THE ROLE AND INTERPRETATION OF DAMPING IN THE PREDICTION OF HUMAN INDUCED FLOOR VIBRATION RESPONSE LEVELS

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ABSTRACT: The incidence of human-induced vibrations in floor systems in newly constructed commercial buildings that are perceptible, or even worse, annoying, seems to have escalated in recent times. This situation is considered to have arisen as a result of the confluence of a number of contributing factors, mainly that of increased span lengths in flooring systems and lower levels of damping associated with the modern workforces’ shift to the ‘paperless office’. This paper investigates the latter of these factors further by analysing vibration response measurements on four separate, nominally structurally, identical floor systems (four stories in the same office building). Two of the floors were fully outfitted for imminent release and occupation, one was partly outfitted and the other consisted of just the bare structure with installed services but no floor coverings or office equipment. Difficulties encountered in extracting reportable values through the authors’ modelling interpretations are also discussed.

KEYWORDS: Floor Vibrations, Damping, footfall excitation

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1 INTRODUCTION

The topic of human induced floor vibrations is becoming more prevalent in the modern world of today. Many cases of perceptible and disturbing vibrations are being reported by building occupants, conveying the need for in-depth research to be undertaken which will lead to a better understanding of how these vibrations can impact structures. There are numerous factors which can play a role in increasing vibration levels in floors, some of which include:

(i) Progressively increasing span lengths in floor systems in modern buildings - This not only has the effect of leading to a reduction in natural modal frequencies in these floor systems, placing these modal frequencies closer to lower harmonics of the pacing rates of office workers, but also leads to a larger number of steps to cross between supports by walkers thus further amplifying vibrational levels.

(ii) More efficient and compact reticulation services for power, water, air conditioning and waste removal between the ceiling and the floor of successive storeys in such buildings - This leads to lower mass (and decreased damping), but signifies a larger reduction in stiffness, further reducing modal frequencies in these floor systems and increasing the opportunity of coincidence with lower harmonics of the pacing rates of office workers and hence amplification of human induced vibrations.

(iii) Moves to the “paperless office” environment with fewer partitions, filing cabinets/other storage units, and the use of “hubs” or “pods” as clustered workspaces with lightweight computers and screens on table tops, as opposed to desks with drawers - Reductions in design floor loads, leads to lower stiffness floor support, lowering modal frequencies and increasing the opportunity of coincidence with lower harmonics of the pacing rates of office workers and hence amplification of human induced vibrations. - In addition, these effects also lead to a reduction in damping contributions from reductions in on-floor furniture and office equipment.

(iv) Designing for two-way, as opposed to one-way floor slab systems, resulting in higher densities of closely spaced modes and hence once again increased opportunities of lower harmonics of pacing rates of office workers to coincide with these and promote vibratory response

(v) Design guidelines and methods of assessment of human-induced vibrations that appear not to be structured well enough to more accurately account for the above factors.

The authors are of the belief that item (v) which to a large degree encapsulates all of the preceding items, deserves being investigated in some detail and depth if improvements are to be realised by designers of floor systems that more accurately predict human-induced vibration levels and hence lessen the incidence of newly designed floor systems not satisfying acceptability criteria for such vibrations.

One of the key parameters that features largely as a contributing factor to the increase in vibratory response levels of floor systems to human induced excitation is the reduction in damping levels that seems to have progressively occurred over the years. But just what are these levels of damping nowadays and what can we expect them to be for given floor design conditions? The answers to such questions can only be based upon experience and this experience can only be gained through measured identification of this parameter on floor systems over a wide range of conditions for these answers to be credible.

2 VIBRATIONS IN BUILDING FLOORS

High levels of vibration can occur in floor systems due to excitation from human activities such as walking, exercise and aerobics. In building floors, excessive vibrations are generally not a safety concern but can be a source of annoyance and discomfort for occupants [7, 12]. It is accepted by practicing engineers that for new construction, it is preferable to address and resolve any potential floor vibration issues during the design phase than to react to subsequent problems after the building has been completed and occupied [7].

2.1 BASICS OF VIBRATIONS IN FLOORS FROM FOOTFALL EXCITATION

A vibration problem can be characterised by three components, namely the vibration source, transmission path and receiver [6]. In the context of this paper, the vibration source is the person who is walking across the building floor which is considered to be the transmission path. The receiver is another person in the vicinity of the source who may be affected by the vibrations. The source of the vibration being human footfall can vary greatly from person to person. The pacing (walking) frequency can also vary depending on the layout of the area in which these people are walking. For an open plan office, an upper limit of 2.1 Hz is an acceptable pacing frequency to expect for walking. For low height partitioned office spaces and labs, 1.8 Hz is more appropriate [2, 9, 11]. The pacing frequency for a slow walk would
be in the order of 1.4 Hz. Pacing frequencies ranging between 1.4 to 2.2 Hz, for slow to fast walking rates would therefore be typical for reasonably unconstrained walking paths. The three main factors which govern the vibration response of a floor are its mass; stiffness (flexural rigidity, EI) and damping [7]. Other factors which can impact the transmission path of the vibration include the extent of cracking, (I\textsubscript{cracked} instead of I\textsubscript{gross}), if any, and post-tensioning. For the scope of this paper, the focus will be on the three main factors listed above.

The mass to be used is the total modal mass of the floor including any superimposed load and it is expressed as weight/gravity. The weight of a floor system can be easily determined by using the density of concrete and volume of the floor whilst including any other dead loads.

In order to determine the stiffness of the floor, the modulus of the elasticity must be determined. This is fairly straightforward; however, it should be noted that the modulus of elasticity for concrete is larger for dynamic analysis than it is for static analysis. A recommended increase of 35% than the static modulus of elasticity is commonly adopted throughout the industry and noted in the relevant literature [1, 9].

Damping refers to the loss of mechanical energy in a vibrating system [9]. The higher the damping, the faster the vibrations will dissipate their response energy and the less likelihood that discomfort will be experienced by the occupants [4].

2.2 “RESONANCE” FROM FOOTFALL EXCITATION

Resonance can occur if the forcing frequency coincides with or is close to a harmonic of the natural frequency [2, 9]. Vibration amplitudes are substantially amplified at resonance and can only be controlled by the ability of the system to limit them through damping [9,10]. Herein lies the issue of controlling vibration response levels. Different structures and structural features can exhibit different damping levels, and different walking characteristics can cause the structure to behave in different ways, so assessing floor vibration from footfall excitation is a fairly challenging exercise.

3 OVERVIEW OF REAL FLOOR VIBRATION RESPONSE MEASUREMENTS

Experiments were undertaken to identify floor response accelerations under these different sets of circumstances. This testing was conducted in an attempt to gain a better understanding of the complex characteristics that can be exhibited in the vibration response of floors to human-induced vibrations.

An office building in Melbourne’s CBD was tested in 2014 following suspicions that the floor system adopted (two-way RC slab on steel beam) had potential for lively response from footfall activity. To gain a thorough understanding of the dynamic characteristics of the floor structure, four levels of the building were tested for footfall excitation characteristics from walking and heel-drop testing. The storeys analysed consisted of:

- two fully fitted-out floors, (which included desks, computers, office chairs etc). These were identified as floors 9 and 10, (see Figure 1).
- a partially fitted-out floor (which included desks but no computers or chairs). This floor was the next storey up from the first two – floor 11, and
- a floor which consisted of only the bare structure, (no on floor fittings), identified as floor 14, (see Figure 2).

Except for differences in fit-out conditions, the inter-storey services and structural features of these floors were nominally identical. On each level, the testing was performed at approx. 1m to North-West of centre of the North-East corner span of the building.

Two men, identified as NH and DG, of different weight (85 and 110kg) respectively, but also of different stature and walking style, performed walking and heel-drop tests on these test floors.

Figure 1: Fully fitted out floor 9 (walker DG)

Figure 2: Bare unfitted floor 14 (walker DG)
4 INSTRUMENTATION/ANALYSIS METHODOLOGY

Data capture for this investigation was performed using a single Gulf Coast Dynamics Corporation model GCDC X2-1 accelerometers attached to the primary steel beam below the floor slab of each storey level tested, (see Figure 3). This type of accelerometer can be selected to record in its most sensitive response range (0 – 1.25g) with a resolution of ~60 micro-g at a sampling rate chosen from 8, 16, 32, 64, 128, 256, or 512 Hertz. A fully charged accelerometer has the capacity to record continuously for up to 16 hours at a sample rate of 128Hz. The data files, saved as .CSV files, can be easily transferred from the SD-RAM card resident on the device to a computer via a USB cable.

In these tests, contiguous data files from repetitive test sequences were selected to be 64 seconds long with a sampling rate of 128 Hz, producing acceleration response records of 8192 data points. In addition to analysis in the time domain, spectral analysis was performed on the data recorded on the test floors of this CBD building.

Spectral Analysis provides a measure of energy per unit frequency, where energy is presented in terms of the quantity being sampled. In the case of acceleration vibration response records, spectra would exhibit contributions from participating modes excited by the input forcing function on the floor as generated by a particular person walking along different available paths back and forth over the full span at reasonably brisk pacing rates, or from a sequence of heel-drop test episodes created by that person close to mid-span of the test floor.

4.1 ACCELERANCE FITTING PROCEDURE

It is possible to estimate modal properties of the participating modes in the acceleration response data, by investigating “decoupled” modal features in the acceleration response spectrum. The assumption made here is that the Forcing spectrum (impossible to be measured here), is near constant over the “resonant bandwidth” of the acceleration response spectrum, so that the acceleration response spectrum itself is then considered to simply be a scaled version of the Accelerance at “modal peaks” within this spectrum. In order to then investigate key modal properties via this assumption, a method such as the Haritos “Equivalent Area” Method (HEAM) can be used [5]. This method uses the Solver function in MS Excel to equate the area under the spectral data curve, \( S_a(f) \) surrounding a modal “spike”, from \( f_L \) to \( f_R \), to that of the fitted theoretical Accelerance function that optimises on parameters \( A_o \) (a scale factor), \( f_o \) (the modal frequency) and \( \zeta \) (the modal damping ratio), in this fit, as per equation (1) below

\[
\int_{f_L}^{f_R} S_a(f) \, df = \int_{f_L}^{f_R} A_o \left( \frac{2\pi f}{f_o} \right)^4 \frac{A_o (2\pi f)^4}{\left( 1 - \frac{f^2}{f_o^2} \right)^2 + \left( 2\zeta \frac{f}{f_o} \right)^2} \, df
\]

The modal frequency of a selected mode, \( f_o \), is easily determined from the position of the peaks along the horizontal (frequency) axis of the acceleration response spectrum, \( S_a(f) \).

The damping ratio, \( \zeta \), has the ability to change the shape of the spectral curve - a taller, (narrower) peak indicates a lower level of damping associated with that modal contribution whereas, a shorter and wider peak is indicative of a higher damping level. The GRG nonlinear option of optimisation in Solver within EXCEL was adopted to perform the fitting procedure described above. To better condition this optimiser for this purpose, spectra were evaluated in (mm/s^2) units as opposed to (m/s^2) or (g’s) units where g is the acceleration due to gravity (9.81 m/s^2). The disparity in magnitude between parameters in the fit, \( A_0 \), \( \zeta \) and \( f_o \), is greatly reduced using these units and the fitting is observed by eye to be more efficient and effective.

In addition, since 3 or 4 repeat test records of 64 second duration were captured for each walker on each test floor, spectra from the repeat test records were averaged to reduce on their “noisiness” before performing the optimised fits using Solver. It should be noted that EXCEL’s FFT function (required for performing Spectral density evaluations from the time series data) can only operate on a maximum of 4096 data points of a regularly spaced vector of a time-trace. Consequently MATLAB was used to facilitate production of spectra from the 8192 point data series and results saved as .CSV files for subsequent analysis using EXCEL.

Figure 3: Accelerometer located on steel beam
5 INVESTIGATION OF WALKING RESPONSE RECORDS

Figures 4 and 5 present sample time domain traces of the acceleration response generated by the two different walkers, NH and DG on floor 9 considered typical of the data capture of these tests. The characteristics of these traces reflect the back-forth walking strategy via different pathways available to cross the floor passing near the data collection point location.

It is also clear from these typical records that the peak response amplitude of vibration is generally below the widely adopted value of 0.5%g (0.05 m/s²) for acceptability of floor vibrations in offices. Figures 6 and 7 depict the acceleration spectra for the time domain records corresponding to traces in Figures 4 and 5 respectively. These are truncated to 16 Hz as beyond 16 Hz up to the Nyquist of 64 Hz (half the sampling rate) the energy plateaued to white “noise” levels for the accelerometer.

It is clear from these plots that there are two dominant modes excited by both walkers - at frequencies just over 5 Hz and just over 7 Hz.

![Figure 4: Response record - NH floor 9 (Data009)](image)

![Figure 5: Response record - DG floor 9 (Data013)](image)

![Figure 6: Acceleration Response Spectrum (Fig. 4)](image)

![Figure 7: Acceleration Response Spectrum (Fig. 5)](image)

A small amount of activity in the response is observed at around 2 Hz (the reasonably quick walking pace adopted by both walkers), and small clusters of activity in some other distinct locations, that differ in extent and position between the walkers.

Since the area under the acceleration response spectrum represents the variance of the acceleration response time trace from which it has been obtained, these other clusters of frequency associated with other participating modes in the response contribute very little to the vibration response characteristics at the measurement point.

These small features are not so visible in the Linear-Linear scale adopted for presenting Figures 6 and 7, but can still contain valuable information regarding the dynamic properties of the floor.

Figure 6 is therefore re-plotted as a Log-Linear variation in Figure 8 to amplify these features. They are now clearly observed to show similarities in shape akin to the two more dominant modes of vibration that were clearly identified earlier.

Figure 8 as well as depicting the dominant modes of vibration clearly shows the presence of similar “spiky” features that may be associated with contributions from other participating modes at much lower levels.

Figure 8 also depicts the recorded presence of some energy located at the step/pacing frequency and a much smaller contribution at twice this pacing frequency.

![Figure 8: Log-Linear version of Figure 6 above](image)
It is clear that by averaging spectra from repeat test records from the same walker at each of the test floors a set of spectral data would be available to not only extract estimates of modal properties of natural frequency and damping from the two principal participating modes, but also estimates of these properties for a larger number of participating modes of smaller amplitude, that have been excited by the two walkers. The differences in modal properties that may be exhibited between the different floors at various stages of fit-out and between the two walkers generating the response data would also be of interest.

6 MODAL PROPERTIES FROM HARITOS EQUIVALENT AREA METHOD

6.1 MODAL RESULTS FOR NH DATA

Figures 9 to 12 depict the Acceleration response spectra for floors 9, 10, 11 and 14 respectively in Log-Linear form. Also depicted thereon, are fits in the region of these peaks of the Accelerance based upon HEMA. Upon inspection, all of the Figures 9-12, exhibit similar features. Figures 9-11 are closely similar, with Figure 12 (floor 14 totally unfitted out) showing some departures from the first three floors tested. The distinct presence of an intermediate mode to the two dominant modes has now become apparent. The reason for this is that there were many other possible random pathways that could be (and were) selected to produce excitation of the floor 14 as there were no obstructions, (such as chairs and desks), on this floor to inhibit walking. This allows the opportunity to excite modes that the restricted pathways on fitted floors would at best otherwise show only weakly participation.

6.2 MODAL RESULTS FOR DG DATA

Figures 13 to 16 depict the Acceleration response spectra for floors 9, 10, 11 and 14 respectively in Log-Linear form. Also depicted thereon, are fits in the region of these peaks from HEMA.

Figure 9: Solver Modal Fits – Floor 9

Figure 10: Solver Modal Fits – Floor 10

Figure 11: Solver Modal Fits – Floor 11

Figure 12: Solver Modal Fits – Floor 14

Figure 13: Solver Modal Fits – Floor 9
As was the case in the results presented in §6.1, these fits are considered to be quite effective in their ability to capture the principal details of the resonant peaks. Again, upon inspection, although all of the Figures 13-16, exhibit some similarities in their features, there are also significant differences in the details. Figures 13 and 15 exhibit the presence of a significant intermediate mode to those originally identified as dominant modes generated by walker NH. In fact, the response from walker DG in this intermediate mode resulted in a slightly higher contribution than the second dominant mode excited by walker NH for the case of both floors 9 and 11. The distinct presence of an intermediate mode to the two dominant modes has now become apparent for floors 9 and 11, but seems to have all but “disappeared” from the test data generated by walker DG in the case of floors 10 and 14. This suggests there to be significant walker-dependent differences (weight, pacing rate, footfall characteristics) that would affect the character of the resultant floor excitation from any one walker.

6.3 RESULTS FOR FITTED MODAL PROPERTIES

Tables 1 and 2 present the results from the Haritos Equivalent Area method of the modal frequencies and damping values where this fitting was able to be performed for walker NH whilst Tables 3 and 4 present these corresponding results from walker DG.

These tables have been organised so that the modal sequence of identified modes is a merging of those identified from the separate response records from both walkers NH and DG. By merging in this way it can be clearly noted that some modes that appeared to be excited by one of the walkers, (albeit possibly a quite small contribution), were virtually not distinguishable as a contribution from the response records of the other walker. Walker NH did not excite modes 2, 5, 6 and 8 and only on floor 14, the bare floor, was it possible for him to excite mode 3. Walker DG did not excite mode 7 on all test floors and varying “mixes” of modes appeared to be excited on different floors by him. Floor 14, the bare floor, stood out to be “different” from the others in terms of its response characteristics, not only in the response spectra (Figures 12 and 16), but also quite clearly from the reported results in these tables.

7 DISCUSSION OF RESULTS

From inspection of Tables 1 and 3, it is apparent that frequencies of nominally corresponding modes are in close agreement (within just a few per cent) for all four floors tested. This suggests that mass, and possibly stiffness changes due to the fit-out elements, (and any possible differences in construction replication from floor to floor for that matter), pose only a small influence on the floor vibration frequencies for this building.

What seems to be a more noticeable trend in the influence of fit-out elements on the floor modal characteristics is the apparent reduction in damping levels observed in floors 11 and 14 (with part and no fit-out, respectively). This differs from the fully fitted out floors 9 and 10 in practically all modes where comparisons could be made, with just a couple of exceptions.
Table 1: Modal results for natural frequency in Hz (walker NH)

<table>
<thead>
<tr>
<th>Floor</th>
<th>Fitout Status</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
<th>Mode 7</th>
<th>Mode 8</th>
<th>Mode 9</th>
<th>Mode 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor 9</td>
<td>Complete Fitout</td>
<td><strong>5.41</strong></td>
<td>-</td>
<td>-</td>
<td><strong>7.13</strong></td>
<td>-</td>
<td>-</td>
<td><strong>8.85</strong></td>
<td>-</td>
<td>10.7</td>
<td>12.3</td>
</tr>
<tr>
<td>Floor 10</td>
<td>Complete Fitout</td>
<td><strong>5.30</strong></td>
<td>-</td>
<td>-</td>
<td><strong>6.96</strong></td>
<td>-</td>
<td>-</td>
<td><strong>8.7</strong></td>
<td>-</td>
<td>10.7</td>
<td>12.3</td>
</tr>
<tr>
<td>Floor 11</td>
<td>Part Fitout</td>
<td><strong>5.23</strong></td>
<td>-</td>
<td>-</td>
<td><strong>6.95</strong></td>
<td>-</td>
<td>-</td>
<td><strong>8.64</strong></td>
<td>-</td>
<td>10.5</td>
<td>12.2</td>
</tr>
<tr>
<td>Floor 14</td>
<td>Bare structure</td>
<td><strong>5.36</strong></td>
<td>-</td>
<td>6.30</td>
<td><strong>7.14</strong></td>
<td>-</td>
<td>-</td>
<td><strong>8.85</strong></td>
<td>-</td>
<td>10.6</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Legend: **Bolded** values correspond to dominant modes in the response  
Progressively smaller font sizes are indicative of modes with lower participation in the response  
*Italicised* entries are indicative of modes with very small participation in the response

Table 2: Modal results for critical damping ratio (walker NH)

<table>
<thead>
<tr>
<th>Floor</th>
<th>Fitout Status</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
<th>Mode 7</th>
<th>Mode 8</th>
<th>Mode 9</th>
<th>Mode 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor 9</td>
<td>Complete Fitout</td>
<td><strong>1.20%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>1.20%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>1.00%</strong></td>
<td>-</td>
<td>2.13%</td>
<td>4.00%</td>
</tr>
<tr>
<td>Floor 10</td>
<td>Complete Fitout</td>
<td><strong>1.20%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>1.58%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>1.60%</strong></td>
<td>-</td>
<td>1.79%</td>
<td>1.70%</td>
</tr>
<tr>
<td>Floor 11</td>
<td>Part Fitout</td>
<td><strong>0.90%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>1.40%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>1.33%</strong></td>
<td>-</td>
<td>1.32%</td>
<td>1.43%</td>
</tr>
<tr>
<td>Floor 14</td>
<td>Bare structure</td>
<td><strong>1.00%</strong></td>
<td>-</td>
<td>1.22%</td>
<td><strong>0.90%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>1.16%</strong></td>
<td>-</td>
<td>2.51%</td>
<td>1.16%</td>
</tr>
</tbody>
</table>

Table 3: Modal results for natural frequency in Hz (walker DG)

<table>
<thead>
<tr>
<th>Floor</th>
<th>Fitout Status</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
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<th>Mode 9</th>
<th>Mode10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor 9</td>
<td>Complete Fitout</td>
<td><strong>5.38</strong></td>
<td>-</td>
<td><strong>6.24</strong></td>
<td><strong>7.10</strong></td>
<td>-</td>
<td>8.39</td>
<td>-</td>
<td>-</td>
<td>10.49</td>
<td>12.5</td>
</tr>
<tr>
<td>Floor 10</td>
<td>Complete Fitout</td>
<td><strong>5.60</strong></td>
<td>5.89</td>
<td>-</td>
<td>-</td>
<td><strong>7.94</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.94</td>
<td>11.9</td>
</tr>
<tr>
<td>Floor 11</td>
<td>Part Fitout</td>
<td><strong>5.18</strong></td>
<td>5.78</td>
<td>-</td>
<td><strong>6.86</strong></td>
<td><strong>7.73</strong></td>
<td>8.49</td>
<td>-</td>
<td>-</td>
<td>9.69</td>
<td>11.8</td>
</tr>
<tr>
<td>Floor 14</td>
<td>Bare structure</td>
<td>-</td>
<td>-</td>
<td><strong>6.37</strong></td>
<td>-</td>
<td>8.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.6</td>
<td>12.5</td>
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Table 4: Modal results for critical damping ratio (walker DG)

<table>
<thead>
<tr>
<th>Floor</th>
<th>Fitout Status</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
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<th>Mode10</th>
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<tbody>
<tr>
<td>Floor 9</td>
<td>Complete Fitout</td>
<td><strong>0.80%</strong></td>
<td>-</td>
<td><strong>1.40%</strong></td>
<td><strong>1.50%</strong></td>
<td>-</td>
<td>3.38%</td>
<td>-</td>
<td>-</td>
<td>1.94%</td>
<td>3.40%</td>
</tr>
<tr>
<td>Floor 10</td>
<td>Complete Fitout</td>
<td><strong>2.40%</strong></td>
<td><strong>2.49%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>2.00%</strong></td>
<td>-</td>
<td>-</td>
<td>2.86%</td>
<td>2.67%</td>
<td></td>
</tr>
<tr>
<td>Floor 11</td>
<td>Part Fitout</td>
<td><strong>1.16%</strong></td>
<td><strong>2.31%</strong></td>
<td>-</td>
<td><strong>1.30%</strong></td>
<td><strong>1.37%</strong></td>
<td>1.29%</td>
<td>-</td>
<td>1.80%</td>
<td>2.20%</td>
<td></td>
</tr>
<tr>
<td>Floor 14</td>
<td>Bare structure</td>
<td>-</td>
<td>-</td>
<td><strong>0.77%</strong></td>
<td>-</td>
<td>-</td>
<td><strong>1.00%</strong></td>
<td>-</td>
<td>-</td>
<td>2.50%</td>
<td>2.08%</td>
</tr>
</tbody>
</table>

Another clear observation from this set of tables (Tables 1 to 4) is that the two walkers seemed to consistently excite dominant modes peculiar to and different from each other.

Walker NH excited modes 1 and 4 as dominant modes in floors 9, 10 and 11, with mode 1 being of higher contribution but the same pair of dominant modes except “switched” the other way around in terms of energy contribution in floor 14 (bare floor) with mode 4 now being of higher contribution.

Walker DG on the other hand excited modes 1, 3 and 4 as dominant modes in floors 9, with all three modes making comparable energy contributions to the acceleration response. In the case of floor 11, (partly fitted out), modes 1, 2 (not 3) and 4 became the three dominant modes making comparable energy contributions to the acceleration response.

For floor 10, walker DG excited only modes 1 and 2 as dominant modes with near equal contributions to overall acceleration response for this floor, whereas in floor 14 only mode 3 clearly dominated over mode 6 in contributing to floor response. For those modes with frequency and damping values presented in italics in Tables 1 to 4, (modes 7, 8, 9 and 10), to signify virtually negligible contribution towards the acceleration response of the floor levels concerned, it was still possible to nonetheless extract modal properties using the Haritos Equivalent Area method (HEMA) of fitting for the Accelerance.

It is also interesting to note that modes 9 and 10 are closely matched in their reported characteristics for both walkers NH and DG. These two modes were present for all 4 floors tested from the data for walker NH, whereas only mode 10 was present for all test floor data for walker DG. However, mode 9 did still have a detectable presence for floors 9 and 14 for walker DG in this data.

It becomes very clear from the experience of conducting these floor vibration response measurements that the excitation and resultant
acceleration response characteristics of the floor are very much dependent on the walker. Factors contributing to generating variability in vibratory response, include but are not limited to: their weight; walking pace; variability in this pace during a walking episode; the pathway chosen when walking over the floor; characteristics of the footfall interaction with the floor (footwear and floor covering on the floor would also have an influence). It is therefore apparent that human-induced vibration of floors is indeed a very complex phenomenon.

It is also clear that damping levels in office floors of open plan design can exhibit quite low values of damping (order of 1% to 1.5% critical) in their principal modes of vibration and that these levels of damping can be even lower than 1% critical for floors that are bare (not fitted out).

These results for damping appear to be somewhat lower than those reported by Marks (2006) and obtained from floor acceleration vibration data generated using an instrumented impact hammer.

Marks tested two floor plates on successively fitted floors of composite steel girder concrete slab construction in the Southern Cross building (Exhibition Street, Melbourne), then under reconstruction, using this testing technique. Floor 17 was completely bare whilst floor 18 was fitted for an open office design with mid-height partitions and carpet at the time of testing.

Marks reported a dominant first mode of vibration in the acceleration response records for both floors that exhibited an identical modal frequency of 5.50 Hz. The damping value for the bare floor was estimated at 2.0% critical damping and that for the carpeted and half-height partitioned floor to be 2.5% critical.

The technique for estimating the damping was not spelt out in this paper but it is suspected that the “half power” bandwidth method on a frequency-smoothed acceleration response spectrum was adopted as this method was “fashionable” at the time.

Marks also reported values of natural frequency and damping level of the dominant mode of vibration from floor acceleration response data captured on a bare floor on level 20 of the Urban Workshop building in Lonsdale Street Melbourne.

The floors of this building were also of composite RC slab on steel beam construction. The first mode response values reported were 6.8 Hz for frequency and 1.8% for damping.

8 CONCLUDING REMARKS

A testing opportunity to report on the susceptibility to human-induced floor vibrations of the composite RC slab on steel beam design adopted for a new building under construction in the Melbourne CBD presented itself in 2014.

A series of test acceleration vibration response records, near (but 1m to the side) of mid-span location of a corner floor plate were captured using a GCDC X2-1 USB accelerometer.

Responses measured were from excitation due to walking by two different male walkers (identified as NH and DG in this paper), and also from a series of successive heel-drop tests near the location of the measurement accelerometer generated by these same male testers.

Four separate floors were tested in this way. Only the records from the walking excitation tests from both walkers NH and DG have been analysed and reported in this paper.

Acceleration response levels on the two fitted floors and the partially fitted floor all exhibited peak accelerations of less than 0.5%g, generally adopted as the level for peak acceleration acceptability for the design of floors in office buildings. Only on floor 14 (the bare floor) were levels higher than this able to be generated by walking from walkers NH and DG, both of whom (at 85kg and 110kg) were heavier than the 75kg “standard” adopted for a walker when dealing with acceptability limits for human-induced vibration in design guidelines.

The analysis performed on the records for the test floors allowed for some interesting results to be extracted from them that are summarised in dot point form below.

• Different walkers (different weight, pacing frequency, footwear, walking path adopted, walking style, etc), can excite different modes in a floor plate with different levels of modal participation in the resultant acceleration response records

• Some modes in a floor plate can be closely spaced in modal frequency – unlike for the case of one-way slab construction where the modes are more beam-like so that successively higher modes show a greater spread in modal frequency

• Damping levels of strongly participating modes of floors with open plan fit-out (such as call centres) appear to have quite low damping levels (vicinity of 1% to 1.5% critical) whereas completely bare floors may exhibit damping levels slightly under 1% critical.

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REFERENCES


