Chapter 14
Probabilistic Assessment of Footfall Vibration

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Abstract As one of the serviceability limit states of structural design, excessive vibration has attracted more attention in recent years, with the design trend moving toward lighter and more slender structures. Footfall vibration contains high uncertainties in nature, with significant variations in walker weight, walking speeds, and dynamic load factor. Since conservative designs can often lead to significant cost premiums, this study focuses on the stochastic assessment of footfall vibration of on a composite steel floor to better understand the variation in performance of various design factors and better inform the ultimate decision-makers. To close the knowledge gap between academia and industry in this area, San Francisco State University and the University of South Carolina partnered with Arup through an NSF-funded Research Experience for Undergraduates (REU) program. A composite steel structure was modeled to resemble a typical office bay. The model was developed and analyzed in Oasys GSA. Monte Carlo simulation was used to quantify the probability of exceeding certain common vibration criteria. The results of this study would provide actionable guidance to stakeholders to weigh the benefits and costs between performance targets.

Keywords Footfall vibration · MC · Academia and industry collaboration

14.1 Introduction

With the design trend moving toward lighter and more slender structures, excessive vibration, as one of the serviceability limit states of structural design, has attracted more attention in recent years. Two of the most famous and publicized cases of vibration serviceability problem caused by footfall vibration are probably the pont de Solférino in Paris [1] and London Millennium Bridge [2, 3]. While the vibration serviceability problem of bridges is well studied, the vibration serviceability for floor design is less regulated as the primary concern is typically focused on the ultimate limit state [4]. Several design guidelines, such as ATC Design Guide 1 [5], the National Building Code of Canada [6], the AISC Design Guide 11 [7], and A Design Guide for Footfall Induced Vibration of Structures (CCIP-016) [8], were developed to guide designers through the process. Several studies have tried to model the footfall problem by representing human behavior based on different assumptions (e.g., the traditional mass model [9, 10]), and recent studies have shown that the human body can be modeled

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using different approaches as a mass-damper-spring (MDS) systems [11, 12] or more recently as a PID controller system which can react to varying levels of excitation [13]. Floor vibration serviceability is commonly addressed at the design stage by either putting a constraint on the minimum fundamental frequency of the floor to avoid resonance induced by footfall [14] or using a performance-based approach by setting an upper bound for the floor vibration response based on certain design criteria [4]. In either approach, the evaluation process is in a deterministic fashion in current practice. Based on the authors' experience in the design practice, the design could vary largely when adopting the different design guidelines, and it is currently unclear how that affects the probability of excess footfall-induced floor vibrations. Variability of factors, such as walker weight, speed, or walker style as well as unreliable prediction of modal properties, could be some of the reasons in the design stage that contribute to the uncertainties in the results.

14.2 Proposed Solution

Currently, footfall analysis is performed with a given walking frequency and walker weight. These two singular values are used in the calculations to return a response factor. A response factor (RF) is used to describe the intensity of vibration felt by an occupant; it is a scaled value with an RF = 1 being the threshold of human perception [8]. Through the opportunity provided by an NSF-funded Research Experience for Undergraduates (REU) program established by San Francisco State University and the University of South Carolina, the REU participants (the first two authors) were working together with faculty advisors in academia and industrial mentors from Arup, a leader in engineering consulting and structural design, to start exploring floor vibrations in a probabilistic way. In this study, Monte Carlo simulation was used to obtain the probability of exceeding common RF criteria. The simulation combined normal distributions of walker frequency and walker weight to evaluate the ability of the model to meet RF criteria. This project utilized a typical central bay of a composite steel structure, the structural type that is more vulnerable to floor vibration problem, to simulate different design configurations through Oasys GSA - Structural Design & Analysis Software and evaluate each design's performance in achieving RF criteria through Monte Carlo simulation. Probabilistic analysis was performed in MC Walker, an Arup internal software extension for GSA. Different parameters were varied in the simulations such as beam and girder section sizes, concrete weight and thickness, and the number of beams per bay. The results from the simulations were analyzed to find which design factors had the greatest impact on footfall vibration within the structure.

14.3 Methodology

In order to evaluate the effects of the various parameters mentioned above, a large number of simulations needed to be run. To avoid tedious adjustment of parameters, an automated framework was developed to facilitate the process. Figure 14.1 below shows the framework that was followed throughout this project.

The steel composite model was first developed in Rhino (Fig. 14.2), a computer-aided design software, after which GSA was used to perform dynamic modal analysis and dynamic response footfall analysis (Fig. 14.3). Compared to the current practice of analyzing structures for footfall vibration, this study includes a probabilistic approach by utilizing MC Walker, which accounts for the walker weight and walking frequency. The parameters in MC Walker are shown in Table 14.1. To meet a certain RF value, certain structural properties such as section size, concrete weight, and the number of beams per bay were adjusted to find the optimal design. A script was set up via Python to alter the beam and girder section sizes of the composite steel model. For each section size changed, a footfall analysis was performed using calculations set forth in the design guide CCIP-016, and the model and its results were stored. A total of 220 beam/girder configurations were analyzed for each change of concrete thickness. This amounted to 1320 models for the 2-beam structure (two interior beams between column lines; see Fig. 14.2) and another 1320 models for the 3-beam structure (three interior beams between column lines), respectively. Note that a 9-bay model was created for each model, while only the middle bay was analyzed to mitigate the effects on the support boundaries.

After the pool of outputs were collected, two models were selected for each of the following RF design criteria: RF 6, 4, 2, and 1. The two models were selected based on a large difference in steel weight (psf) and a similar maximum response factor, within 0.10 of one another. The steel weight was calculated by summing the weight of all beams and girders and dividing by the area of the 9-bay model (8100 ft^2). The RF for each of the selected models had to be within 0.20 of the RF design criteria (e.g., 5.85 max RF for the RF 6 Design would suffice). For each model, a Monte Carlo simulation was performed to assess the probability of exceeding RF 8, 6, 4, 2, and 1. The simulation randomized the walking frequency and

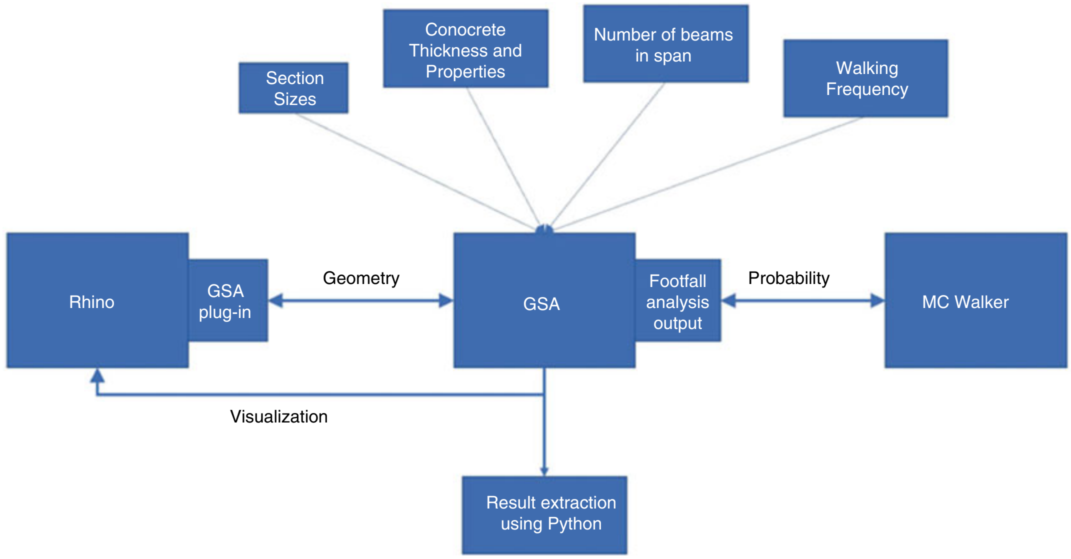

Fig. 14.1 Framework for designing, constructing, and analyzing structural testbed models

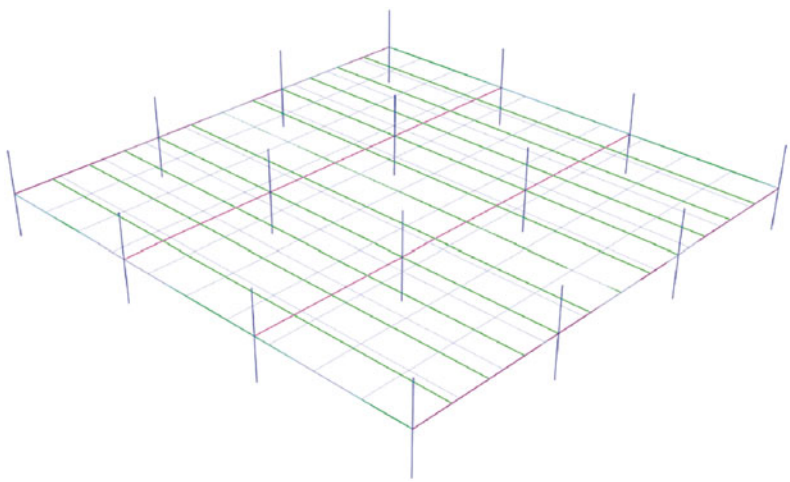

Fig. 14.2 Three beam steel model construct in Rhino 3D designing software

walker weight for each of the models through 750 cycles using Latin hypercube sampling. The walking frequency followed a normal distribution with a median of 2.0 Hz and standard deviation of 0.25 Hz in accordance with the research by Stuart Kerr [15]. The walker weight was randomized following a standard deviation with a mean of 74.5 kg and a standard deviation of 13.5 kg, with values based on research by the Australian Bureau of Statistics [16].

14.4 Results

Following each property change made on the model in GSA, specific outputs such as max response factor and fundamental frequency were extracted using Python and stored into a data frame. By tracking the many iterations performed on the steel model, relationships could easily be identified between a multitude of factors. Figure 14.4 shows the relationship between section size and RF as changes were made to the beams and girders within the model. Although the model varied in section sizes, the 2-beam structure's concrete slab was held constant at 4.5 inches thick of normal weight concrete (150 pcf). As section size increases, the structure gains more mass and does a better job absorbing the footfall vibration. As section size increases, the structure gets stiffer and gains more mass resulting in smaller footfall vibration.

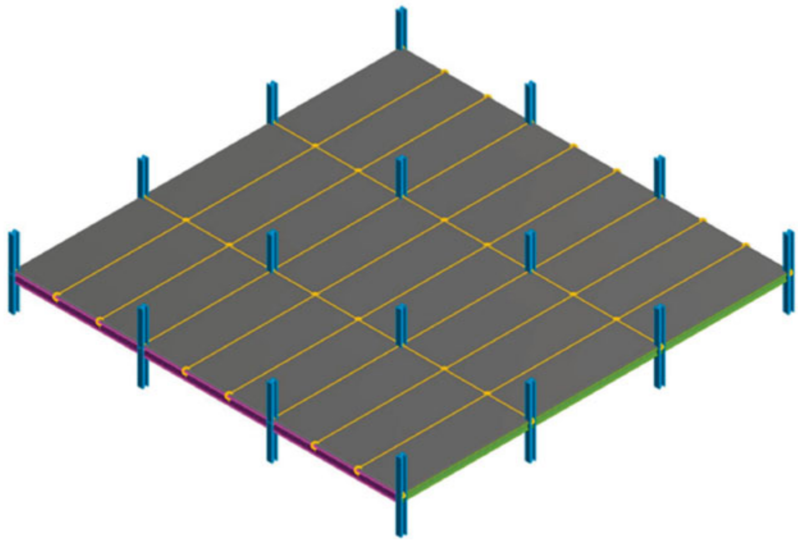

Fig. 14.3 Two beam steel model in GSA structural analysis software

Table 14.1 MC walker parameters

MC Walker parameter (assumed normal distribution)		
Statistics	Walker frequency (Hz)	Weight of walker (kg)
Mean	2.00	74.5
Standard deviation	0.25	13.5
Minimum	1.00	20.0
Maximum	3.00	200.0

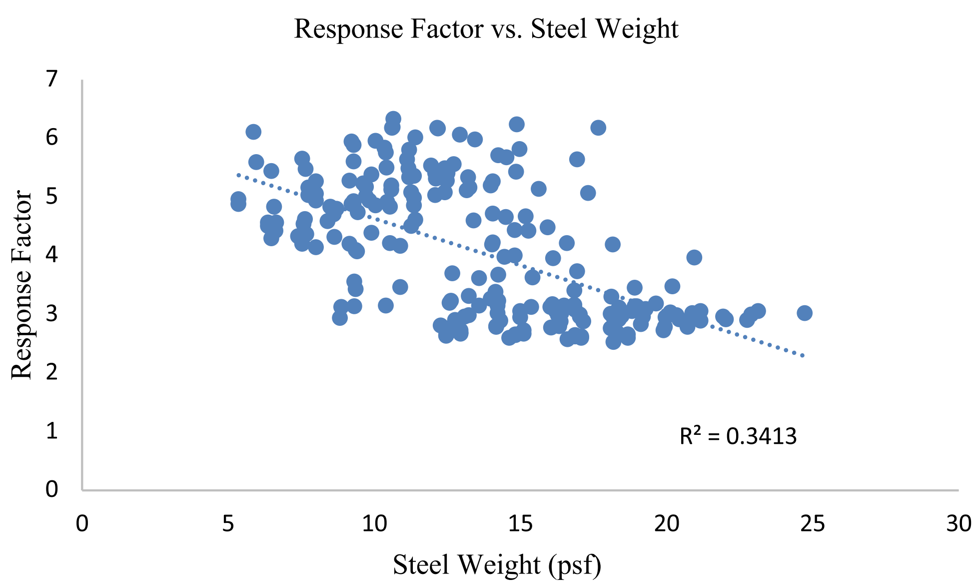

Fig. 14.4 The effect increasing section sizes has on RF for a 2-beam structure with a 4.5 in. NWC slab

Increasing the weight of the structure can also decrease footfall vibration. Concrete is an effective tool to so increase mass. Figure 14.5 shows the effect concrete thickness had on the RF for a given model with beams sized at W18 × 60 and girders sized at W21 × 44 to maintain a constant steel weight. As can be seen from Fig. 14.5, concrete has an approximately linear relationship with the RF and is an efficient way to reduce footfall vibration, if that design intervention is possible.

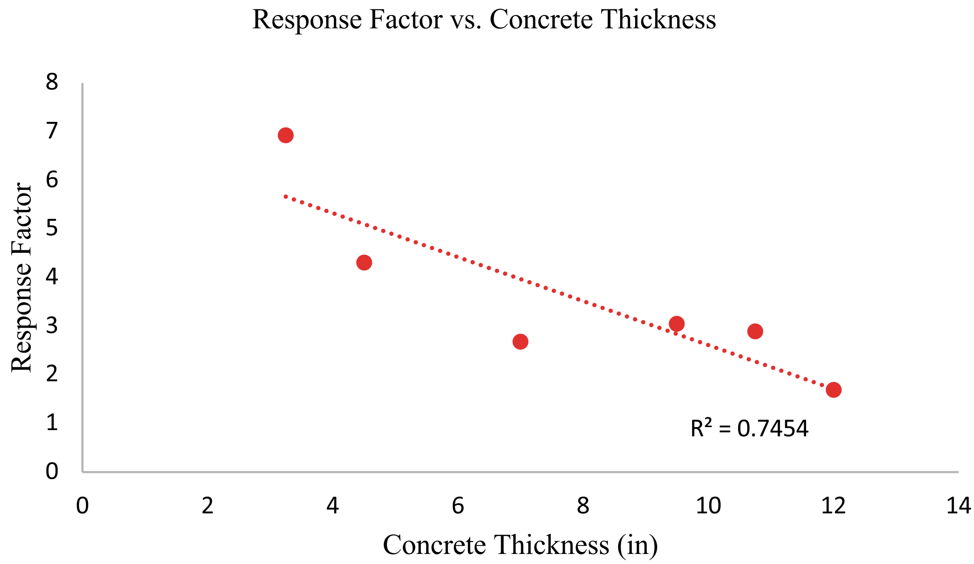

Fig. 14.5 The effect increasing concrete slab thickness has on RF for a 2-beam structure with W18 × 35 beams and W21 × 44 girders

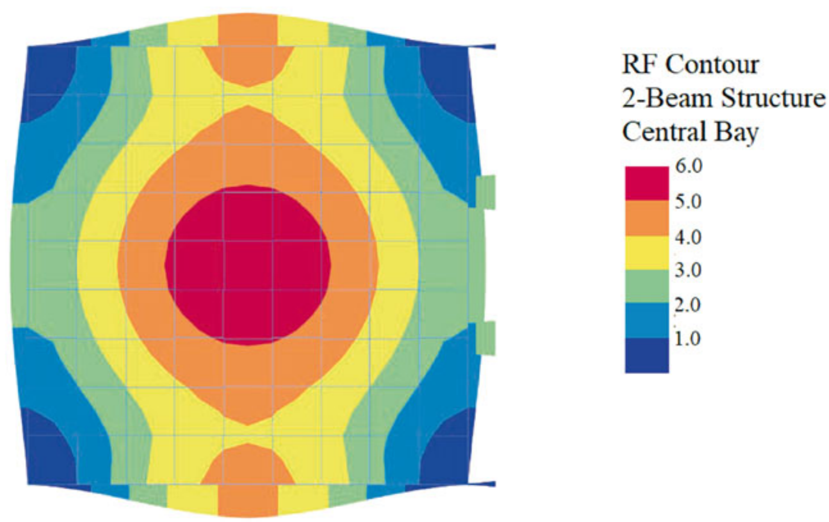

Fig. 14.6 Contour plot of response factor for composite steel bay

The results use the standard RF as a measure for the floor vibration. The output from GSA can be seen as a contour plot of the central office bay in Fig. 14.6. This image shows the magnitude of the RF across the entire bay with the most severe vibration occurring at the center.

After the footfall analysis in GSA, a Monte Carlo simulation was used to calculate the probability of exceeding a specific RF. The simulation repeated the footfall analysis for 750 samples by varying the walking frequency and walker weights as discussed in the methodology section. Figure 14.7 reveals the contour plot generated by the Monte Carlo simulation. The bay shown was designed to meet RF 6 criteria and has only a 5% chance of exceeding RF 6 at the center of the bay.

Throughout the course of this project, more questions arose regarding the probability of a specific design exciding different multiple RF criteria. A test matrix was developed to include all parameters that were tested and evaluated for the steel model. Table 14.2 contains models for a two beams per bay model (2-beam structure) and their respective probabilities of exceeding certain response factors. The highlighted cells indicate the probability of exceeding the vibration criteria required for that specific design. For each RF design, the two models that were chosen had similar maximum RF values within 0.10 of one another and were within 0.20 of the design criteria. The difference in steel weight was around 8–10 psf for the two models. A light steel structure was able to have a similar maximum RF to the heavy steel structure because of an increase in concrete thickness. Table 14.2 shows the difficulty in achieving perfect design of low RF criteria. There was a slight challenge in

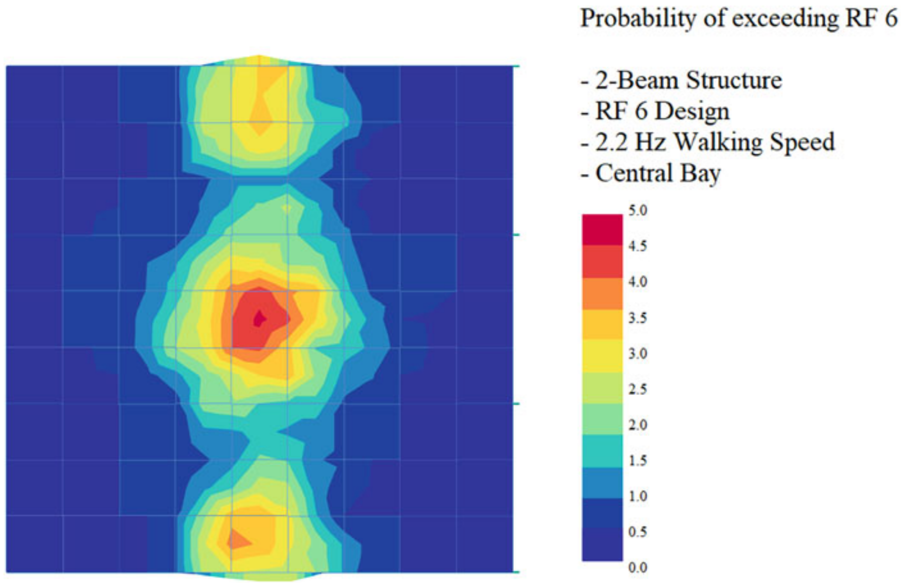

Fig. 14.7 Contour plot showing the probability of exceeding a response factor of 6

Table 14.2 Properties and probabilities of exceedance for two beams per bay composite steel models

Two beams per bay model						
		Probability of exceeding RF (MC Walker)				
RF design criteria	Model type	RF 8	RF 6	RF 4	RF 2	RF 1
RF 6	Light steel	9.2	16.8	31.6	68.0	90.3
	Heavy steel	5.2	10.0	21.6	58.7	81.3
RF 4	Light steel	1.5	3.2	8.9	25.5	52.5
	Heavy steel	1.3	2.9	9.7	25.5	53.5
RF 2	Light steel	0.1	0.3	1.6	12.8	40.5
	Heavy steel	0.0	0.8	2.8	16.1	41.2
RF 1	Light steel	0.0	0.1	1.9	9.2	27.2
	Heavy steel	0.0	0.0	0.0	1.5	12.9

designing a structure to not exceed RF 4 more than 10% of the time, but an RF 1 design would still exceed its limit more than a quarter of its lifespan.

Figure 14.8 below shows the comparison of the 2-beam structure and 3-beam structure models using a 2.2 Hz design walking frequency. The 3-beam models seem to be generally more efficient design especially for low RF as design with similar steel weight achieves lower RF compared to the 2-beam structure.

Figures 14.9a, 14.9b, and 14.9c represent the extended probability of exceeding various design criteria after running the MC Walker Monte Carlo simulation on three different models. The model in Fig. 14.9a is 2-beam structure that was analyzed with a maximum walking frequency of 1.6Hz in GSA. Figure 14.9b also has a 2-beam structure, but the maximum frequency was set to 2.2 Hz. Figure 14.9c shows a 3-beam model with a maximum walking frequency of 2.2 Hz.

14.5 Conclusion

Regarding the factors influencing the analysis, the relationship between structural steel weight and RF was consistent, as increasing section sizes provided more mass and stiffness to the structure allowing a better absorption of the vibration. The increase in slab thickness proved to be a more effective tool in mitigating floor vibration. The slab of the concrete spanning the entirety of the bay added more mass than that of steel members and had a stronger relationship with lowering RF. The heavier concrete design generally performs similar or better, primarily the 3-beam model for design criteria. Another key takeaway is the rapid increase in the probability of exceeding various RF criteria for a specific design. The 3-beam design

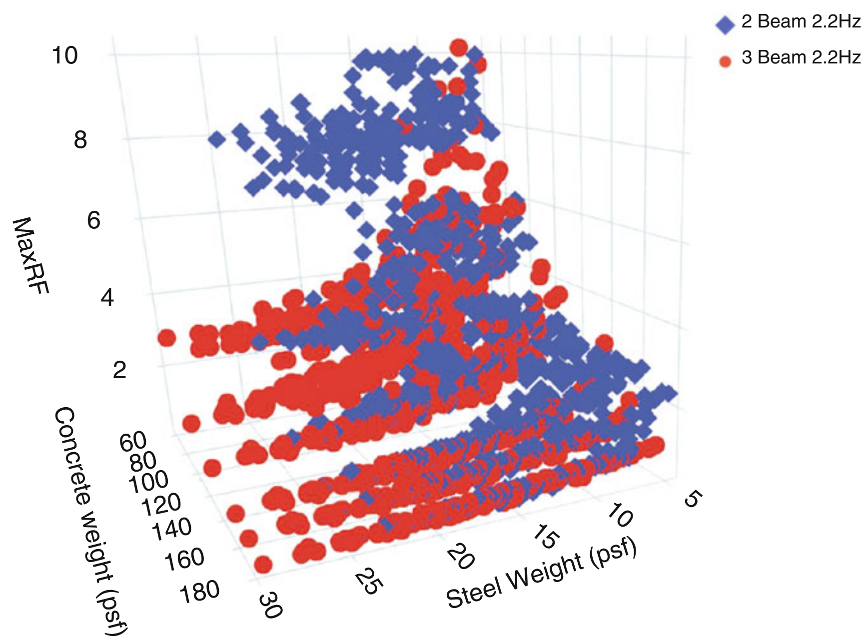

Fig. 14.8 3-beam and 2-beam comparison of steel weight and concrete weight vs max RF at a walking speed of 2.2Hz

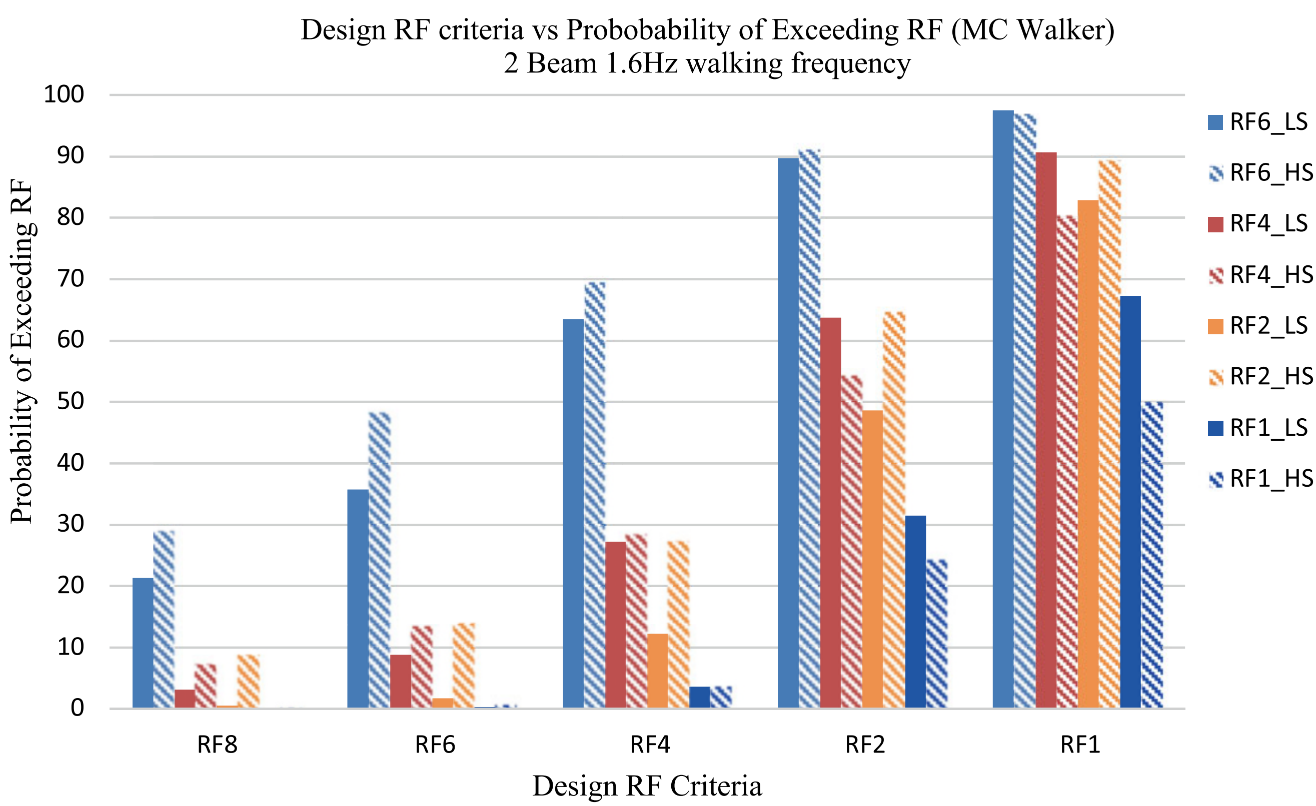

Fig. 14.9a Probability of exceeding certain design criteria with 2-beam 1.6Hz walking frequency model (*LS* light steel design and *HS* heavy steel design)

was more efficient for more stringent criteria without sacrificing performance. Designing to a 1.6 Hz vs 2.2 Hz can result in significant difference in probability of exceeding criteria, especially for the designs targeting more stringent criteria. There is an exponential trend upward as a design is tested against lower RF criteria. It is important to note that there is no single

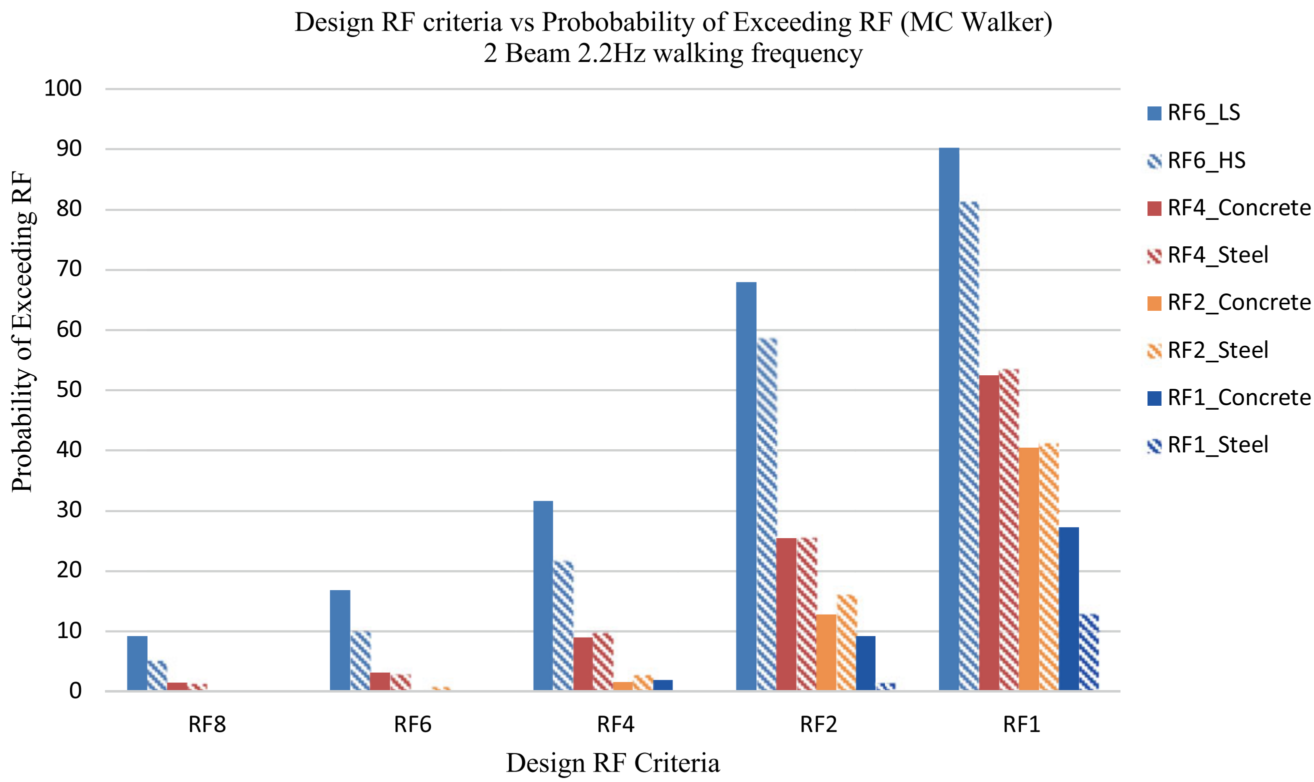

Fig. 14.9b Probability of exceeding certain design criteria with 2-beam 2.2Hz walking frequency model

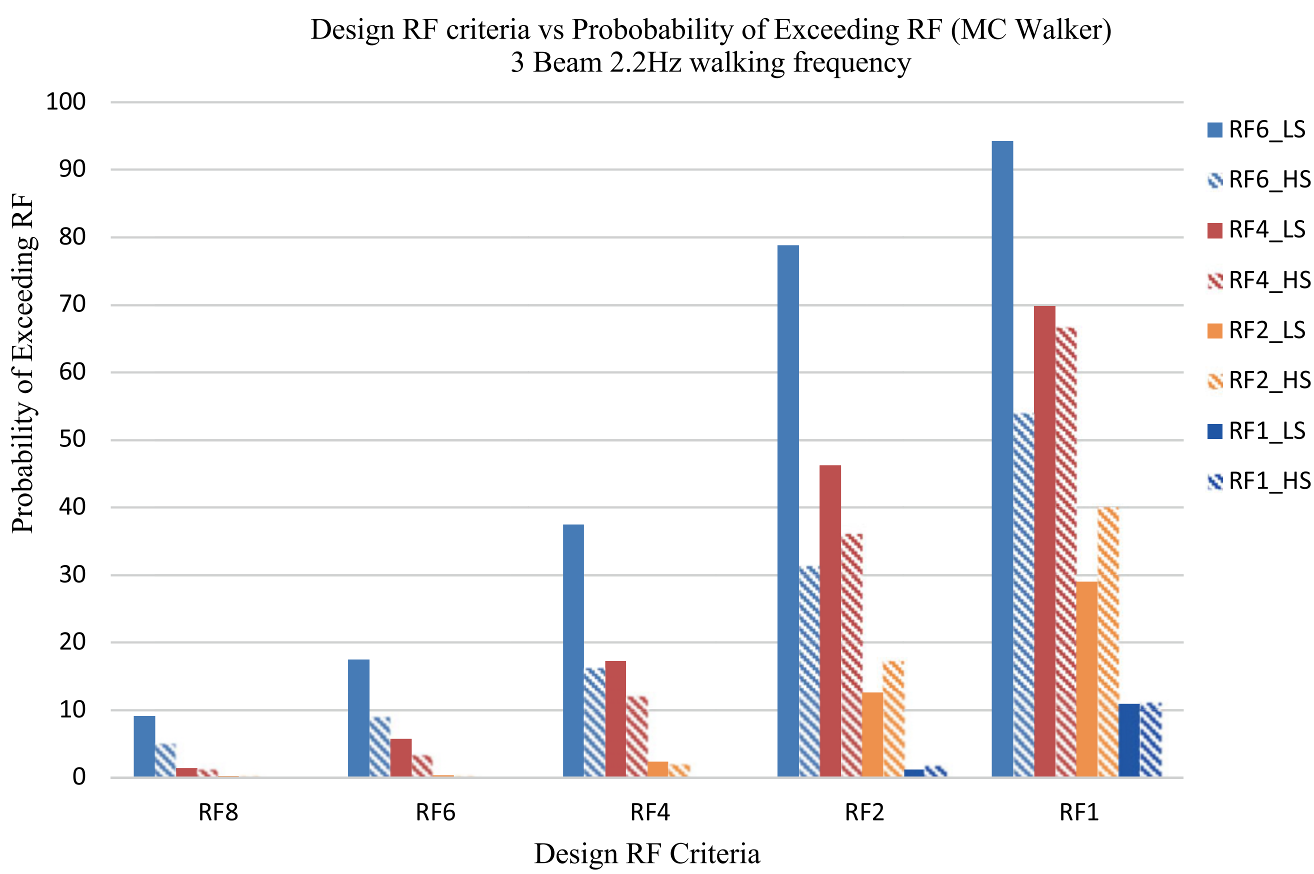

Fig. 14.9c Probability of exceeding certain design criteria with 3-beam 2.2Hz walking frequency model (*LS* light steel design and *HS* heavy steel design)

absolute design in reducing footfall vibration, and many methods can be used to meet a specific constraint set by the client. The results from this study give reason to believe a heavier concrete structure performs better at reducing footfall-induced vibration; however, it may not always be feasible due to its higher seismic mass. The results gathered from this research can be useful for engineering firms to design for footfall vibration and will become more applicable as the focus on vibration increases. As this research continues, more trends between structure properties and floor vibration will be discovered outside of steel weight and concrete weight.

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