the usual range for composite floor systems and footbridges, which is from 1% to 5% according to AISC/CISC (MURRAY; ALLEN; UNGAR, 2003) and 1% to 4% according to HIVOSS (HUMAN..., 2008). The greatest ratio of damping obtained was equal to 3.51% and belongs to case 1. Usually, the damping for this type of structure is around 1% according to Murray, Allen and Ungar (2003). The damping ratio is greater than the values normally obtained. This damping is assigned to the existence of an intermediate load composed by concrete filling, see Figure 5. The concrete filling increases the weight and the stiffness of the ramp critical section, interfering in the obtained damping value.

The obtained lower ratio of damping was equal to 2.05% and it belongs to case 3. This value was obtained because the test was carried out in the walkway without cover and a wall of insulated panels.

Footfall-induced test

Human walking frequencies were calculated with the goal of exciting the first natural frequency of the analyzed floors obtained through the impact tests. The range of 1.7 Hz to 2.3 Hz (BACHMANN *et al*., 1995) was considered the calculation of this frequency. Table 5 shows the main results of the walking test.

Table 4 – **Modal damping of the studied cases**

Case	Critical point	Fundamental frequency (Hz)	Damping (%)	Peak number	Coefficient of variation C.V. (%)
1	P02	6.64	3.51	10	7.80
2	P01	6.35	3.23	14	14.40
3	P02	7.81	2.05	50	9.36
4	P01	11.20	2.20	49	17.76

Figure 5 – **Intermediate load composed by concrete filling**

Table 5 – **Walking test results**

Case	Critical point	Human walking frequency (f_w)	Natural frequency of the system floor (f_n)	$\frac{f_n}{f_w}$	Peak acceleration (% g)
1	P03	1.66 Hz	6.64 Hz	4	2.25 %
		2.21 Hz	6.64 Hz	3	2.82 %
2	P01	2.12 Hz	6.35 Hz	3	5.09 %
3	P01	2.05 Hz	8.20 Hz	4	3.58 %
	P02	1.95 Hz	7.81 Hz	4	2.09 %
4	P01	2.24 Hz	11.20 Hz	5	Imperceptible

Human walking was effective in exciting the floors with lower fundamental frequencies. The ratio between the human walking frequency (f_w) and the natural frequency of the excited system floor (f_n) supports this statement. When the value of f_n/f_w was greater than 4, the peak acceleration was imperceptible.

The lower the fundamental frequency of a system floor is, the easier it is to be excited by human walking. The peak acceleration values of case 1 are lower than the values of case 3, despite the first case presented a fundamental frequency lower than the third case. This result is justified by the greater damping ratio of case 1. The damping ratio of this floor causes a great energy dissipation, resulting in low values of peak acceleration.

Case 4 presented a peak acceleration imperceptible for a human walking frequency equal to 2.44 Hz, where its fifth harmonic excites the fundamental frequency of the system floor. This result is justified by the low energy provided by the fifth harmonic of human walking and this energy is easily dissipated in the system floor.

Vibration assessment considering human comfort

Vibration assessment of the study cases were carried out using Design Guide 11 (MURRAY; ALEN; UNGAR, 2003) and SCI Publication P 354 (SMITH; HICKS; DEVINE, 2009) thought the obtained values of fundamental frequency and rms peak acceleration. Figure 6 presents the obtained results for cases 1 to 3. The case 4 is not evaluated, since the peak acceleration was imperceptible.

SCI Publication P 354 (SMITH; HICKS; DEVINE, 2009) and Design Guide 11 (MURRAY; ALEN; UNGAR, 2003) recommends that the limit curve is defined by the multiplication of the BS 6472 base curve (BRITISH..., 1992) for 22 and 30, respectively, for indoor footbridges and walkways. These limit curves are defined in Figure 6 and the rms peak accelerations obtained through the walking test were greater than the recommended for cases 1 to 3.

The results obtained by the international criteria suggest that the cases 1 to 3 are not adequate to human comfort, despite NBR 8800 (ABNT, 2008) that suggests the opposite.

Discussion

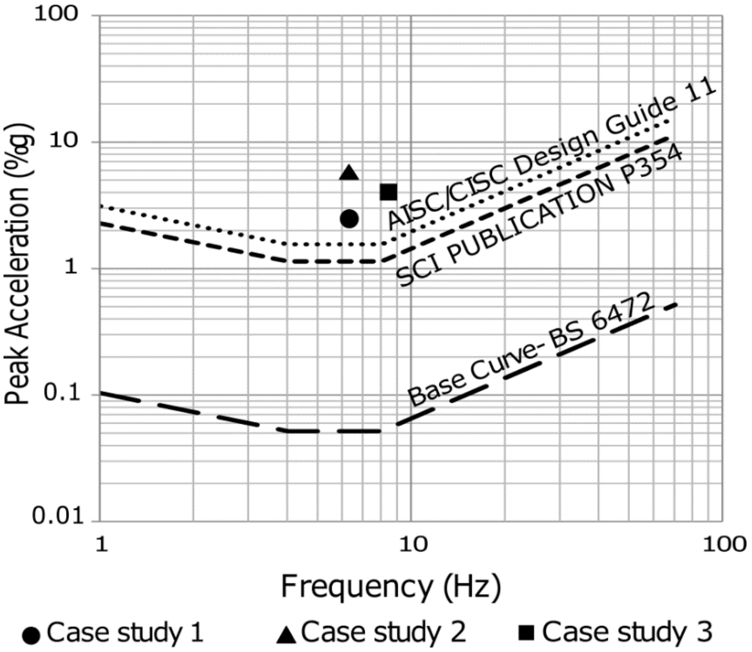
In this research, the international criteria, SCI Publication P 354 (SMITH; HICKS; DEVINE, 2009) and Design Guide 11 (MURRAY; ALEN; UNGAR, 2003), and the Brazilian standard NBR 8800 (ABNT, 2008) provides different conclusions concerning to the assessment of walking induced vibrations in floors considering human comfort.

The discomfort caused by human walking is proportional to peak acceleration when the vibration frequency has value in a range of 1 to 10 Hz (BACHMANN *et al.*, 1995). Brazilian standard NBR 8800 (ABNT, 2008) does not use this variable for evaluation of human comfort due to induced vibrations and it was not efficient to analyze the floors that presented fundamental frequencies in the range (case 1 to 3).

Case 4 presented fundamental frequency equal to 11.20 Hz and imperceptible peak acceleration. Therefore, the human walking was not capable of providing enough excitation in the system floor and, consequently, its vibrations do not cause human discomfort.

System floors with value of fundamental frequency close to minimum values proposed by NBR 8800 (ABNT, 2008) can have vibration problems. In these cases, this research suggests a careful analysis of the induced vibrations caused by walking, considering the assessment of human comfort through international criteria.

Figure 6 – **Vibration assessment of case studies 1 to 3**



The logarithmic decrement method was efficient to estimate the modal damping of the studied floors since the obtained values are in the range of 1% to 5%, as suggested in literature. The variation coefficients presented values lower than 20% and present a high or medium accuracy, according to Gomes (2009).

The studied structures with higher damping ratios presented smaller acceleration peaks induced by human walking, though they presented low fundamental frequency. Therefore, the increase of a structure damping is a good alternative to reduce the footfall-induced vibrations of a system floor.

Conclusions

The dynamic tests carried out in this research present the advantage of being non-destructive and they were effective to obtain the modal characteristics and to evaluate the footfall-induced vibrations in the analyzed structures.

The study cases pointed out the importance of the evaluation of the peak acceleration obtained through walking tests, providing a better knowledge by the dynamic behavior of system floors and footbridges considering the human comfort. Differently from international criteria, NBR 8800 (ABNT, 2008) was not effective in vibration assessment considering human comfort of the study cases due to not considering the peak accelerations.

The research suggests that the vibration control in composite systems with long free spans, low strength and low damping ratio is a concern in vibration assessment considering human comfort. The NBR 8800 proved to be not effective for comfort evaluation by human walking induced vibrations in this type of structure. The authors suggest a modification in the standard, through the inclusion of the peak acceleration obtained through footfall-induced tests in the analysis.

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