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VIBRATIONS OF A LOW-FREQUENCY FLOOR UNDER VARIOUS PEDESTRIAN LOADING SCENARIOS

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Abstract

Contemporary floor vibration guidelines limit the discussion of walking-induced vibrations to single-pedestrian loading scenario. Nevertheless, the inclusion of more than one pedestrian in the vibration evaluation would result in a more realistic range of floor responses. In this paper, an attempt was made to experimentally and numerically investigate the combined effect of two persons walking simultaneously on an actual building floor. The floor fundamental frequency and damping ratio were obtained from physical heel drop tests and the footfall response was measured in a series of walking tests. A finite element model was created for prediction of floor responses under different walking scenarios. A probabilistic prediction was also performed where random variations in pacing rates, body weights and arrival times of the pedestrians were considered in a large number of Monte Carlo simulations. It was showed that the response due to a single person with resonant step frequency can be greater than that due to two persons walking at off-resonant pacing rates. However, the resonant response induced by two pedestrians can be 1.29–1.38 times greater than that caused by a pedestrian.

Keywords: **Coordination; Floor vibrations; Probability; Resonance; Walking excitation.**

1. INTRODUCTION

As modern floors tend to be slender and are being constructed with longer spans, serviceability requirements relating to human-induced vibrations have become a critically important design criterion. Constraining the vibration response to tolerable levels is crucial for ensuring the comfort of the floor occupants and/or the safety of vibration sensitive equipment that might be on the floor [1]. Acoustic problems caused by floor vibrations would also worsen human comfort. It has been found that floor impact sound induced by footsteps may be a serious social issue in many densely populated countries [2]. There has been an increase in the number of real-life building floors that were reported to exhibit excessive vibrations due to normal walking traffic. These problematic floors cover a variety of popular construction types including lightweight steel frame, lightweight concrete, steel-concrete composite and reinforced concrete [3–5]. In regard to walking-induced vibrations, floor systems are normally categorized into low frequency floors in which resonance may cause severe vibration amplification and high frequency floors where resonance becomes less important compared with transient response. The cut-off frequency above which resonant build-up of response is not significant can be taken as 9–10 Hz [6, 7]. Nevertheless, it has also been suggested that both low and high frequency components of response may need to be considered in order to gain a better response prediction, especially for floors with fundamental natural frequencies being close to the "cut-off" frequency [8].

At the design stage, current guidelines such as the Steel Construction Insitute SCI P354, AISC DG 11, Concrete Centre CCIP-016, and European EUR 21972 EN are often employed to predict floor vibrations [6, 7, 9, 10]. According to these guidelines as well as the International standard ISO 10137 [11], the vertical dynamic force produced by successive steps of a person walking can be represented by a Fourier series:

$$F(t) = Q\left[1 + \sum_{i=1}^{k} \alpha_i \sin\left(2\pi i f_p t + \phi_i\right)\right] \quad (1)$$

in which Q is the static weight of the person, f_p is the step frequency, α_i and ϕ_i are the dynamic load factor (DLF) and phase angle of the i-th harmonic component respectively. A body weight of 750 N (76 kg) is usually assumed for a standard pedestrian [6, 9]. The number of harmonics k is normally taken as 3–5. Bachmann and Ammann [12] suggested an average speed of 1.5 m/s, step frequency of 2.0 Hz and step length of 0.75 m for normal walking. Kerr and Bishop [13] reported a step frequency range of 1.7−2.1 Hz with an average of 1.9 Hz for comfortable walking. Kasperski and Sahnaci [14] found that people tend to walk comfortably at a speed of 1.37 m/s, step frequency of 1.86 Hz and step length of 0.74 m. Ji and Pachi [15] observed mean pacing rate of 2.00 Hz with a standard deviation of 0.11 Hz on two shopping floors. Recent European researches showed that the distribution of footfall frequencies were lognormal with a mean frequency of 2.0 Hz and a standard deviation of 0.17 Hz [10]. Design values for the DLFs given in the ISO 10137 are $\alpha_1 = 0.37(f_p - 1)$; $\alpha_2 = 0.1$ and $\alpha_3 = \alpha_4 = \alpha_5 = 0.06$. The phase angles, which have been found to scatter significantly by relevant literature, are normally assigned with quite arbitrary values. The SCI P354 suggests that phase angles should be taken as 0, -π/2, π and π/2 for the first, second, third and fourth harmonics respectively. Toso et al. [16] argued that persons with the same body mass and pacing rate could produce different dynamic load factors due to different structure stiffness and damping. Whilst the walking force model recommended by current guidelines and the ISO 10137 is based on a deterministic periodic function, a few probabilistic force models have also been explored. Brownjohn et al. [17] introduced a force model in the frequency domain which used Gaussian distribution of stepping rates as input parameter. Zivanovic and Pavic [8] performed a probabilistic modeling of footfall excitation for beam-and-block floors. Racic and Brownjohn [18] developed a stochastic and narrow-band force model which included variations of time intervals between footsteps, shapes and impulses of footfall forces. Hudson and Reynolds [19] considered multipedestrian walking on random paths within an office floor area. Chen et al. [20] proposed an experiment based power spectral density model to consider the stochastic character of people walking. The dynamic interaction between walking people and lightweight floors with low damping or slender footbridges was also explored, considering both human biomechanics and dynamic properties of the supporting structures [21–24].

Whilst there are a variety of proposals for DLFs for single-person walking [25], the number of similar works on DLFs for group walking traffic is minimal [26, 27]. Ellis [28] noticed that floor response to human groups of size up to 32 was approximately twice of that produced by a single pedestrian. Pan et al. [29] studied the response of a biotechnology lab under pacing rates of 1.5, 2.0 and 2.3 Hz and found that the vibration due to multi people stepping at 2.3 Hz would exceed acceptable thresholds whilst the response induced by a single person well met acceptance criteria for all the step frequencies. Footbridge guidelines such as the French Sétra normally include a simple method by which the action from a group of N people crossing a bridge can be approximated as the action due to a single person multiplied by a factor of $\sqrt{N}$ [25, 30]. Similarly, the ISO 10137 introduces a coordination factor $C(N)$ to represent dynamic actions of group of N participants. The group action $F(t)_N$ can be determined as:

$$F(t)_N = F(t)\, C(N) \quad (2)$$

where the forcing function $F(t)$ is calculated from Eq. (1) with the static weight Q being taken as the estimated weight of the group of participants. For coordinated groups of no more than 5 people, a coordination factor of 1 is recommended. For the case of uncoordinated group movements, the coordination factor is given by:

$$C(N) = \sqrt{N}/N \quad (3)$$

Although contemporary guidelines [6, 7, 9, 10] focus only on the single-person loading scenario when evaluating walking-induced floor vibrations, predictions of likely responses caused by more than one person would be instructive for designers and developers of building floors. The current paper compares the vibration response due to a single person with that caused by two persons via experimental and numerical investigations of an actual office floor. The paper is organized into five sections. After this introduction, a description of vibration testing including pedestrian response measurements conducted on the case study floor is provided. A detailed finite element (FE) model of the test floor is presented in the third section for estimation of the response under a number of walking excitation scenarios. This is followed by a Monte Carlo probability-based prediction of floor response where stepping rates, pedestrian weights and arrival times are treated as random input parameters. The last section summarizes key findings on the combined effect of two pedestrians on the floor response.

2. DYNAMIC TESTING OF A CASE STUDY FLOOR

2.1. Description of case study floor

Fig. 1 depicts a plan view of the framing layout of a building floor with the test area being defined by gridlines E-F-2-3. The floor is of prestressed concrete construction with 180–200 mm thick post-tensioned concrete slab spanning 10.2 m between concrete band beams which are 2400 mm wide and 300–350 mm deep. The columns along gridlines E and G stop at the level of the investigated floor whilst the remaining columns continue to the upper floors of the building. Dynamic testing was carried out on the floor when the building was under construction and the floor was unfurnished. The investigated floor area is intended for office usage after the building construction is completed. The floor is designed with an intermediate corridor running through the entire span of the floor bay and passing the bay mid-span. A number of repeat physical heel drop tests were conducted to acquire information on the floor's modal frequency and damping ratio. In addition, a series of walking tests were performed to estimate the floor response under various walking scenarios including one person walking and two persons walking. The test walking path was located along the design corridor of the floor when in use. This path was about 10 m long and in the direction of the beam span (Fig. 1). Acceleration responses were recorded at a sampling rate of 128 Hz using Dytran seismic accelerometers of 5 V/g sensitivity located around the floor bay mid-span. A laptop-controlled data acquisition system was employed at test site, allowing real-time observation of the floor response.

2.2. Natural frequency and damping measurements

Excitation in the heel drop test was provided by a person rising onto his toes with his heels about 65 mm off the floor and suddenly dropping his heels to the floor. The resultant floor response in the frequency domain is provided in Fig. 2, which was averaged over data obtained from a series of 10 heel drop tests. The 7.60-Hz frequency associated with the highest response magnitude observed on the spectrum can be considered as the fundamental frequency, f, of the floor bay under consideration. The damping ratio ζ of the fundamental mode can be computed using the half-power bandwidth method as $\zeta = (f_2 - f_1)/(2f)$ where f_1 and f_2 are the two frequencies associated with the half power points on either side of the highest point [31]. In a magnitude versus frequency plot like the one presented in Fig. 2, the half power points are where the magnitude of response equals $1/\sqrt{2}$ times of the maximum magnitude. Using the half-power approach, the damping ratio of the test floor was estimated at 1.40%. The measured damping of the test floor appears to compare well with recommended values by current design guides [6, 11]. This damping level will be used in the numerical investigation discussed later in the paper.

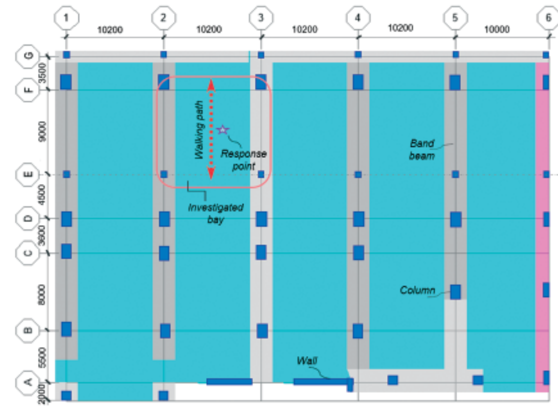

Figure 1.
Floor framing layout

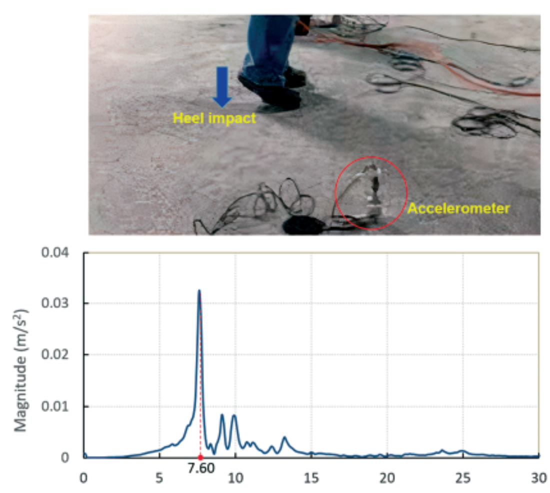

Figure 2.
Floor response to heel drop

2.3. Pedestrian response measurements

Having a fundamental frequency less than 9 Hz, the test floor can be classified as a low-frequency floor and the worst case scenario would occur when the floor is forced at resonant condition. A total of 18 repeat tests for one person walking and 24 tests for two persons walking were performed. The one-person walking tests were carried out with a single person weighing about 80 kg walking along the full length of the bay span and back again. In addition to this pedestrian, a second person weighing 65 kg participated in the two-person walking tests where the two pedestrians were about 1.0–1.5 m apart. In 6 tests with one person walking and 8 tests with two persons walking, the pedestrians were requested to maintain a step frequency of around 1.90 Hz, controlled by a metronome, so that its fourth harmonic could excite the 7.60 Hz mode of the floor. The other walking tests were conducted with self-selected pacing rates.

The measured data were post-processed as follows. Firstly, scale factors of 76/80 and (76+76)/(80+65) were applied to the response due to one person and two persons respectively, to roughly take account of the difference between the actual pedestrians weight and a standard weight of 76 kg. The response was then filtered to remove high frequency content above 15 Hz to which humans are insensitive [7]. This can be done by using the Fourier transform and inverse Fourier transform technique [32]. For instance, a typical acceleration time trace due to two persons walking is shown in Fig. 3. The response history was recorded over a 16 second period, during which the test persons walked from one end of the floor span to the other end and back again. The response was converted into the frequency domain using fast Fourier transform (FFT), which is shown in Fig. 4. After the FFT magnitudes corresponding to frequencies above 15 Hz were removed, a filtered acceleration time trace was obtained via an inverse Fourier transform (Fig. 5). It can be seen that the response was attenuated after being filtered. Similarly, Fig. 6 depicts a typical filtered floor acceleration time history due to a single person walking. A rolling root-mean-square (RMS) acceleration time trace can then be obtained. An RMS acceleration value a_{RMS} was calculated from a set of acceleration values $a(t)$ using the following expression:

$$a_{RMS} = \sqrt{\frac{1}{T}\int_0^T a(t)^2 dt} \tag{4}$$

It is recommended that the integration time T in Eq. (4) is taken as 1 second for response due to walking. The peak of the rolling RMS is referred to as the maximum transient vibration value which can be compared with tolerable thresholds to check the floor acceptability for human comfort [6, 9, 11, 33].

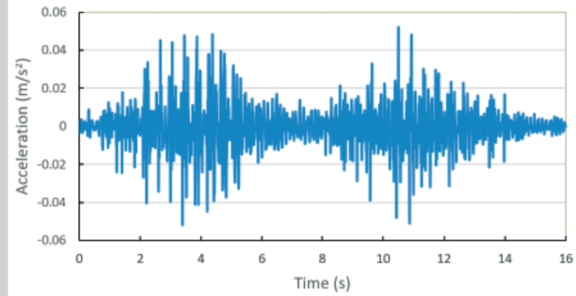

Figure 3.
Unfiltered response to two persons walking

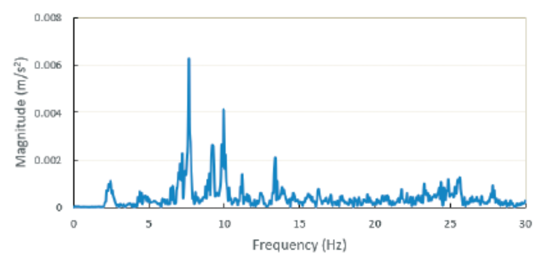

Figure 4.
FFT for response to two persons walking

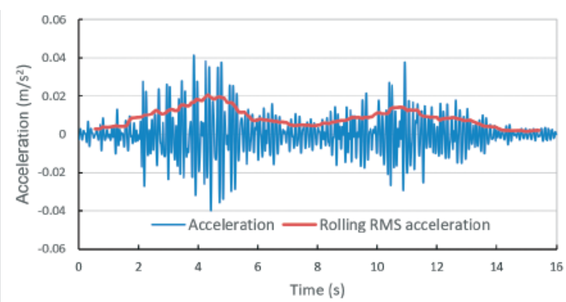

Figure 5.
Filtered response to two persons walking

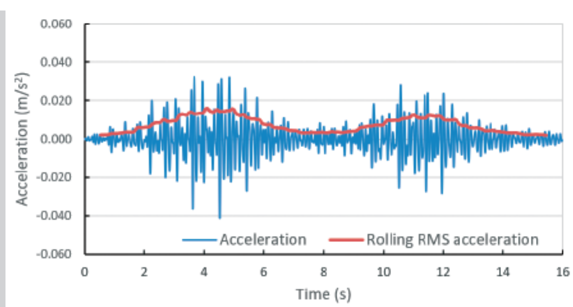

Figure 6.
Filtered response due to one person walking

The discussed post-processing procedure was applied to all the walking tests from which the maximum RMS accelerations of the floor due to one person walking and two persons walking can be acquired (Figs. 7 and 8). For the tests 7–12 of Fig. 7 and tests 9–16 of Fig. 8, the test subjects attempted to maintain their pacing rates at around 1.90 Hz whose fourth harmonics closely matched the floor fundamental frequency, hence greater response levels. However, a perfect resonant condition was unlikely to be always achieved. For the remaining tests, the persons walked naturally at their self-selected speeds. The peak RMS acceleration due to a single person fluctuated between 0.0080 and 0.0159 m/s^2 with an average of 0.0115 m/s^2. The vibration response due to two persons walking was found to be in the range from 0.0094 to 0.0220 m/s^2 with an average of 0.0146 m/s^2. There are still cases where the response level due to two persons was lower than that caused by one person. Nevertheless, the maximum response induced by two pedestrians was found to be 38% greater than the peak response due to a single pedestrian when all the test results were taken into account.

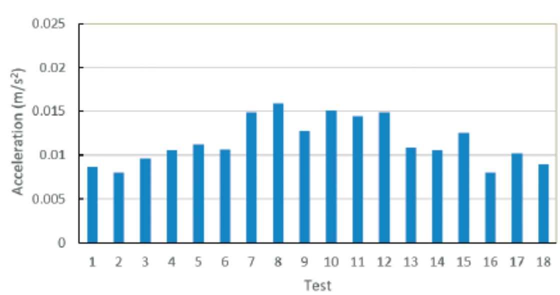

Figure 7.
Summary of RMS acceleration due to one person walking

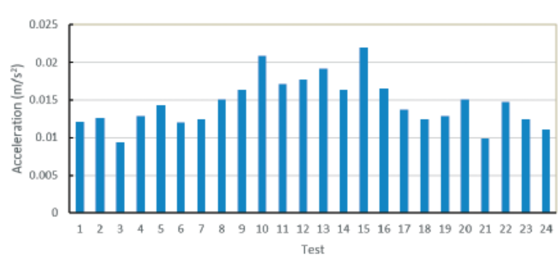

Figure 8.
Summary of RMS acceleration due to two persons walking

3. FE MODELING

3.1. Modal analysis

An FE model of the case study floor was created using SAP2000 software [34] in which the slab and band beams were represented by shell elements. The concrete columns and walls attached to the floor were assumed to be fixed one story below and above the floor under consideration. Element offset technique was employed to allow for the eccentricity between structural members (beam-beam, beam-slab). The band beams and slab objects were meshed into 3180 four-node shell elements, typically with 4 elements per 2.4 m beam width and 8 elements per 7.8 m spacing between two adjacement band beams. The concrete material was assumed to be isotropic with a linear stress-strain relationship. The dynamic modulus of elasticity for the 40 MPa normal-weight concrete of the slab was taken as 38000 MPa as suggested by the SCI and CCIP guidelines [6, 9]. A modal analysis or eigenvector analysis was used to determine the undamped free-vibration mode shapes and frequencies of the floor system [34]. A study of various mode shapes obtained from the FE modal analysis could assist in identifying the vibration mode that would be most critical to the bay of interest. Fig. 9 shows the mass-normalized modal displacement contours of a natural mode with a frequency f_n of 7.56 Hz. Antinodes with maximum modal displacements can be seen to be located around the central area of the investigated bay. This 7.56 Hz mode can hence be considered as the resonant mode or fundamental mode of the floor bay. The corresponding modal mass was found to be 49900 kg. The FE-predicted natural frequency compared well with the floor natural frequency identified from the physical heel drop tests.

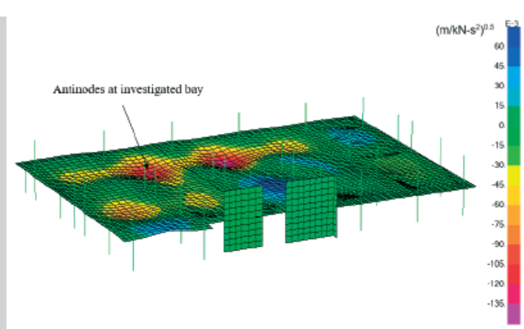

Figure 9.
Fundamental mode shape of test bay

3.2. Pedestrian response calculations

The floor response to several walking scenarios was calculated via SAP2000 time history analysis which requires modeling of the walking force. The time history analysis was performed using the modal superposition technique [34]. Contemporary guidelines suggest that the dynamic load induced by a pedestrian can be represented by a concentrated time-dependent force applied at a point, usually of maximum modal displacement, on the floor [6, 7, 9, 11]. However, as the forcing function in the form of Eq. (1) is for a stationay walk, modication was needed to take account of the translation of the excitation force from one end of the span to the other end during a walking event. This can be done by incorporating the mode shape values into the stationary-walk forcing function. The variation of the fundamental modal displacements along the walking path was simplified by a half-sine function in the form of $u(x) = \sin(\pi x/L)$ where $u(x)$ was the unity normalized amplitude at position x from one end of the span and L was the span length of the floor bay. Let v_p be the walking speed assumed to be constant along the walking path. The relationship between the walking frequency f_p and speed v_p was approximated by the following expression [6, 12]:

$$v_p = 1.67f_p^2 - 4.83f_p + 4.5 \tag{5}$$

The position of the pedestrian at time t can be expressed as $x = v_p t$ from which $u(x)$ became a function of time. The equivalent concentrated force that represents a walking event can be written as:

$$F(t) = Q\sum_{i=1}^{5} \alpha_i \, sin\left(2\pi i f_p t + \phi_i\right) sin\left(\pi \, v_p t/L\right) \tag{6}$$

where Q = 750 N; α_1 = 0.37(f_p − 1); α_2 = 0.1; $\alpha_3 = \alpha_4 = \alpha_5 = 0.06$; ϕ_1 = 0; ϕ_2 = -π/2; ϕ_3 =π; ϕ_4 = π/2 and ϕ_5 = 0. It should be noted that the static component (the number 1 after the open bracket in Eq. (1)) was subtracted from Eq. (6) so that only the dynamic variation in forces was used in the time history analysis.

An example of the simulated walking force induced by a person walking at a pacing rate of 1.90 Hz is illustrated in Fig. 10. This force was applied to the midpoint of the investigated bay to represent a walking event. The walking speed in accordance with the 1.90-Hz step frequency was v_p = 1.352 m/s and the duration for the person to pass across the 10-m long floor span was L/v_p= 7.40 seconds. Fig. 11 shows the acceleration time history of the floor midpoint, which was calculated using a modal damping ratio of 1.40% as identified by the heel drop tests. The corresponding rolling RMS acceleration trace was also constructed using Eq. (4) from which the maximum RMS acceleration was found to be 0.0163 m/s^2. Response prediction was also made for the scenario where the floor vibration was induced by two pedestrians who were assumed to be about 1 m apart. The load case was defined as a combination of two single-person walking forces of Eq. (6) with the second force having a later arrival time. A standard body weight of 750 N was assumed for each pedestrian. For instance, the FE-computed floor response due to a person walking at 1.90 Hz who was followed by another person walking at 1.80 Hz is shown in Fig. 12. The peak RMS acceleration response due to this walking scenario was estimated at 0.0200 m/s^2.

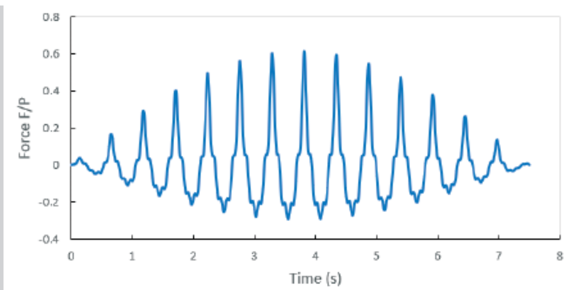

Figure 10.
Simulated dynamic load induced by a person walking at 1.90 Hz

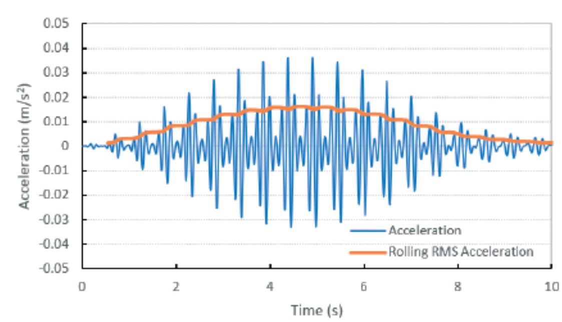

Figure 11.
Response due to a person walking at 1.90 Hz

The influence of forcing frequency on the floor response level was investigated in which common pacing rates of 1.8–2.2 Hz were used in increments of 0.1 Hz. Walking at the 1.90-Hz step frequency was expected to excite the 7.56-Hz fundamental mode in resonance. The analysis results are summarized in

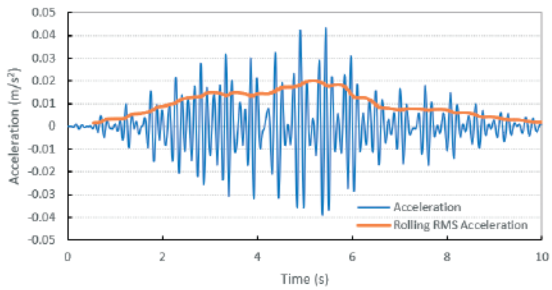

Figure 12.
Response due to a 1.90-Hz person followed by a 1.80-Hz person

Table 1 for both one-person walking events (f_{p1} = 1.8–2.2 Hz, f_{p2} = 0) and two-person walking events (f_{p1}, f_{p2} = 1.8–2.2 Hz). The predicted maximum transient vibration values were in a range of 0.0062–0.0163 m/s^2 for one-person and 0.0075–0.0211 m/s^2 for two-person loading scenarios respectively. Some observations can be made:

– In the event that two persons walked at off-resonant pacing rates, the resulting response can even be lower than that caused by a single pedestrian with resonant step frequency. For instance, the RMS acceleration response under fast footsteps of 2.20 Hz performed simultaneously by two pedestrians was just about 46% of that produced by a pedestrian pacing at 1.90 Hz. On the other hand, the worst case response occurred when both pedestrians excited the floor with the 1.90-Hz resonant step frequency.

– The maximum response obtained from the single-person loading scenario was about 77% of that resulted from the two-person loading scenario. In other words, a response prediction that considers multi-person walking would lead to a more conservative design.

Table 1.
Summary of FE results for different walking scenarios

f_{p2} (Hz)	RMS acceleration (m/s^2) for f_{p1} (Hz)				
	1.8	1.9	2	2.1	2.2
0	0.0062	0.0163	0.0070	0.0052	0.0071
1.8	0.0107	0.0200	0.0102	0.0080	0.0100
1.9		0.0211	0.0195	0.0167	0.0167
2			0.0082	0.0098	0.0105
2.1				0.0075	0.0089
2.2					0.0075

4. PROBABILISTIC ESTIMATION OF FLOOR RESPONSE TO VARIOUS WALKING SCENARIOS

4.1. Methods

Whilst the response prediction using FE modeling presented earlier followed a deterministic approach, some aspects of randomness in pacing rate, body weight and arrival time of pedestrians are considered in this section via a simple probabilistic vibration analysis. The floor bay of interest was idealized as a single degree of freedom (SDOF) system vibrating in its fundamental mode. The governing equation of motion of the SDOF system subjected to walking excitation from two pedestrians is given by:

$$m\ddot{u} + c\dot{u} + ku = F_1(t) + F_2(t) \qquad (7)$$

in which *u, m, c, k* are the time-dependent displacement, modal mass, damping coefficient and stiffness of the floor. The *c* and *k* values were computed using the modal mass *m* and natural frequency *f* identified from the FE modal analysis and the damping ratio ζ estimated from the heel drop tests. We have $c = 2m\omega\zeta = 66368$ Ns/m; $k = m\omega^2 = 112.59\times10^6$ N/m where $\omega = 2\pi f = 47.50$ rad/s is the angular natural frequency [31].

Similar to Eq. (6), the dynamic load $F_1(t)$ and $F_2(t)$ induced by the first and second pedestrians respectively when crossing the floor span can be written as:

$$F_1(t) = Q_1 \sum_{i=1}^{5} \alpha_i \, sin(2\pi i f_{p1} t + \phi_i) sin(\pi \, v_{p1} t / L) \qquad (8)$$

$$F_2(t) = Q_2 \sum_{i=1}^{5} \alpha_i \, sin(2\pi i f_{p2} t + \phi_i) sin(\pi \, v_{p2} t / L) \qquad (9)$$

in which the step frequencies f_{p1} and f_{p2} were assumed to have a lognormal distribution with a mean of 2.00 Hz and standard deviation of 0.17 Hz as recommended in [10]. The pedestrian weights Q_1 and Q_2 were assumed to be normally distributed with a mean of 750 N and standard deviation of 50 N. The arrival time for $F_1(t)$ was taken as zero whilst that for $F_2(t)$ was randomly selected between 0.5 and 1.0 second to allow for a distance of around 0.7–1.5 m between the two pedestrians in each simulation. Equation (7) can be solved using a numerical integration method, which is a derivative of the general Newmarkβ-

method [31]. Solutions are to be found at each successive time step. This method assumes a linear variation in acceleration within a time step Δt. The response values at time t and their variations during Δt are used to calculate the response values at the next time step $(t+\Delta t)$. In order for this integration method to be stable and accurate, the time step should be less than 1/10 of the natural period of the structure. This condition was definitely satisfied because the time increment used in the present paper was taken as low as 0.005 seconds.

A set of routines written in MATLAB [35] was used to conduct the random vibration analysis. A total of 400000 Monte Carlo simulations [36] for two-person walking scenarios were performed. A further increase in the number of simulations was found not to practically change the results. Each simulation involved random selections of pedestrian weights Q_1 and Q_2, pacing rates f_{p1} and f_{p2}, and a lag in arrival time τ between the two pedestrians. The walking speeds v_{p1} and v_{p2} associated with f_{p1} and f_{p2} respectively were calculated using Eq. (5). Similar simulations were conducted for the case of single-person walking in which Q_2 was taken as zero. Equation (7) was solved to acquire the acceleration time history whose the corresponding rolling RMS acceleration trace can then be produced using Eq. (4), for each simulation.

4.2. Results and discussions

Fig. 13 illustrates a typical random walking scenario where the input parameters for two pedestrians produced by the MATLAB code were f_{p1} = 1.915 Hz, f_{p2} = 1.782 Hz, Q_1 = 795.3 N, Q_2 = 802.5 N and τ = 0.640 seconds. With v_{p1} = 1.375 m/s and v_{p2} = 1.196 m/s, it took the first and second persons 7.273 and 8.361 seconds respectively to cross the 10-m long walking path. As can be seen in Fig. 13a, only the first person was on the floor during the first 0.640 seconds. The floor was then excited by both persons for the next 6.633 seconds, and finally by only the second person for the rest 1.728 seconds. The response time history resulting from this walking scenario is presented in Fig. 13b with the maximum transient vibration value being 0.0208 m/s^2.

The results from all the simulated walking scenarios were statistically analyzed. Fig. 14 presents the histograms of maximum RMS acceleration response. The means of maximum transient vibration value were estimated at 0.0078 m/s^2 for single-person traffic and 0.0126 m/s^2 for two-person traffic. The cumulative distribution functions of peak RMS acceleration plotted in Fig. 15 allow comparisons between the predicted reponse induced by a single person and that caused by two pedestrians at any level of confidence. For instance, the 90-th percentile RMS accelerations due to single-person and two-person walking were found to be 0.0167 and 0.0216 m/s^2 respectively.

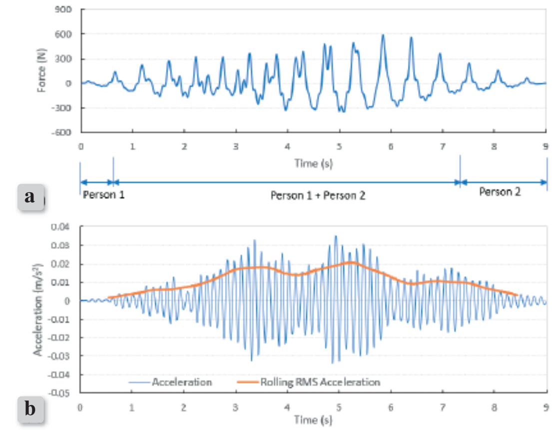

Figure 13.
A random scenario of two persons walking: a) loading function; b) floor response

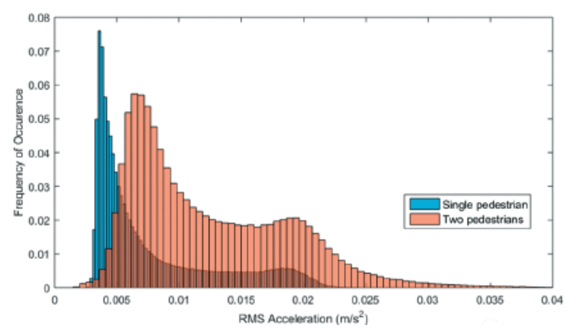

Figure 14.
Distribution of acceleration response

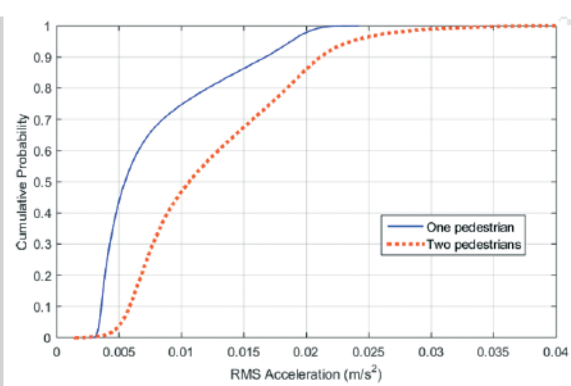

Figure 15.
Cumulative distribution functions of acceleration response

4.3. Comparison of prediction methods

The 90-th percentile response obtained from the probabilistic prediction method can be considered as a metric for vibration serviceability assessment of the floor. The vibration levels predicted by this method agreed well with those obtained from the FE modeling and field measurements, as summarized in Table 2. Moreover, it can be inferred from the footbridge guideline Sétra [30] that the action from a group of 2 persons could be approximated by the action induced by a single person multiplied by a factor of $\sqrt{2} = 1.41$. Utilizing the ISO 10137 [11] could give the same result when a coordination factor of $\sqrt{2}/2$ for an uncoordinated group is to be applied to the action from a perfectly coordinated group of 2 people. For the case study floor, it was found from both the random simulation and the FE time history analysis that the maximum response induced by two pedestrians was 1.29 times higher than that caused by a single pedestrian. In the walking tests, the maximum response was also found to increase by 1.38 times following the participation of the second pedestrian.

Table 2.
Summary of response levels

Excitation	Maximum a_{RMS} (m/s^2) identified by		
	Experiment	FE model	Random simulation
One person	0.0159	0.0163	0.0167
Two persons	0.0220	0.0211	0.0216

5. CONCLUSIONS

In contemporary guidelines, guidance relating to group excitations is only provided for floors subjected to rhythmic activities such as dancing, lively concert, aerobics and jumping. The design guides limit the discussion of walking-induced vibrations to single-person load scenario probably because this load scenario occurs frequently in floors and is difficult to isolate. The paper has discussed the combined effect of two persons walking simultaneously on an actual concrete floor which can be classified as a low frequency floor based on its measured fundamental frequency.

In evaluating the maximum two-pedestrian response, the numerical results acquired from both the deterministic FE time history analysis and the probabilistic analysis of a simplified SDOF model closely matched the experimental findings with a difference of just 2–4%. It was observed in the real walking tests that even when the two test subjects attempted to walk in unison, a perfect synchronization was unlikely to be achieved. Also, the response due to a single person exciting the floor at the resonant step frequency can even be greater than that due to two persons walking at off-resonant pacing rates, as clearly shown in the FE modeling. Of the walking scenarios investigated, the vibration was seen to increase significantly when the floor fundamental frequency was excited by one or both of the pedestrians. Compared with the resonant response induced by a single pedestrian, the resonant response due to two pedestrians walking simultaneously was found to be 29–38% higher. Generally speaking, a wider and more realistic range of responses would be obtained when likely multi-pedestrian loading scenarios are considered in the vibration analysis and/or testing, particularly for floors with long straight walking paths crossing center bay. Furthermore, the $\sqrt{N}$ rule recommended by the footbridge guideline Sétra and the ISO 10137 appears to provide a reasonably conservative estimation of the two-pedestrian loading scenario from the single-pedestrian loading scenario for the case study floor.

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