# Evaluation of Contemporary Guidelines for Floor Vibration Serviceability Assessment

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## ABSTRACT

Technological advances in the construction sector and innovative lightweight and large span structural layouts in modern building floors increasingly mean that vibration serviceability is the governing design criterion. As this trend continues, excessive vibrations induced by human activities are becoming a significant concern. Prediction of floor vibrations at the design stage is often done using currently available design guidelines, such as AISC Design Guide 11, Concrete Society Technical Report 43 Appendix G, SCI P354, Concrete Centre CCIP-016 and HiVoSS.

In this paper, the aforementioned design guidelines are used to predict the vibration responses of a typical office floor, which are then compared with the actual measured responses. It is clear that different guidelines provide different tolerance limits which make the satisfactory/unsatisfactory decision imprecise. The results show that the case-study floor is unsatisfactory according to CSTR43 App G and CCIP-016, whereas it satisfies the requirements of AISC-DG11, SCI P354 and HiVoSS. Nevertheless, the experimental vibration response indicates that there is a perceptible level of vibrations but with no adverse comments. These discrepancies highlight the need for a better prediction techniques and more reliable assessment criteria.

Keywords: Vibration serviceability, floors, design guidelines, R factor, pedestrian Loading

## 1 INTRODUCTION

Vibration serviceability of building floors is an area of particular interest in light of advancements in construction technologies and efficient use of materials. Driven by architectural demands for innovative and aesthetically pleasing designs, modern office floors have ever more open-plan layouts and longer spans with fewer internal partitions. In these floors, significant reductions in mass and damping are reported [1,2] due to the modern paperless offices (computerised layouts) rather than conventional heavy offices (compartmentalised layouts). As a consequence, floors are becoming ever more prone to exhibit excessive vibrations in the range of frequencies generated by human activities, such as walking.

A number of design guidelines, available at the design stage, have been developed to predict the vibration performance of floors and their ability to satisfy prescribed serviceability thresholds. These include:

- American Institute of Steel Construction Design Guide 11 2016 (AISC DG11) [3]
- Concrete Society Technical Report 43 Appendix G 2005 (CSTR43 App G) [4]
- Concrete Centre Industry Publication 016 2006 (CCIP-016) [5]

- European guideline, Human Induced Vibration of Steel Structures 2007 (HiVoSS) [6]
- Steel Construction Institute publication 354 2009 (SCI P354) [7]

These design codes have provided methodologies to predict the vibration responses of floor systems using multi-mode SDOF approach under single person loading scenario. However, their reliabilities and limitations have not yet been fully investigated, in particular where the floors are on the borderline of being acceptable or unacceptable in terms of vibration response. Amongst the aforementioned guidelines there are different vibration design procedures which vary in both the serviceability assessment and the tolerance limits.

This paper examines the application of the above design guidelines for predicting the vibration response of a typical office floor using the design procedures provided by each guideline and evaluates them against actual vibration responses measured under a single person walking. The paper starts with a description of the case study floor, followed by a description of the measurement campaign and FE analysis. Then, the design guidelines with their procedures are employed to predict the vibration response and comparisons are made. The outcome of the analysis is discussed, both in terms of the reliability of the methods to predict accurate response levels and also with respect to the appropriateness of the various tolerance limits.

## 2 EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF CASE STUDY FLOOR

### 2.1 Floor configuration

The floor is a composite steel-concrete construction in a steel framed office building. This floor is irregular by design with the primary beams varying from 7.193 m to 10.013 m in length and spanning between column lines, as shown in Figure 1. The secondary beams also range from 9.53 m to 13.0 m in length. The floor features composite steel beams supporting slabs cast of light weight concrete poured over steel profiled decking. A total height of 130 mm of concrete slab is used acting compositely with the secondary beams. The majority of the floor area is open plan office space furnished and there are few partition walls. Columns are located along the two sides of the building as well as along the centrelines.

### 2.2 Data acquisition

Experimental Modal Analysis (EMA) was performed to find modal properties (i.e natural frequencies, modal damping and mode shapes) of the floor, which are shown in Figure 2. Full details of the modal testing and vibration monitoring are discussed elsewhere [8] and some key points are repeated here. Four electrodynamic shakers were used to excite the floor and responses were measured using high quality accelerometers (Honeywell QA750). A test gird of 65 test points were utilised for acquisition of frequency response functions (FRF). For walking responses, the accelerometers were located at a point of high response and data were acquired at different pacing rates ranging from 104 steps per minute to 132 steps per minute. The walking path was between grid line D-1 and E-6 (Figure 1), since it was noticed that the lowest mode shapes were concentrated in this region and it was within the reach of walking frequency ranges. The response data were sampled at 204 Hz and subsequent to the measurements the following steps were performed to obtain the measured vibration responses:

- BS6841 $W_b$ frequency weighting was applied to the acceleration time history, which takes into account the variation of human perception of vibration at different frequencies.
- Running root-mean-square (RMS) trends were calculated for the 1 s integration time for the weighted acceleration.
- The RMS values for all the weighted accelerations were found.
- The peak of running RMS trends was found, which is termed as maximum transient vibration value (MTVV).
- Response factor (R-factor) was calculated by dividing the MTVV value by the base curve value of 0.005 m/s$^2$.

### 2.3 FE analysis

A 3D FE model of the floor structure was developed in ANSYS from the structural drawings. SHELL63 elements were utilised to model the orthotropic composite floor and BEAM188 was assumed to model all the beams and columns. Manual model updating

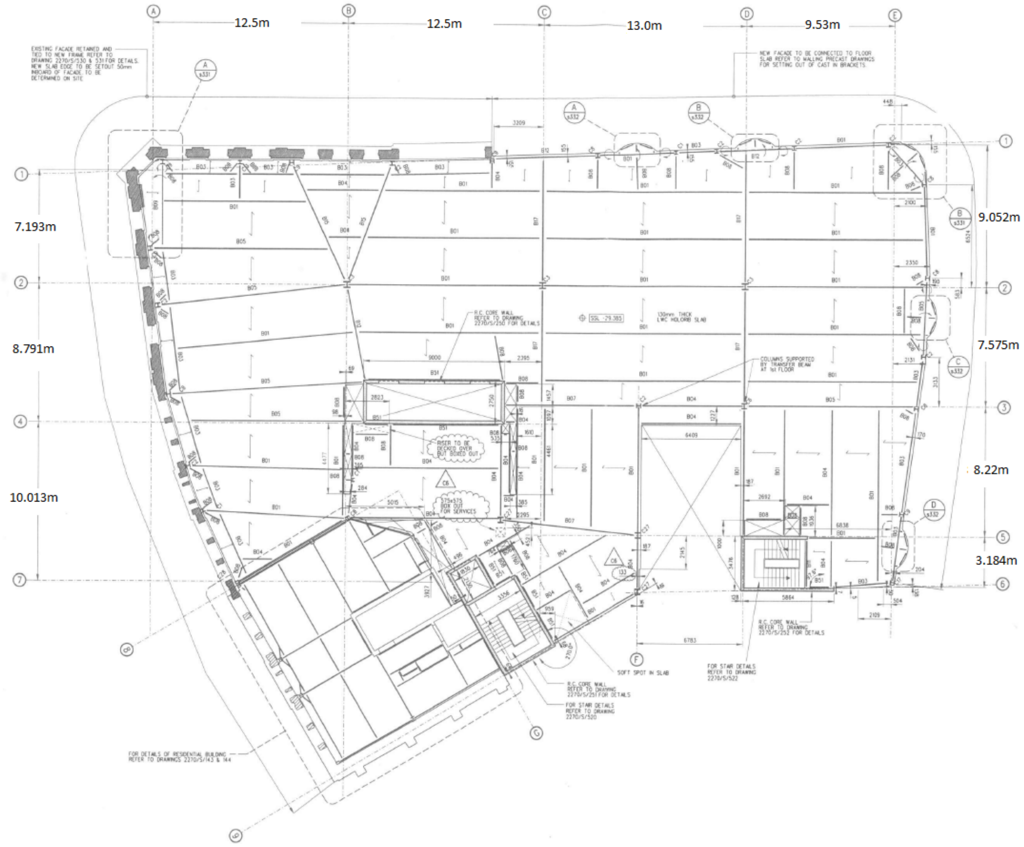


Figure 1: Plan of floor configuration

was performed to match the measured frequencies. A modal analysis was conducted to obtain natural frequencies and mode shapes of the floor. There are a significant number of vibration modes less than 12 Hz and due to space limits only the first four mode shapes are shown in Figure 2.

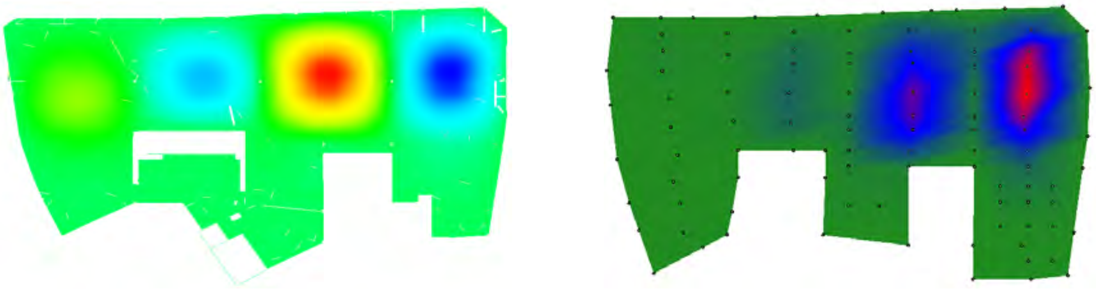
## 3 VIBRATION RESPONSES USING CURRENT GUIDELINES

This section presents the design procedures available in the vibration guidelines, i.e [3–7] to estimate the vibration responses to a single person walking. The design methodologies of each guideline are briefly discussed, then the results are presented with the corresponding tolerance limits.

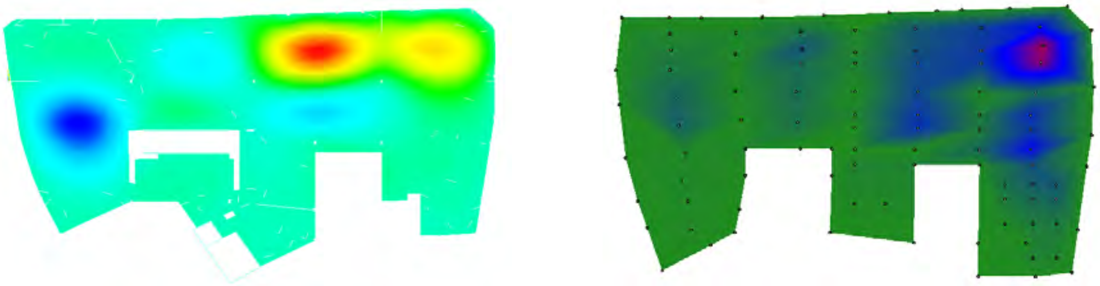
### 3.1 Source of excitation: walking loads

The walking load model described by each guideline is different and takes various forms. It is widely accepted by the available guidelines that vibration responses of floors are in two types: a resonance build-up for low-frequency floors and a transient response for high-frequency floors. The threshold frequency between these two categories is around 10 Hz. For the considered office floor, the fundamental frequency is less than 10 Hz; hence, the walking load model only relevant to the low-frequency floors is discussed.

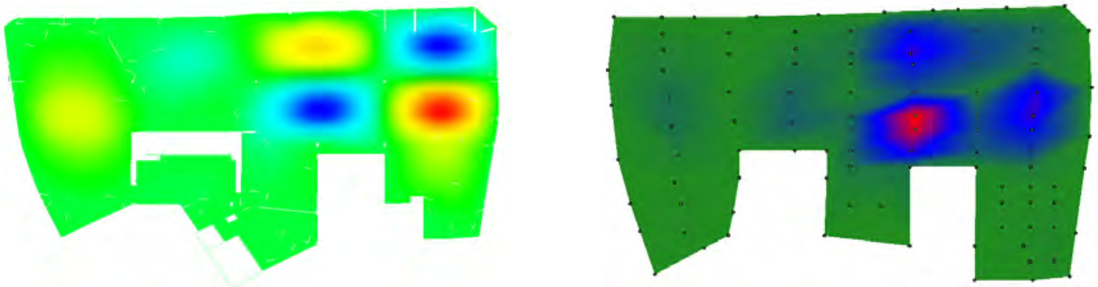
The walking load model used in AISC DG11, CSTR43 App G, CCIP-016, and SCI P354 is a Fourier series representation considering only the first four harmonics [3–5, 7], the general from is shown in equation 1.



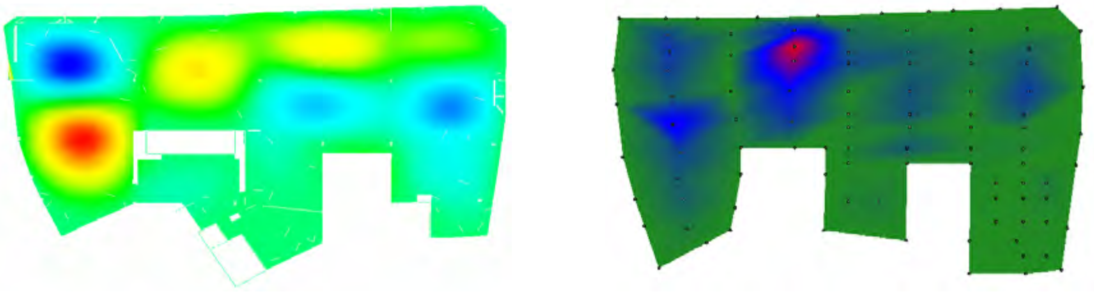
(a) FE analysis, $f_1$ = 5.23 Hz, m = 36.02 tonnes (b) EMA $f_1$ = 5.24 Hz, $\zeta$ = 3.16 %



(c) FE analysis, $f_2$ = 6.52 Hz, m = 28.54 tonnes (d) EMA $f_2$ = 6.06 Hz, $\zeta$ = 2.24 %



(e) FE analysis, $f_3$ = 6.33 Hz, m = 35.95 tonnes (f) EMA $f_3$ = 6.58 Hz, $\zeta$ = 1.87 %



(g) FE analysis, $f_4$ = 6.87 Hz, m = 39.95 tonnes (h) EMA $f_4$ = 7.31 Hz, $\zeta$ = 2.60 %

Figure 2: First four modes from FE Analysis and Experimental Modal Analysis

$$F(t) = G\left[1 + \sum_{n=1}^{N} \alpha_n \sin(n2\pi f_p t + \Phi_n)\right] \tag{1}$$

where, $F(t)$= walking load time history (N); $G$ = static weight of a person ( (168 lb) 750 N in AISC DG11; 700 N in both CSTR43 App G, CCIP-016 and 746 N in SCI P354); $\alpha$ = Dynamic Load Factors (DLFs); n = order of harmonic of the walking rate (n = 1, ...); $f_p$ = pacing frequency (Hz); t = time (sec); $\Phi$ = harmonic phase angle; N = total number of harmonics.

The values of DLFs provided by CSTR43 App G and CCIP-016 are statistically defined to have 25 % chance of being exceeded, while in AISC DG11 deterministic values are used and in SCI P354 the values depend on pacing frequencies. Also, the pacing frequency ranges between 1.0 Hz to 2.8 Hz in CSTR43 App G and CCIP-016, whereas the design range covered by SCI P354 and AISC DG 11 is narrowed down to 1.8-2.2 Hz and 1.6-2.2 Hz, respectively.

HiVoSS [6, 9], however, assumes a completely different approach by modelling walking as a step-by-step polynomial function with eight terms. The pacing frequency and pedestrian weight is defined probabilistically and it is a cumulative distribution for each combination of the pacing frequency and pedestrian weight.

### 3.2 Dynamic properties of the floor by the guidelines

The current guidelines characterise the dynamic properties of the floors by modal parameters, such as natural frequency of the floor, modal mass and damping ratio. Among the design guidelines, CSTR43 App G allows to use the measured modal parameters and it is applicable to all materials of construction. HiVoSS presents slightly a different approach to include transfer function procedure to estimate the modal properties; however, graphs are provided by HiVoSS as a result of beforehand calculation of the transfer function to find the vibration responses. Hence, the graphs can be used directly by reading off the vibration responses. This guideline is only applicable to steel structures, which implies a significant limitation of the use of this guideline.

CCIP-016 [5], similar to CSTR43 App G, is applicable to any construction materials, with the extension of being applicable to floors as well as footbridges. Both AISC DG11 and SCI P354 are only applicable to steel structures.

### 3.3 Vibration response estimation and evaluation

For low-frequency floors, the resonant response occurs when one of the harmonics of walking matches a frequency of the floor. Mode superposition is an effective tool in all the guidelines to obtain the final response. The guidelines calculate acceleration responses of each mode, then by using the mode superposition the final outcome is obtained. AISC DG11 [3], in particular, suggests using analytical FRFs to determine which mode provides the highest response and thus the peak magnitude of the FRF will be used to estimate the acceleration response. For the considered floor, the peak FRF value obtained from harmonic (steady state) analysis (see Figure 3) is $0.80 \times 10^{-3}$ m/s$^2$/N, which occurred between grid line B-1 and C-2 (Figure 1).

Different vibration criteria are provided to evaluate the vibration responses predicted by each guideline. CSTR43 App G and CCIP-016 calculate the response factor (R factor), which is then compared to recommended tolerance limits based on the floor usage. For office floors, similar to the case study floor, the recommend vibration limit is an R factor of 4. However, SCI P354 only provides a higher recommended limit, which is R factor of 8.

On the other hand, AISC DG 11 only sets the peak acceleration as the vibration limit, which is 0.5 %g for office floors, this value corresponds to an equivalent R factor of 7. HiVoSS considers a different criterion, which is one step root-mean-square (OS-RMS). This value has a dimension of mm/s. It is based on the peak root mean square velocity calculated from the inverse of Fourier transformation of the weighted velocity response [10]. This value provides different “recommended class” as acceptable criteria, which ranges from class A (highly recommend) to class F (not recommended). The OS-RMS for each class is calculated from a combination of walking frequency and pedestrian weights, the 90 % percentile of those values are considered to be the highest response under the walking load. In calculating the OS-RMS$_{90}$ value, the walking path is not taken into account, this implies that the excitation point is kept fixed. Hence, this method is believed to be “semi-probabilistic” [11]. The OS-RMS$_{90}$ multiplied by a value of 10 gives the equivalent R factor [10]. The recommended values for office floors according to HiVoSS is between a lower limit (5% probability of complaints) of OS-RMS$_{90}$ = 0.8 mm/s and upper limit (95% probability of complaints) of OS-RMS$_{90}$ = 3.2 mm/s, which corresponds to an R factor of 32.

## 4 RESULTS AND DISCUSSION

The vibration serviceability assessment is performed based on the tuned FE model for all the modes less than 12 Hz for CSTR 43 App G, and SCI P354, while 15 Hz for the CCIP-016. The FRF for AISC DG 11 was performed up to frequency of 10 Hz under a unit amplitude load at location of the highest mode amplitude and the response was measured at the same point (Figure

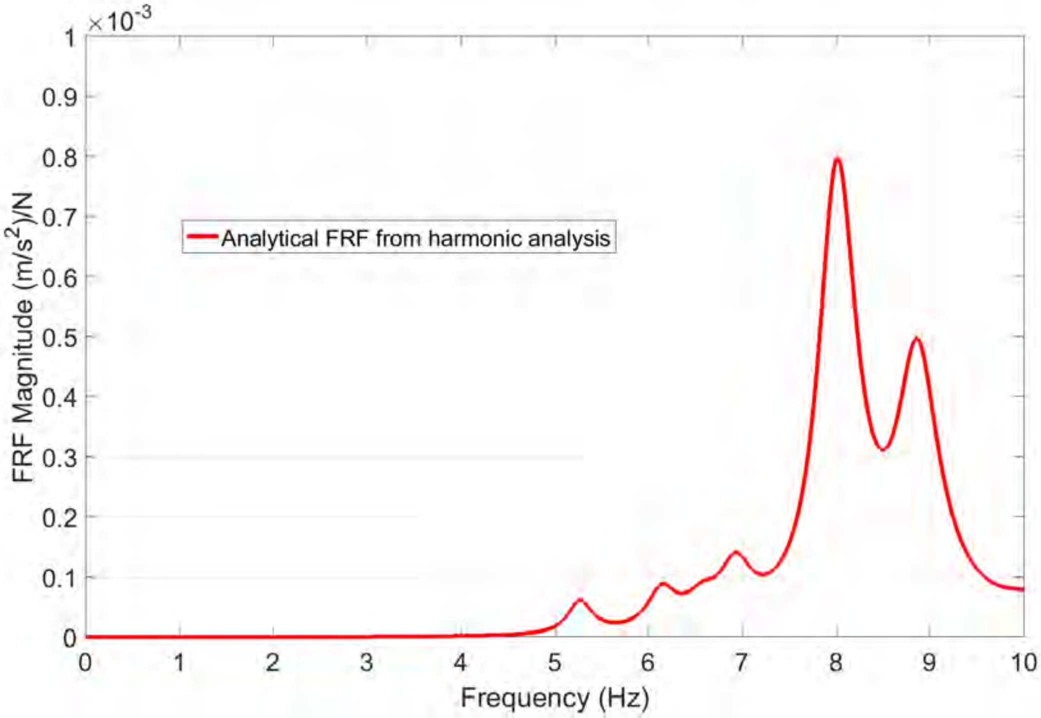


Figure 3: Peak FRF magnitude from FE harmonic analysis between grid line B-1 & C-2

3). The modal damping ratio of 3 % was assumed for all modes of vibration. The response was calculated for a range of the floor frequencies to obtain the peak vibration response (i.e R factor).

The results of the maximum predicted R factor are shown in Figure 4. It can be seen that all the guidelines predict different values of R factor. CSTR43 App G and CCIP-016 predict an R factor of greater than 4, which results in an unsatisfactory floor evaluation. SCI P354 gives an R factor of 7.86 from the calculations, which results in a positive assessment of the floor. Both AISC DG 11 and HiVoSS predict the equivalent R factor of 4.19 (0.30 %g) and 12.75 (OS-RMS$_{90}$ = 1.275 mm/s), respectively. Hence, the floor is acceptable by AISC and it is within the recommended region by HiVoSS. Also, the distribution of R factor under various pacing frequencies is presented in Figure 5. It is clear that there are R factor values predicted by a wide range of pacing frequencies from CSTR43 App G and CCIP-016, whereas SCI P354 range of pacing frequencies seems to be inadequate.

From the actual response standpoint, the measured R factor is 5.3 (MTVV = 0.026 m/s$^2$). This value corresponds “subjectively” to a perceptible level of the vibration by floor occupants, but it resulted in no adverse comments. It is worth noting that the peak values predicted by the guidelines are scattered in comparison to the actual response. The predicted values provide only a single value for prediction with different descriptors (peak acceleration, peak R factor and OS-RMS$_{90}$), which do not give reliable information on the event occurrence. These peak values may not occur as frequently as predicted (i.e the probability of occurrence and exceedance is not known), despite being assessed as unacceptable/acceptable according to the provided recommended limits.

These discrepancies highlight that the current design guidelines can potentially result in unreliable assessment of floor vibrations, which may lead to imprecise assessment as satisfactory/unsatisfactory. Therefore, better calculation techniques and more reliable criteria are required to predict more reliably the vibration responses of floors [12].

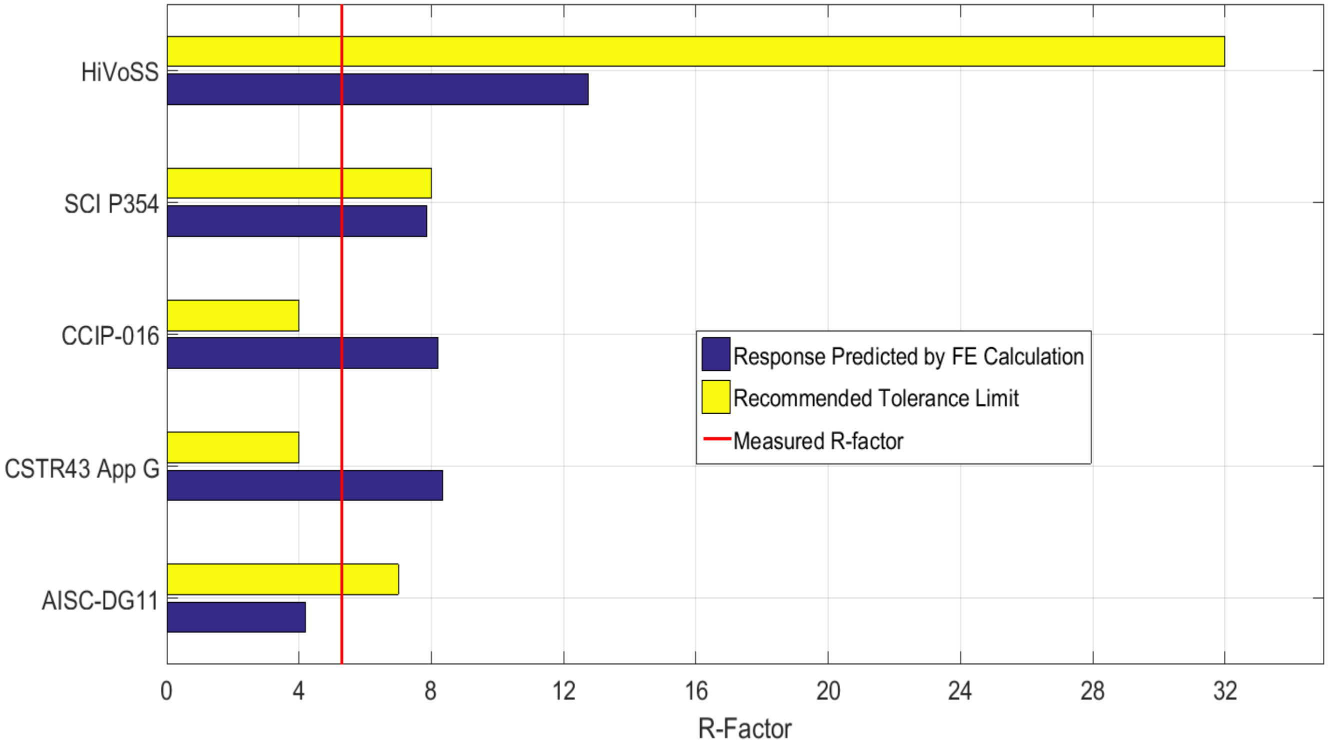
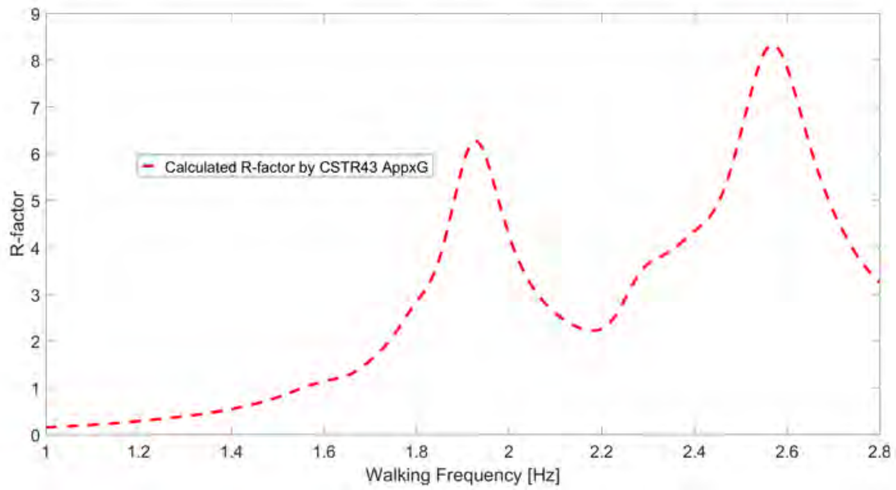
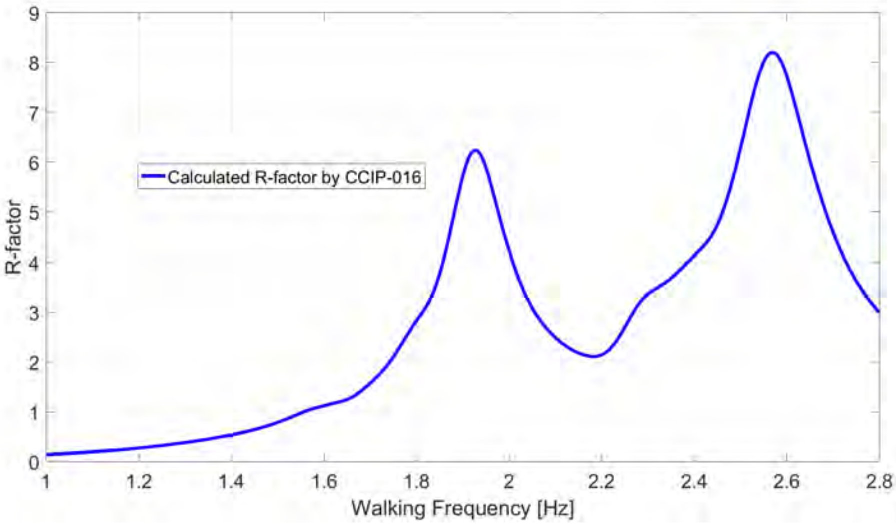


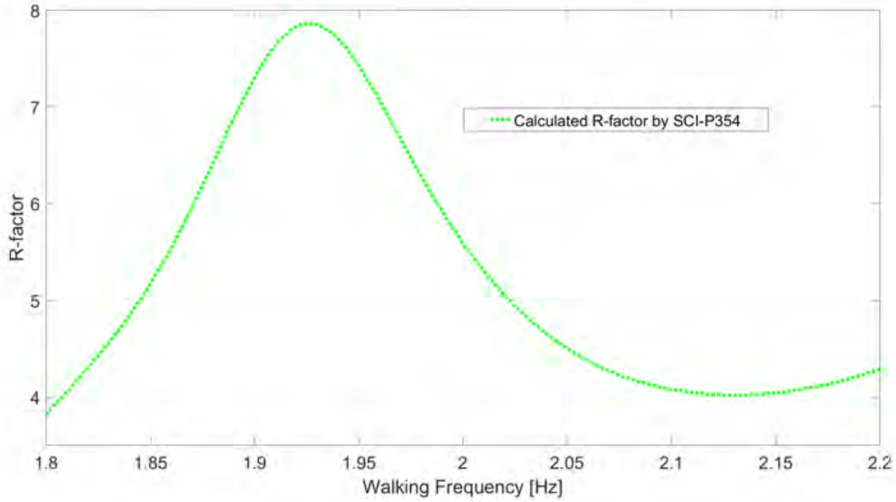
Figure 4: Predicted R factor by different guidelines with recommended tolerance limits



(a) Distribution of pacing frequency against R-factor in CSTR43 App G



(b) Distribution of pacing frequency against R-factor in CCIP-016



(c) Distribution of pacing frequency against R-factor in SCI P354

Figure 5: Distribution of different pacing frequency against R-factor in guidelines

## 5 CONCLUSION

This paper has highlighted vibration response prediction by contemporary guidelines relative to the measured response obtained from experimental walking measurements. The response prediction is based on a single peak value of acceleration or R factor, which is not a representative value and may not occur as often as expected by the guidances. Also, the response criteria provided by HiVoSS is obviously much higher than its counterparts, despite being on the basis of a probabilistic approach. Whilst different guidelines provide various assessment criteria, the satisfactory and unsatisfactory decision seem to be imprecise. As a result, the serviceability assessment procedure and recommended vibration tolerance limits of different guidelines seem to be unreliable and misleading, since the prediction is based on a single person loading and the single peak value. Hence, various probability of exceedance needs to be defined in order to reflect the actual behaviour of the floor at different excitations. It is clear that there is a need for further research and investigations to carry out extensive work in in-servicing office environments and develop or improve a more reliable assessment tools.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] C. M. Hewitt and T. M. Murray, “Office Fit-Out and Floor Vibrations,” *Modern Steel Construction*, pp. 35–38, 2004.

[2] C. Middleton and J. Brownjohn, “Simplified Methods for Estimating the Response of Floors to a Footfall,” in *Structures Congress 2011*, vol. 41171, (Las Vegas, Nevada, USA), pp. 383–403, ASCE, 2011.

[3] T. M. Murray, D. E. Allen, E. E. Ungar, and D. B. Davis, *Vibrations of Steel-Framed Structural Systems Due to Human Activity: AISC DG11 Second Edition*. 2016.

[4] A. Pavic and M. Willford, *Vibration serviceability of post- tensioned concrete oors. Appendix G, Technical Report 43.* Slough, UK: Concrete Society, second ed., 2005.

[5] M. Willford and P. Young, *A Design guide for footfall induced vibration of structures - CCIP-016*. Surrey, UK: The Concrete Centre, 2006.

[6] HiVoSS, *Human induced vibrations of steel structures-vibration design of floors (HiVoSS) : Guideline*. European Commission, 2007.

[7] A. Smith, S. Hicks, and P. Devine, *Design of floors for vibration: A new approach(SCI P354)*. Berkshire, UK: Steel Construction Institute (SCI), 2009.

[8] E. J. Hudson and P. Reynolds, “Implications of structural design on the effectiveness of active vibration control of floor structures,” *Structural Control and Health Monitoring*, vol. 21, no. 5, pp. 685–704, 2014.

[9] HiVoSS, *Human induced vibrations of steel structures-vibration design of floors (HiVoSS) : Background Document*. European Commission, 2007.

[10] K. Van Nimmen, B. Gezels, G. De Roeck, and P. Van Den Broeck, “The effect of modelling uncertainties on the vibration serviceability assessment of floors,” in *Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014*, (Porto, Portugal), pp. 959–966, 2014.

[11] O. A. B. Hassan and U. A. Girhammar, “Assessment of footfall-induced vibrations in timber and lightweight composite floors,” *International Journal of Structural Stability and Dynamics*, vol. 13, no. 2, p. 26, 2013.

[12] P. Reynolds and A. Pavic, “Reliability of assessment criteria for office floor vibrations,” in *50th United Kingdom Conference on Human Responses to Vibration*, (Southampton, UK), 2015.