

Article

Finite Element Model for Vibration Serviceability Evaluation of a Suspended Floor with and without Tuned Mass Dampers

Zhihao Wang ^{1,*}, Luyao Song ¹, Zhipeng Cheng ^{1,2,*} , Hui Yang ³, Jinlong Wen ¹ and Meng Qi ¹

¹ School of Civil Engineering and Communication, North China University of Water Resources and Electric Power, Zhengzhou 450045, China

² Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China

³ China Construction Third Engineering Bureau Group Co., Ltd., Wuhan 430064, China

* Correspondence: wangzhihao@ncwu.edu.cn (Z.W.); chengzhipeng1107@163.com (Z.C.)

Abstract: This study aims to provide an accurate finite element (FE) modeling method for structural vibration serviceability evaluation of the suspended floor under human-induced excitation. The fundamental dynamic characteristics and human-induced vibration responses of a typical suspended floor were first measured via a series of field tests. Subsequently, the overall and local equivalent FE models of the suspended floor were respectively established, and their applicability was then verified by comparing the predicted dynamic characteristics and responses of the suspended floor with the corresponding field test results. Finally, passive tuned mass dampers (TMDs) were designed for vibration control of the suspended floor using the local equivalent FE model, and the applicability of the local FE model in assessing the vibration serviceability of the suspended floor with TMDs was further confirmed via pedestrian-induced vibration tests. Results demonstrate that the simplified local equivalent FE model proposed in this study can well replace the complicated overall FE model to evaluate the vibration serviceability of the suspended floor with and without TMDs.

Keywords: suspended floor; vibration serviceability evaluation; finite element (FE) model; field test; tuned mass damper (TMD)



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1. Introduction

Currently, lightweight building materials and diversified building functions present a promising prospect in the development of modern architecture [1–3]. To meet people's demand for the flexibility and usability of the architectural space, an increasing number of large-span and lightweight structures have been constructed. However, these flexible structures with low natural frequencies are often prone to pedestrian-induced excessive vibration, thus facing the issue of structural vibration serviceability [4–7]. Consequently, it is necessary to accurately evaluate the vibration serviceability of flexible structures during their design phase.

The accuracy of numerical methodologies for evaluating the vibration serviceability of large-span structures is dependent on efficient finite element (FE) modeling methods, computational precision of the modal parameters, and evaluation criteria of the structural vibration serviceability [8–10]. The influences of non-structural components with weak constraint effect of glass curtain walls on the vibration characteristics of the cantilevered floor have been investigated by Zhu et al. [11,12], demonstrating that the finite element (FE) modeling method neglecting the weak constraint effect of glass curtain walls may lead to conservative design results for structural vibration serviceability evaluation. It was also confirmed that appropriate modal parameters are the prerequisite for numerical analysis on structural dynamic response, which significantly dominates the accuracy of structural vibration serviceability evaluation [13–17]. Additionally, available guidelines including ISO 10137:2007 [18,19], AISC Design Guide #11 [20], and JGJ/T441-2019 [21] stipulated

limits for the fundamental frequency of the structure and the perceptibility of humans. Nevertheless, the criteria of each guideline for assessing structural vibration serviceability are not unified. For example, evaluation index for structural vibration serviceability in AISC Design Guide #11 and JGJ/T441-2019 is peak acceleration, while that in ISO 10137:2007 is the root mean square (RMS) acceleration.

For structures that cannot satisfy the specified limits of vibration serviceability evaluation criteria, tuned mass dampers (TMDs) have been widely used to suppress their excessive vibration [22–24]. To improve the control performance of TMDs, lots of novel TMDs, such as semi-active TMD (SA-TMD) [25], semi-active independent variable mass TMD (SAVM-TMD) [26], adaptive variable mass passive TMD (APVM-TMD) [27], and rotational inertial double-TMD (RID-TMD), have been well developed [28]. Moreover, the effectiveness of TMDs in mitigating human-induced vibrations of the floor was well verified numerically and experimentally [29,30].

It is necessary to establish a reliable finite element (FE) model for vibration serviceability evaluation [31,32] and optimum TMD design [33,34] of the suspended floor. Compared with the traditional column-supported or wall-supported floor system, a suspended floor system is lifted by hanging pillars or cables, which makes its vertical stiffness weaker than the traditional floor, and it is more sensitive to human-induced dynamic loads [35,36]. Lv et al. [37] conducted field tests on a suspended floor to investigate dynamic characteristics and human-induced vibration serviceability, which has provided a fundamental test basis to fill the lack of vibration serviceability research on the suspended floor. However, there are some non-negligible factors in achieving precise finite element modeling and numerical analysis for the dynamic characteristics and responses of the suspended floor, especially the structural inter-story coupling effect. Costa-Neves et al. [38] found that there was coupled phenomenon between different floors in the overall FE model for multi-story structures. Wang et al. [39] compared the vertical dynamic characteristics of a large-span suspended steel space frame-glass composite floor (SSSF-GCF) between the overall FE model and local equivalent FE model, indicating that the inaccurately simplified global FE model significantly would underestimate vertical human-induced acceleration response of the floor. Consequently, it is urgent to develop a precise FE modeling method for evaluating the vibration serviceability of the suspended floor.

This study presents experimental measurements and numerical analyses on the vibration serviceability of a 36 m long suspended floor in Nanjing Global Trading Plaza, China. First, the dynamic characteristics of the suspended floor were experimentally identified. Subsequently, the overall and corresponding local equivalent FE models of the suspended floor were developed. Finally, the applicability of the local FE model for vibration serviceability evaluation of the suspended floor with passive tuned mass dampers (TMDs) was demonstrated.

2. Field Test

In this section, the fundamental dynamic characteristics and human-induced vibration responses of a typical suspended floor were measured through ambient excitation and human-induced vibration tests, respectively. The natural frequency and damping ratio of the suspended floor in the first mode were identified.

2.1. Basic Overview of the Structure

As shown in Figure 1, the 50 m height suspended corridor of Nanjing Global Trading Plaza spans 36 m between two ultra-high-rise towers, including zones A, B, and C. The suspended part consists of a steel frame-support structure, where the load is transferred by hanging pillars into the core tubes or giant frames. The steel structural components (such as steel beams, frame columns, and hanging pillars) are made of Q345 steel, whose elastic modulus, Poisson's ratio, and density are 2×10^{11} N/mm², 0.3, and 7850 kg/m³, respectively. The ribbed floor is made of C30 concrete, whose elastic modulus, Poisson's

ratio, and density are 3×10^{10} N/mm, 0.2, and 2400 kg/m^3 , respectively. The component parameters of the second-story suspended floor in zone B are listed in Table 1.

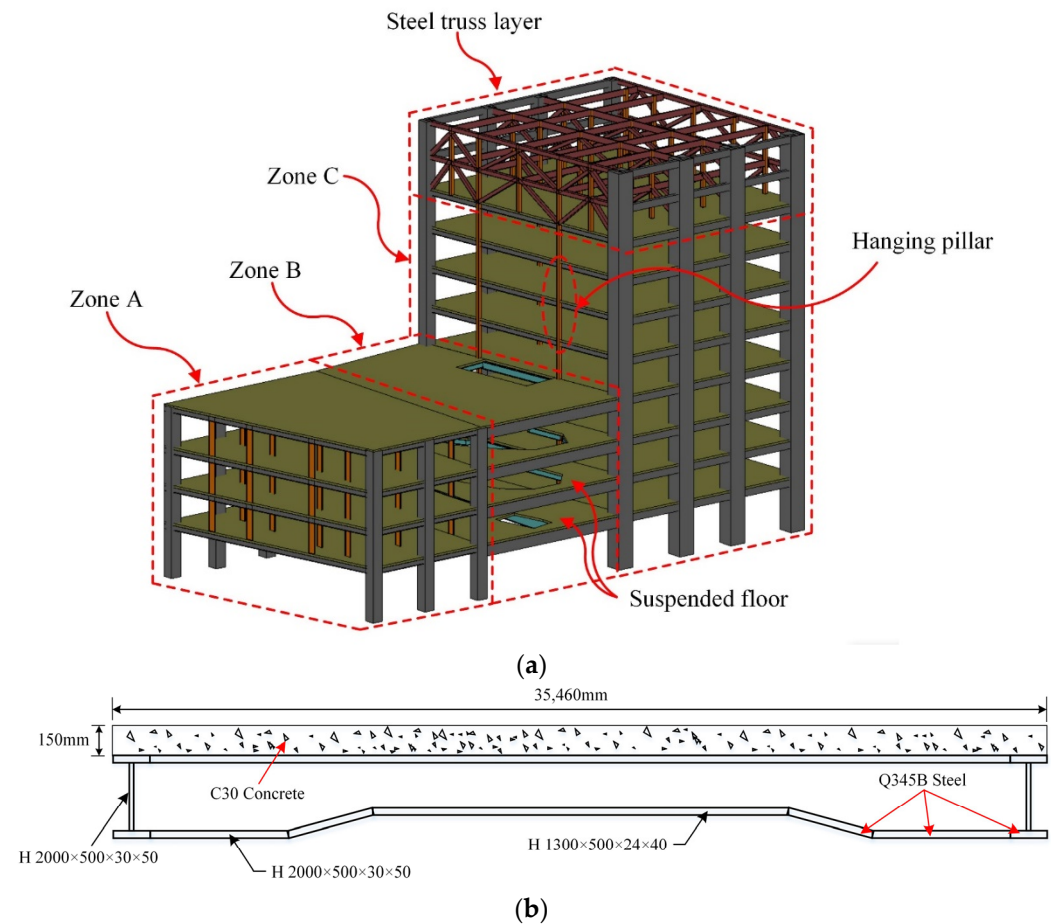


Figure 1. The suspended structure: (a) structural configuration; (b) details of the second-story suspended floor in zone B.

Table 1. Component parameters of the second-story suspended floor in zone B.

Structural Components	Sectional Specification	Section Type	Remarks
GKL-1	H1000 × 500 × 30 × 40	Welding H-shape	Frame beam
GKL-2	H1300 × 500 × 24 × 40	Welding H-shape	Frame beam
GKL-3	H1450 × 500 × 30 × 50	Welding H-shape	Frame beam
GCL-2	H1500 × 400 × 20 × 30	Welding H-shape	Secondary beam
GCL-3	H700 × 300 × 13 × 24	Welding H-shape	Secondary beam
GCL-4	H600 × 350 × 8 × 14	Welding H-shape	Secondary beam
DZ-1	H1000 × 500 × 20 × 34	Welding H-shape	Hanging pillars
DZ-2	B500 × 500 × 35 × 35	Welding Box-shape	Hanging pillars

2.2. Dynamic Characteristic Test

The schematic diagram of the test setup for measuring the fundamental dynamic characteristics of the suspended floor is illustrated at four measuring points in Figure 2. As illustrated in Figure 3a, a 16-channel portable COINV-DASP-V10 data acquisition instrument is employed to record the vibration data with a 204.8 Hz sampling frequency, which contains performance indexes including a resolution of 24-bit, a dynamic range of 0 dB~120 dB, and the highest sampling frequency of 51.2 kHz. As shown in Figure 3b, an ultra-low frequency version type of the DH610V magnetolectric vertical acceleration sensor was used to measure the vertical acceleration response of the suspended floor, which

contains performance indexes including nominal sensitivity of $0.3 \text{ V/m}\cdot\text{s}^{-2}$, a maximum measurement range of $20 \text{ m}\cdot\text{s}^{-2}$, a frequency range of $0.25 \text{ Hz}\sim 100 \text{ Hz}$, and a test resolution of $3 \times 10^{-3} \text{ mm/s}^2$ [40].

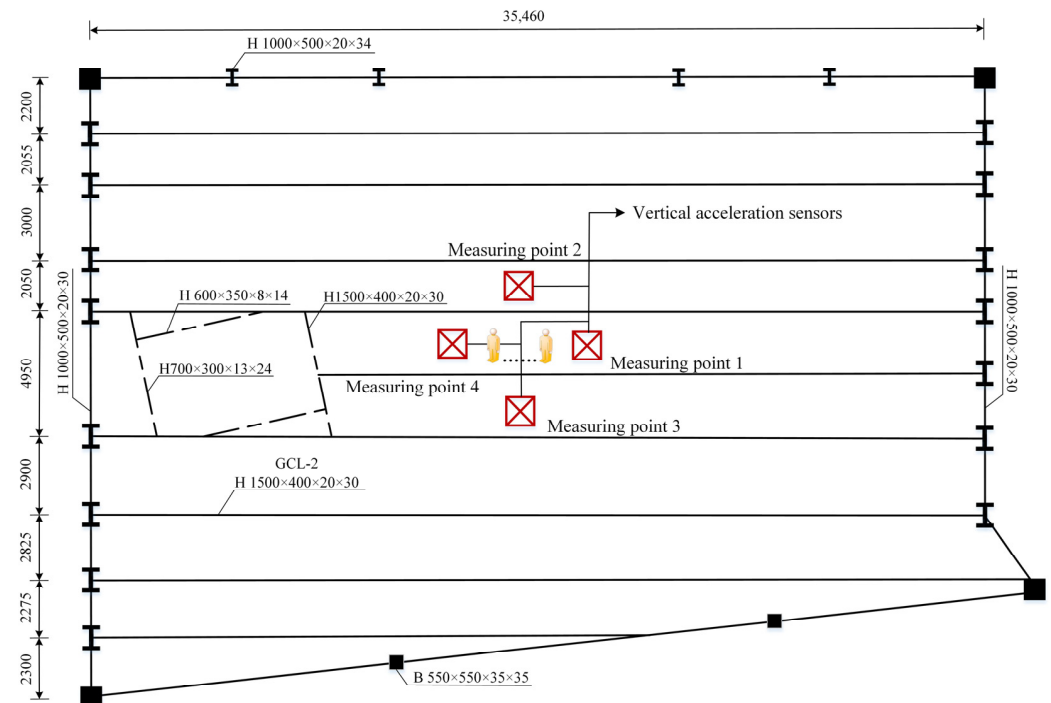


Figure 2. The schematic diagram of the test setup for the dynamic characteristic test.

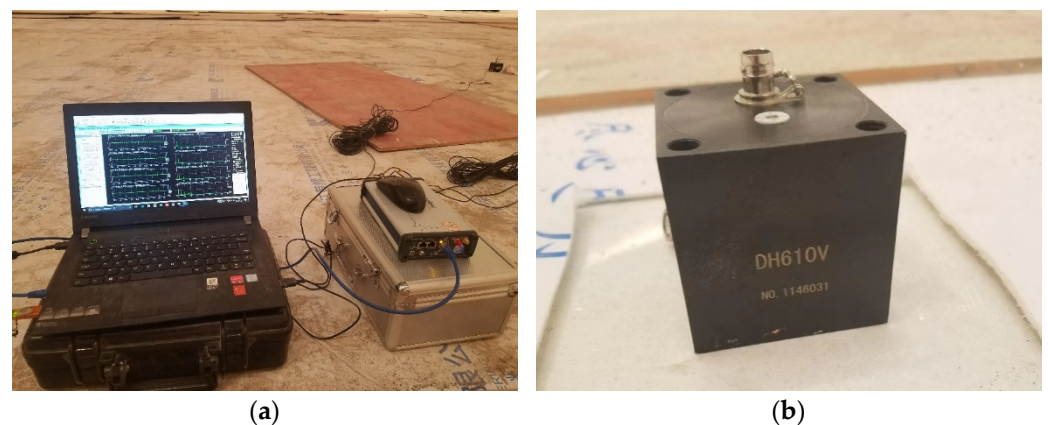


Figure 3. The schematic diagram of the test setup: (a) data acquisition instrument; (b) magnetolectric vertical acceleration sensor.

2.2.1. Eigenfrequency Analysis

Figure 4 shows the acceleration response and corresponding fast Fourier transformation (FFT) spectra of the suspended floor at measurement point 1 under ambient excitation. It is noteworthy that taking a lowpass filter to remove the mixed noise of the frequency above 10 Hz [41–43]. In Figure 4b, the peak frequency is about 3.54 Hz, which is the first modal fundamental frequency of the suspended floor.

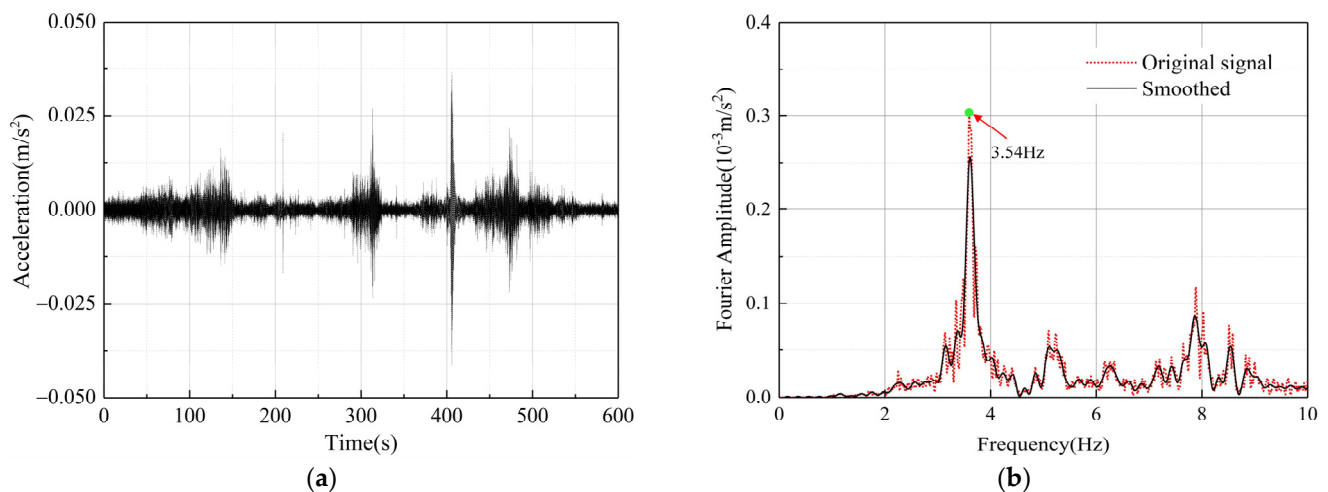


Figure 4. Acceleration response and corresponding FFT spectra of the suspended floor at the measurement point 1 under ambient excitation: (a) acceleration time history; (b) FFT spectra.

2.2.2. Damping Ratio

Free vibration tests were conducted by applying heel impact on the structure [44–46]. A typical free-decay acceleration response of the suspended floor at test point 1 is presented in Figure 5. The modal damping ratio of the suspended floor was identified using the exponential function to fit the envelope curve of the free-decay acceleration response. Accordingly, the first-order vertical modal damping ratio of the suspended floor was determined as 2.10%.

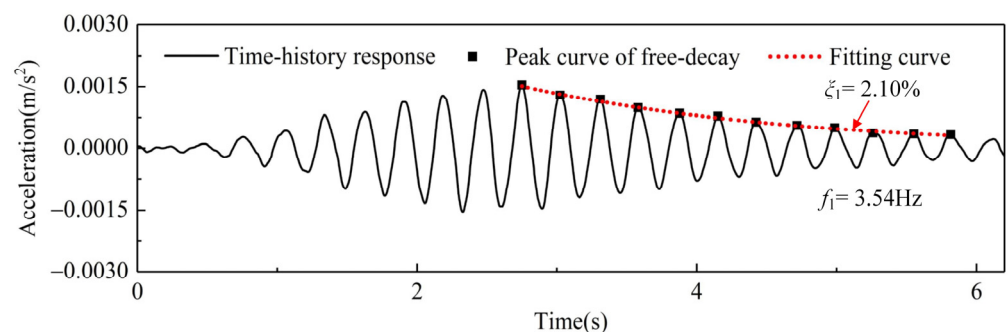


Figure 5. Free-decay acceleration response of the suspended floor at test point 1.

2.3. Human-Induced Vibration Test

2.3.1. Test Scenarios

According to the American Road Traffic Capacity Manual HCM2000 [47], the densely populated state of 1 pedestrian/m² corresponds to 4 people walking synchronously, which is equivalent to 20 people moving freely [48]. For the case of queue congestion, the crowd density is determined as 2 pedestrians/m², and the maximum number of pedestrians is 40, equivalent to 200 people moving freely. As illustrated in Figure 6b, the pedestrian-induced load is applied in the scope of 10 m × 10 m as a vibration-sensitive location.

2.3.2. Test Results

Since root mean square (RMS) acceleration is commonly applied to quantify the amplitude of the structural acceleration response, it is introduced to characterize the dynamic response of the suspended floor [18,19], which can be calculated by:

$$a_{RMS} = \sqrt{\frac{1}{T} \int_0^T a_w^2(t) dt} \quad (1)$$

where $a_w(t)$ denotes the frequency weighted acceleration; T denotes the duration of the vibration caused by excitation.

Figure 7 presents the dynamic responses of the suspended floor when the pedestrians walk in place (WP) and run in place (RP). Cases WP-1~WP-4 represent one to four pedestrians on the floor. For the cases of pedestrians walking in place, the RMS accelerations of cases WP-2, WP-3, and WP-4 are 1.21, 1.52, and 1.77 times that of case WP-1, respectively. For the cases of pedestrians running in place, the RMS accelerations of cases RP-2, RP-3, and RP-4 are 1.56, 2.14, and 2.37 times that of case RP-1, respectively. It can be found that the per-person RMS acceleration decreases as the number of pedestrians increases, which is attributed to the fact that it is difficult to synchronize the step frequency for multi-person scenarios.



Figure 6. Field tests of human-induced vibration: (a) single pedestrian walking in place; (b) 40 pedestrians walking in place.

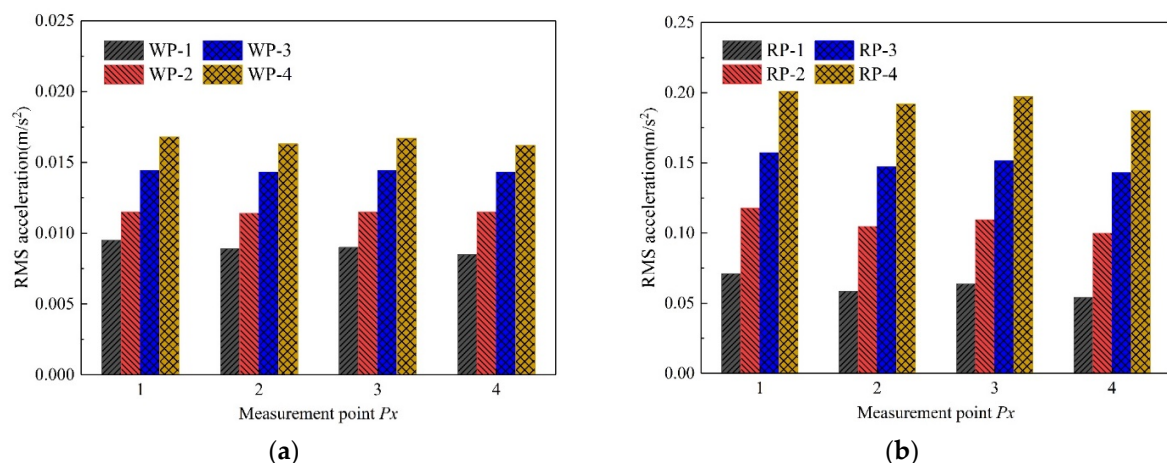


Figure 7. Comparisons of RMS accelerations at different measuring points under human-induced dynamic loads: (a) walking in place (1.77 Hz); (b) running in place (3.54 Hz).

3. Finite Element Modeling of the Suspended Floor

In this section, the overall and local equivalent FE models of the suspended floor were first established, respectively. Subsequently, the dynamic characteristics and responses of the suspended floor predicted with the two models were compared with the corresponding field test results, which verified the applicability of the two models in assessing the vibration serviceability of the suspended floor.

3.1. Overall FE Model

3.1.1. Model Parameters

Using the usual mesh refinement techniques implemented in ANSYS software, the overall FE model of the suspended floor was established in this study. The steel structural components such as beams and columns were modeled by the three-dimensional beam elements (BEAM188) with tension, compression, torsion, and bending capabilities, while the reinforced concrete slab was modeled by the shell finite element (SHELL63) with both bending and membrane capabilities. Moreover, considering the effect of non-structural components on structural vibration characteristics, glass, external walls, and partition walls were regarded as the additional stiffness applied to the floor [16]. Due to the similarity of material physical parameters between the concrete slab and decorative surface, the effect of the decorative layer on the natural frequency was represented by the principle of equivalent stiffness [8], and thus the thickness of the floor was determined as 200 mm. Additionally, taking into account the rationality of the structural dynamic calculation, the additional live load on the structure was regarded as the vibration participating mass. According to the equivalent mass principle, the density of C30 concrete for modal analysis was adjusted to 2931 kg/m^3 , and its elastic modulus was magnified 1.35 times.

3.1.2. Boundary Condition

Suspended structures have no vertical grounding components at the location of hanging pillars, resulting in insufficient supporting stiffness and a significant inter-story coupling effect. Hence, to ensure the accuracy of the numerical analysis for structural dynamic responses, the precise definition of structural boundary conditions is crucial.

Figure 8 shows the overall FE model of the suspended floor. Considering the complete interaction between the concrete slab and rib-beams, the suspended floor's FE model coupled all nodes between the slab and beams to prevent the occurrence of any slip. Near the right side of the high-rise tower, the deformation joint was represented by releasing slight displacement along the X-direction. Additionally, the structural characteristic of the beam-to-hanging pillar connections in the suspended floor was simulated by the hinges.

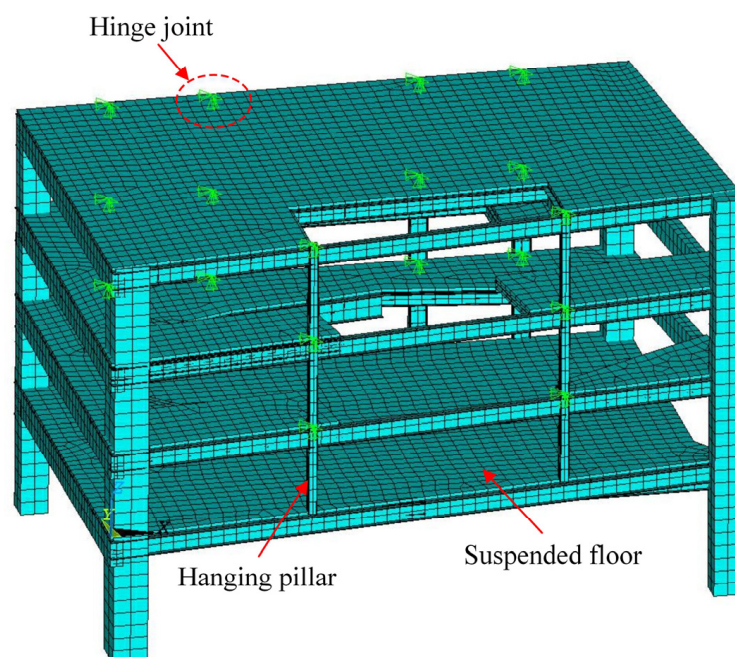


Figure 8. The overall FE model of the suspended floor in zone B.

3.2. Local Equivalent FE Model

Compared with the overall FE model, the local equivalent FE model has the advantages of model simplicity, computation efficiency, and practicality [39]. It is found that the impact of inter-story coupling effects on evaluating the structural vibration serviceability can be attributed to the superposition of vertical acceleration between different stories. Accordingly, a local equivalent FE model is further proposed for the suspended floor, which is illustrated in Figure 9. The modeling process is divided into the following three steps. First, the hanging pillar was simplified as the equivalent mass distributed along its vertical position. Second, the COMBIN14 spring element with three degrees of freedom per node was used to simulate the elastic support with adjustable vertical stiffness at the lifting point, which helps to improve the synergy between beams and columns. Third, the axial stiffness of the hanging pillars was used to estimate the vertical elastic support stiffness.

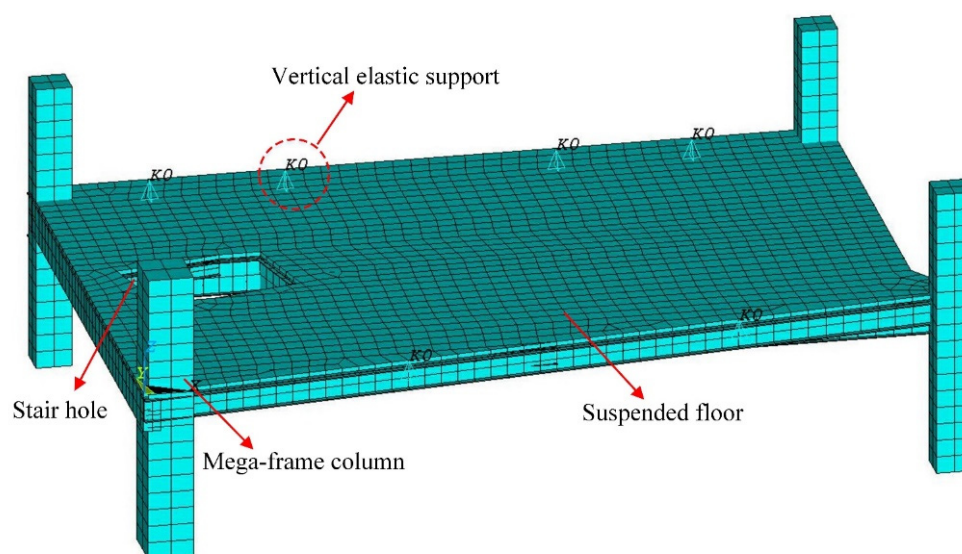


Figure 9. The local equivalent FE model of the suspended floor.

3.3. Dynamic Characteristics Comparisons

3.3.1. Fundamental Frequency

Table 2 compares the fundamental frequencies of the second-story suspended floor obtained by numerical analysis and field test. As listed in Table 2, the error of the suspended floor's fundamental frequency between the overall FE model and the corresponding field test result is only 0.56%, while the error of the suspended floor's fundamental frequency between the local equivalent FE model and the corresponding field test result is only 0.28%.

Table 2. Comparison of the fundamental frequencies of the second-story suspended floor obtained by numerical analysis and field test.

FE Model Type	Numerical Analysis (Hz)	Field Test (Hz)	Error (%)
Overall FE model	3.56	3.54	0.56
Local equivalent FE model	3.53		0.28

3.3.2. Mode Shape

Figure 10 demonstrates the first-order mode shape of the suspended floor predicted with the two FE models. The inter-story coupling effect in the overall FE model mainly behaves in the vibration of the top floor slab, which increases the modal participation mass. Notice that the first-order modal masses of the overall FE model and the local equivalent FE model are calculated to be 125,207.67 kg and 121,009.81 kg, respectively.

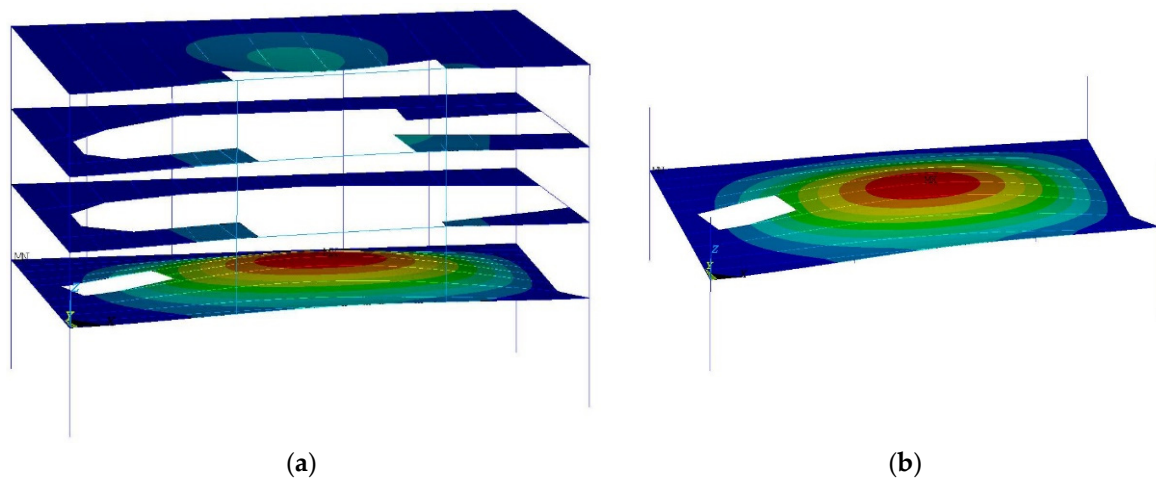


Figure 10. Mode shapes of the suspended floor predicted with the two FE models: (a) overall FE model; (b) local equivalent FE model.

As an important index to indicate the relevance of the different vibration mode shapes, the modal assurance criterion (MAC) is normally used to evaluate the modal similarity of two dynamic systems [49]. The formula for calculating MAC value can be expressed as:

$$\text{MAC}(\Phi_i, \Phi_j) = \frac{|\Phi_i^T, \Phi_j|^2}{(\Phi_i^T, \Phi_i)(\Phi_j^T, \Phi_j)} \quad (2)$$

where Φ_i and Φ_j are the structural mode shape of the overall FE model and the local equivalent FE model, respectively.

The MAC values between the overall and the local equivalent FE model come to 99.77%, indicating that the mode shapes of the suspended floor predicted with two FE models are approximately consistent.

3.4. Comparisons of Numerical and Measured Dynamic Responses of the Suspended Floor

To verify the applicability of the two models in assessing the vibration serviceability of the suspended floor, the pedestrian-induced loads were applied in the FE model of the suspended floor to obtain its numerical dynamic responses, and the numerical results were further compared with the corresponding field test results.

Figures 11–13 compare the numerical and measured vertical acceleration time-history responses and vertical RMS acceleration of the suspended floor subjected to pedestrian-induced loads under cases WP-1, WP-2, and WP-4. With the increasing number of pedestrians, numerical acceleration responses are significantly higher than the corresponding field test results. It can be concluded that there are minor differences in pedestrian walking frequency, which enhances the randomness of the crowd and reduces the actual vibration responses of the suspended floor. Additionally, it has been found that the predicting value considering the crowd-structure interaction (CSI) effect is much closer to the measured acceleration than that without considering the CSI effect [50]. It is noteworthy that the RMS acceleration responses predicted with the overall FE model are in good agreement with those of the local equivalent FE model, and thus the simplified local equivalent FE model can replace the complicated overall FE model to predict the practical dynamic responses of the floor subjected to pedestrian excitations.

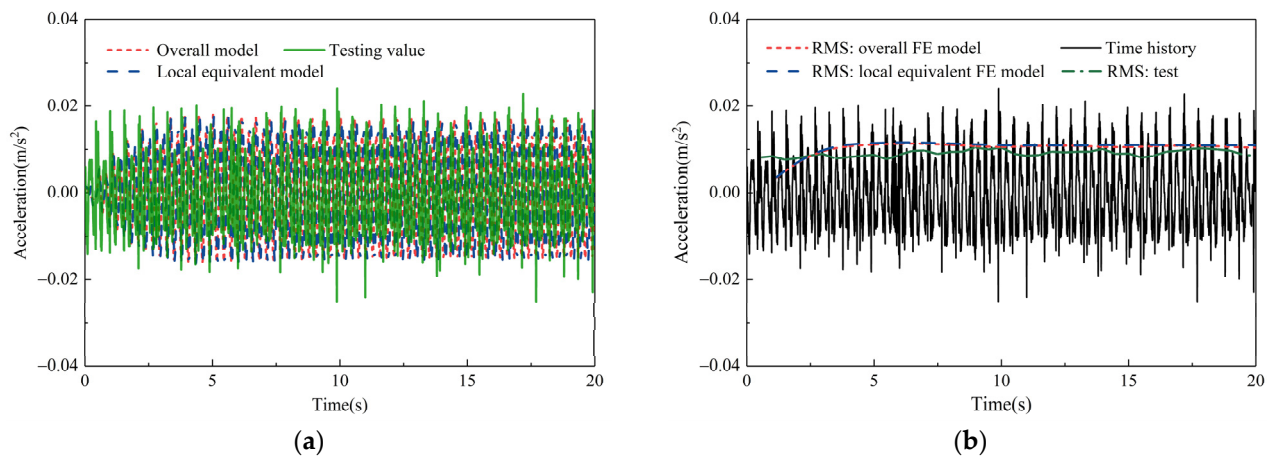


Figure 11. Comparison of numerical and measured acceleration time-history responses and 20 s RMS acceleration of the suspended floor under case WP-1: (a) acceleration time-history responses; (b) RMS acceleration.

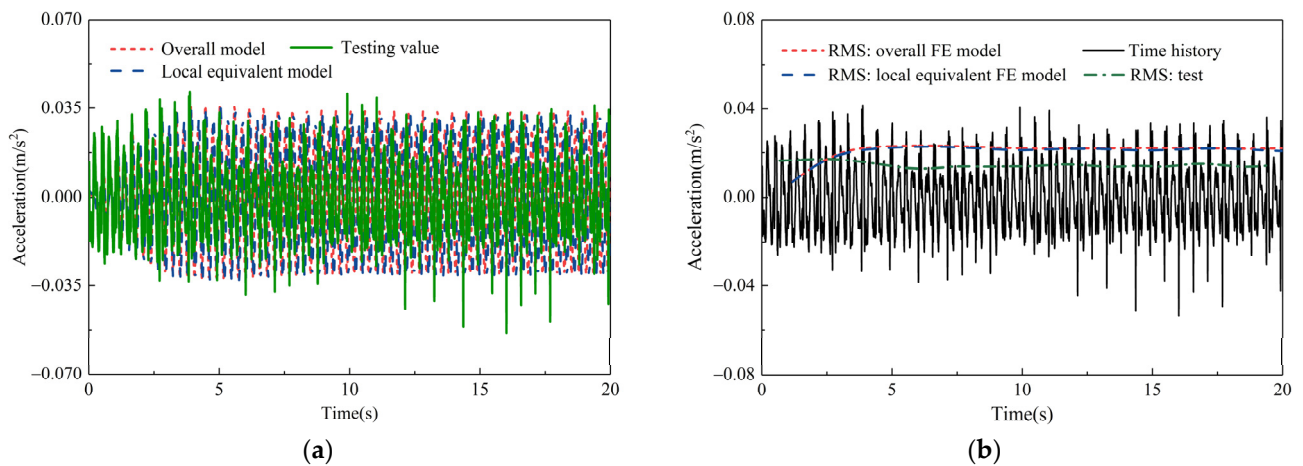


Figure 12. Comparison of numerical and measured acceleration time-history responses and 20 s RMS acceleration of the suspended floor under case WP-2: (a) acceleration time-history responses; (b) RMS acceleration.

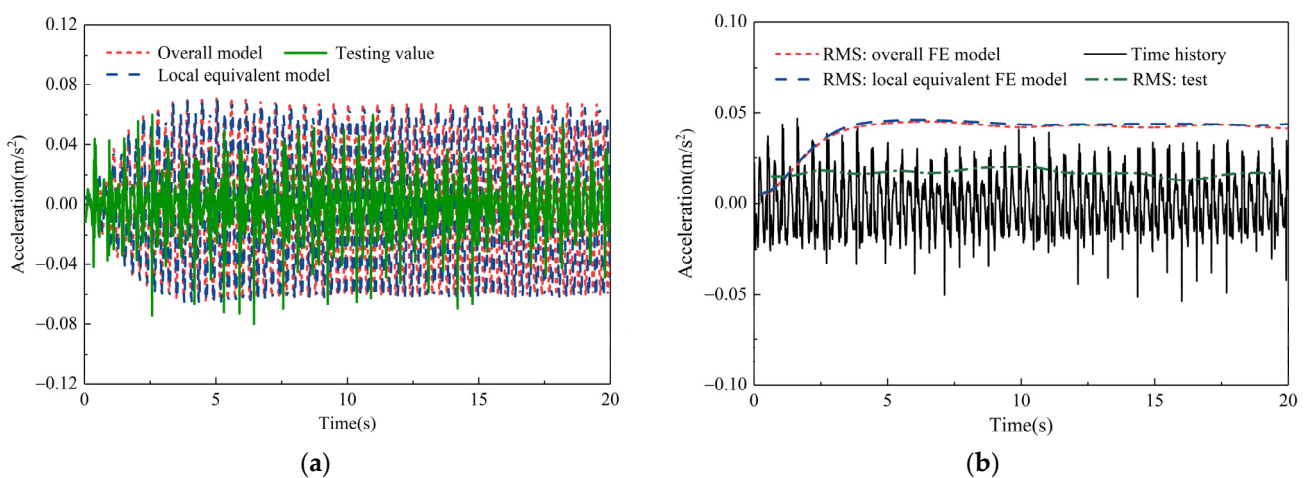


Figure 13. Comparison of numerical and measured acceleration time-history responses and 20 s RMS acceleration of the suspended floor under case WP-4: (a) acceleration time-history responses; (b) RMS acceleration.

4. Vibration Serviceability Evaluation of the Suspended Floor with TMDs

In this section, vibration serviceability evaluation of the suspended floor with TMDs was conducted. Using the local equivalent FE model, passive tuned mass dampers (TMDs) were designed for vibration control of the suspended floor. In order to confirm the applicability of the local FE model in assessing the vibration serviceability of the suspended floor with TMDs, the numerical and measured human-induced dynamic responses of the suspended floor with TMDs were further compared.

4.1. Vibration Serviceability Evaluation

Figure 14 compares the measured RMS accelerations in all test cases and the reference limits under different environments specified in ISO 10137. It can be observed that the RMS accelerations of the cases of WP-1, WP-2, WP-3, and WP-4 with a 1.77 Hz step frequency meet the vibration serviceability limits for residences, office buildings, and workshops, while the RMS accelerations of the cases of RP-1, RP-2, RP-3, and RP-4 with a 3.54 step frequency exceed the vibration serviceability limits for the workshop. If the structures cannot meet the vibration serviceability criteria shown in Figure 14, efficient control devices need to be adopted to control their vibrations. As one of the most common and effective control devices, passive TMD is widely used to control structural vibrations [29,30]. Therefore, passive TMDs were designed for vibration control of the suspended floor to improve its vibration serviceability in the following sections.

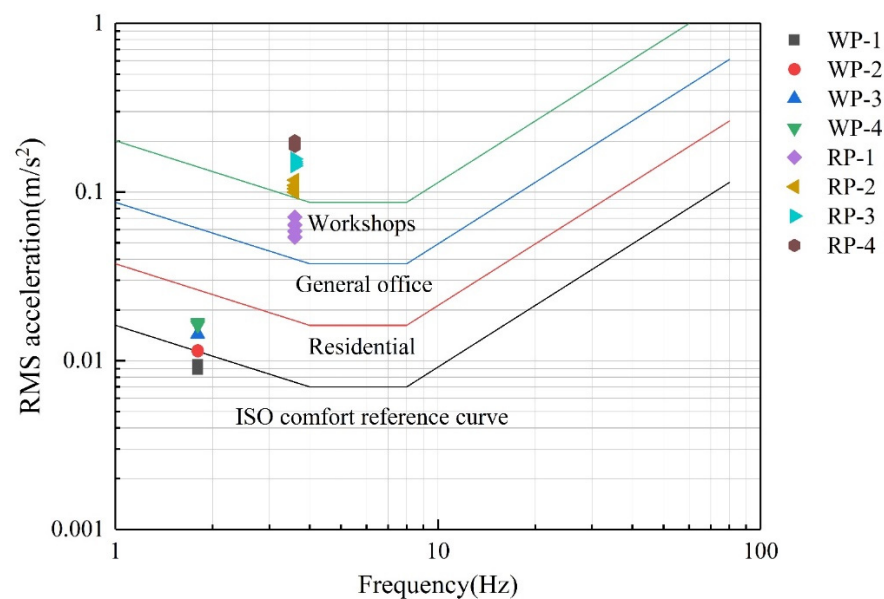


Figure 14. Vibration serviceability evaluation of the measured RMS accelerations according to ISO 10137: 2007.

4.2. Numerical Analysis for TMD Parameter Design

The stiffness and damping parameters of TMDs for vibration control of the suspended floor were calculated according to the optimal frequency ratio f_{opt} and optimal damping ratio ξ_{opt} , which can be expressed as [51]:

$$f_{opt} = \frac{1}{1 + \mu} \quad (3)$$

$$\xi_{opt} = \sqrt{\frac{3\mu}{8(1 + \mu)}} \quad (4)$$

where μ denotes the mass ratio of TMDs installed on the structure.

Considering the engineering purpose of cost saving and easy installation, the mass ratio of TMDs installed on the structure is determined to be $\mu = 3\%$, and its specific design parameters are listed in Table 3. The number of TMDs was determined to be five, and the installation locations of TMDs on the suspended floor are shown in Figure 15.

Table 3. The design parameters of TMDs for mitigating vibration of the suspended floor.

Mass (kg)	Stiffness (N/m)	Damping (N·s/m)	Frequency (Hz)	Number
720	349,956.78	1495.17	3.54	5

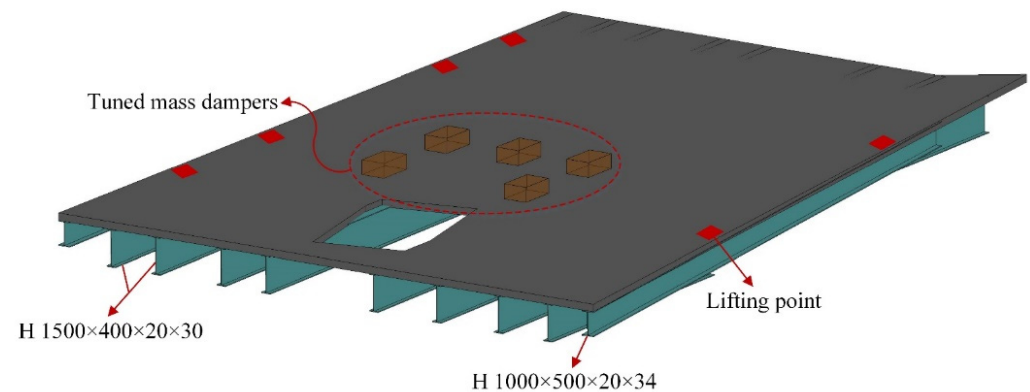


Figure 15. Installation locations of TMDs on the suspended floor.

Based on the local equivalent FE model of the suspended floor, the dynamic characteristics of the suspended floor with TMDs were investigated. Five MASS21 element nodes representing the quality of TMDs were established below 30 cm of the TMDs installation position. The COMBIN14 element was also adopted to simulate the spring-damper components of TMDs, whose spring stiffness and damping parameter were defined via the real constant. Meanwhile, pedestrian-induced loads were reloaded to the local equivalent FE model of the suspended floor.

Figure 16 compares the acceleration time-history response of the suspended floor with and without TMD under case WP-1. As illustrated in Figure 16, the acceleration response of the suspended floor with TMDs is significantly reduced in comparison with the suspended floor without TMDs.

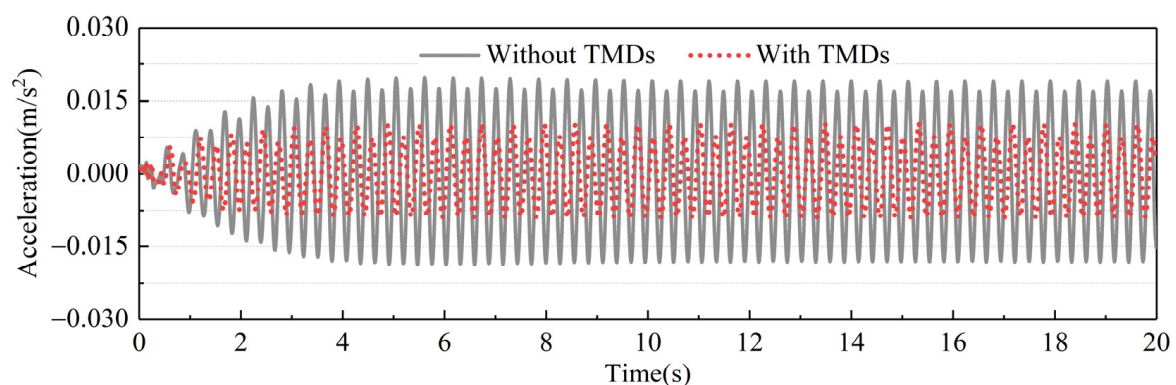


Figure 16. Acceleration time-history responses of the suspended floor with and without TMD under case WP-1.

4.3. Dynamic Testing for the Suspended Floor with TMDs

To further verify the effectiveness of TMDs in improving the vibration serviceability of the suspended floor, dynamic testing for the suspended floor with TMDs under pedestrian loads was conducted. The test setup, measuring point arrangement, and loading

mode adopted in this section are the same as that adopted in Section 2. On-site complete installations of TMDs are illustrated in Figure 17.



Figure 17. TMDs installed on-site.

For the case of walking in place, it can be observed from Figure 18 that the peak acceleration decreased from 0.0095 m/s^2 to 0.0061 m/s^2 . The maximum RMS value induced by a single pedestrian is reduced by approximately 35.79%, indicating that TMDs can effectively mitigate the structural vibration response.

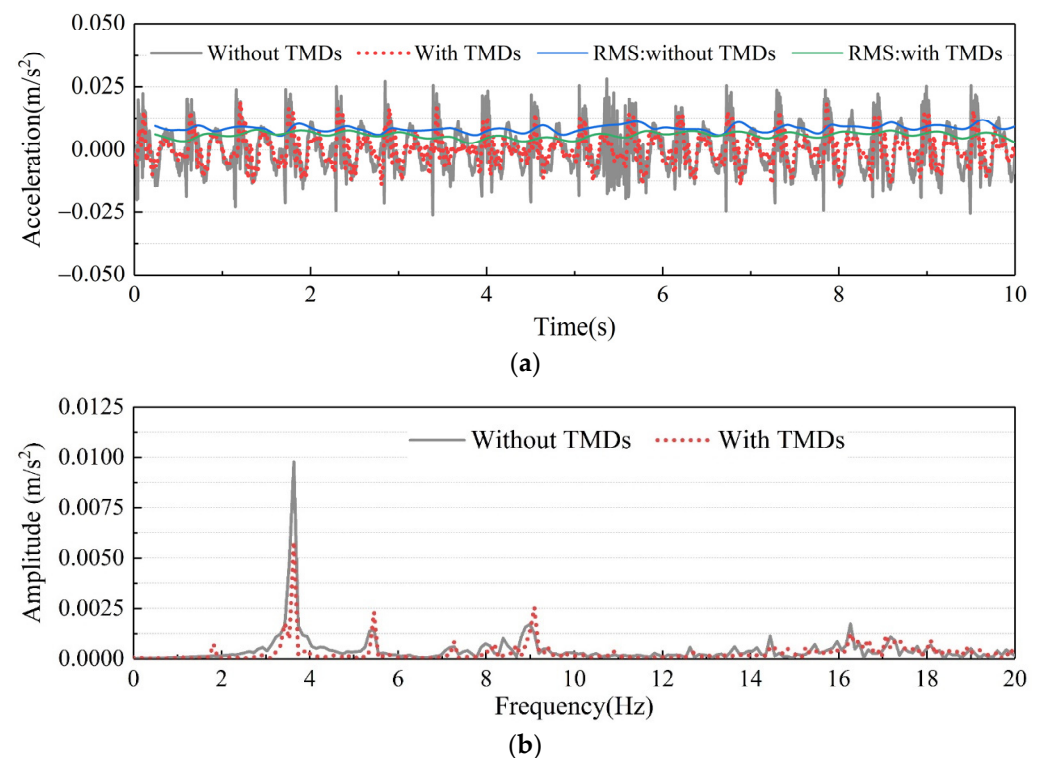


Figure 18. Comparison of the measured acceleration time time-history responses and corresponding FFT spectrum of the suspended floor with and without TMDs under case WP-1: (a) acceleration time-history response; (b) FFT spectrum.

4.4. Comparisons of Numerical and Measured Dynamic Responses of the Suspended Floor with TMDs

Table 4 compares the numerical and measured RMS acceleration of the suspended floor with and without TMDs under pedestrian-induced loads. Compared with the suspended floor without TMDs, the reduction rates of RMS accelerations of the suspended floor with TMDs are 43.93%, 43.66%, and 43.29% for numerical simulation under the cases of WP-1, WP-2, and WP-4, respectively, while the reduction rates of RMS accelerations of the suspended floor with TMDs are 35.79%, 34.78%, and 35.71% for field tests under the cases of WP-1, WP-2, and WP-4, respectively. The difference between numerical and measured acceleration responses is mainly attributed to the high sensitivity of TMD control performance to its frequency and damping.

Table 4. Comparison of numerical and measured RMS acceleration of the suspended floor with and without TMDs under pedestrian loads.

Test Conditions	TMDs Installation	RMS Acceleration (m/s ²)			
		Testing	Reduction Rate (%)	Simulation	Reduction Rate (%)
WP-1	W/O	0.0095	35.79	0.0107	43.93
	W/	0.0061		0.0060	
WP-2	W/O	0.0115	34.78	0.0213	43.66
	W/	0.0075		0.0120	
WP-4	W/O	0.0168	35.71	0.0425	43.29
	W/	0.0108		0.0241	

Note: W/O and W/ represent the suspended floor without and with TMDs, respectively.

The RMS accelerations of the suspended floor with and without TMDs under case WP-1 are further compared in Figure 19. For the suspended floor without TMDs, the suspended floor's RMS acceleration responses predicted by its overall FE model and local equivalent FE model under case WP-1 reach 0.0104 m/s² and 0.0107 m/s², respectively, which agree well with the corresponding field test result of 0.0095 m/s². For the suspended floor with TMDs, the suspended floor's RMS acceleration predicted with its overall FE model and local equivalent FE model under case WP-1 reach 0.0054 m/s² and 0.0060 m/s², respectively, which are in good agreement with the corresponding field test result of 0.0061 m/s². Therefore, it can be concluded that the simplified local equivalent FE model can replace the complicated overall FE model to predict the human-induced dynamic responses of the suspended floor.

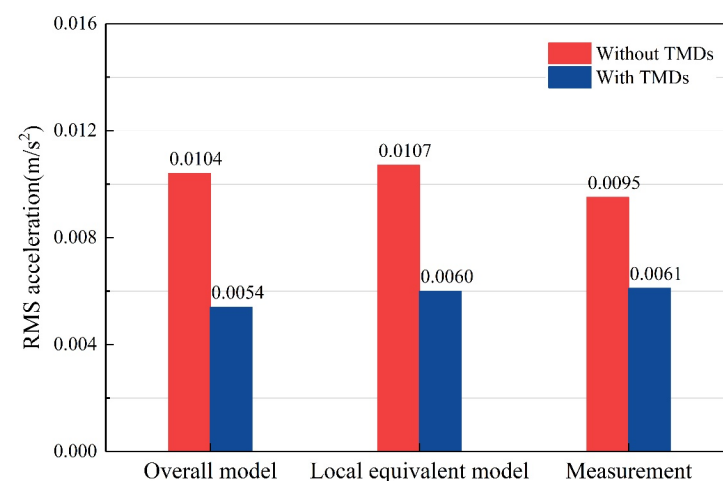


Figure 19. Comparison of RMS acceleration predicted with two FE models and corresponding field test results of the suspended floor with and without TMDs under case WP-1.

5. Conclusions

Recently, the vibration serviceability of the suspended floor has received more and more attentions from engineers and researchers. In fact, unlike traditional floor systems, there are some non-negligible factors in achieving precise finite element modeling and numerical analysis for the dynamic characteristics and responses of the suspended floor, especially the structural inter-story coupling effect. Thus, it is urgent to develop a precise FE modeling method for evaluating the vibration serviceability of the suspended floor. Under this circumstance, taking a 36 m long suspended floor system as a case study, this study proposes accurate finite element (FE) modeling methods for human-induced vibration serviceability evaluation of the suspended floor. The main findings are summarized as follows:

- (1) The overall FE model can be established and updated by addressing the effect of decorative layer and structural additional mass, and the connection relationship of beam-to-hanging pillars in the suspended floor is suggested to be hinged. The fundamental frequency of the suspended floor and the vertical RMS acceleration responses of single pedestrian walking predicted with the overall FE model are found to be consistent with the field test results.
- (2) The local equivalent FE model of the suspended floor can be proposed by simplifying the hanging pillar as the elastic support with adjustable vertical stiffness. The fundamental frequency and mode shape of the suspended floor predicted with the local equivalent FE model are found to be consistent with the overall FE model. Moreover, the RMS acceleration responses predicted with the local equivalent FE model agree well with the corresponding experimental results for the case of single pedestrian walking.
- (3) The simplified local equivalent FE model can replace the complicated overall FE model to evaluate the vibration serviceability of the suspended floor. For the suspended floor with and without TMDs in this study, the error of RMS acceleration responses between two FE models and corresponding field test results ranges from 1.64% to 11.48% when a single pedestrian is walking in place.

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References

1. Hassanieh, A.; Chiniforush, A.A.; Valipour, H.R.; Bradford, M.A. Vibration behaviour of steel-timber composite floors, part (2): Evaluation of human-induced vibrations. *J. Constr. Steel Res.* **2019**, *158*, 156–170. [\[CrossRef\]](#)
2. Ferrante, C.; Andrade, S.; Lima, L.; Vellasco, P. Analytical study and experimental tests on innovative steel-concrete composite floorings. *J. Constr. Steel Res.* **2019**, *168*, 105868. [\[CrossRef\]](#)
3. Ahmed, I.M.; Tsavdaridis, K.D. The evolution of composite flooring systems: Applications, testing, modelling and eurocode design approaches. *J. Constr. Steel Res.* **2019**, *155*, 286–300. [\[CrossRef\]](#)
4. Xie, Z.; Hu, X.; Du, H.; Zhang, X. Vibration behavior of timber-concrete composite floors under human-induced excitation. *J. Build. Eng.* **2020**, *32*, 101744. [\[CrossRef\]](#)

5. Abdeljabber, O.; Hussein, M.; Avci, O.; Davis, B.; Reynolds, P. A novel video-vibration monitoring system for walking pattern identification on floors. *Adv. Eng. Softw.* **2020**, *139*, 102710. [\[CrossRef\]](#)
6. Van Engelen, N.C.; Graham, J. Comparison of prediction and measurement techniques for pedestrian-induced vibrations of a low-frequency floor. *Struct. Control Health Monit.* **2019**, *26*, e2294. [\[CrossRef\]](#)
7. Cai, Y.; Gong, G.; Xia, J.; He, J.; Hao, J. Simulations of human-induced floor vibrations considering walking overlap. *Appl. Sci.* **2020**, *2*, 19. [\[CrossRef\]](#)
8. Devin, A.; Fanning, P.J.; Pavic, A. Modelling effect of non-structural partitions on floor modal properties. *Eng. Struct.* **2014**, *91*, 58–69. [\[CrossRef\]](#)
9. Jarnerö, K.; Brandt, A.; Olsson, A. Vibration properties of a timber floor assessed in laboratory and during construction. *Eng. Struct.* **2015**, *82*, 44–54. [\[CrossRef\]](#)
10. Jiang, L.; Cheng, R.; Zhang, H.; Ma, K. Human-induced-vibration response analysis and comfort evaluation method of large-span steel vierendeel sandwich plate. *Buildings* **2022**, *12*, 1228. [\[CrossRef\]](#)
11. Zhu, Q.; Liu, K.; Liu, L.; Du, Y.; Zivanovic, S. Experimental and numerical analysis on serviceability of cantilevered floor based on human-structure interaction. *J. Constr. Steel Res.* **2020**, *173*, 106184. [\[CrossRef\]](#)
12. Liu, K.; Liu, L.; Zhu, Q.; Liu, Y.; Zhou, F. Dynamic testing and numerical simulation of human-induced vibration of cantilevered floor with tuned mass dampers. *Structures* **2021**, *34*, 1475–1488. [\[CrossRef\]](#)
13. Wei, X.; Wan, H.P.; Russell, J.; Živanović, S.; He, X. Influence of mechanical uncertainties on dynamic responses of a full-scale all-FRP footbridge. *Compos. Struct.* **2019**, *223*, 110964. [\[CrossRef\]](#)
14. Silva, J.G.; Andrade, S.A.; Lopes, E.D. Parametric modelling of the dynamic behaviour of a steel–concrete composite floor. *Eng. Struct.* **2014**, *75*, 327–339. [\[CrossRef\]](#)
15. Wei, X.; Russell, J.; Živanović, S.; Mottram, J.T. Measured dynamic properties for FRP footbridges and their critical comparison against structures made of conventional construction materials. *Compos. Struct.* **2019**, *223*, 110956. [\[CrossRef\]](#)
16. Miskovic, Z.; Pavic, A.; Reynolds, P. Effects of full-height nonstructural partitions on modal properties of two nominally identical building floors. *Can. J. Civ. Eng.* **2009**, *36*, 1121–1132. [\[CrossRef\]](#)
17. Huang, H.; Gao, Y.; Chang, W.S. Human-induced vibration of cross-laminated timber (CLT) floor under different boundary conditions. *Eng. Struct.* **2020**, *204*, 110016. [\[CrossRef\]](#)
18. ISO 2631-1; Mechanical Vibration and Shock-Evaluation of Human Exposure to Whole-Body Vibration. International Organization for Standardisation: Genève, Switzerland, 1997.
19. ISO 10137; Bases for Design of Structures-Serviceability of Buildings and Walkways against Vibration. International Organization for Standardisation: Genève, Switzerland, 2007.
20. AISC811-97; Steel Design Guide Series 11: Floor Vibrations Due to Human Activity. American Institute of Steel Construction: Chicago, IL, USA, 1997.
21. JGJ/T441-2019; Technical Standard for Human Comfort of the Floor Vibration. China Construction Industry Press: Beijing, China, 2019.
22. Mokrani, B.; Tian, Z.; Alaluf, D.; Meng, F.; Preumont, A. Passive damping of suspension bridges using multi-degree of freedom tuned mass dampers. *Eng. Struct.* **2017**, *153*, 749–756. [\[CrossRef\]](#)
23. Li, Q.; Fan, J.; Nie, J.; Li, Q.; Chen, Y. Crowd-induced random vibration of footbridge and vibration control using multiple tuned mass dampers. *J. Sound Vib.* **2010**, *329*, 4068–4092. [\[CrossRef\]](#)
24. Chen, J.; Han, Z.; Xu, R. Effects of human-induced load models on tuned mass damper in reducing floor vibration. *Adv. Struct. Eng.* **2019**, *22*, 2449–2463. [\[CrossRef\]](#)
25. Wang, L.; Nagarajaiah, S.; Shi, W.; Zhou, Y. Semi-active control of walking-induced vibrations in bridges using adaptive tuned mass damper considering human-structure-interaction. *Eng. Struct.* **2021**, *244*, 112743. [\[CrossRef\]](#)
26. Maślanka, M. Optimised semi-active tuned mass damper with acceleration and relative motion feedbacks. *Mech Syst. Signal Process.* **2019**, *130*, 707–731. [\[CrossRef\]](#)
27. Wang, L.; Shi, W.; Zhang, Q.; Zhou, Y. Study on adaptive-passive multiple tuned mass damper with variable mass for a large-span floor structure. *Eng. Struct.* **2020**, *209*, 110010. [\[CrossRef\]](#)
28. Wang, P.; Chen, J.; Han, Z. Rotational inertial double tuned mass damper for human-induced floor vibration control. *Struct. Eng. Mech.* **2022**, *82*, 283–294.
29. Van Nimmen, K.; Verbeke, P.; Lombaert, G.; Roeck, G.; Van den Broeck, P. Numerical and experimental evaluation of the dynamic performance of a footbridge with tuned mass dampers. *J. Bridge Eng.* **2016**, *21*, C4016001. [\[CrossRef\]](#)
30. Zhang, Z.; Guo, T.; Yang, K. Simulation and measurement of human-induced vibrations of the Beijing Olympic watchtower with tuned mass dampers. *J. Perform. Constr. Facil.* **2017**, *31*, 04017095. [\[CrossRef\]](#)
31. Robertson, M.; Holloway, D.; Taoum, A. Vibration of suspended solid-timber slabs without intermediate support: Assessment for human comfort. *Aust. J. Struct. Eng.* **2018**, *19*, 266–278. [\[CrossRef\]](#)
32. Caballero-Garatachea, O.; Juárez-Luna, G.; Sandoval-Hernández, M.E.R. Methods for the vibration analysis of reinforced concrete precast one-way joist slab floor systems under human walking. *J. Build. Eng.* **2021**, *43*, 103217. [\[CrossRef\]](#)
33. Jimenez-Alonso, J.F.; Saez, A. Motion-based design of TMD for vibrating footbridges under uncertainty conditions. *Smart Struct. Syst.* **2018**, *21*, 727–740.

34. Lievens, K.; Lombaert, G.; De Roeck, G.; Van den Broeck, P. Robust design of a TMD for the vibration serviceability of a footbridge. *Eng. Struct.* **2016**, *123*, 408–418. [\[CrossRef\]](#)
35. Chulahwat, A.; Mahmoud, H. A combinatorial optimization approach for multi-hazard design of building systems with suspended floor slabs under wind and seismic hazards. *Eng. Struct.* **2017**, *137*, 268–284. [\[CrossRef\]](#)
36. Shahabi, A.B.; Ahari, G.Z.; Barghian, M. Suspended columns for seismic isolation in structures (SCSI): Experimental and numerical studies. *Earthq. Struct.* **2020**, *19*, 17–28.
37. Lv, Q.; Lu, Y.; Liu, Y. Vibration serviceability of suspended floor: Full-scale experimental study and assessment. *Structures* **2021**, *34*, 1651–1664. [\[CrossRef\]](#)
38. Costa-Neves, L.F.; Silva, J.S.; Lima, L.R.O.; Jordão, S. Multi-storey, multi-bay buildings with composite steel-deck floors under human-induced loads: The human comfort issue. *Comput. Struct.* **2014**, *136*, 34–46. [\[CrossRef\]](#)
39. Wang, Z.; Qi, X.; Huang, Y.; Fan, B.; Li, X. Dynamic behavior of a suspended steel space frame-glass composite floor. *Adv. Civ. Eng.* **2021**, 8382585. [\[CrossRef\]](#)
40. Komarizadehasl, S.; Komary, M.; Alahmad, A.; Lozano-Galant, J.A.; Ramos, G.; Turmo, J. A novel wireless low-cost inclinometer made from combining the measurements of multiple MEMS gyroscopes and accelerometers. *Sensors* **2022**, *22*, 5605. [\[CrossRef\]](#)
41. Komarizadehasl, S.; Huguenet, P.; Lozano, F.; Lozano-Galant, J.A.; Turmo, J. Operational and analytical modal analysis of a bridge using low-cost wireless Arduino-based accelerometers. *Sensors* **2022**, *22*, 9808. [\[CrossRef\]](#)
42. Zhang, X.; Li, Q.; Wang, Y.; Wang, Q. Vibration of a U-shaped steel-concrete composite hollow waffle floor under human-induced excitations. *Adv. Struct. Eng.* **2020**, *23*, 2996–3008. [\[CrossRef\]](#)
43. Wang, D.; Wu, C.; Zhang, Y.; Li, S. Study on vertical vibration control of long-span steel footbridge with tuned mass dampers under pedestrian excitation. *J. Constr. Steel Res.* **2019**, *154*, 84–98. [\[CrossRef\]](#)
44. An, Q.; Ren, Q.; Liu, H.; Yan, X.; Chen, Z. Dynamic performance characteristics of an innovative cable supported beam structure–concrete slab composite floor system under human-induced loads. *Eng. Struct.* **2016**, *117*, 40–57. [\[CrossRef\]](#)
45. Abeysinghe, C.M.; Thambiratnam, D.P.; Perera, N.J. Dynamic performance characteristics of an innovative hybrid composite floor plate system under human-induced loads. *Compos. Struct.* **2013**, *96*, 590–600. [\[CrossRef\]](#)
46. Varela, W.D.; Battista, R.C. Control of vibrations induced by people walking on large span composite floor decks. *Eng. Struct.* **2011**, *33*, 2485–2494. [\[CrossRef\]](#)
47. Transportation Research Board. *Highway Capacity Manual*; Transportation Research Board: Washington, DC, USA, 2000.
48. Fujino, Y.; Pacheco, B.M.; Nakamura, S.I.; Warnitchai, P. Synchronization of human walking observed during lateral vibration of a congested pedestrian bridge. *Earthq Eng. Struct Dyn.* **1993**, *22*, 741–758. [\[CrossRef\]](#)
49. Jaishi, B.; Ren, W.X. Structural finite element model updating using ambient vibration test results. *J. Struct. Eng.* **2005**, *131*, 617–628. [\[CrossRef\]](#)
50. Zeng, D.; Wang, H.; Chen, J. Dynamic reliability analysis of large-span structures under crowd bouncing excitation. *Buildings* **2022**, *12*, 332. [\[CrossRef\]](#)
51. Den Hartog, J.P. *Mechanical Vibrations*; Courier Corporation: New York, NY, USA, 1985.

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