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CROWD SIZE EFFECT ON FLOOR VIBRATION RESPONSE DUE TO RANDOM AND RHYTHMIC EXCITATIONS

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In order to investigate crowd size effect on building floors response, human-induced vibrations have been measured on a flexible composite floor exposed to various activities. Experimental Modal Analysis has revealed the existence of 20 mode shapes below 10Hz, with a fundamental frequency of 3.56Hz. The floor has then been exposed to various human-induced activities, covering both sedentary rhythmic activities (skipping and jumping) and activities where the individuals were moving randomly across the floor (walking and running). Accelerations have been registered at 10 different locations. By repeating these activities with a number of 1, 2, 4, 8, 16 and 32 participants, the group size effect has been evaluated through the measured accelerations. The observed trends not only differ for each activity but also slightly depart from well-accepted laws proposed by current design guidelines. A comprehensive data analysis and discussion is provided in order to support the proposal of size-effect laws for these types of activities that will allow a more realistic vibration serviceability assessment of building floors with multiple usages.
Keywords: Composite floor, human-induced vibration, crowd effect, synchronization

1. Introduction

Structural development of floors in buildings has remarkably changed their performance in the serviceability limit state. In fact, floors are becoming increasingly slender, flexible and lightweight, due to architectural considerations and increasing trends to open spaces, which makes them prone to excessive vibrations, especially those induced by human activities such as walking, running or jumping. This effect is more pronounced in presence of a group of persons exciting the floor especially with a high degree of synchronization.

Zhu et al. [1] investigated experimentally the response of a cantilever floor while crowds were walking. An et al. [2] performed a large experimental study of the crowd effect on the response of an innovative composite floor under various activities (skipping, running and jumping). The crowd size effect is typically expressed through a less-than-proportional increase of human excitation forces comparing to the number of individuals in the considered crowd. Ebrahimpour et al. [3] highlighted experimentally the dependence of group effect on harmonic components. Ellis et al. [4] confirmed these conclusions and suggested dynamic load factors for a moderate group size of people exerting “normal jumping”. These proposals were later adopted by the load model of SCI P354 design guide [5]. ISO 10137 [6] provides coordination factors which depended on harmonics for jumping activity whereas a unique coordination factor is given for walking. Máca et al. [7] established a literature review of these factors from various authors. However, these research works have not investigated the effect of crowd size on the floor vibration response. In addition, the human activities considered in these studies are limited.

The study described in this paper aimed to investigate the crowd size effect on a multiple-mode flexible floor in order to establish acceleration response trends for various activities, which makes this study quite specific with regards to the floor vibrations that have been examined so far in the literature. Experimental and numerical methods are described in Section 2. Next, the results are presented and discussed. The estimated group size effect laws are compared against the predictions given by current design guidelines.

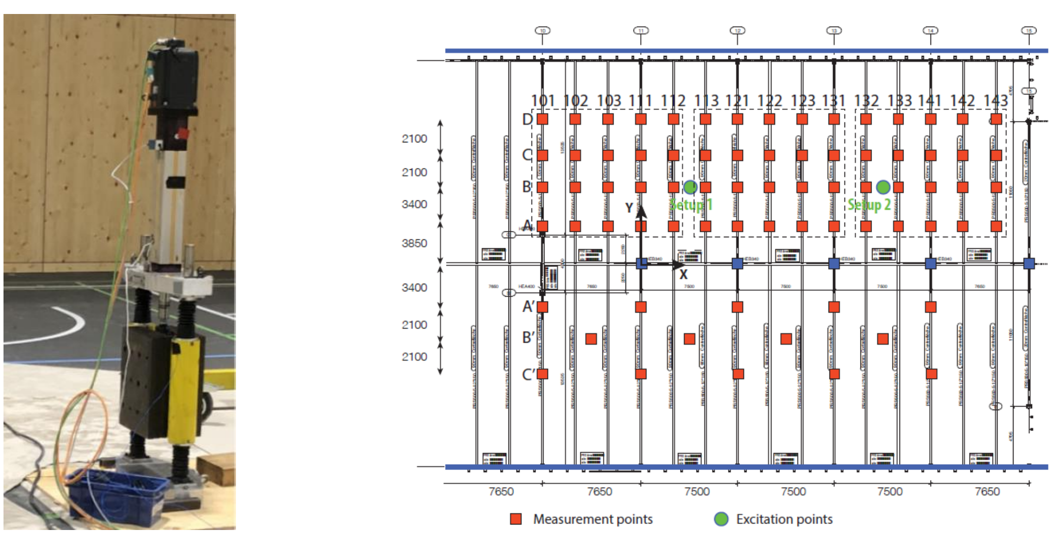
2. Method

2.1 Tested floor

Experimental tests were carried out on a 3-storey steel-concrete composite parking structure located in Nantes, France. The tested floor, located at 3m above the ground, consisted of welded plate girders (for beams and columns) fully connected to a composite concrete deck with a thickness of 13cm and a total area of about 4200m². A rectangular zone of 22.5m × 15.875m near to the floor centre was selected for testing.

2.2 Modal analysis

The first test campaign aimed to characterize modal properties of the floor using Experimental Modal Analysis (EMA) [8]. The structure was excited by a digitally controlled electrodynamic shaker (see Fig. 1-a), located at two positions labelled Setup 1 and Setup 2 in Fig. 1-b. For each position of the shaker, white noise excitation allowed the detection of modal frequencies ranging between 3 and 10Hz, which is within the range of natural frequencies of interest. Then, the frequency of excitation was tuned onto each frequency detected and responses measured by wireless accelerometers placed at different points around the structure as shown in Fig. 1-b. A synchronous measurement of the acceleration near the shaker provides the frequency response functions (FRFs) that are necessary to determine the modal properties of the floor such as the mode shapes, modal mass and damping ratios.



(a) (b)

Figure 1: Modal analysis setup: (a) electrodynamic shaker; (b) shaker and accelerometers' positions

2.3 Human-induced vibration tests

A series of tests was conducted in order to measure the floor acceleration under various human-induced loads, including excitations where individuals were moving randomly (walking and running) and sedentary rhythmic excitations (skipping and jumping). In order to assess the crowd size effect on the floor response, tests were divided into six series, with 1, 2, 4, 8, 16 and 32 persons, respectively.

For random movements, participants were asked to walk or jog during 4 minutes in the monitored area (see Fig. 2) along random straight paths without controlled pacing frequency. These activities have been repeated three times. For rhythmic activities, participants were asked to stay at fixed positions (as illustrated in Fig. 2 for the case of 32 persons) and participate in rhythmic activities under the guidance of an experimented sports coach in order to achieve as much synchronization as possible. In this case, each activity lasted 1 minute and was repeated 9 times. Corresponding accelerations were measured using 10 cabled accelerometers installed below the studied floor, which are shown in Fig. 2.

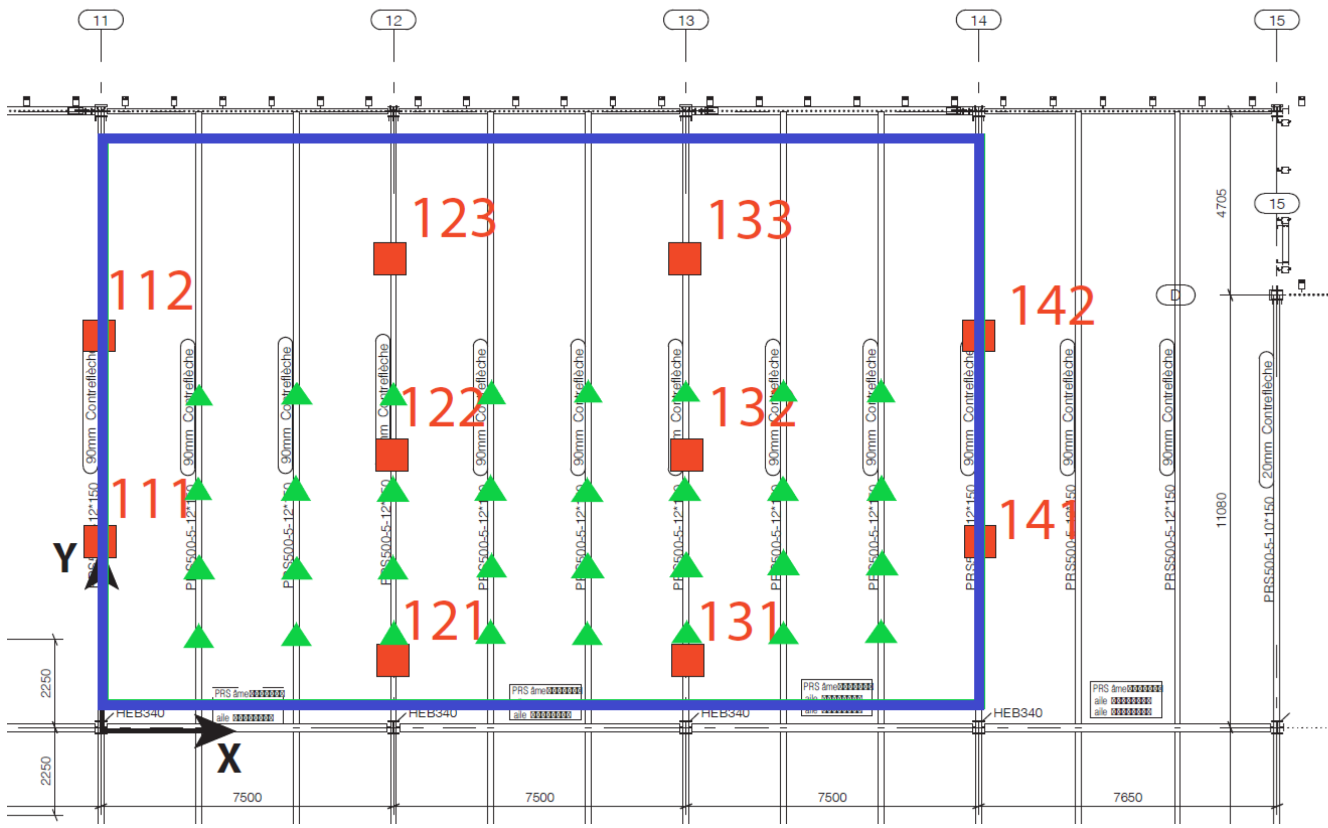


Figure 2: Accelerometers' locations below the floor (red rectangles); random activities' area (blue box); 32 individuals' positions for rhythmic activities (green triangles)

A total of 35 individuals (26 men and 9 women) were involved in the experiments. The subjects' ages ranged from 18 to 58 years (mean: 28 years and standard deviation: 12 years) and their weights varied from 52.3 to 126.6kg (mean: 75.8kg and standard deviation: 15.4kg). A total of 5 hours of response data were recorded during this campaign. An example of a recording by one accelerometer for activities involving 16 persons is given in Fig. 3.

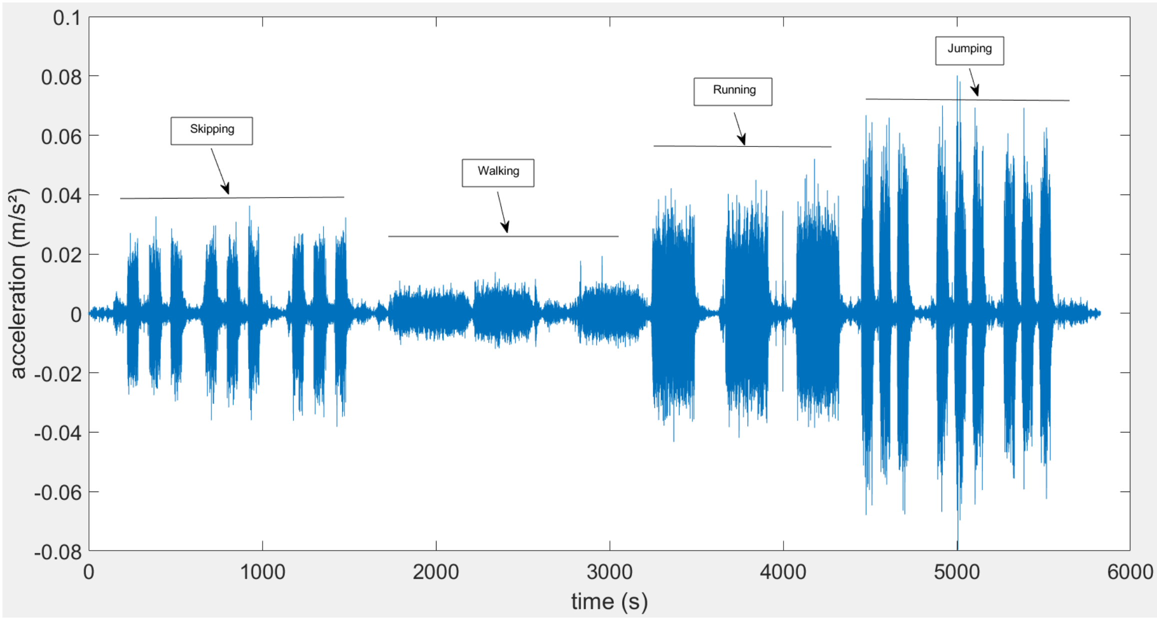


Figure 3: Accelerations measured by one accelerometer for activities involving 16 persons

2.4 Data processing

All response records were processed using Matlab software. Each signal is bandpass-filtered in the band of [1.2; 10] Hz. For each activity, number of persons and accelerometer, statistically reliable values of the RMS acceleration have been selected (median RMS for rhythmic loads, mean of representative RMS for random loads). In order to eliminate the mass effect, all RMS accelerations were normalized by the mass of participants in each test and re-scaled by the mean mass of participants (75.8 kg). Outliers have been detected using DFFITS criterion [9] and eliminated from the data processing. Finally, Mean RMS accelerations, averaged over the 10 accelerometers in the setup, have been calculated in order to obtain a globalized experimental crowd size effect for each studied activity.

The dependence of the number N of participants upon the Mean RMS accelerations in each activity has been fitted by a nonlinear law of the type $a_{rms} = \varepsilon + aN^r$ (1) using nonlinear GRG algorithm in Excel software. The choice of this 2-parameter model is supported by the aim to remove the influence of the (small) ambient noise ε and to quantify the crowd size effect by means of a power law.

3. Results

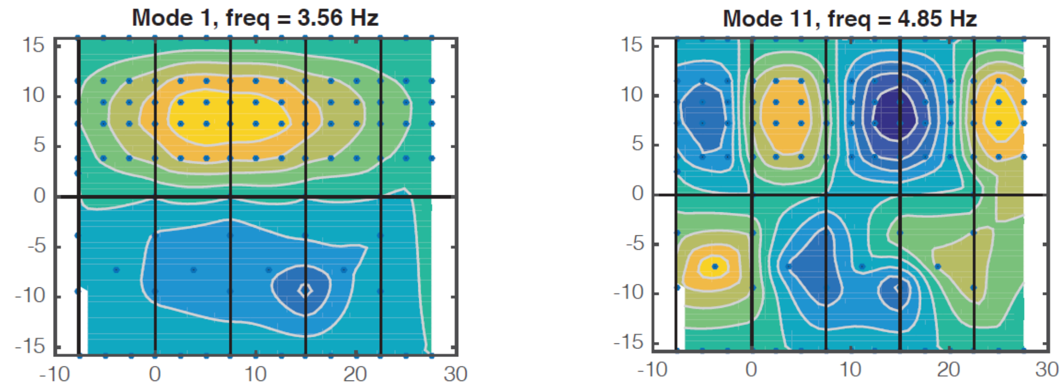
3.1 Modal properties

Modal analysis of the analysed floor revealed the existence of 20 vibrational modes with a natural frequency below 10Hz, and a fundamental frequency of 3.56Hz. The structure is thus a low-frequency floor [4], sensitive to human excitation. Natural frequencies, modal masses and damping ratios of the first four modes are presented in Table 1.

Table1: Scalar modal parameters of the floor

Mode	Frequency (Hz)	Modal mass (t)	Damping ratio (%)
1	3.56	297	0.44
2	3.68	174	0.45
3	3.84	127	0.69
4	3.91	167	0.57

Corresponding identified mode shapes are shown for Modes 1 and 11 in Fig. 4. Mode 1 is a global mode, higher modes are more local.



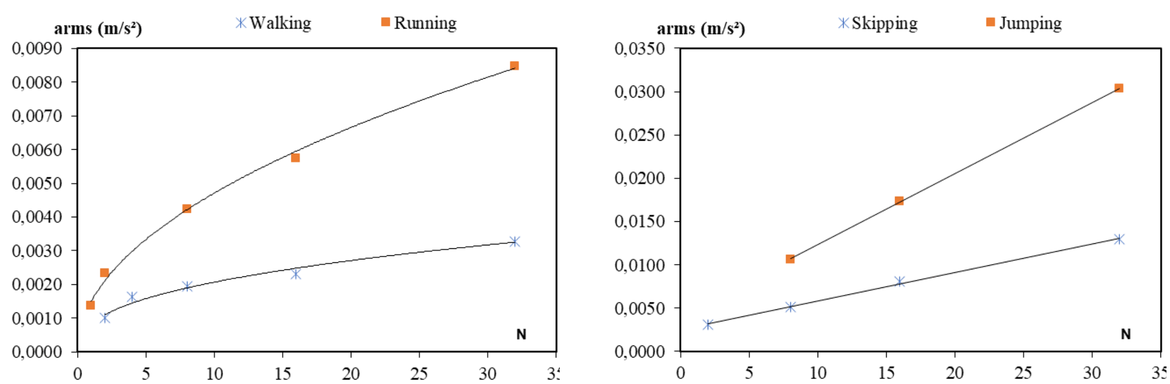
(a) (b)

Solid black lines represent supporting beams. Dimensions in m.

Figure 4: Mode shapes: (a) Mode 1; (b) Mode 11.

3.2 Mean RMS accelerations

For each activity, the Mean RMS acceleration (average over the tested floor) is established as a function of the number of participants. Power-law trends (for random activities) or linear trends (for rhythmic activities) are matched to the data, as illustrated in Fig. 5. RMS acceleration levels gradually increase from walking to jumping.



(a) Random activities (b) Rhythmic activities

Figure 5: Experimental RMS acceleration general trends against participants' number

3.3 Crowd size effect

Results of curve fitting for running activity are provided for illustration. The best-fit parameters of the nonlinear regression according to Eq. (1) are:

$$\varepsilon = 3 \times 10^{-4}\ m/s^2,\ \ a = 1.3 \times 10^{-3}\ m/s^2 \text{ and } r = 0.53$$

The result of this curve fitting is also illustrated in Fig. 6.

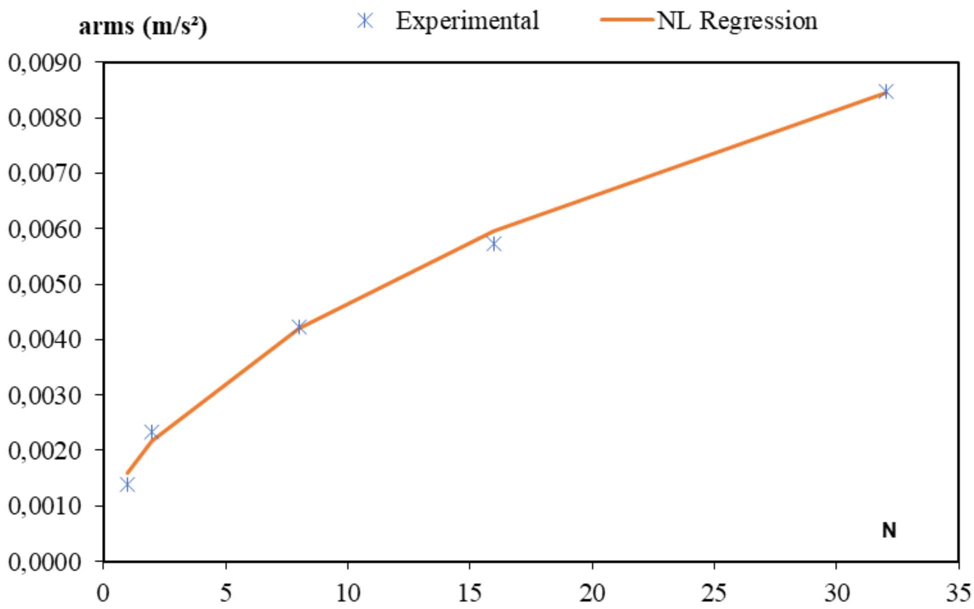


Figure 6: Experimental RMS acceleration with nonlinear regression against crowd size

The results of the curve fitting after noise elimination are given in Table 2, including specific values of 1 person's acceleration for the analysed floor.

Table 2: Mean RMS acceleration against group size

Activity	RMS acceleration law	$a_{rms,1p}$ (m/s²)	R^2 coefficient
Walking (random)	$a_{rms,w} = a_{rms,1p,w}\ N^{0.48}$	6×10^{-4}	0.959
Running (random)	$a_{rms,r} = a_{rms,1p,r}\ N^{0.53}$	1.3×10^{-3}	0.996
Skipping (rhythmic)	$a_{rms,s} = a_{rms,1p,s}\ N^{0.68}$	1.1×10^{-3}	0.992
Jumping (rhythmic)	$a_{rms,j} = a_{rms,1p,j}\ N^{0.81}$	1.7×10^{-3}	0.997

N group size;
a_{1p} response (acceleration) for one person;
R^2 determination coefficient (with noise).

4. Discussion

4.1 Group effect analysis

The exponent of the observed group-size effect is larger in rhythmic activities than in random activities (see Table 2). It could be partially explained by a better synchronization in addition to the permanent excitation of the fundamental mode shape independently of the crowd size in the first category compared to the second. Furthermore, running has a slightly larger exponent than walking probably due to the higher pacing frequency and velocity which may lead to different interaction among participants. Coordination between individuals was higher in jumping than skipping activities resulting in different group coefficients.

4.2 Comparison with current design guidelines

For walking and jumping activities, the measured accelerations have been compared against current design guidelines. SCI P354 design guide [5] was used to calculate the RMS acceleration for one person (for jumping, low and high impact aerobics have been considered), relative to the first two dominant natural modes for each activity. Then, coordination factors proposed by ISO 10137 [6] and given in Table 3 were used for each activity to calculate RMS response for 1, 2, 4, 8, 16 and 32 participants. For jumping, the lowest coordination factors, although corresponding to $N \geq 50$, were chosen for calculation (if they showed conservative results, it would necessarily be the case for higher factors).

Table 3: Coordination factors corresponding to ISO 10137 [6]

$a_{rms}(N) = C(N)\, a_{rms,1p}$		
Activity	Coordination - harmonic	Coordination factor
Walking	All	$C(N) = \sqrt{N}$
Jumping	Medium – 1st harmonic	$C(N) = 0.67\, N$
Jumping	Medium – 2nd harmonic	$C(N) = 0.5\, N$

RMS accelerations evaluated experimentally and by design guidelines are presented in Fig. 7 as a function of the number of participants for walking and jumping activities.

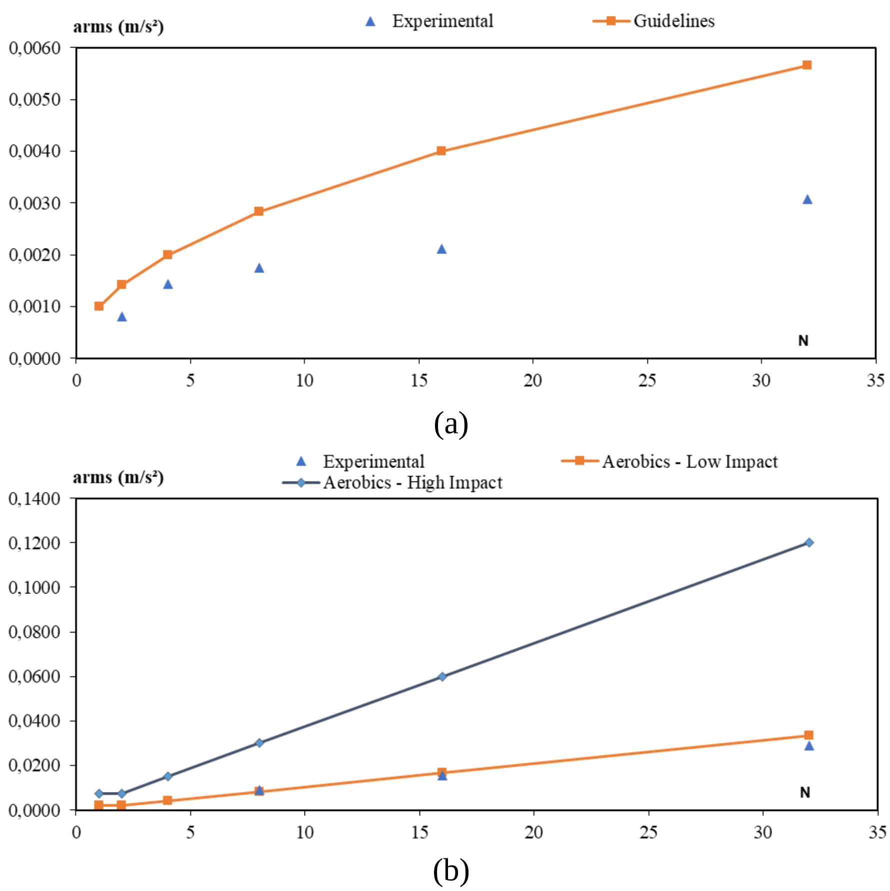


Figure 7: RMS acceleration against group size: (a) walking; (b) jumping

In the analysed case, the investigated design guidelines strongly overestimate the RMS acceleration compared to experimental data and lead to conservative results. For walking activity, it occurred because the one person's calculated acceleration is slightly higher and the proposed coordination factor had a coefficient of 0.5 against 0.48 obtained from our experimental results. For jumping, although with the smallest coordination factors, high impact aerobics, which is near to experimental jumping activity type, resulted in a greatly higher level of RMS accelerations. Low impact aerobics' RMS were closer but still conservative. This is due to the linear law proposed for each harmonic (against power law obtained experimentally) which overestimated responses especially for a more considerable number of persons.

As a consequence, experimental laws obtained from the tests described in this paper could be used for more accurate estimation of human-induced vibrations ensuring reliable serviceability assessment of building floors.

5. Conclusion

The analysed structure was a low-frequency floor with a fundamental frequency of 3.56Hz. The evolution of the Mean RMS acceleration as a function of the crowd size has been approximated by a power law for each activity. For random activities, walking and running, the curve was quite close to a square-root as suggested by previous research and design guidelines (for walking). For rhythmic activities, skipping and jumping, the exponent was higher and comprised between 0.68 and 0.81 but clearly lower than existing proposals that suggest a linear curve (for jumping). These preliminary results show that a more economical design guidelines for floors against human-induced vibrations with multiple usages (residential, commercial, sports/fitness, etc.) can be developed.

As a perspective, it is intended to perform the same statistical analysis on the dynamic loading instead of the measured RMS accelerations and assess whether the same conclusions can be drawn from the dynamic loading. These loads will be identified with inverse dynamics procedures. Besides, further experimental tests on other floors with various types and shapes must be carried out in order to confirm and generalize these findings.

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