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Acceleration Response Analysis of a Steel-wood Composite Floor System under Human-induced Vibration

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Authors' contributions

This work was carried out in collaboration between both authors. Author DY designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author CL managed the analyses of the study. Author DY managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

To investigate the vibration response of a steel-wood composite floor system under walking and jump excitation. The ABAQUS subroutine Vdload is used to simulate the human walking and jumping process on the structure, while the human-induced excitation is equated to a combination of a Fourier-scale load model and a biomechanical model of mass, stiffness, and damping (MSD) to study the human-induced vibration response under human-structure interaction (HSI). The effects of walking and jumping excitation on the peak acceleration of the structure are also considered. The results show that the peak acceleration of the structure considering the human-structure interaction is significantly smaller than that without the human-structure interaction, and the results obtained from the numerical simulation analysis are more consistent with the experimental situation. In addition, the acceleration response of the steel-wood composite floor system under jump excitation is larger than that of walking excitation, and the peak acceleration increases with the increase of jump frequency. Then: any floor, no matter its structural configuration and material, is prone to vibrate under walking and jumpimg excitation if the excitation frequency is in resonance with one of its main frequencies. The induced vibrations affect the floor

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serviceability, when the induced peak acceleration exceeds the comfort requirements. The magnitude of the induced peak acceleration is the larger, the larger the acting force and the lower the vibrating floor mass and its damping.

Keywords: Steel-wood composite floor system; walking excitation; jumping excitation; human-structure interaction; peak acceleration.

1. INTRODUCTION

With the initial results of China's policy of returning farmland to forests, the recovery of forest resources and the import of a large number of wood products, wood structures are being used again. At present, the application of plywood in engineering structures in China is still in the initial stage, but China is the largest country in the world in terms of poplar plantation area, the area of poplar forest has exceeded hundreds of millions of mu, of which, poplar, cedar and other excellent alternative forest resources are very rich, producing more than 100 million cubic meters of wood per year [1]. Scholars at home and abroad have conducted in-depth research on plywood as a light wood structure cladding, and have placed that plywood has good physical mechanics and superior performance, and that plywood can be used as an alternative to coated light wood structures [2]. On this basis, it is proposed to combine plywood and light steel plates to form steel-wood composite panels, which can be applied to residential buildings. The focus of this paper is to investigate the vertical vibration acceleration response of such composite panels under human-induced loads, so as to lay the foundation for the design and application of steel-wood composite panels.

More types of wood flooring have been developed abroad in recent years.Chang et al. [3] measured the vibration of different wood flooring systems, for example, orthogonal glued wood flooring and joist flooring. Zhang et al. [4] studied conventional wood flooring and observed that the number and spacing of metal web joists and back support do not affect the lower order frequencies of the structure, but do affect the frequencies of the higher modes.Koyam et al. [5] found that steel and wood vertical screw connectors have negligible effect on flooring vibration. In the above studies, the effect of boundary conditions on the response of wood floor human-induced vibration was not fully investigated. In the calculations related to wood floors in various engineering standards, the boundary conditions are simplified to simply supported, so in the numerical simulations, the boundary conditions are simplified to simply constrained.Glisovic and Stevanovic [6] used SAP2000 software to perform finite element simulation of joist wooden floor under artificially induced excitation. They found that the added mass on the floor has a significant effect on its vibration performance.

With the development of the construction industry and the improvement of people's living standard, the residents have higher and higher requirements for the vibration comfort of the floor slab. People's related activities will cause vertical vibration of the floor slab. If this vibration exceeds a certain limit, it will cause psychological discomfort to the residents, which in turn will affect their normal learning and living conditions [7]. As a new type of floor cover, the study of vibration comfort is an indispensable part in the process of promoting its application. However, most of the research on the vibration comfort of steel-wood floor coverings is focused on the dynamic characteristics of the floor, and there are few reports on the influence of human-induced excitation on the vibration comfort of steel-wood composite floor system [8]. In this paper, the finite element software ABAQUS is used to simulate the steel wood composite floor, and the self-made Vdload and Dload subroutines are used to exert human induced excitation. Through numerical modeling, the acceleration response of steel wood composite floor under walking excitation is analyzed considering the human structure interaction.

2. FINITE ELEMENT NUMERICAL SIMULATION

2.1 Structural Finite Element Model

In this paper, an experimental model of the steel-wood composite floor system from the literature [9] is used, as shown in Fig. 1, which consists of a hybrid structure of wooden floor and steel frame. In this study, a wooden floor thickness is 120mm.The longitudinal and transverse spans of the wood floor are 9.0 m and 6.6 m, respectively. The longitudinal direction is supported by three I-beams CL-2 of size UB406*140*46, while the transverse direction is supported by four main I-beams ZL-1 of size UB203*133*30. In the actual case, screws are used to connect the wooden floor and steel beams with a screw spacing of 500mm, on the longitudinal steel beam, at a distance of 300mm from the end of the beam.

In the calculation model, the density of I-beam is taken as 7800 kg/m^3 , Young's modulus is 200GPa and shear modulus is 79.3Gpa; the density of wooden floor is 500kg/m^3, Poisson's ratio is 0.4, modulus of elasticity in parallel direction is 10767Mpa and modulus of elasticity in vertical direction is 979Mpa. In order to avoid the influence of screw in the simulation, the screw is modeled by the spring with super large stiffness value. According to the anti sliding stiffness value of the screw connector in the normal use stage given in the literature, the stiffness value of the spring is taken as 49kN/mm, and the wooden floor is assumed to be rigidly connected with the support beam. In the literature [9], the two ends of the beam were restrained in three dimensions. The reason for modelling the beam stipulation during this manner is that the beam ends square measure normally restrained by columns, and therefore the deformation of the column–beam connections thanks to floor vibration is unnoticed during this study. The damping ratio of the floor system is set to 3.04%.

2.2 Modal Analysis Verification

The finite element model of the steel-wood composite floor cover established by ABAQUS is shown in Fig. 3. The modal analysis of this model was carried out to obtain its first three orders of vibration inherent frequencies and compared with the experimental values given in the literature [9], and the results are shown in Table 1. Overall, the finite element simulation results are still in good agreement with the experimental results.

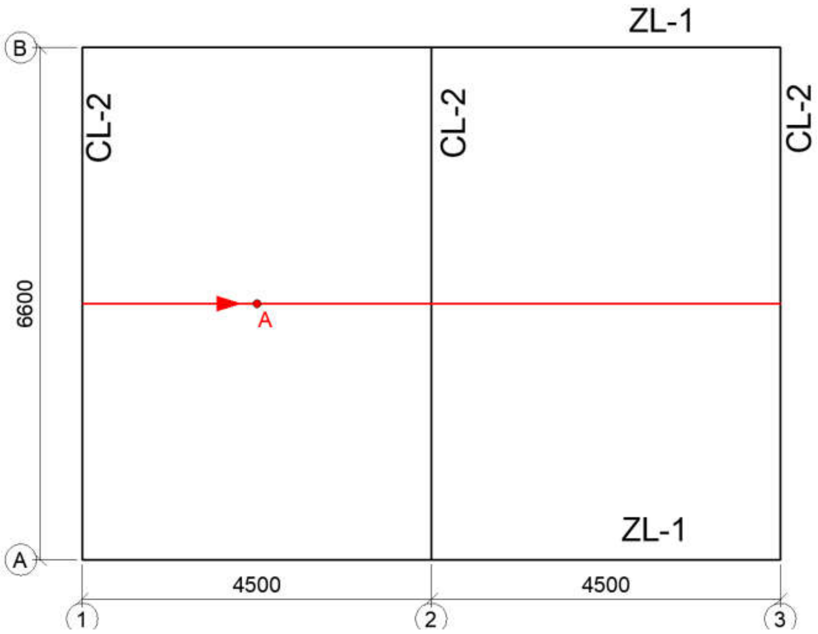


Fig. 1. Floor model plan

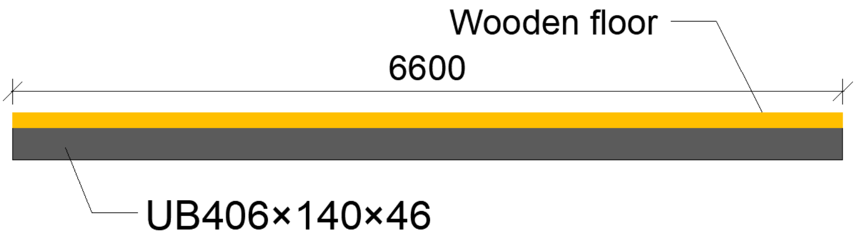


Fig. 2. Steel beam supporting wooden floor

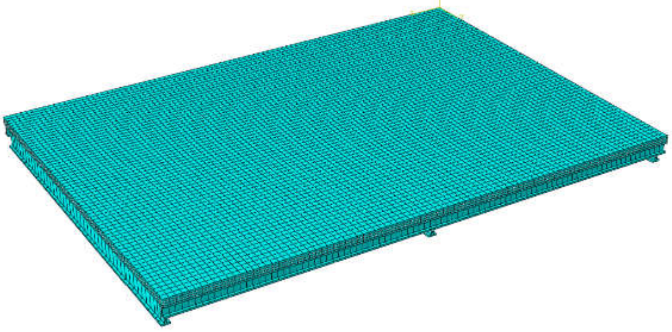


Fig. 3. Finite element model

Table 1. Structural natural frequencies simulated by finite element method and measured results

Mode	Numerical Modelling(Hz)	Experimental Testing(Hz)	Error(%)
1	7.766	7.6	2.18
2	9.977	10.0	0.23
3	13.153	14.4	8.6

2.3 Experimental and Simulation Validation

As shown in the literature [9] study, the walking load was used as the load excitation in the literature test, and the motion path was carried out along the path shown in Fig. 1, with an acceleration sensor placed at point A to record its structural acceleration at a sampling frequency of 200 Hz. In this paper the load force is programmed using Vdload subroutine and applied to the combined floor cover. Spring unit is added to the walking path by defining constants to consider the stiffness k and damping c in the human-structure interaction. A comparing of the time course curve of structural acceleration at point A in the experimental and simulated cases is shown in Fig. 4. The response of the vibration acceleration of the simulated combined building cover is basically consistent with the experimentally measured response.

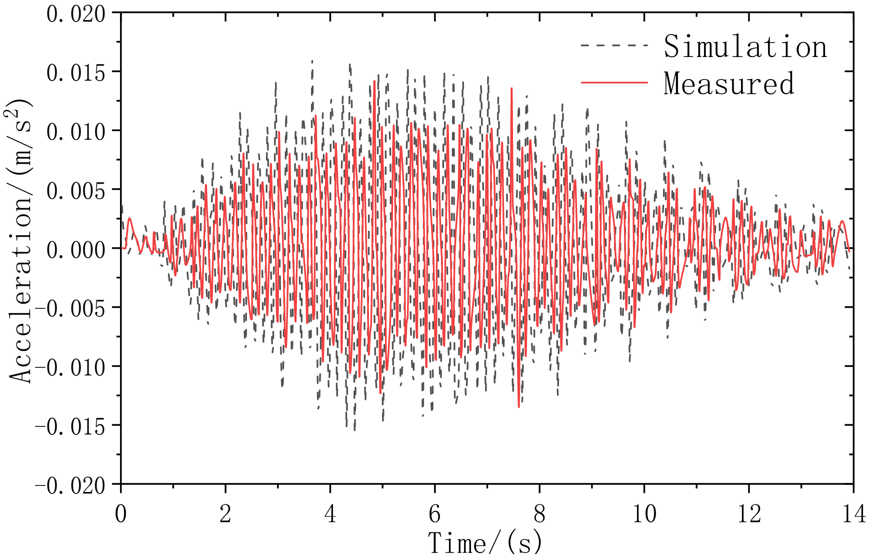


Fig. 4. Comparison of acceleration test and simulation at point A under walking load

3. ANALYSIS OF ACCELERATION RESPONSE OF STEEL-WOOD COMPOSITE FLOOR SYSTEM UNDER WALKING EXCITATION

Most of the structural vibration caused by human-induced excitation is caused by walking excitation, and there is no relevant code to guide the design of vibration comfort of steel-wood composite floor system under walking load, so it is necessary to study and analyze the vibration response of steel-wood combined floor under walking load. The “Design Guide on the Vibration of Floors” (Wyatt, SCI Publivation 076, U.K.,1989) can be used to design any kind of floor. One needs to know the floor frequency, its vibrating mass and the critical amping ratio. However it does not not cover the human jumping.

In order to study the vibration comfort of steel-wood composite floor system, it is particularly important to establish an accurate mathematical model for walking [10]. In contemporary research, domestic and foreign scholars usually classify walking load mathematical models into two broad categories: stochastic walking load models [11] and deterministic walking load models. The differences among people and the differences in each step of a person's own walking lead to certain differences in the parameters of human body weight, step frequency, step length, and other dynamic characteristics. Therefore, the stochastic walking load model is based on the use of Monte Carlo method to randomly generate characteristic parameters such as body weight, step frequency, phase angle and then wait for the single person walking load curve.

For the convenience of the study, without considering the individual variability among pedestrians and intra-individual randomness, the expected weight and step frequency of pedestrians do not change once they are set, so the walking load generated by pedestrian walking can be represented by a Fourier series model as follows.

$$F_p(t) = G + G\sum_{i=1}^{n} \alpha_i sin\left(2\pi i f_p t - \phi_i\right) \quad （1）$$

f_p is the pedestrian walking frequency (Hz), G is the human mass, taken as 0.6KN, ϕ_i is the ith order phase angle, n is the number of orders considered in the load analysis. This paper adopts the single pedestrian walking load model recommended by the International Association of Bridges and Engineering IABSE [12], considering only the vibration response analysis of the structure under vertical pedestrian excitation, and taking the first three orders of vibration model to calculate as follows $\alpha_1 = 0.4 + 0.25(f_s - 2), \alpha_2 = \alpha_3 = 0.1, \varphi_1 = 0, \varphi_2 = \varphi_3 = \pi/2$.

The time history of the walking load excitation is shown in Fig. 5.

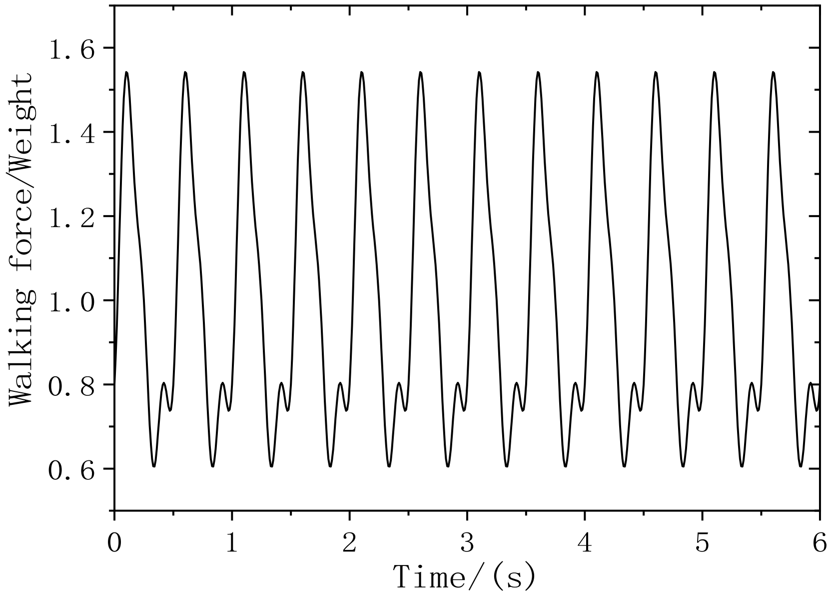


Fig. 5. Time curve of single person walking load excitation

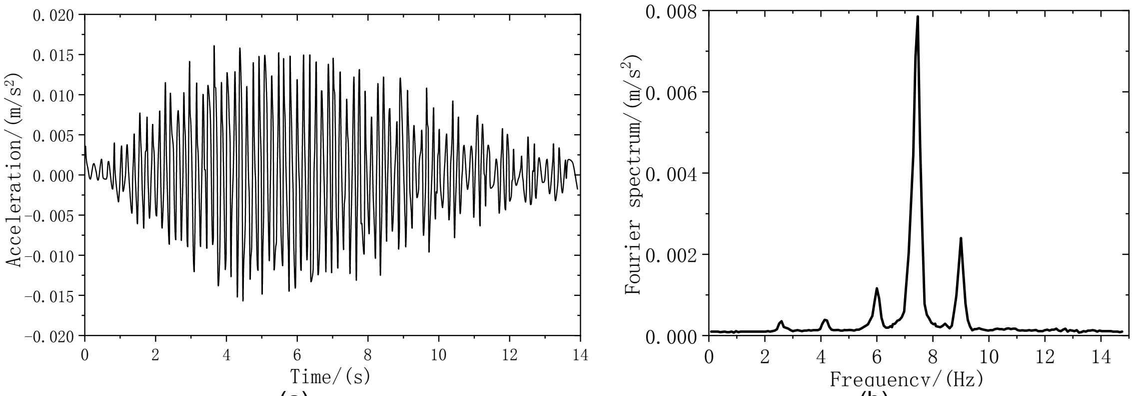
3.1 Analysis of Structural Vibration Response Without Considering Human-Structure Interaction

Considering that the first-order frequency of the steel wood composite floor is 7.766 Hz, the most unfavorable loading condition is adopted in the simulation loading, that is, pedestrians walk at the frequency of 2.6 Hz. That is to say, the third harmonic load excited by walking can cause the resonance of the structure, and the walking path is shown in Fig. 5. Through ABAQUS finite element dynamic analysis, the acceleration time history curve of point a of composite floor is obtained, as shown in Fig. 6.

It can be seen from Fig. 6(a) that the peak acceleration of the structure under walking load excitation is $0.0159m/s^2$, which is less than the 0.05 m/s^2 acceleration limit specified in the Technical Regulations for Concrete Structures of Tall Buildings in China, and Fig. 6(b) indicates the acceleration amplitude spectrum of the structure during walking load loading, which can be seen that the resonance of the structure is caused by walking alone, under the excitation of the 1st order modal.

3.2 Structural Vibration Response when Considering Human-Structure Interaction

The vibration characteristics of a steel-wood composite floor system under walking load excitation will change. In order to obtain reliable structural vibration acceleration responses, the literature [13,14] shows that it is crucial to consider human-structure interactions. The pedestrian is equated to a single degree of freedom biotechnical model with mass-stiffness-damping, and this model is used together with a Fourier series model to represent the walking behavior of a single person. u_p represents the vertical displacement of the pedestrian, u represents the vertical displacement of the structure, F_t represents the pedestrian load, and m_p, k_p, and c_p represent the human model mass, stiffness, and damping, respectively.



(a) (b)

Fig. 6. Acceleration time history (a) and FFT spectrum (b) of a single pedestrian walk

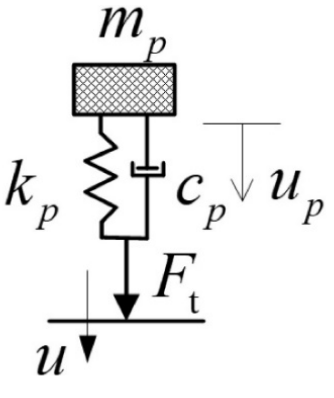


Fig. 7. Single degree of freedom biomechanical model

When considering the human-structure interaction, the human body weight is still chosen to be 600 N and the walking frequency is $f_p = 2.6\text{Hz}$ in order to ensure the influence of other parameters. Considering the dynamic properties of the Human biomechanical model, the regression expression for the human parameters can be expressed as a function of body weight M and walking frequency f_p , as shown in the following equation

$$m_p = 97.082 + 0.275M - 37.518f_p \qquad (2)$$

$$c_p = 29.041m_p^{0.883} \qquad (3)$$

$$k_p = 30351.744 - 50.261c_p + 0.035c_p^2 \qquad (4)$$

The equivalent mass of human body $m_p = 16.04kg$, the equivalent damping coefficient of human body $c = 1079.24N \cdot s/m$ and the equivalent stiffness of human body $k = 16874.49N/m$ were obtained by calculation(when $M = 60\text{kg}$, $f_p = 2.6\text{Hz}$). Then, using the Vusdfld subroutine, the biomechanical model at the unloaded point is deleted and the biomechanical model at the loaded point is activated to obtain the acceleration time curve at the most unfavorable point of the structure as shown in Fig. 8. The red line is the acceleration time curve considering the human-structure interaction. Comparing the two, the peak acceleration of 0.0134 m/s^2under the action of a single person walking is found to be 15.7% less than the peak acceleration of 0.0159 m/s^2 without considering the human-structure interaction.

The peak acceleration of the structure when considering the human-structure interaction (0.0134 m/s^2), deviates from the experimentally obtained peak structural acceleration of 0.0125 m/s^2, by 7.2%, while the one calculated without considering HIS (0.0159 deviates by 27,2%. There is a significant effect of considering the HSI on the vibration response of the structure under walking load This is consistent with that expressed in the literature [13,14]. Therefore, human biomechanical modeling is important to further explore the pedestrian-structure interaction.

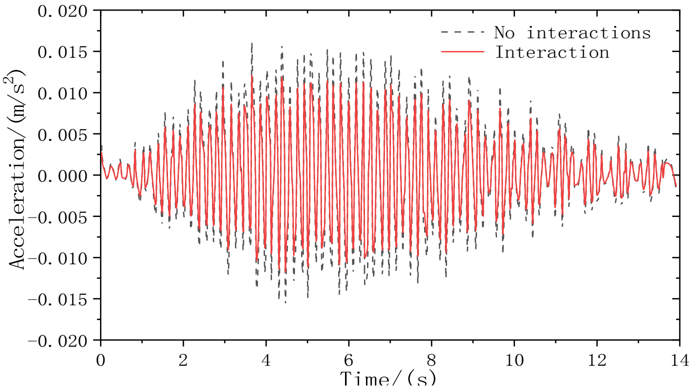


Fig. 8. Accelerations induced by a single person walking

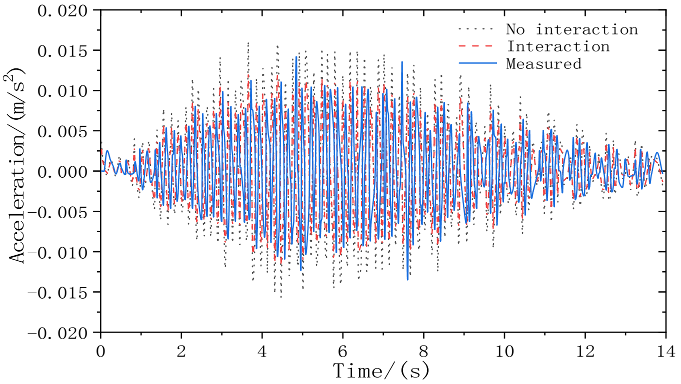


Fig. 9. Comparison of vertical accelerations calculated and measured

4. ACCELERATION RESPONSE ANALYSIS OF STEEL-WOOD COMPOSITE FLOOR SLAB UNDER JUMPING EXCITATION

The human jumping process is divided into three stages, including jumping, vacating and landing. In order to ensure that the human jump has the stage of vacating, the two stages of jumping and landing will produce a huge impact force on the ground, so unlike the walking load human walking force, the jumping force generated by the jumping load is more undulating, which has a greater impact on the time course change of the vibration acceleration response of the large span structure.

For the jump load model, Chen Jun et al. [15] conducted a large number of experimental tests based on force plates. The analysis through three-dimensional motion capture technology, pointed out that the half-sine model would underestimate the response of the structure and could not accurately reflect the high-frequency jump load action. Therefore, the jump load model was modified on the basis of the half-sine model, and a half-sine square model was established, as shown in Eq. (5)

$$F(t) = \begin{cases} K_p\, G \sin\left(\frac{\pi t}{t_p}\right) & 0 \leqslant t < t_p,\ f_p \leqslant 1.5Hz \\ K_p G\, \sin^2\left(\frac{\pi t}{t_p}\right) & 0 \leqslant t < t_p,\ 1.5Hz < f_p \leqslant 3.5Hz \\ 0 & t_p \leqslant t \leqslant T_p \end{cases} \quad (5)$$

α is the contact rate, $\alpha = t_p/T_p$; K_P is the dynamic amplification factor; t_p is the contact time; T_p is the time period of a complete jump.

The time course curve of jump load excitation is shown in Fig. 10.

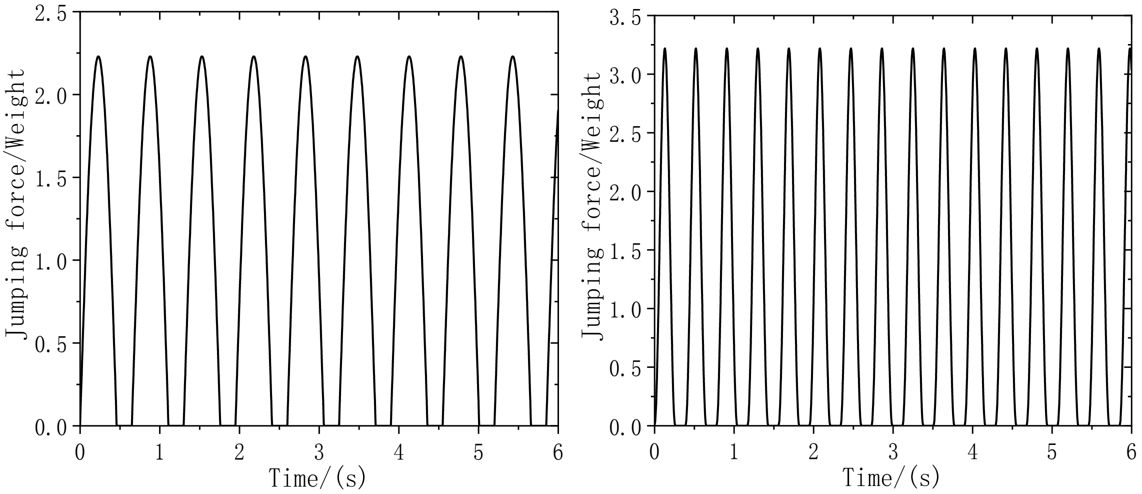
4.1 Analysis of Structural Vibration Response without Considering Human-Structure Interaction

The effects of two jump frequencies have been analysed.

(1) 1.5 Hz jump frequency

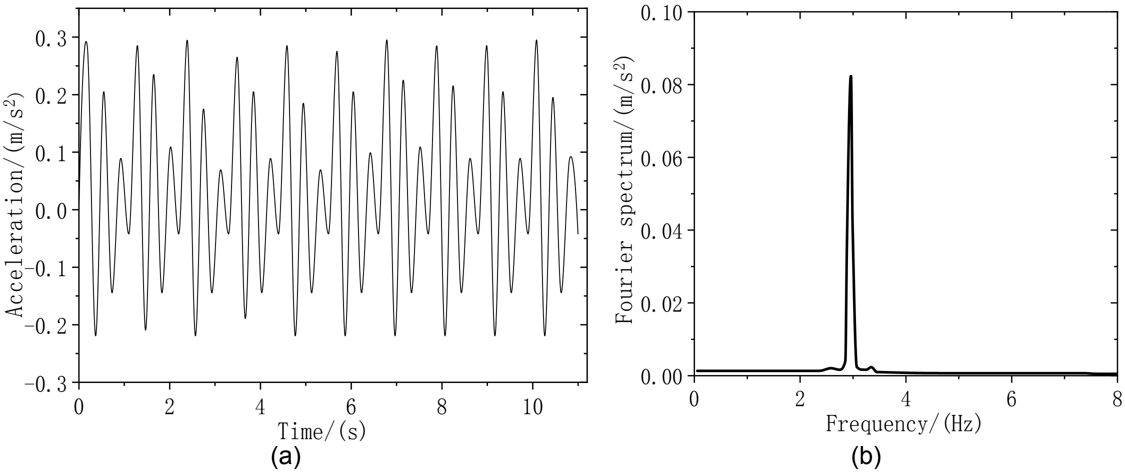
A half-sine model established by Chen Jun's group at Tongji University through extensive experimental research is used for simulation analysis. When the jump frequency is 1.5 Hz, the amplification factor K_P is 2.32, the contact time $t_p$is 0.46, the complete cycle time T_p is 0.64, and the contact rate T_p is 0.71. When the frequency is 1.5 Hz, the time history of the acceleration response of the combined building cover model structure is shown in Fig. 11. The jump load is excited at point A shown in Fig. 1. at a fixed point.

Fig. 11. shows that when the frequency of single fixed-point jump is low, the effect on the structural vibration response has obvious periodicity, and the size of the period is basically the same as the whole jump frequency cycle time. The peak acceleration of the structure is 0.295 m/s^2.



(a) 1.5Hz frequency (b) 2.67Hz frequency

Fig. 10. Jump excitation curve of half sine squared model



(a) (b)

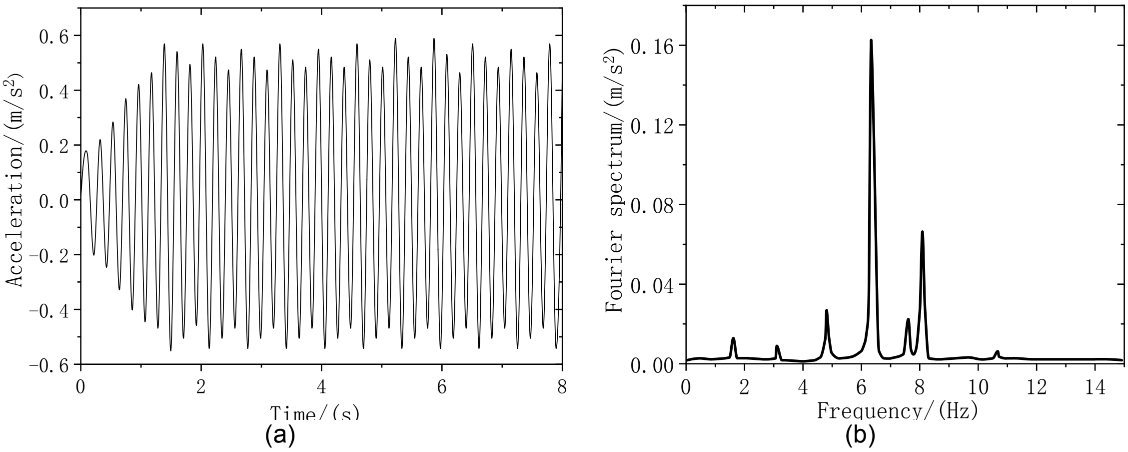
Fig. 11. Acceleration time history (a) and FFT spectrum (b) of a single pedestrian 1.5 Hz jump

(2) 2.67 Hz jump frequency

When the jump frequency reaches 2.67 Hz, the amplification factor K_P is 3.22, the contact time t_p is 0.26, the complete cycle time T_p is 0.38, and the contact rate α is 0.67 based on the results of literature research. The vibration acceleration curve of the combined floor structure under jump load excitation as calculated by ABAQUS explicit dynamics analysis, is shown in Fig. 12. When the high-frequency jump load of 2.67 Hz is applied, the vibration acceleration generated by the structure is similar to that of the low-frequency jump load of 1.5Hz in general, and both have obvious periodic changes, but the peak acceleration is higher, reaching 0.569 m/s^2. In the same time, the vibration acceleration of the structure under jump excitation is much larger than the vertical acceleration of the structure under walking excitation at the same frequency. This is quite since the load value of jump excitation is much larger than that of walking excitation.

4.2 Structural Vibration Response when Human-Structure Interaction is Considered

The peak acceleration response of the structure under the jump load when human-structure interaction is considered is analyzed by replacing the previous walking load with the jump load and, at the same time, by simulating the jump load using Dload programming, and the human-structure interaction. The results of the acceleration time history of the building cover structure under a single person fixed-point 1.5 Hz jump load are shown in Fig. 13.



(a) (b)

Fig. 12. Acceleration time history (a) and FFT spectrum (b) of a single pedestrian 2.67 Hz jump

The human single-degree-of-freedom biomechanical model and the jump load Fourier series model were used for the fixed-point loading under the jump load condition. The peak acceleration time history of the structure under jump excitation at 1.5 Hz and 2.67 Hz are presented in Fig. 13. and Fig. 14., respectively. The structural acceleration time course curves when pedestrian-structure interaction is not considered are shown by the black dashed line, and the structural acceleration time course curves when pedestrian-structure interaction is considered are shown by the red solid line. The peak acceleration of the structure under 1.5Hz jump excitation is 0.2947 m/s^2 , which is 15.7% less than the peak acceleration of the structure without human-structure interaction of 0.2483 m/s^2 ; the peak acceleration of the structure under 2.67 Hz jump excitation is 0.4826 m/s^2 , which is 19.2% less than the peak acceleration of the structure without human-structure interaction of 0.5974 m/s^2 . The peak acceleration of the structure under 2.67 Hz jump excitation is 0.4826 m/s^2 , which is 19.2% lower than that of the structure without human-structure interaction. From the above analysis, it can be seen that the effect of considering human-structure interaction more walking on the vibration response of the structure under the jump load is more obvious.

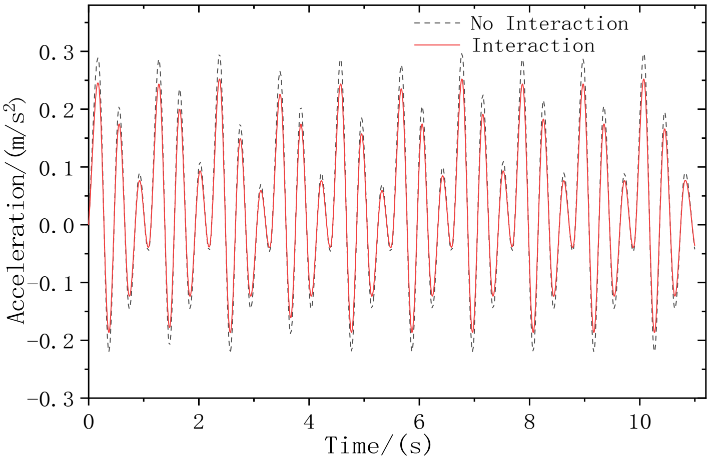


Fig. 13. Acceleration time history under 1.5 Hz jump load with single person at the fixed point A in Fig. 1

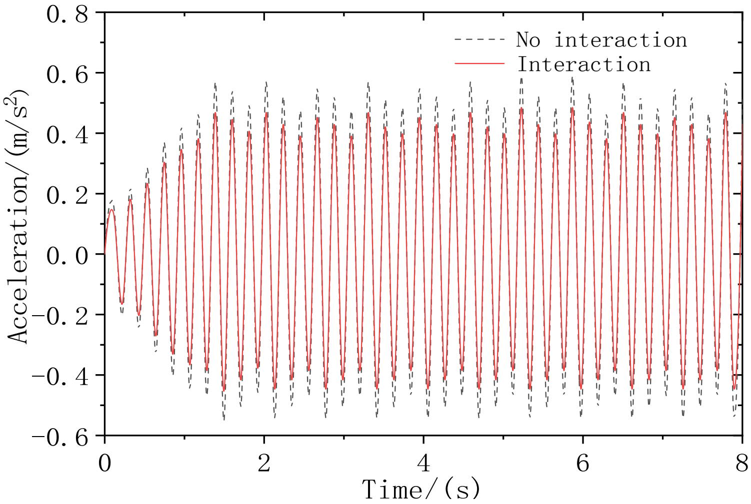


Fig.14. Acceleration time history under 2.67 Hz jump load with single person at the fixed point A in Fig. 1

5. CONCLUSION

In this paper, numerical analysis modeling of a steel-wood composite floor system was performed. A systematic analysis of human-induced vibration was carried out and the results were compared with experimental tests to confirm the importance of considering human-structure interactions. Reference is provided for the analysis of human-induced load vibration in steel-wood composite floor covers.

1. By comparing the numerical results of the acceleration response of the structure with and without considering the human-structure interaction, the latter case overestimates the structural response. When single-person walking is performed, the peak acceleration considering human-structure interaction is $0.0134m/s^2$, which is lower than the peak acceleration when human-structure interaction is not considered. Therefore, considering the human-structure interaction leads to different results for the acceleration response.
2. Comparing the result of the structural response analysis under the combination of the Fourier-scale load model and the MSD model with those of the experimental results, it was found that the structural response analysis under the consideration of human-structure interaction was proved to be more consistent with the experimental results. Therefore, in order to obtain more accurate human-induced load response analysis in the FEA, human-structure interaction should be considered.
3. The results of the finite element analysis show that the peak acceleration of the steel-wood composite floor system is as expected larger by jumping excitation than by walking excitation. By considering the human-structure interaction the reduction of the peak acceleration of the structure is larger under jumping excitation than under walking loading. This conclusion seems to suggest that, the larger the acceleration response of the structure, the larger the effect of considering human-structure interaction on its acceleration response.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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