Check for updates

Dynamic Properties and Response of Total-prefabricated Steel Floor Slabs

Bin Xia[1], Xiaotong Peng[1*], Xin Wang[2], and Chen Lin[3]

[1] School of Civil Engineering and Architecture University of Jinan, Jinan 250022, Shandong, China

[2] School of Qilu Transportation Shandong University, Jinan 250002, Shandong, China

[3] School of Architecture and Landscape Design Shandong University of Art & Design, Jinan 250399, Shandong, China

*pengxito@163.com

Abstract. In response to the problems of numerous wet operations, low assembly efficiency, and imperfect design specifications of traditional prefabricated floor slabs, a total-prefabricated steel floor slab was proposed. The floor slabs with various stiffeners were selected on the basis of the load-bearing capacity. Based on that, the finite element models were established to study the dynamic response and the dynamic properties of the steel floor slabs to provide a reference for structural design and comfort calculation. The results show that the basis frequencies of the four types of floor slabs with trapezoidal stiffeners can meet the code requirements. The acceleration of the SCP70-320-670 floor slab does not meet the standard limit requirements under normal pedestrian load excitation, which should be dampened in design. To ensure that the floor slabs can meet people's requirements for vibration comfort during use, it is necessary to consider the dual limit values of the frequency and acceleration.

Keywords: Total-prefabricated Steel Floor Slab, Dynamic Response, Dynamic Properties, Natural Frequency, Acceleration.

1 Introduction

As one of the three major types of prefabricated buildings, prefabricated steel structures are highly industrialized, with fast construction, good seismic performance, and low environmental pollution [1]. As one of the key factors in the development of prefabricated steel structure buildings, the floor system usually adopts composite floor slabs with a high degree of assembly. At present, domestic and foreign scholars mainly conduct research on the vibration comfort of composite floor slabs through on-site measurement, experimental research, numerical simulation, and other methods. Most research focuses on the vibration comfort problem of floor slabs caused by human walking [2]. Allen and Murray [3] studied the dynamic response of steel structure under walking load. When the natural frequency of the structure is less than 9 Hz,

D. Li et al. (eds.), *Proceedings of the 2023 9th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2023)*, Advances in Engineering Research 228,
https://doi.org/10.2991/978-94-6463-336-8_25

peak acceleration should be used to characterize the vibration comfort of shopping malls, offices and other places.

However, the above floor slabs have problems such as low assembly rate, more wet work, self-sustaining weight, and imperfect design and construction standards. In response to the above issues, a Total Prefabricated Steel Floor Slabs (TPSF) [4] that matched with prefabricated steel structure residential buildings has been developed in this article. In preliminary research [5], TPSF has great mechanical properties and meets the load-bearing design requirements. However, on account of its lightweight and low stiffness, residents' daily activities are more likely to cause vibration reactions on the floor. Existing research on TPSF is limited to its static performance. In addition, there is a lack of systematic research on its dynamic response and comfort performance. This article uses ABAQUS finite element software to conduct dynamic analysis on the composite floor slab. Firstly, the floor slab is selected, and a model is established. Then, modal analysis is conducted on the dynamic response of the floor slab. Finally, the dynamic response of the floor slab under pedestrian, running, and jumping loads is studied. Its comfort is evaluated, providing a reference for structural design and comfort calculation.

2 The model selection of floor

This article has designed four types of special corrugated plates (Fig. 1). There are Plate type A with trapezoidal stiffeners at the flange, Plate type B with triangular stiffeners, Plate type C with U-shaped stiffeners, and Plate type D without stiffeners.

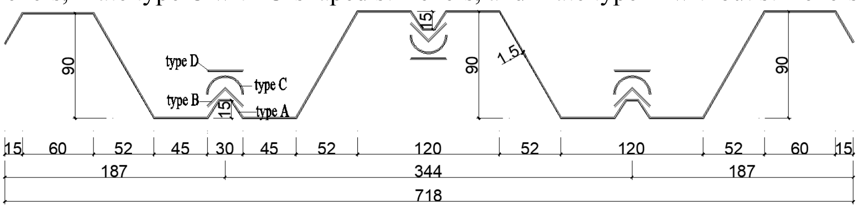

Fig. 1. Special corrugated plate type

The four types of plates adopt a unified width of 718 mm, span of 3600 mm, height of 90 mm, thickness of 1.5 mm, and steel Q355B. The theoretical calculation of the TPSF special corrugated plate under the condition of fixed support is carried out to obtain the q_{σ} and q_{ω} of each plate type (Table 1). The q_{σ} and q_{ω} of plate type A are higher than those of other plate types, with a maximum of 12.3% and 10.1%, respectively. It can be seen that the bearing capacity of trapezoidal stiffener floor slabs is greater than that of other plate types. The following analysis selects trapezoidal stiffeners for special corrugated plates.

Table 1. Floor bearing capacity (kN/m^2)

Plate type	$q_{\omega i}/q_{\omega D}$ ($i = A$、B、C)	q_{ω}	q_{σ}	$q_{\sigma i}/q_{\sigma D}$ ($i = A$、B、C)
Plate type A	23.07	1.123	29.33	1.101
Plate type B	22.09	1.115	29.11	1.092
Plate type C	22.58	1.099	28.71	1.077
Plate type D	20.54	1.000	26.65	1.000

Based on the above and related engineering application experience, four basic floor slabs are designed for special corrugated boards for different types of residential buildings. They have wave heights of 70 mm, 90 mm (Fig. 2), 110 mm, and 130 mm, respectively. The cross-sectional geometric parameters are shown in Table 2.

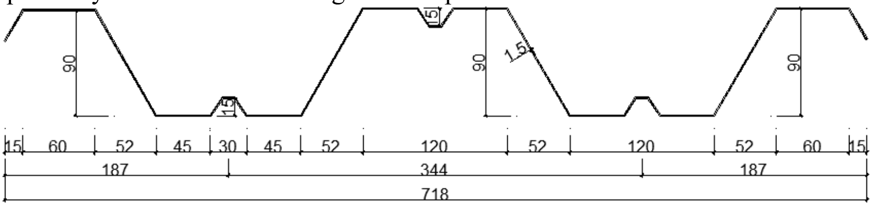

Fig. 2. Basic dimensions of SCP70-320-670

Table 2. Geometric parameters of special corrugated plate section (kN/m^2)

Floor type	a1	a2	a3	t	b	H	B
SCP70-320-670	45	30	40	1.5	320	70	670
SCP90-344-718	45	30	52	1.5	344	90	718
SCP110-368-766	45	30	64	1.5	368	110	766
SCP130-392-814	45	30	76	1.5	392	130	814

3 Finite element simulation

3.1 Finite element model

The finite element software ABAQUS is used to study the dynamic performance of the special corrugated steel plate. Considering that the walking load is relatively light, and the floor is in the stage of elastic-plastic deformation, the linear elastic Constitutive equation is adopted. The special corrugated steel plate adopts Q355B steel with an elastic modulus of 2.06×10^5 MPa, and Poisson's ratio is 0.3.

3.2 Model validation

To verify the accuracy of the modeling, a finite element model under simple support constraints was established for the vibration performance test of the steel-wood composite floor [6]. The specimen structure and finite element model are shown in Fig. 3 and Fig. 4.

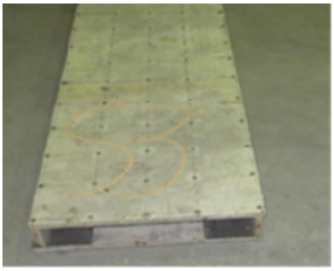

Fig. 3. Specimen structure

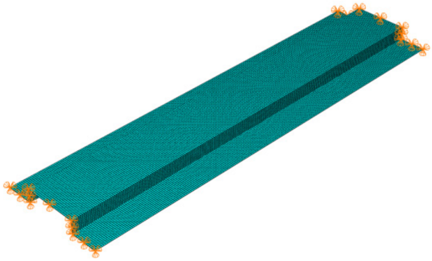

Fig. 4. Finite element model

The test and finite element simulation results are listed in Table 3. By comparison, the maximum error between the simulation value and the test value data is 4.69%.

Table 3. Natural frequency and peak acceleration of steel-wood composite floor slab

Numerical value	Natural frequency /Hz		Peak acceleration (m/s^2)	
	Bare board	Placing heavy objects	Bare board	Placing heavy objects
Test value	38.650	21.010	1.754	1.714
Imitate value	36.920	20.270	1.793	1.705

3.3 The analysis of dynamic property

The first three modes of the composite floor are characterized by the overall vibration of the structure. The first mode only contains one wave, the second mode has two anti-symmetric waves, and the third mode has four.

The first three frequencies of each board type are summarized in Table 4. As can be seen from the table, the board height increases from 70 to 90 mm, and the floor frequency increases. From 90 to 130 mm, the frequency decreases, and the vibration response increases. The increase in slab height from 70 to 90 mm results in a more significant increase in slab stiffness than in mass, while from 90 to 130 mm, it results in a more significant increase in slab mass than in stiffness. All four basic floor slabs meet the frequency ≥ 3 Hz limit specification [7] requirements.

Table 4. The first three frequencies of four types of floor slabs (Hz)

Floor type	First order frequency	Second order frequency	Third order frequency
SCP70-320-670	21.888	33.702	40.784
SCP90-344-718	25.152	28.458	38.394
SCP110-368-766	24.357	27.516	35.505
SCP130-392-814	21.246	27.404	33.891

3.4 The analysis of dynamic response

Pedestrian load excitation, jumping load excitation, and running load excitation can be expressed in the Fourier series, as shown in the equation:

$$F(t) = G[1 + \sum_{i=1}^{N} \alpha_i \sin(2\pi i f_s t - \psi_i)] \tag{1}$$

where G is human body weight; t is time; f_s is pedestrian frequency; a_i is dynamic load factor; Ψ_i is the phase angle of the i-th order load; i is harmonic order; and N is the total harmonic number of loads.

Pedestrian load excitation.
Using the relevant provisions of national regulations [8] on dynamic load factor and phase angle, this article only takes the first three orders for calculation. The values of dynamic load factor and phase angle are: $\alpha_1 = 0.5, \alpha_2 = 0.2, \alpha_3 = 0.1$; $\psi_1 = 0, \psi_2 = \pi/2, \psi_3 = \pi/2$. Considering a reduction coefficient of 0.5, the pedestrian frequency is taken as 2 Hz, and the pedestrian load equation is as follows:

$$F(t) = 350 + 175\sin(4\pi t) + 70\sin(8\pi t - \pi/2) + 35\sin(12\pi t - \pi/2) \tag{2}$$

Running load excitation.
The Fourier series load model proposed in [9] is selected. The value of dynamic load factor and phase angle are: $\alpha_1 = 1.25, \alpha_2 = 0.3, \alpha_3 = 0.1$; $\psi_1 = \pi/6, \psi_2 = 5\pi/6, \psi_3 = \pi/2$. The jogging frequency is 2.5 Hz, and the equation for running load is as follows:

$$F(t) = 350 + 437.5\sin(5\pi t + \pi/6) + 175\sin(10\pi t + 5\pi/6) + 35\sin(15\pi t + \pi/2) \tag{3}$$

Jumping load excitation.
The Fourier series load model proposed by Chen et al. [10] is selected, and the dynamic load factor and phase angle are taken as: $\alpha_1 = 1.47, \alpha_2 = 0.576,$

$\alpha_3 = 0.152; \psi_1 = 1.59, \psi_2 = 1.6, \psi_3 = 1.58$. The jump frequency is taken as 2.675 Hz, and the equation for running load is as follows:

$$F(t) = 350 + 514.5\sin(5.35\pi t + 1.59) + 210.6\sin(10.7\pi t + 0.576) + 53.2\sin(16.05\pi t - 1.58) \quad (4)$$

From Table 5, it can be seen that the dynamic response of the floor slab is the highest under the excitation of jumping loads. SCP70-320-670 has the highest vibration response among the four types of plates. SCP70-320-670: Under the excitation of walking load, the acceleration is 3.6 times that of SCP90-344-718. Under the excitation of running load, it is 4.07 times that of SCP110-368-766. Under the excitation of jumping loads, it is 3.55 times that of SCP110-368-766. Some vibration reduction measures need to be taken during the design phase for SCP70-320-670.

Table 5. Basic plate acceleration (mm/s^2)

Basic board type	Walking excitation	Running excitation	Jumping excitation
SCP70-320-670	72.060	189.725	265.910
SCP90-344-718	19.795	54.764	112.867
SCP110-368-766	21.734	47.005	74.959
SCP130-392-814	28.692	54.913	89.137

4 Conclusion

1) The finite element simulation based on the test is consistent with the test results, which confirms the correctness and reliability of the finite element model.

2) The first three vibration modes of the composite floor slab with trapezoidal stiffeners are the overall structural vibration. The SCP90-344-718 floor slab has the highest frequency among the four types of floor slabs, which meets the specification requirement of frequency ≥ 3 Hz limit.

3) The SCP70-320-670 floor slab does not meet the standard limit requirements under normal walking load. Apart from that, the other three types of floor slabs all meet the comfort requirements of the design standards of China and of the AISC11 of the United States.

5 References

1. Mortazavi. M., Sharafi, P., Kildashti. K., et al. Prefabricated hybrid steel wall panels for mid-rise construction in seismic regions[J]. Journal of Building Engineering. 2020, 27.
2. Zhe, X.X., Chen J. Summary of research on vibration comfort of large-span floors [J] Structural Engineer, 2009, 25 (6): 144-149.
3. Allen, D.E., Murray, T.M. Design criterion for vibrations due to walking[J]. AISC Engineering Journal, 1993, 4: 1117-129.
4. Peng, X.T., Li Y.J., Lin C., et al. A Picatini floor slab: CN215253841U [P] December 21, 2021.
5. Qi, Z.H. Analysis of the mechanical performance of a new fully assembled steel structure floor system [D] Jinan: University of Jinan, 2021.

6. Tullini, N., Minghini, F. Nonlinear analysis of composite beams with concrete-encased steel truss[J]. Journal of Constructional Steel Research, 2013, 91: 1-13.
7. GB50017-2017, Design Standard for Steel Structures [S] Beijing: China Construction Industry Press, 2017.
8. MURRAY, T.M., ALLEN, D.E., UNGAR, E.E. Floor vibration due to human activity [J]. American Institute of Steel Construction, 1997: 1-44.
9. Chen, J., Wang, H.Q., Peng, Y.X. Experimental study on Fourier series model of walking excitation and its parameters [J] Vibration and Shock, 2014, 33 (8): 11-15.
10. Chen, J., Wang L., Wang H.Q. Single person jump load model and its parameter values [J] Journal of Tongji University (Natural Science Edition), 2014, 42 (6): 0859-0866.