Experimental and numerical study on the in-plane behaviour of a new long-span assembly composite floor system under lateral load

Zaihua Zhang, Ran He, Gangxiang Mao and Xingping Shu

ABSTRACT
A new long-span assembly composite floor system for use in multi-column frame-tube structure is presented. The basic assembly unit consists of steel truss keel and profile sheet concrete composite slab, which of the two parts are combined together through shear stud. By means of standardized assembly connection structure, such a new floor system can realize a rapid assembly of floor and support frame. Based on test research of 1/3 scale model, the paper discusses the in-plane mechanical performance of the new floor system. Through loading at the direction of parallel to the assembly slab seam and perpendicular to the assembly slab seam, respectively, the influence of assembly orientation of floor units on the failure modes, distribution and transmission performance of the horizontal loads, and the in-plane stiffness were identified in detail. A numerical model was developed with its input parameters calibrated from full-scale experimental tests. Based on model analysis, the influence of thickness of concrete slab on the in-plane stiffness was discussed.

1. Introduction

Floor diaphragms are important structural elements in a building system, with the purpose of carrying both vertical and lateral loads. Usually in structural design, a great deal of attention is given to the vertical lateral load resisting elements (moment frames, shear walls and bracing), while the equally critical horizontal lateral load resisting elements (diaphragms) are usually ignored (Scarry 2014). In fact, as the horizontal resistance component of the structure, the floor system contains most of the gravity of the building structure, once the diaphragms cannot sustain the seismic forces they are subjected to, and transfer those forces properly to the vertical lateral load resisting elements, those vertical lateral load resisting elements may as well not be there. Especially for assembly floor structures, the connection between the assembled units is relatively weak, and the in-plane performance of this type of floor should be paid more attention.

The research on the in-plane performance of floor systems mainly examines the distribution and transmission of the horizontal load in the plane of the floor and the overall deformation performance of the system. Aiming at the forces in the plane floor, Scarry, Bull, Cowie, Gardiner et al. carried out a more detailed study (Bull 2004; Cowie et al. 2014a, 2014b; Gardiner, Bull, and Carr 2008a, 2008b), revealing three types of forces in the plane floor (Inertial Loads, Transfer Forces, Compatibility Forces). For the overall deformation in the floor plane, in-plane stiffness is a key parameter. In various types of prefabricated floor systems, there are many experimental studies on the in-plane mechanical properties of prefabricated wooden floor (steel-wood floor) systems: Brignola, Pampanin, and Podesta (2012) performed different prefabricated wooden floor systems. The in-plane rigidity performance was tested by horizontal reciprocating loading quasi-static test, and the test specimens with different boundary conditions were tested. A simplified calculation formula for evaluating the stiffness characteristics of prefabricated wooden floor was proposed. Sebastian Fuentes (Sebastian, Eric, and Abdelhamid 2014) carried out an experimental study on the in-plane stiffness of a typical wooden grid cladding panel assembled wooden floor system. The test obtained the load–displacement curve of the floor and the degradation of the floor stiffness under cyclic effects. The influence of the grid brace on the in-plane performance of the floor was analyzed through comparative experiments, but the in-plane stiffness of the floor was not quantitatively analyzed. Moroder (2016) discussed the internal force transmission method of the wooden floor, and proposed an equivalent truss model of the analysis of the in-plane performance. For a modular steel-timber composite floor, Loss, Piazza, and Zandonini (2016a, 2016b) and Loss and Frangi (2017) analyzed and studied the in-plane stiffness and bearing capacity of the floor system, and some relevant design suggestions are put forward. D’Arenzo et al. (2019) proposed an equivalent frame model to model the in-plane deformation characteristics of...
prefabricated wooden floor, which can quickly obtain
the in-plane stiffness of the floor. Ma, He, and Ma
(2014a) pointed out that the assembly direction has
a great influence on the mechanical performance of
floor, compared with loading parallel to joist, loading
perpendicular to joist could greatly facilitate the floor
system to achieve higher strength and in-plane rigidity,
but all of the values of in-plane rigidity were lower than
10 kN/mm under both loading modes. It is not difficult
to find that the horizontal bearing capacity of the wo-
den floor (steel-wood floor) in the above studies is small,
and it is not suitable for high-rise buildings where ho-
izontal loads control.

In addition, the in-plane properties of prefabricated
concrete floor systems have also been studied. A typi-
cal representative is the research on the precast
cement composite floor system by the DSM project supported
by the PCI/NSF collaborative research project. This
project took the double-T type assembled concrete
floor system as the research object, and systematically
studied the performance and design method of the
assembly floor from the connection to the floor to the
overall structure (Fleischman and Farrow 2003;
Fleischman et al. 2005; Fleischman, Ghosh, and Naito
et al. 2005; Naito, Peter, and Cao 2006; Fleischman et al.
2013), which greatly promoted the application and
development of such floor system. Prefabricated pre-
stressed concrete hollow floor is a form of assembly
floor with a long history of application. PCI MANUAL
(Buettner and Becker 1985) specifies the in-plane per-
formance requirements and design methods of this
type of floor. proposed an evaluation method for the
in-plane seismic performance of prefabricated hollow
floors used in New Zealand. Bernardi et al. (2016) pro-
posed a prefabricated floor design model considering
the in-plane force distribution, and proposed a specific
design method. At present, the assembled hollow con-
crete floor has developed various forms of assembly
structure. Pang, Liang, and Zhu (2010), Pang, Xu, and
Liang et al. (2012), Pang, Liang, and Zhu (2012), Yan
(2018), and Pang, Li, and Wang et al. (2019) proposed
da dry assembly hollow floor system with grooves and
conducted extensive research on the assembly con-
nection and floor performance of the system, which
also greatly promoted the popularization and appli-
ca tion of this type of floor. Li, Ge, and Han (2016); Li, Li,
and Weishan (2016), Han, Zhang, and Li (2016), and
Han (2016) proposed a wet-assembled hollow floor
system with cast-in-place joints, and tested the
mechanical properties of the joints and the overall
performance in the plane of the floor through experi-
mental research. The research results show that the in-
plane stiffness of the test assembly floor is about 6
times greater than that of the general assembly floor,
and such kind of assembly floor has the feasibility of
replacing the integral cast-in-place floor or the com-
mon prefabricated floor with cast-in-place coating.

Existing research results show that the assembled
wood floor, steel-wood floor and concrete floor can
meet the performance requirements of the floor system
under the horizontal force through reasonable design.
Steel-concrete composite floor is the most commonly
used floor structure in steel structure engineering, and it
is widely used in large-span floor structures (Celikag
2004; Zhang, Ma, and Zhong 2013; Su 2019). With the
continuous improvement of the industrialization of
buildings, the prefabricated steel-concrete composite
floor system has gradually attracted the attention of
the engineering community, especially the application of
steel-concrete composite steel beams with precast
cement hollow-core slabs (Lam 1998; Lam, Elliott, and
Nethercot 2000a, 2000b) and the application of the slim-
floor system (De Nardin and El Debs 2012; Hegger,
Roggendorf, and Kerkeni 2009; Lam et al. 2015;
Lawson et al. 2015). Both are beneficial to promote the
development of prefabrication of steel-concrete floor
systems (Brambilla et al. 2019; Girbacea, Nijgh, and
Veljkovic 2019). However, the current research on pre-
fabricated assembled steel-concrete composite floors
basically focused on the vertical mechanical beha-
vior, and less attention has been paid to the in-plane
mechanical behavior of this type of floor.

Aiming at the large-span high-rise building floor
system, this paper proposes a composite floor struc-
ture suitable for industrial assembly. It uses steel
trusses as the main keel of the floor structure. Through
the combined action of the steel truss beam and pro-
filled sheeting concrete composite
slab, the floor system can achieve a large spanning
ability, and by means of standardized assembly con-
nection structure, it can realize a rapid assembly of
floor and support frame. Based on the experimental
study of the scale model, this paper discusses and
analyzes the in-plane mechanical performance of
the new floor system, and the relevant influencing
factors of the mechanical properties are also ana-
yzed through finite element analysis and simul-
a tion, which provides theoretical support for the
engineering application of this type of floor.

2. Experimental work

2.1. Specimen design and structure

The proposed new assembly truss composite floor sys-
tem is shown in Figure 1. The system was assembled by
four major slab units (truss composite floor system) and
its plane size was 15.6 m × 15.6 m. The surrounding 16
columns were arranged uniformly at an interval of 3.9 m.
Figure 2 reveals the assembly connection construction of
slab–column and slab–slab. Finally, basing on the four
types of connections, a multi-column frame-tube struc-
ture was formed by connecting the surrounding frame
beams and the floor.
As an anisotropic mechanical system, the in-plane performance of prefabricated floor system can significantly vary in different loading direction (Sarkissian, K K, and Zahrai 2006; Ma, He, and Ma 2014b). In order to analyze the in-plane behaviour of the proposed floor system in different directions, two test pieces of 2 two-story single-tube frame models with the scale of 1/3 structures were designed and completed, named LG-1 and LG-2, respectively. LG1 is used to analyze the in-plane performance when the horizontal force on the floor is parallel to the direction of assembly slab seam, and LG2 is used to test the performance under the direction of perpendicular to the assembly slab seam. The assembly and loading situation of the two test specimens is shown in Figure 3, the first and second floors of each test piece are identical, and the second floor is used as the test object. The layout of the floor structure and the details of the top composite slab are shown in Figures 4 and 5 respectively. Figure 6 shows the arrangement of slab unit's steel truss keel. The cross-sectional dimensions and material properties of the components of the test piece are shown in Table 1. The general appearance of assembling specimens is shown in Figure 7.

2.2. Property of material and connections

2.2.1. Characterization of materials

In the proposed floor system, the Q235B profiled steel sheet with a concrete strength of C30 was used. The test
The test results concerning other major material’s mechanical property are shown in Table 2.

Figure 3. Assembly and loading condition of different specimens.

Figure 4. Floor structure of specimens.

Figure 5. Configuration of profile sheet concrete composite slabs.

The value of the average compressive strength of floor fine aggregate concrete is 31.8Mpa. The test results are shown in Table 2.
2.2.2. Mechanical property of the critical connection

Figure 2 shows the specific construction of the four types of key assembly connections of the proposed floor system. Based on the analysis of in-plane performance by the equivalent beam theory (Zheng and Oliva 2005), it can be known that in this floor system, the key assembly connections are basically in the state of tension (compression)-shear.

In order to obtain the mechanical behavior of various types of key connections, full-scale models were designed and tested. The shear performance of pin–slab–column connection with a relatively complex

| Composition    | Member     | Section specification     | Material          |
|----------------|------------|----------------------------|-------------------|
| Diaphragm      | ZL1        | Chord                      | Cold-Formed Channel Steel C67 × 26 × 3 Q235B |
|                | ZL2        | Web member                 | Cold-Formed Channel Steel C25 × 20 × 1.5 Q235B |
|                | BL         | Chord                      | Cold-Formed Channel Steel C25 × 20 × 1.5 Q235B |
|                | CL         | Web member                 | Cold-Formed Channel Steel C16 × 15 × 1 Q235B |
| Monocular frame| Column     | Corner column              | Box 300 × 146 × 16 × 16 Q345B |
|                | Mid-column |                            | H343 × 136 × 10 × 16 Q345B |
|                | Beam       | Frame beam                 | H270 × 100 × 5 × 8 Q345B |
| Panel          | Profiled steel sheet |                        | Plate thickness 0.3 mm Q235B |
|                |            | Panel concrete             | Plate thickness 20 mm Q235B |

| Steel specification | Yield strength $f_y/\text{MPa}$ | Ultimate strength $f_u/\text{MPa}$ | Elasticity modulus $E/\text{MPa}$ |
|---------------------|---------------------------------|----------------------------------|-------------------------------|
| 0.3 mm-thick steel plate | 295                            | 382                              | $2.6 \times 10^5$             |
| 1.0 mm-thick steel plate | 328.4                           | 442.4                            | $2.09 \times 10^6$            |
| 1.5 mm-thick steel plate | 316.8                           | 420.5                            | $2.09 \times 10^6$            |
| 3 mm-thick steel plate | 308.4                           | 454.8                            | $2.09 \times 10^6$            |
| 8 mm-thick steel plate | 418.5                           | 508.5                            | $2.05 \times 10^6$            |
| 16 mm-thick steel plate | 389.8                           | 515.2                            | $2.05 \times 10^6$            |
| Slab concrete      | –                               | 31.8                             | $3.45 \times 10^6$            |

Figure 6. Arrangement of steel truss keel in the prefabricated slab unit.

Table 1. Sectional dimensions for components of specimens.

Table 2. Mechanical properties of the major components.
Figure 8. Load–displacement curves for the key assembly connections under the action of tensile force or shear.

Table 3. Elastic stiffness of the key assembly joints for the new assembly floor system.

| Connection type       | Slab-middle column-I | Slab-middle column-II | Slab-corner column-III | Slab–slab |
|-----------------------|-----------------------|------------------------|------------------------|-----------|
|                       | Shear stiffness       | Tensile stiffness      | Shear stiffness        | Tensile stiffness | Shear stiffness | Tensile stiffness | Shear stiffness | Tensile stiffness |
| Full scale model      | 275                   | 1492.23                | 37.5                   | 1492.23            | 335.6          | 844.8            | 1125.2         | 4675.3               |
| Scale model           | 30.6                  | 165.8                  | 4.17                   | 165.8              | 37.28          | 93.87            | 125.02         | 519.5 (48.4)          | (201.1)
construction was tested under reciprocating load, while the performance of other high-strength bolt assembly connections was studied by unidirectional loading. Figure 8 shows the performance curves of some key assembly connections under the action of tension and shear. The elastic connection stiffness of various types of connections is shown in Table 3. For the connection behaviour of 1/3 scale test floor specimens, it can be analyzed based on the similarity theory. Based on the dimensional analysis, the similarity constants for the shear stiffness (GA) and tensile stiffness (EA) of the assembly connections of test floor specimens are 1/9. Table 3 summarizes the stiffness of slab–slab connection for scale model, and the values in brackets are described in section 3.2.

2.3. Loading scheme

The whole structure is designed according to the requirements of 7 degree seismic fortification, which requires the floor to be able to have basically intact performance under the action of 7 degree rare earthquake (the designed seismic accelerated speed is 0.1 g). Based on this design goal, the control load in the test floor could be determined by equivalent static method (Bull 2004). That is to say, the horizontal force applied on the slab of the floor system is determined by the product of the representative gravity load of the floor and seismic influence coefficient. When determining the control loads for test, the seismic influence coefficient is defined as the maximum value (0.5) that is equivalent to the rare 7 degree seismic loads. Since the surface load of the floor prototype structure is 12$kN/m^2$, the horizontal applied force on the floor plane under the action of strong seismic loads is defined as $F_w=1460$ kN. The load similarity ratio of the model test is $\lambda_p=1/9$ and the horizontal control load in the test is 162 kN.

According to structural layouts and loading conditions of specimens, the loading process was accomplished by the mode shown in Figure 3. The second floor of each specimen was investigated and the way of three-point loading was employed on the investigated floor. That is to say, loads were applied at 1 axis $\times$ B axis, 1 axis $\times$ C axis and 1 axis $\times$ D axis in the parallel direction (parallel to the slab seams) or at A axis $\times$ 2 axis, A axis $\times$ 3 axis and A axis $\times$ 4 axis in the perpendicular direction (perpendicular to the slab seams). The line of applied load pointed to the centroid of the composite beam section. Next, 500 kN jack was placed at each loading point so as to apply the horizontal load in the monotonous mode. At each point, loads increased by 10 kN every time until the failure of specimens. The self-balancing loading device in the test is shown in Figure 9.

2.4. Measurement scheme

The test mainly measured different load levels and the corresponding in-plane displacement of the floor system. Figure 10 shows layout of displacement transducers for different specimens.

In order to investigate the distribution performance of the floor to the horizontal shear force, the test inspected the frame column shear force through the measurement of column strain. Figure 11 shows the strain gauge arrangement of the partial frame posts on the axis parallel to loading direction, where the steel column strain gauges are arranged on the outer side of the frame post and the lower ends of the flange, respectively, as shown in Figure 12a.

Figure 9. Self-balancing loading device.
Moreover, in the course of test, the occurrence and development of cracks in concrete slab of all specimens were recorded in real time.

3. Analysis and discussion of experimental results

3.1. Floor crack pattern

The occurrence and development of cracks in concrete slab of the prefabricated floor system under the action of horizontal load can reflect the overall property of the floor system visually. Crack extension and distribution of specimens under different load levels are presented in

Figure 10. Layout of displacement transducers for specimens.

Figure 11. Layout of displacement transducers for the columns of each specimen.

Figure 12. Location of strain measuring points and shear calculation for frame-columns.

Figure 13. Typical crack extensions on specimens are displayed in Figure 14. The initial horizontal cracking loads of LG1 and LG2 are 210 kN and 180 kN, respectively. Compared with the designed horizontal load (162 kN) of the floor systems corresponding to the load in case of the strong earthquake, the cracking loads of all specimens are no lower than 162 kN. Both the pieces can meet the design requirements.

For the crack distribution characteristics of the test floor slab, there is a significant difference between LG1 and LG2. When the force is parallel to the direction of the assembly slab seam (LG1), the cracks basically develop obliquely from the slab–column assembly connection points on both sides of the floor to the
loading point, which basically accords with the overall bending of the floor. This can indicate that the overall performance of the assembly floor is better when the force is applied parallel to the direction of assembly seam. When the force is perpendicular to the direction of the assembly slab seam (LG2), the cracks first appear in the slab-to-slab splicing area along the transverse slab seam. In the early stage of loading, the cracks mainly appear at the slab unit near the loading point, with the increase of horizontal load, the cracks develop towards the distant slab unit. The internal cracks of each plate element basically develop diagonally to the position of the slab-to-slab connection node, but the regular is not as obvious as that of situation parallel to the assembly slab seam. From the overall situation of the occurrence and development of cracks, the floor is in a state of bending of each assembly slab unit, which indicates that the integrity of the assembly floor should be further improved when loaded in the direction of perpendicular to the assembly slab seam.

3.2. Relative slippage of slab–slab connection

Figure 15 shows the relative deformation of both sides of the slab–slab assembly connection of specimen LG1. As can be seen from the figure that: when the horizontal load does not reach the design level load (162 kN), the slab–slab assembly connection has already produced a relative
slip, and when the load reaches the design level load, the slip value reached to 0.155 mm. Due to the test floor is a 1/3 scale model, the assembly space of connection node is limited. During the assembly construction, part of the connection of high-strength bolts failed to meet the design requirements, which in turn results in the relative slip of the slab–slab assembly connection. Based on the distribution of the slab-to-slab and the tested load-slip values, the initial shear stiffness of the single slab-to-slab connection can be calculated to be 48.4 kN/mm, which is shown in the parentheses of Table 3. Due to the deviation of the pretension of high-strength bolts, the initial stiffness of the slab-to-slab connection is reduced by 61.2%.

3.3. Horizontal shear force distribution

Figure 16 shows the development of the frame column strain at the A axes and 1 axes which parallel to the loading direction of the floor. It can be seen from the figure that the load–strain relationship of the frame column is linearly developed before the cracking of the floor, but the load–strain relationship of the frame column is no longer linearly developed when the concrete slab is cracked, but during the whole loading process the frame columns are in the elastic stage. This indicates that under the design of 7-degree earthquake (this value is less than the cracking load of each test floor), the new assembly composite floor has a stable ability to transfer horizontal loads, but after the concrete slab cracked, such ability has decreased.

The column shear force $V$ of each frame column can be determined by equation (1) before the floor panel is cracked.

$$V = \left( |M_t + M_o| \right) / L \left( \varepsilon_{KL} - \varepsilon_{SR} + \varepsilon_{BR} \right) E W / 2L \quad (1)$$

In formulation (1), $M_t$ and $M_o$ are the column section bending moment of upper and lower sections, respectively, $L$ is the length of the column; $\varepsilon_{KL}$, $\varepsilon_{SR}$ is the left- and right-side strain value of the top flange of the column section; $\varepsilon_{BR}$ is the left- and right-side strain value of the bottom flange of the column; $E$, $W$ are the elastic modulus of the steel and the cross-section modulus of the column, respectively.

According to the formula (1), we can get the shear force of each adjacent frame column. Figure 17 shows the distribution of shear force in the columns under the influence of 7-degree earthquake, the test shear force of some columns in the figure is obtained from the analysis based on the structural symmetry. At the same time, the shear forces of frame columns analyzed...
basing on the rigid floor assumptions are also shown in the Figure. The data in the figure shows that, most of the horizontal loads on the floor are borne by the main lateral frame which is on the both sides of the single-tube structure parallel to the loading direction (such as axis A, B for GL1 and axis 1, 5 for GL2). The figure also shows that there is still a gap between the distribution of horizontal forces on the test floor and that of the rigid floor, especially in the case of loaded perpendicular to the assembly slab seam, in the main lateral frame plane, the maximum deviation exceeds 20%.

3.4. Overall deformation and in-plane stiffness of floor systems

The deformations of the second floor in both two specimens are investigated in detail. Figures 18 and 19 show the overall deformation of each specimen in the loading plane, respectively. Moreover, the horizontal displacements of floor systems at the proximal and distal ends under the designed horizontal load equivalent to strong earthquake were compared. Likewise, the horizontal displacements of floor systems at the far-loading end under different load levels were compared. Finally, the load–displacement distribution at key points on the middle axis of all specimens under different horizontal load levels was further analyzed.

Based on the analysis of the horizontal displacements of both the test floor systems, Table 4 summarizes the overall deformations of the loaded floors under the designed horizontal load. The maximum relative deformation of floor refers to the difference between the average middle-span displacement at far loading axis and the average displacement on both sides. The overall horizontal displacement of floor refers to the horizontal displacement of the floor at centroid (the average displacement at near and far loading ends).

The maximum relative deformation of the floor is the basic parameter that determines the floor rigidity. For example, ASTM E455-2011 (American Society for Testing and Materials 2011a) determines the shear rigidity of the floor by measuring the maximum relative deformation. Based on a contrastive analysis on displacement of floor specimens, it can be found that:

1. The maximum relative deformation of LG1 is 2.2 times that of LG2, which indicates that, for the in-plane shear stiffness of proposed new floor system, the stiffness value under the loading situation of parallel to the assembly slab seam is smaller than that of the situation perpendicular to the assembly slab seam. The assembly direction of floor system has a great influence on the in-plane mechanical property.

2. Although the relative deformation in the plane of LG2 is smaller than that of LG1, but the overall horizontal displacement of LG2 is about 1.5 times that of LG1. This is because the lateral rigidity of the box-shaped corner column (strong axis) under the parallel loads is higher than that under the perpendicular loads, and the truss section rigidity of specimens under the parallel loads is larger than that under the perpendicular loads.

Based on the concept of equivalent shear rigidity in Ge (2007), the equivalent shear stiffness \( k_e \) of the proposed new prefabricated composite floor system can be determined according to Equation (2):

\[
 k_e = \frac{F}{\Delta} \quad (2)
\]

where \( F \) is the total horizontal load of the floor system and \( \Delta \) is the mid-span (far loading end) maximum displacement under the corresponding
(a) Comparison of horizontal displacements at 1-axis (near end) and 5-axis (far end) under the designed horizontal loads.

(b) Horizontal displacement distribution curve of 5-axis (far end) under different horizontal load levels.

(c) Load-displacement curve at different measuring points of C-axis.

Figure 18. The horizontal displacement parallel to the slab seam for the top chord of truss beam (LG-1).

Figure 19. The horizontal displacement perpendicular to the slab seam for the top chord of truss beam (LG-2).

horizontal load. According to the evaluation method of floor stiffness that is reported by ASTM2126-11 (American Society for Testing and Materials 2011b), $0.4F_{\text{max}}$ and the maximum relative horizontal displacement of the floor system are used. In this paper, $F_{\text{max}}W$ as the designed horizontal load (162 kN) equivalent to the 7-degree strong earthquake. The equivalent shear rigidity of floor
system is calculated according to Equation (2). The corresponding result of each test floor is listed in Table 4. Considering the similarity ratio $\lambda$ of the experimental model is 9, the in-plane stiffness of proposed floor system is also calculated and listed in the table.

As for the in-plane shear stiffness of floor system, some research achievements have been indicated already: for cast-in-situ concrete floors, the value is about $2 \times 10^6$ kN (Pang 2008), and for general fabricated hollow concrete floors, the value is about $1 \times 10^6$ kN (Liu, Zeng, and Wang 2007). As can be seen from the results in Table 4, the in-plane stiffness of the proposed new long-span assembly floor system is more than 10 times that of general fabricated hollow concrete floor system, but slightly less than the cast-in-place concrete floor system.

### Table 4. Displacements of each loaded floor under the designed horizontal load.

| Specimens | Maximum relative deformation (mm) | Overall horizontal displacement (mm) | Equivalent shear stiffness of test floor (kN/m) | Equivalent shear stiffness of proposed floor system (kN/m) |
|-----------|---------------------------------|-------------------------------------|---------------------------------|---------------------------------|
| LG1       | 0.73                            | 1.19                                | 122,300                         | 1.1x10^6                       |
| LG2       | 0.33                            | 1.96                                | 131,900                         | 1.187x10^6                     |

**Figure 20.** Layout of the spring unit.

**Figure 21.** Analytical model of the test floors. (a) Model of LG1; (b) Model of LG2.

### 4. Numerical study

The actual configuration of the new assembly composite floor system is relatively complicated. In order to simplify the analytical model, the following simplifications and basic assumptions are made on the floor system during the finite element analysis:

1. **Simplification of the concrete slab on the upper part of the floor:** In the analysis, the profiled steel sheet-concrete composite slab was simplified into a single concrete slab based on the principle of equivalent stiffness;

2. **Hypothesis of combined action between truss beam and concrete slab:** It is assumed that there is no slippage between the upper chord of the steel truss beam and the simplified concrete slab;
(3) Simplification of the key connections: In the overall FE model, the key connections are equivalent to connecting springs, and the tensile and shear performance of the connections are simulated by controlling the axial stiffness of the connection springs;

(4) Assumption of assembly connection stiffness: When determining the equivalent spring stiffness of the key connections, it is assumed that all the springs are linear elastic, and the non-linear development of the connection is not considered. At the same time, in the structural

Figure 22. The basic results of FE analysis on the each test floor system under the designed horizontal force.
analysis process, the spring tension and compression stiffness are considered equal.

4.1. Analytical model

Structural analysis was performed using Midas/Gen finite element program. When establishing the model, the solid element is used to simulate the frame beams and columns; the concrete slab is simulated by slab element; and the truss beam members are simulated by beam element (truss element). As for the key assembly connections, the spring units are used to simulate them. The interior of each assembly slab unit is continuous as a whole, and each the assembly unit is connected into a whole floor by a series of spring units. The arrangement of the spring units is shown in Figures 20 and 21 which show the analysis model of the test floors. Material and connection performance are determined according to the instructions in section 2.2 of this article. Considering the relative slip between the slab–slab connection of the test specimen, the stiffness of the slab–slab connection was reduced based on the actual load–displacement situation. During the analysis of the test floor, the stiffness of the slab-to-slab connection is taken from the values in parentheses in Table 3.

5. Simulation results and model validation

For the test floors of LG1 and LG2, simulation analysis is carried out based on the models of Figures 21 and 22 which show the main results of the finite element analysis under the design load corresponding to the 7-degree rare earthquake, including the overall deformation of the floor system, the overall deformation of the loading floor, and the stress distribution of the beam and column skeleton of the test floor system.

Analyzing the deformation of the second floor of GL1 (Figure 22(b)), it can be seen that the deformation of the floor is not continuous at the far-loading end (near the 5 axis), there is slippage between the slab–slab connection, and the maximum slippage occurs on the B and D axes. The amount of slip is 0.17 mm. Meanwhile, Figure 22(f) shows that each of the four assembly units seems to be in the state of bending respectively. The above analysis results are basically consistent with the experimental phenomenon.

The results of the stress cloud analysis (Figure 22(d)) show that when the load is parallel to the direction of the assembly seam, on both sides of the floor near the loading end (near the A, E axis), there is a tension zone on concrete slab, and the cracks in the slab floor should first appear in such area, which is consistent with the experimental observations. At the same time, the stress distribution of LG2 concrete slabs in Figure 22(h) also illustrates the basic characteristics of the, respectively, bending of each slab unit when the floor is loaded at the direction of perpendicular to the assembly seam.

Based on the stress distribution of the beam-column solid elements in the test floor analysis model of Figure 22(c, f), the shear force of each frame column under the horizontal load can be calculated. Table 5 summarizes and compares the FE analysis results with the test results for the shear forces of the adjacent frame columns. The comparison results show that the analysis results agree well with the test results, with a maximum deviation of about 10%.

Table 6 summarizes the in-plane deformation of each loading floor under the designed horizontal load, where δ is the maximum relative deformation of the floor at the far-loading end, and Δ is the overall horizontal displacement of the loading floor. As can be seen from the table, the analysis results are basically consistent with the test results, with a maximum deviation of about 27%.

Based on the above comparative analysis, it can be seen that the Midas analysis model based on the basic assumptions of this paper and the elastic stiffness value of the key assembly connections reflects the main mechanical characteristics of the new fabricated floor system, which can better simulate the stress and deformation performance of the floor system.

5.1. Analysis of influence of floor concrete slab thickness on in-plane performance of floor

In the new assembly composite floor system, the thickness of concrete slab directly affects the in-plane stiffness of each assembly unit, and therefore it will also have a greater impact on the stiffness of the overall assembly floor system. Based on the Midas analysis model of this paper, the influence of the concrete slab thickness on the in-plane performance of the floor system can be analyzed.

The analysis is based on the full-scale floor shown in Figure 1, and the full-scale floor models corresponding to the test floors LG1 and LG2 are ZCLG1 and ZCLG2, respectively. Based on ZCLG1 and ZCLG2, the full-scale floor analysis models ZCLG1α, ZCLG1β and ZCLG2α, ZCLG2β were constructed which have the same steel truss keel but different thickness of the concrete slab. Table 7 shows the concrete slab thickness and loading model of each full-scale floor model. The thickness of slab in the table refers to the equivalent thickness of the steel-concrete composite slab in the floor system.

During the analysis, the spring stiffness of the assembled connection shown in Figure 20 was determined according to the full-scale test. The designed horizontal load value F of the floor under the 7-degree earthquake is 1460 kN, and 0.4 F (584 kN) is used as the horizontal load for the simulation analysis. The in-
6. Conclusions

In this study, a composite floor structure suitable for industrial assembly was proposed. The in-plane geometric and mechanical performance was investigated through 1/3-scale experimental tests and FE analysis. Through experimental testing, the failure modes, distribution and transmission performance for horizontal force of floor in-plane and the in-plane stiffness were identified at the direction of parallel to the assembly slab seam and perpendicular to the assembly slab seam, respectively. An FE model was established for the proposed floor system and validated with experimental tests. Based on the finite element model analysis, the influence of the thickness of the concrete panel on the in-plane performance of the floor was discussed. The main conclusions are as follows:

### Table 5. Comparison of frame-column shear between test and FE analysis values for the test specimens.

| Specimens | Location of column | Experimental results | FE analysis results | n   |
|-----------|--------------------|----------------------|-------------------|-----|
|           |                    | V_{test}/kN          | V_{analysis}/kN   |     |
| LG1       | 1-axis/A-axis      | 12.1                 | 11.4              | 5.80%|
|           | 2-axis/A-axis      | 17.9                 | 17.5              | 2.20%|
|           | 3-axis/A-axis      | 17.7                 | 17.2              | 2.80%|
| LG2       | 1-axis/E-axis      | 11.3                 | 10.1              | 10.6%|
|           | 1-axis/D-axis      | 18.5                 | 17.9              | 3.20%|
|           | 1-axis/C-axis      | 18.1                 | 18.4              | −1.70%|

Note: n = (experimental result – EE analysis result)/experimental result.

### Table 8. Comparison of in-plane displacements for the analysis floor models loaded at the direction parallel to the assembly slab seam (mm).

| Slab thickness/mm | Displacement at the far loading end/mm | Equivalent shear rigidity (kN/m) |
|-------------------|----------------------------------------|---------------------------------|
| 1.511             | 1.022                                  | 1.196x10^6                     |
| 1.541             | 1.075                                  | 2.349x10^6                     |
| 1.547             | 1.077                                  | 2.479x10^6                     |

### Table 9. Comparison of in-plane displacements for the analysis floor models loaded at the direction perpendicular to the assembly slab seam.

| Slab thickness/mm | Displacement at the far loading end/mm | Equivalent shear rigidity (kN/m) |
|-------------------|----------------------------------------|---------------------------------|
| 1.022             | 1.075                                  | 1.196x10^6                     |
| 1.075             | 1.077                                  | 2.349x10^6                     |
| 1.077             | 1.077                                  | 2.479x10^6                     |

### Table 6. Comparison of the deformation of loaded floor for each test model under the designed horizontal force.

| Specimens | Experimental result | FE results | Deviation | Experimental result | FE results | Deviation |
|-----------|---------------------|------------|-----------|---------------------|------------|-----------|
|           | δ/mm                | δ/mm       |           | Δ/mm                | Δ/mm       |           |
| LG1       | 0.73                | 0.53       | 27%       | 1.19                | 1.04       | 12.7%     |
| LG2       | 0.33                | 0.29       | 12.1%     | 1.96                | 1.51       | 22.9%     |

Deviation = (experimental result−FE results)/experimental results.

### Table 7. Basic parameter and loading model of full-scale floor analysis model.

| Model   | ZCLG1      | ZCLG1a     | ZCLG1b     | ZCLG2   | ZCLG2a    | ZCLG2b    |
|---------|------------|------------|------------|---------|-----------|-----------|
| Slab thickness/mm | 60         | 100        | 120        | 60      | 100       | 120       |
| Loading mode     | Loading parallel to the direction of the assembly slab seam | Loading perpendicular to the direction of the assembly slab seam |
(1) Under the action of horizontal load in the floor plane, the cracking loads of test floor LG1 and LG2 are 210 kN and 180 kN, respectively, which exceed the design floor horizontal force (162 kN) corresponding to the 7-degree earthquake. The new prefabricated composite floor can be in an elastic working state under the condition of 7-degree seismic fortification.

(2) At the direction of parallel to the assembly slab seam and perpendicular to the assembly slab seam, the in-plane stiffness of the new prefabricated composite floor is $1.1 \times 10^6 \text{kNm}$ and $1.187 \times 10^6 \text{kNm}$ respectively when the thickness of concrete slab is 60 mm. The values of stiffness of the floor system are relatively close in both directions, and the influence of assembly orientation of slab units is not significant on the in-plane stiffness of the new floor system.

(3) The thickness of the concrete slab is an important factor for the in-plane stiffness of the new prefabricated composite floor system. When the concrete slab thickness increases from 60 mm to 100 mm, the in-plane stiffness of the floor system in the two directions of parallel and perpendicular to the assembly slab seam increases by 2.35 times and 2.37 times, respectively, the stiffness increases significantly, while, as the thickness of the slab is further increased, this increasing trend slows down significantly.

(4) The assembly orientation of slab units has a greater influence on the overall deformation performance of the new floor system. When loaded at the direction of parallel to the assembly slab seam, the overall deformation performance of the floor system is similar to that of the deep beam, while, when it is loaded at the direction of perpendicular to the assembly slab seam, each assembly slab unit of the floor system shows an independent bending state, the integrity of the floor system needs to be improved. Follow-up research should further consider how to improve the overall performance of the floor.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

**Funding**

The research work was supported by the National Natural Science Foundation of China [No. 50978089], Natural Science Foundation of Hunan Province [No. 2018JJ2020] and Scientific Research Project of Hunan Provincial Department of Education [19A095].

**References**

American Society for Testing and Materials. 2011a. E455: Standard Test Method for Static Load Testing of Framed Floor or Roof Diaphragm Construction for Buildings. West Conshohocken,PA.

American Society for Testing and Materials. 2011b. E2216: Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings. West Conshohocken,PA.

Bernardi, P., R. Cerioni, F. Leurini, E. Michelini. 2016. “A Design Method for the Prediction of Load Distribution in Hollow-core Floors”. Engineering Structures 123: 473–481. doi:10.1016/j.engstruct.2016.06.008

Brambilla, G., M. Lavagna, G. Vasdavellis, C. A. Castiglioni, et al. 2019. “Environmental Benefits Arising from Demountable Steel-concrete Composite Floor Systems in...
Han, C. “Study on Seismic Performance Test and Design Method of Prefabricated New Floor Structure.” PhD thesis, Xi’an University of Architecture and Technology, 2016. (In Chinese).

Han, C., Y. Zhang, and Q. Li. 2016. “Experimental Study on Shear Connection of Fully-assembled Concrete Floor at Horizontal Joints.” Industrial Building 46 (11): 80–85. (In Chinese).

Hegger, J., T. Roggendorf, and N. Kerkeni. 2009. “Shear Capacity of Prestressed Hollow Core Slabs in Slim Floor Constructions.” Engineering Structures 31 (2): 551–559. doi:10.1016/j.engstruct.2008.10.006.

Lam, D. 1998. “Composite Steel Beams Using Precast Concrete Hollow Core Floor Slabs.” PhD thesis, University of Nottingham.

Lam, D., K. S. Elliott, and D. A. Nethercote. 2000a. “Experiments on Composite Steel Beams with Precast Concrete Hollow Core Floor Slabs.” Proceedings of the Institution of Civil Engineers - Structures and Buildings 140 (2): 127–138. doi:10.1680/stbu.2000.140.2.127.

Lam, D., K. S. Elliott, and D. A. Nethercote. 2000b. “Designing Composite Steel Beams with Precast Concrete Hollow-core Slabs.” Proceedings of the Institution of Civil Engineers - Structures and Buildings 140 (2): 139–149. doi:10.1680/stbu.2000.140.2.139.

Lam, D., X. Dai, U. Kuhlmann, J. Raichle, M. Braun et al. 2015. “Slim-floor Construction–design for Ultimate Limit State.” Steel Construction 8 (2): 79–84. DOI:10.1002/stco.201510019.

Lawson, M., P. Beguin, R. Obiala, M. Braun et al. 2015. “Slim-floor Construction Using Hollow-core and Composite Decking Systems.” Steel Construction 8 (2): 85–89. DOI:10.1002/stco.201510018.

Li, Q., L. Ge, and C. Han. 2016. “Experimental Study on In-plane Stiffness of New Fabricated Floor.” Building Structure 46 (10): 50–55. (In Chinese).

Li, Q., S. Li, and J. Weishan. 2016. “Experimental Study on Shear Performance of New Prestressed Hollow Floor.” Building Structure 46 (10): 43–49. (In Chinese).

Liu, D., F. Zeng, and M. Wang. 2007. “Seismic Space Analysis of Building Structure with Semi-rigid Floor System.” Building Construction 37 (10): 30–38. (In Chinese).

Loss, C., and A. Frangi. 2017. “Experimental Investigation on In-plane Stiffness and Strength of Innovative Steel-timber Hybrid Floor Diaphragms.” Engineering Structures 138: 229–244. doi:10.1016/j.engstruct.2017.02.032.

Loss, C., M. Piazza, and R. Zandonini. 2016a. “Connections for Steel-timber Hybrid Prefabricated Buildings. Part I: Experimental Tests.” Construction and Building Materials 122: 781–795. doi:10.1016/j.conbuildmat.2015.12.002.

Loss, C., M. Piazza, and R. Zandonini. 2016b. “Connections for Steel–timber Hybrid Prefabricated Buildings. Part II: Innovative Modular Structures.” Construction and Building Materials 122: 796–808. doi:10.1016/j.conbuildmat.2015.12.001.

Ma, Z., M. He, and R. Ma. 2014b. “Horizontal Lateral Resistance Test of Light Steel-wood Mixed Floor.” Shock and Vibration 33 (8): p. 90–95.

Ma, Z., M. J. He, and R. L. Ma. 2014a. “Tests for a Light Wood–steel Hybrid Diaphragm’s Anti-racking Performance.” Journal of Vibration and Shock 33-B: 90–95. (In Chinese).

Moroder, D. “Floor Diaphragms in Multi-storey Timber Buildings.” PhD thesis, University of Canterbury, 2016, Christchurch, New Zealand.
Naito, C., W. Peter, and L. Cao. 2006. *Development of a Seismic Design Methodology for Precast Diaphragms—Phase 1 Summary Report. ATLSS (Advanced Technology for Large Structural Systems) Report No.06-03.* Bethlehem, PA: ATLSS Center, Lehigh University.

Pang, R., Q. Li, L. Wang, et al. 2019. “Dynamic Characteristics and Seismic Response Analysis of Distributed Connected Fully-Assembled RC Building Structure.” *Earthquake Resistance and Reinforcement of Engineering* 41 (4): 64–72. (In Chinese).

Pang, R., S. Liang, and X. Zhu. 2010. “Research on In-Plane Mechanical Characteristics of New Fully Prefabricated RC Floor.” *Special Structure* 27 (1): 30–35. (In Chinese).

Pang, R., S. Liang, and X. Zhu. 2012. “Experimental Study on Seismic Performance of Fully Assembled RC Floor Joints.” *Journal of Building Materials and Structures* 33 (10): 59–66. (In Chinese).

Pang, R., Q. Li, L. Wang, et al. 2019. “Analysis of Bearing Capacity and In-plane Deformation of New Prefabricated Reinforced Concrete Floor.” PhD thesis, Southeast University, 2008, Nanjing, China. (In Chinese).

Su, T., “Static and Dynamic Performance Analysis of Steel Open Web Truss Beam-Open Web Sandwich Plate Structure System.” Master’s thesis, Guizhou University, 2019. (In Chinese).

Yan, Y. “Research on Calculation Method of In-Plane Stiffness of Distributed Connected Fully-Assembled RC Floor.” Master’s thesis, Henan University of Technology, 2018. (In Chinese).

Zhang, Z.-M., K.-J. Ma, and Y.-L. Zhong. 2013. “Construction and Engineering Application of New Large-span Steel-Concrete Composite Open Web Sandwich Slab Floor.” *Journal of Guizhou University (Natural Sciences)* 30 (5): 113–117. (In Chinese).

Zheng, W., and M. G. Oliva. 2005. “A Practical Method to Estimate Elastic Deformation of Precast Pretopped Double-tee Diaphragms.” *PCI Journal* 50 (2): 213. doi:10.15554/pcij.03012005.44.55.