Chapter 10
Vibration Serviceability Evaluation of an All-Steel Floor System using the High-Frequency Floor Procedure

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Abstract The increasing trend towards open and lightweight office spaces has led to a growing concern about floor vibration serviceability. This study investigates the vibration serviceability of two all-steel floor modules, denoted as SM68_RAF and SM94_RAF, using the high-frequency floor (HFF) procedure outlined in American Institute of Steel Construction's Design Guide 11 (AISC DG-11). The two specimens are 10 ft × 40 ft modules that would form a larger 30 ft × 40 ft bay for a new type of modular floor system made entirely of structural steel. The specimens have the same configuration but vary in beam and plate sizes. Finite element models are created to implement the HFF procedure, which involves determining the walking frequency, calculating peak acceleration responses, and obtaining equivalent sinusoidal peak acceleration (ESPA) values as defined in DG-11. The study highlights the impact of damping on the response, with two damping ratios of 0.75% and 2.25% considered to represent bare-floor laboratory conditions and in-service conditions, respectively. The vibration serviceability of the two specimens is evaluated by comparing the computed ESPA values to the acceleration tolerance limits provided in DG-11. The results indicate that the peak accelerations of the light specimen (SM68_RAF) tend to exceed the allowable limit for both damping ratios, while the heavy specimen (SM94_RAF) remain below the limit for in-service conditions. Even though these results cannot be considered for the overall acceptability of floor concept, the findings of this study provide valuable insights into the vibration serviceability of light-weight floor systems as well as the applicability of the HFF procedure to the non-traditional floor systems.

Keywords Structural floor systems · Floor vibration serviceability · Modular construction · High-frequency floors · Damping

Introduction

Floor vibration serviceability has emerged as a significant concern in modern office buildings, primarily due to the evolution of office layouts and equipment. The trend towards more open and lightweight spaces, characterized by fewer partitions and reduced furniture mass, has contributed to an increase in floor vibration complaints [1]. Human activity, such as walking, can induce resonant responses in floors when the step frequency coincides with a subharmonic of the floor's natural frequency [2, 3, 4]. This can lead to discomfort due to footfall-induced vibrations. This issue is particularly relevant to the all-steel floor system being discussed in this paper. The floor system, which is known as FastFloor, exhibit a combination of relatively light-weight and low inherent damping, which distinguishes them from traditional composite floors. As a result, meeting acceptable vibration performance criteria can be challenging, especially in modern building designs that often require longer beam and girder spans, as noted in [5].

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The FastFloor system discussed in this paper is a new type of modular floor system made entirely of structural steel, designed to increase construction speed by 30-50% compared to traditional composite floors [5, 6, 10]. A typical full-bay FastFloor module measures 30 ft × 40 ft on plan and consists of multiple wide-flange steel beams connected to a steel plate using bolts and staggered welding. The modular units of FastFloor are prefabricated off-site and then transported and erected on steel girders with field connections, allowing for easy installation and significant time and labor cost savings. One of the advantages of FastFloor is its reduced weight and lower carbon footprint [5]. Additionally, the system can accommodate a raised access floor (RAF) installed on top of the steel plate, which provides space for various mechanical system components.

In this study, the vibration serviceability of two FastFloor specimens is investigated using the high-frequency floor (HFF) procedure outlined in American Institute of Steel Construction's Design Guide 11 (AISC DG-11 or simply DG-11). The two specimens are compared, and their predicted vibration levels due to walking are assessed against the acceleration tolerance limits provided by DG-11.

FastFloor Specimens

Two 10 ft × 40 ft floor specimens (Figs. 1 and 2) were fabricated and transported to the West Virginia University for dynamic testing to evaluate their vibration serviceability. Each specimen represents a version of a single module designed to represent a relatively light (SM68_RAF) and a relatively heavy (SM94_RAF) structural framing [6]. The specimens consist of three W24 steel beams topped with a steel plate as shown in Table 1. The beams are spaced 5ft on center with a clear span of 40 ft between supports (Fig. 3) and the plate is connected to the top flange of the beam using Shuriken blind bolts on one side and through staggered welds at the remaining beam-to-plate connection locations (Fig. 4).

To ensure lateral stability for dynamic testing, the W24 beams had web stiffeners around the support locations (Figs. 1 and 2) to prevent sideways movement. The beams were secured to the bearings using C-clamps (Fig. 1) or bolts (Fig. 2), simulating a pinned connection at support locations. Raised access floor (RAF) units were also installed on top of the steel plates, comprising 100 (2x2 ft) raised floor panels on each module supported by 125 steel pedestals with adjustable heights attached to the steel plate. The RAF units are shown in Figs. 1, 2 and 4.

Table 1 Components of the two FastFloor specimens investigated in this paper.

Specimen	SM68_RAF (Light specimen)	SM94_RAF (Heavy specimen)
Beam Sections	W24×68	W24×94
Plate Thickness	3/8 in.	1/2 in
RAF	Standard	Standard

Fig. 1 The light specimen (SM68_RAF) with W24x68 beams, a 3/8 in. thick plate, and raised access floor (RAF).

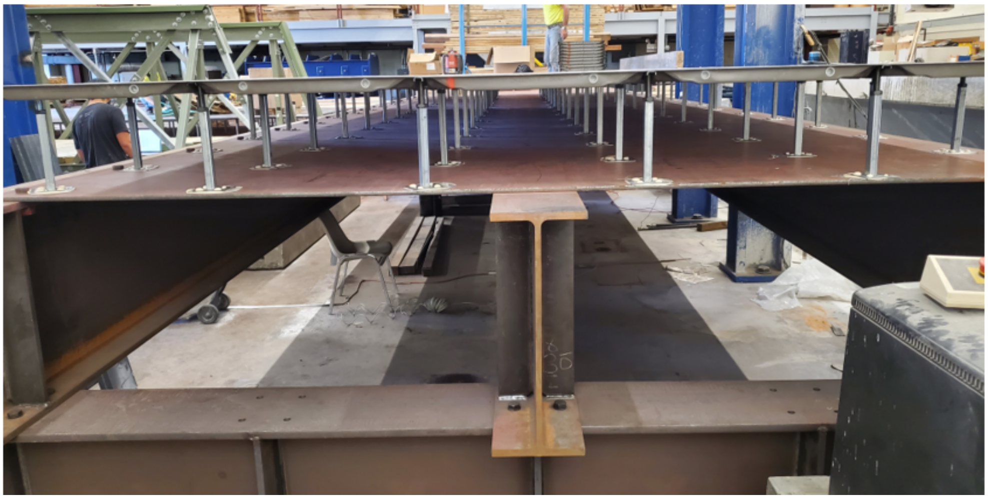

Fig. 2 The heavy specimen (SM94_RAF) with W24x94 beams, a 1/2 in. thick plate, and raised access floor (RAF).

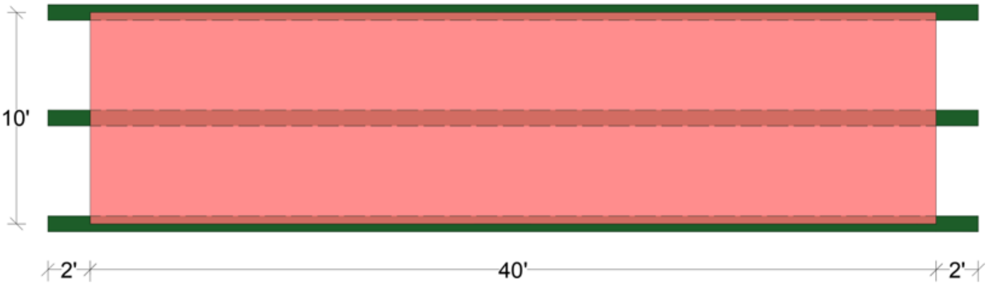

Fig. 3 Plan layout of a typical 10 ft × 40 ft single FastFloor module. The distance between the supports is 40 ft.

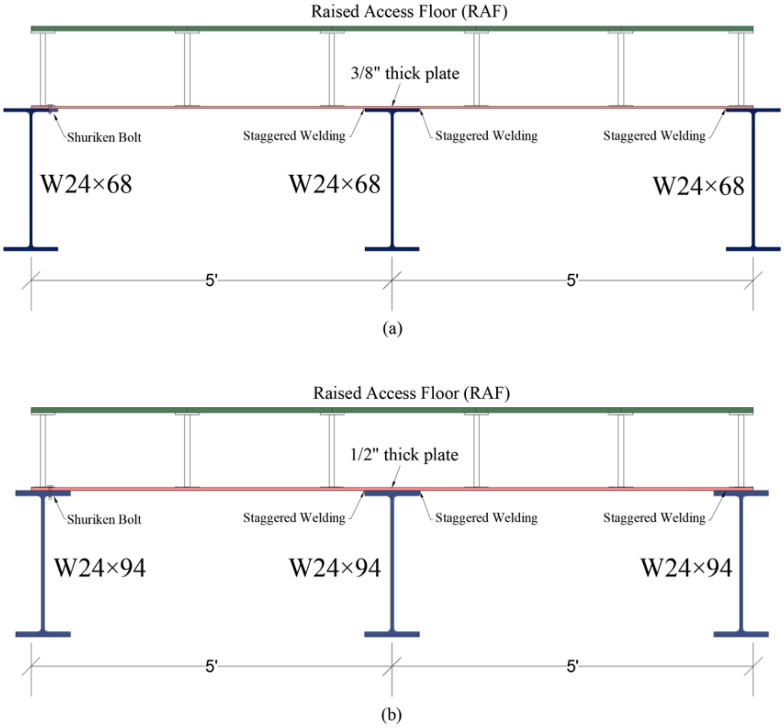

Fig. 4 Sectional view of the 10 ft × 40 ft single FastFloor modules used in vibration serviceability evaluation. (a) Section of the light specimen (SM68_RAF). (b) Section of the heavy specimen (SM94_RAF).

AISC Design Guide 11's high-frequency floor (HFF) procedure for peak acceleration prediction

DG-11 offers a methodology for predicting and evaluating floor vibrations caused by human activity, with a primary focus on walking. As walking is a common activity in most buildings, engineers need to predict vibration levels to ensure floor serviceability. To facilitate this, DG-11 classifies floors and pedestrian bridges into two categories based on their natural frequencies:

1. Low-Frequency Floors (LFFs): floors with at least one natural frequency below 9 Hz.
2. High-Frequency Floors (HFFs): floors with all natural frequencies above 9 Hz.

DG-11 provides two approaches for predicting peak acceleration responses to human activity: equation-based methods and finite-element analysis (FEA) based computational methods [1]. These tools enable engineers to assess floor vibration levels and design floors that meet specific vibration criteria. However, it is important to note that the prediction approaches provided in DG-11 were developed based on data collected from traditional composite floor systems consisting of a concrete deck on steel framing. This raises questions about the applicability of these methods to non-traditional floor systems, such as the all-steel FastFloor system discussed here in this paper.

To predict the peak acceleration caused by a single footstep, the effective impulse method is used, which is based on research by [7, 8]. However, the resulting peak acceleration value is not directly comparable to the sinusoidal peak acceleration limits, so it needs to be converted to an equivalent sinusoidal peak acceleration [1].

To implement the HFF procedure, a finite element (FE) model is created, and then the Frequency Response Function (FRF) magnitude is calculated for a unit load at the walking location (i) and acceleration at the occupant location (j) with the goal to identify the mode with the highest FRF magnitude. Engineering judgment is predominantly required to determine the optimal walking path and locations on the floor being assessed. The walking load location (i) should be placed near the mid-length of a 5-10 ft long unobstructed walking path, which is typically near the maximum mode shape value. If the affected occupant location is unknown, it should be placed near the maximum mode shape value. For regular floor bays or pedestrian bridges, the walking load and affected occupant locations can be conservatively placed at the mid-bay or midspan location [1]. The following steps are typically followed to apply the HFF procedure:

1) The natural frequencies and mode shapes at the walking and occupant locations are determined. The Frequency Response Function (FRF) is then used to identify the dominant mode, which corresponds to the highest FRF peak (not the mode with the lowest frequency).
2) The peak acceleration due to each mode (m) is calculated using Eq. (1), where $f_{n,m}$ represents the step frequency of mode m. The effective impulse ($I_{n,m}$) is computed using Eq. (2), assuming a body weight (Q) of 168 lbs. The step frequency (f_{step}) is determined by dividing the fundamental frequency by the harmonic number, as specified in Table 7-1 of DG-11

$$a_{p,m} = 2\pi f_{n,m} \phi_{i,m} \phi_{j.m} I_{eff,m} \tag{1}$$

$$I_{eff,m} = \left(\frac{{f_{step}}^{1.43}}{{f_n}^{1.30}}\right)\left(\frac{Q}{17.8}\right) \tag{2}$$

3) The individual time series responses for modes with frequencies below 20 Hz are superposed using Eq. (3), which represents the total response between two consecutive footsteps, to obtain the overall response of the floor system.

$$a(t) = \sum_{m=1}^{N} a_{p,m} e^{-2\pi f_{n,m} \beta t} \sin(2\pi f_{n.m} t) \tag{3}$$

4) The peak value of the total response after supposition is not directly compared to the established tolerance limits for sinusoidal peak acceleration in DG-11. For this reason, the equivalent sinusoidal peak acceleration (ESPA) is calculated using Eq. (4), which involves multiplying the root-mean-square (RMS) of the acceleration time history *a(t)* between two footsteps by a factor of $\sqrt{2}$, representing the peak-to-RMS ratio for a sinusoidal signal.

$$a_{ESPA} = \sqrt{2}\sqrt{\frac{1}{T}\int_0^T [a(t)]^2 dt} \approx \sqrt{2}\sqrt{\frac{1}{N}\sum_{k=1}^{N} {a_k}^2} \tag{4}$$

N represents the number of discrete data points in the acceleration time series $a(t)$ for a single footstep which spans a time period T equal to $1/f_{step}$.

Evaluation of the two FastFloor specimens for vibration serviceability

The high-frequency floor (HFF) procedure described earlier is implemented to obtain the equivalent sinusoidal peak accelerations (a_{ESPA}) due to human walking excitations. These values are then compared to the tolerance limits provided in DG-11. First, finite element models of the two floor specimens are created in SAP2000 and updated to ensure that the experimental and analytical frequencies are in close agreement for multiple modes. Fig. 5 shows the 3D finite element model of the light specimen (SM68_RAF) in SAP2000 [9], highlighting the locations of the walking and occupant points that result in the highest mode shape at point (j).

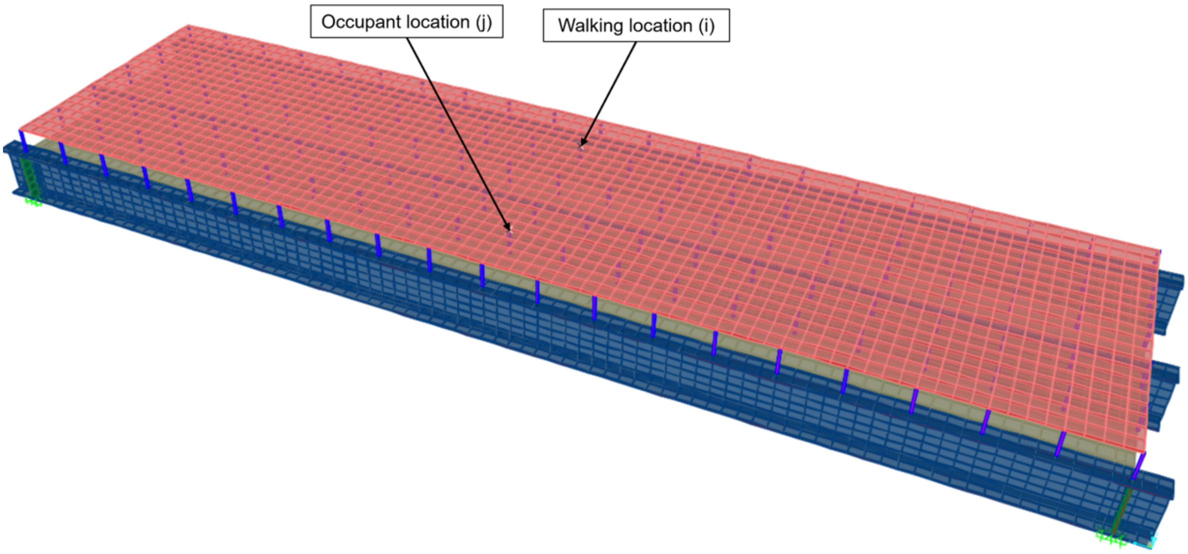

Fig. 5 3D view of the SAP2000 model of the floor specimen, showing the walking and occupant locations.

Notably, two damping ratios are employed in the calculations: $\beta = 0.75\%$ intended to represent the bare test conditions in the laboratory, while $\beta = 2.25\%$ intended to represent the in-service conditions. The dominant frequencies (frequencies of the highest FRF peak) are identified, and the corresponding step frequencies are determined, as presented in Table 2. Following the natural frequency calculations and mode shape determination at the walking and occupant locations, the peak responses and individual time series responses are computed for all modes up to 20 Hz. The time history plots for the dynamic responses are illustrated in Fig. 6 and Fig. 7 for the light specimen (SM68_RAF) and heavy specimen (SM94_RAF), respectively. These figures highlight the significant contribution of the dominant mode to the total response. For both damping ratios, the predicted peak accelerations are higher for SM68_RAF than for SM94_RAF.

Table 2 Dominant and step frequencies used in the HFF procedure.

Specimen	Light specimen(SM68_RAF)	Heavy specimen (SM94_RAF)
Dominant frequency (f_n)	19.25 Hz	16.93 Hz
Harmonic number (h)	9	8
Step frequency (f_{step})	2.14 Hz	2.12 Hz

To be able to compare walking acceleration results of Figs. 6 and 7 with the acceleration tolerance limits of DG-11, the peak accelerations are obtained using the dominant frequencies of the specimens, as shown in Fig. 8. The computed peak acceleration (a_{ESPA}) values are then compared to the obtained tolerance limits. A specimen is considered acceptable for vibration serviceability if its a_{ESPA} value is less than the tolerance limit. Table 3 presents a comparison of these values. The results indicate that the peak accelerations of the light specimen (SM68_RAF) tend to exceed the allowable limit for both damping ratios, rendering it unacceptable for vibration serviceability with the HFF procedure defined in DG-11. In contrast, the heavy specimen (SM94_RAF) has a peak acceleration that slightly exceeds the tolerance limit for $\beta = 0.75\%$ (bare test conditions), but is acceptable for $\beta = 2.25\%$ (in-service conditions), per the same procedure.

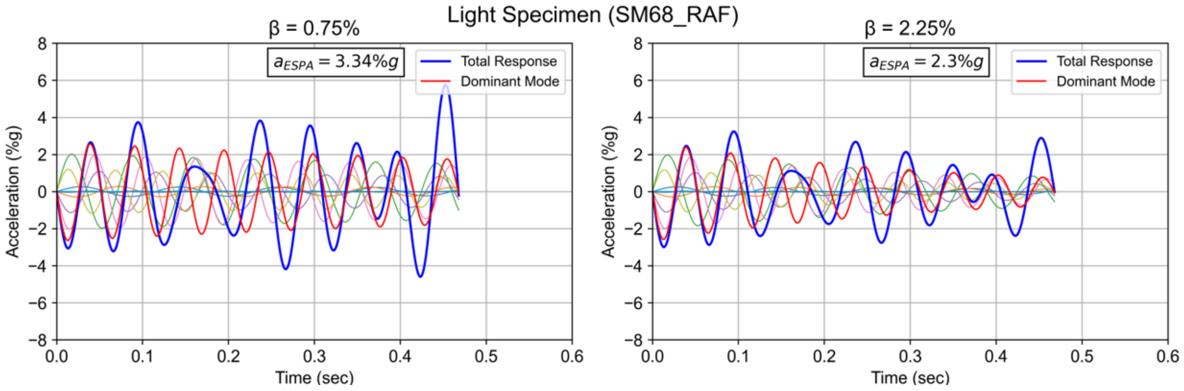

Fig. 6 Acceleration responses and a_{ESPA} values for the light specimen (SM68_RAF) due to walking excitations with laboratory-condition (left) and in-service (right) damping ratios. Dynamic responses of non-dominant modes are not indicated on the legend.

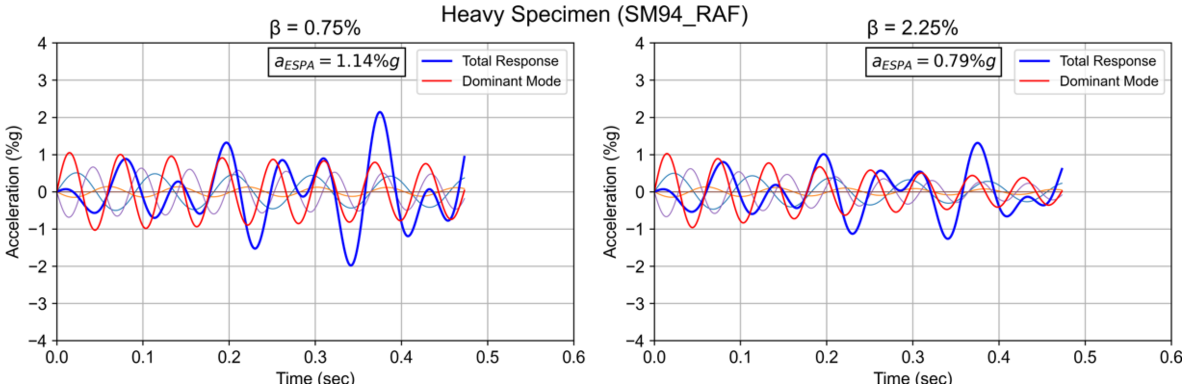

Fig. 7 Acceleration responses and a_{ESPA} values for the heavy specimen (SM94_RAF) due to walking with laboratory-condition (left) and in-service (right) damping ratios. Dynamic responses of non-dominant modes are not indicated on the legend.

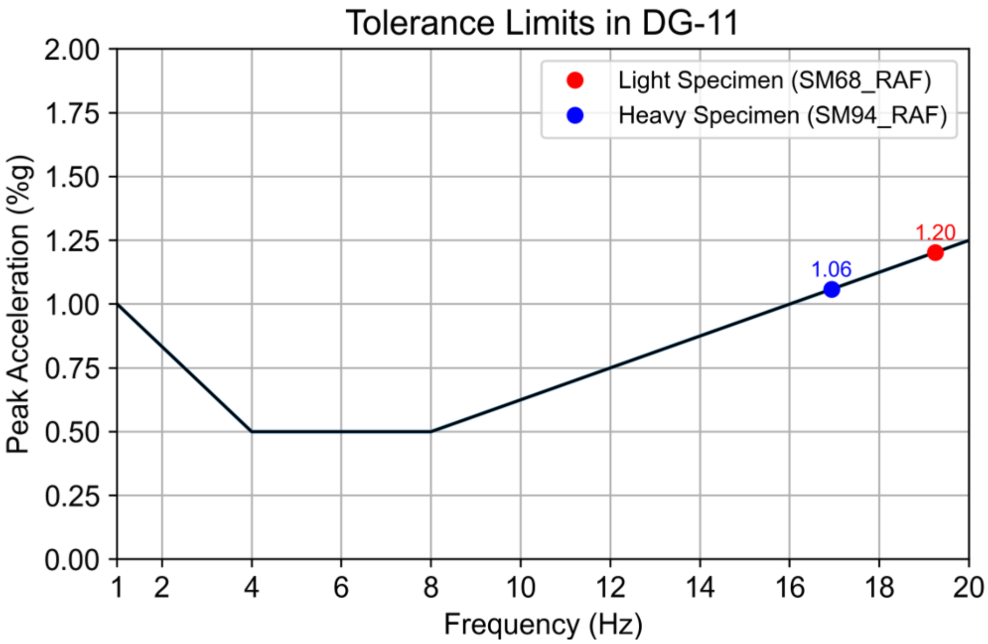

Fig. 8 Acceleration tolerance limits according to DG-11 for offices and residences, calculated for the two specimens.

Table 3 Comparison of predicted peak accelerations with DG-11 tolerance limits for acceptability evaluation.

Specimen	Light specimen(SM68_RAF)		Heavy specimen(SM94_RAF)	
Tolerance Limit	1.20%g		1.06%g	
Damping	β = 0.75%	β = 2.25%	β = 0.75%	β = 2.25%
a_{ESPA}	3.34%g	3.34%g	1.14%g	0.79%g
Acceptability	Not acceptable	Not acceptable	Not acceptable	Acceptable

Conclusions

This study presented the vibration serviceability investigation of two all-steel floor modules, utilizing the high-frequency floor (HFF) procedure described in AISC Design Guide 11 (DG-11). Finite element models are created to implement the HFF procedure, which involves determining the walking frequency, calculation of peak acceleration responses, and then equivalent sinusoidal peak accelerations (ESPA). Two damping ratios were considered for bare floor laboratory conditions (0.75%) and in-service floor conditions (2.25%). The vibration serviceability of the two specimens per HFF procedure is investigated by comparing the computed ESPA values to the acceleration tolerance limits provided in DG-11. As a result, the peak accelerations determined for the light specimen (SM68_RAF) tend to exceed the allowable limit for both damping ratios, while the peak accelerations determined for heavy specimen (SM94_RAF) remain below the limit for in-service conditions.

It is important to note that the analysis presented in this paper has limitations. The results cannot be considered for the overall acceptability of the floor concept, due to several reasons. First, the evaluated specimens are one module only (10 ft × 40 ft) instead of a larger floor bay (30 ft × 40 ft) which requires three of the modules carried on girders. Second, the analysis of the 10 ft × 40 ft modules as described in this paper neglects the influence of the girders on the frequencies and overall dynamic response. However, the findings of this study provide valuable insights into the vibration serviceability evaluation of light-weight floor systems as well as the applicability of the HFF procedure to the non-traditional floor systems.

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