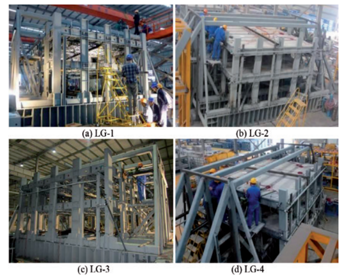
Experimental study on the mechanical properties of a new long-span prefabricated truss composite floor system



Estudio experimental sobre las propiedades mecánicas de un nuevo sistema de forjado de celosía prefabricada para grandes luces

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RESUMEN

- La carga horizontal es el principal factor de control de las estructuras prefabricadas de gran altura y el sistema de forjados es la pieza clave que garantiza la transmisión efectiva de las cargas horizontales al sistema estructural. Sin embargo, las propiedades mecánicas de los sistemas prefabricados tradicionales, incluyendo los de pisos de madera y de hormigón, son pobres. Por lo tanto, ninguno de ellos puede ser adecuado para estructuras prefabricadas de grandes luces. Con el fin de mejorar las propiedades mecánicas de los sistemas de forjado, en este estudio se propone uno nuevo, formado por una celosía y compuesto por cuatro unidades realizadas en fábrica y ensambladas por medio de pernos en obra, que se pueden utilizar en estructuras prefabricadas de grandes luces. Se realizaron pruebas de carga unidireccional horizontales en 4 modelos estructurales de bastidor de dos pisos que fueron diseñados con el concepto del nuevo sistema de forjado. Tomando como objeto de análisis la segunda planta de cada modelo, se analizaron las características de fallo en horizontal, la deformación, y la resistencia al cizallamiento equivalente. Por último, también se evaluó la integridad y la rigidez en horizontal del nuevo forjado. Los resultados indican que todas las cargas de fisuración de la losa de hormigón en el nuevo sistema de forjado son superiores a la carga horizontal equivalente estipulada por la normativa en China en caso de un terremoto poco frecuente de grado 7. Además, medidas adicionales de refuerzo (por ejemplo, el vertido de adhesivos estructurales en la junta de la losa principal y la colocación de una banda in situ entre el forjado y la viga del bastidor) pueden aumentar considerablemente las propiedades mecánicas del nuevo sistema de forjado. El patrón de distribución de las fisuras en la losa de hormigón pasa de una distribución local irregular punteada a una distribución lineal significativa, lo que indica que la integridad del sistema de pisos se fortalece enormemente. Más concretamente, la resistencia de cizallamiento equivalente del forjado es de 3,4-5,3 veces superior a la anterior, en el que no se han tomado medidas de refuerzo y, al mismo tiempo, la rigidez lateral total del sistema se incrementa en 2 veces, lo que significa que la rigidez en horizontal se incrementa significativamente mediante la toma de las medidas de refuerzo. Es decir, el forjado se transforma de un suelo elástico en un forjado rígido. Por lo tanto, el estudio puede proporcionar una referencia para la popularización y aplicación del sistema de forjado mixto de celosía prefabricado propuesto.
- **Palabras clave:** Forjado mixto prefabricado, Sistema de forjado mixto de celosís, Junta de la losa de ensamblaje, Resistencia en horizontal, Integridad del forjado, Forjado rígido, Forjado semi-rígido.

ABSTRACT

Horizontal load is the main controlling factor of high-rise prefabricated structure and floor system is a fundamental part that ensures the effective transmission of horizontal load in the structural system. However, the mechanical properties of traditional prefabricated systems including wooden floor and concrete floor are poor. Thus, neither of them is suitable for long-span prefabricated structures. In order to improve the mechanical properties of floor systems, a new truss composite floor composed of four factory-made floor units and assembled by bolts on site that could be applied to the long-span prefabricated structure was proposed in this study. In-plane unidirectional loading tests were performed on 4 two-story frame structural models in order to study the response of the different parameters involved in the proposed floor system. Taking the second floor of each model as the analysis object, the in-plane failure characteristics, deformation, equivalent shear stiffness were analyzed. At last, the integrality and in-plane stiffness of the new floor were also evaluated further. Test results indicate that all of the cracking loads of concrete slab in the new floor system are greater than the equivalent horizontal force of floor that is stipulated by China code in case of 7-degree rare earthquake. In addition, the reinforcement measures (e.g. pouring structural adhesives into the major slab seam and setting a post-cast stripe between floor and frame beam) can improve the mechanical properties of the new floor system greatly. The distribution pattern of cracks on concrete slab evolves from irregular local dotted distribution into significant linear distribution, which indicates that the integrality of the floor system gets strengthened greatly. More specifically, the in-plane equivalent shear stiffness of the floor is 3.4-5.3 times that of the previous one in which the reinforcement measures are not taken, at the same time, the overall lateral stiffness of the floor system is increased by 2 times, which means that the in-plane rigidity is significantly enhanced after taking the reinforcement measures. That's to say, the floor is transformed from a semi-rigid floor to a rigid floor. Therefore, the experimental study can provide the reference for the popularization and application of the proposed prefabricated truss composite floor system.

Keywords: Prefabricated composite floor, Truss composite floor system, Assembling slab seam, In-plane stiffness, Integrality of floor, Rigid floor, Semi-rigid floor.

1. INTRODUCTION

In the overall structural system of buildings, the floor system plays a fundamental role in the transmission and distribution of vertical and horizontal loads. Under the action of horizontal load, sufficient horizontal stiffness and integrity in the plane of floor system are required. Besides, reliable connection between the floor system and horizontal resistance system against lateral displacement of wall columns is demanded, which assures efficient transmission of vertical and horizontal loads.

Prefabricated floor systems can meet the requirement of industrial production of components to the maximum extent, and promote the industrialization development of architectures significantly so that they can be widely developed and put into use all over the world. With the ever-increasing development of individual demand, building structure is gradually evolving into the large-size and long-span structure [1-2]. Therefore, it is necessary to develop long-span prefabricated floor systems.

The traditional wooden floor and concrete floor composite systems have relatively poor in-plane mechanical properties that render them unsuitable for long-span prefabricated structure [3-4]. On the contrary, ordinary steel-concrete composite floor systems possess better in-plane mechanical properties, but the structural steel beams are also inapplicable to long-span prefabricated structure because of their restricted height [5-6]. In steel truss-concrete composite floor systems, the lower part adopts the steel truss system and the upper part adopts the profiled steel sheet and concrete slab, and the two parts are combined into a steel truss composite floor by the bolts. Thus, they possess good mechanical properties and are applicable to long-span prefabricated structures [7]. Nevertheless, the prefabricated floor system must be transported by vehicles from the factory to the construction site for assembly, which sets limitation on the size of floor. Therefore, long-span prefabricated floor system is generally assembled with several components, which makes the long-span prefabricated floor system significantly different from the traditional integral cast-in-place floor system in terms of in-plane mechanical properties. However, the in-plane stiffness and integrality exert huge impact on the overall structural properties of floor systems.

Currently, there are few studies on in-plane mechanical properties of such prefabricated truss composite floor systems. As a result, how to disclose and improve in-plane mechanical properties of the prefabricated composite floor system is a problem that has to be solved urgently.

For this reason, a new prefabricated steel truss composite floor system which was applicable to long-span structure was proposed and its in-plane mechanical properties including the in-plane stiffness and integrality of the floor were discussed.

2. STATE OF THE ART

Currently, horizontal stress analysis of structures is generally based on the rigid floor hypothesis, which contradicts the fact that under the action of horizontal stress, the in-plane elastic deformation in the floor system will occur, moreover, the in-plane rigidity significantly affects the anti-seismic capability of the whole structure [8]. Generally speaking, in-plane rigidity mainly serves as an indicator to analyze in-plane mechanical properties of the floor system, distribution and transmission of in-plane horizontal load caused by the floor system as well as the overall deformation behaviour of the floor system. On the whole, relevant studies on in-plane mechanical properties of prefabricated floor system have been carried out until recently.

Compared with other types of prefabricated floor systems, existing experimental studies paid much more attention to the in-plane mechanical properties of wooden floor (steel-wooden floor) systems. Fuentes and his team [9] carried out an experimental study on the in-plane rigidity of a typical prefabricated wooden floor system equipped with wooden joist slab and finally got the load-displacement curve and the rigidity degeneration of the floor system under the action of cyclic loads. However, one major drawback of his work is that he didn't conduct a quantitative analysis of in-plane rigidity of the floor system. Anna et al. [10] proposed a simplified calculation formula that can be used to evaluate the rigidity of the prefabricated floor system. Based on a pseudo static test on the light steel-wooden composite floor system, Ma et al. [11] concluded that 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 10kN/mm under both loading modes. The critical problem lies in the fact that the wooden floor systems (steel-wooden floor systems) in above-mentioned studies are commonly characterized by small horizontal bearing capacity and low in-plane rigidity and hence they are inapplicable to the long-span buildings.

Furthermore, experimental studies on in-plane properties of prefabricated concrete floor systems have been reported successively. In order to study the in-plane mechanical properties of fully prefabricated concrete floor system, Pang and his colleagues [12] performed an in-plane pseudo static test on a fully prefabricated reinforced concrete floor system model with a span of 8.4m and proved the necessity of anti-seismic design method relative to elastic floor system, besides, the test results showed that the internal stress distribution pattern of this floor system under in-plane loads was close to that of simply supported beams, but the floor cracks were mainly distributed in the vicinity of the joints of slab seams, presenting local failure characteristics, which meant that the integrality of fully assembled floor system was ordinary. For the purpose of analyzing the in-plane mechanical properties of the prefabricated concrete floor system, Li et al. [13] tested in-plane mechanical properties of a new prefabricated concrete floor system with a span of 3.6m and found that the in-plane rigidity of this floor system was about 6 times higher than those of ordinary prefabricated floor systems, proving that prefabricated integral floor system was superior to fully prefabricated floor system in terms of in-plane properties. However, the post-cast stripe in this prefabricated integral floor system required in-situ formwork, which resulted in a great deal of workload. Through an in-plane mechanical property test on the prefabricated profiled steel sheet composite floor system with monolayer support-steel frame structure, Sarkissian et al. [14] discovered that in-plane mechanical properties perpendicular to the supporting beams were better than that parallel to the supporting beams. This reflected that all of the prefabricated floor system belonged to the anisotropic mechanical system. Hence, the in-plane mechanical properties of the prefabricated floor system in different directions have to be taken into consideration. Bournas [15] and Negro[16] carried out a pseudo-dynamic test on the concrete framework composed of a three-story prefabricated floor system in order to analyze the influence of lateral resistance system type and beam-column connection mode on the in-plane mechanical properties of the floor system. Obviously, all of these similar studies mainly focused on the traditional steel-wooden composite floor system and prefabricated concrete floor system with small span and the majority of scholars were inclined to carry out pseudo-static or pseudodynamic tests. However, few experimental studies focused on the unidirectional in-plane loading process.

Scholars from all over the world have explored the mechanical properties of different types of concrete composite floor systems. Frangi et al. [17] developed a new prefabricated steel-concrete composite floor system by using the T-shaped honeycombed beam and the bending test demonstrated that the molded floor system had desirable overall properties and it could realize the bidirectional transmission of force. It was exactly a prefabricated composite floor system worthy of reference, but its in-plane mechanical properties were not researched. Peng et al. [7] implemented a vertical mechanical model test on a new steel truss-concrete composite floor system with a span of 45m and the results revealed that this floor system possessed good mechanical properties, hence, it was perfectly suitable for the long-span floor system. However, what a pity was that the in-plane horizontal load was not tested yet. In general, a lack of research on whether the prefabricated long-span composite floor system composed of several truss components meets requirements of structural properties still exists.

To overcome the deficiency of existing studies, a new prefabricated truss composite floor system applicable to long-span structure was proposed in this paper. It is composed of four factory-made floor units and assembled by bolts on site. The integrality of the assembled composite floor system is quite different from that of the cast-in-place floor system, and the rigidity of the floor is to be empirically investigated.

In order to study in-plane stiffness property and integrality of the new floor system, an in-plane horizontal mechanical property test was carried out with the scaled model of a monocular structural unit. The in-plane deformation properties of the floor system parallel and perpendicular respectively to the assembling slab seam were studied. Moreover, failure characteristics, equivalent shear stiffness and deformation behaviour of different planes in the floor system were analyzed. Besides, the influence of reinforcement measures (e.g. pouring structural adhesives in major slab seams and setting post-cast stripe between the floor and frame beam) on the properties of the proposed new floor system was discussed. The test and analysis results can provide references for the engineering application and popularization of the new prefabricated composite floor system proposed in this paper.

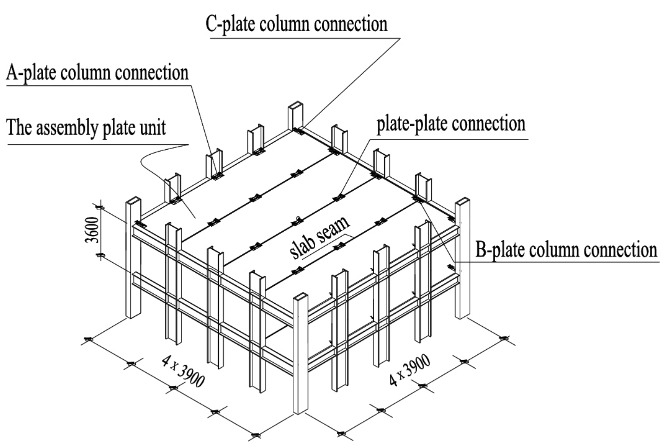


Fig. 1: Structure of the new prefabricated truss composite floor system

The other sections of this study are organized as follows: Section 3 introduces design, structure and test procedures of four specimens. Section 4 carries out the contrastive analysis and discussion including crack distribution on concrete slab in the floor system, failure characteristics of the floor system, deformation behaviour of the floor system and in-plane shear stiffness and evaluates the in-plane rigidity of this type of floor. Section 5 summarizes the conclusions.

3. METHODOLOGY

3.1. SPECIMEN DESIGN AND STRUCTURE

The newly proposed monocular prefabricated truss composite floor system is shown in Fig.1. The system was assembled by four major slab units (truss composite floor system) and its plane size was 15.6mx15.6m. The surrounding 16 columns were arranged uniformly at an interval of 3.9m. Finally, a multi-column frame-tube structure was formed by connecting the surrounding frame beams and the floor.

4 two-story single-tube frame models with the scale of 1/3 structures were designed and built in order to test the in-plane mechanical properties of the proposed floor system. The resemblance constant (ratio of physical parameter of the scale model to that of the real floor) of the model is 1/3, the resemblance constant of the material elastic modulus is 1, and the resemblance constant of other physical parameters is shown in Table 1 (see section: supplementary material).

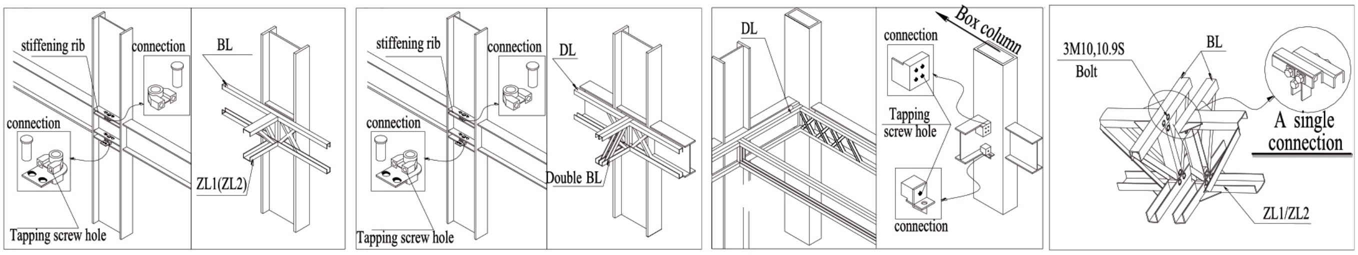
The classification and loading conditions of these test models are shown in Table.2. As an anisotropic mechanical system, the rigidity of prefabricated floor system can significantly vary in different stress directions [11, 14]. In order to analyze the in-plane rigidity of the proposed floor system in different directions and the influence of joint strengthening on its mechanical properties, two forms of prefabricated truss composite floor systems were considered in the study.

Type-I fully prefabricated floor system: the assembling floor system was formed by the way of connecting the major slab units with high-strength bolts. Besides, this assembling floor system is connected with the frame-tube columns through special joints, but there's no connection between the assembling floor system and peripheral frame beams. The fully prefabricated floor system is completed in this way.

Type-II reinforced prefabricated integral floor system: based on the type-I fully prefabricated floor system, the assembly seam be-

Specimen Number	Specification of models and loading conditions
LG-1	Type -I fully prefabricated floor system; Parallel to the slab seam
LG-2	Type-II reinforced prefabricated integral floor system; Parallel to the slab seam
LG-3	Type -I fully prefabricated floor system; Perpendicular to the slab seam
LG-4	Type-II reinforced prefabricated integral floor system; Perpendicular to the slab seam

Table. 2: Classification of model specimens



(a) (b) (c) (d)

Fig. 5: Slab-column connection and slab-slab connection for type-I specimens. (a) Slab-middle column connection (Mode A). (b) Slab-middle column connection (Mode B). (c) Slab-corner column connection (Mode C). (d) Slab-slab connection

(a) LG-1 (b) LG-2

(c) LG-3 (d) LG-4

Fig. 8: The overview of the assembling specimens

tween concrete slabs is poured with SIKA structural adhesives, in addition, the gap between the assembly floor system and the surrounding frame beams is reinforced by the post-cast stripe. In this way, the connection of prefabricated integral floor system is formed.

The structure of the testing floor system is shown in Fig.2 (see section: supplementary material). The steel truss skeleton of assembling slab units in the floor system is shown in Fig.3 (see section: supplementary material). The basic structure of the concrete slab in the type-I fully prefabricated floor system is shown in Fig.4 (see section: supplementary material). The slab-column and slab-slab connections in the type-I fully prefabricated floor system are shown in Fig.5. Two major improvements of the type-II reinforced prefabricated integral floor system based on the type I fully prefabricated floor system are shown in Fig.6 (see section: supplementary material). Assembling structures and loading modes of different specimens are shown in Fig.7 (see section: supplementary material). The cross-sectional dimensions and material properties of the components in the prototype and model floor system are shown in Table 3(see section: supplementary material). The general appearance of assembling specimens is shown in Fig.8, and the connection of the feet of frame columns is considered to be rigid.

3.2. MEASUREMENT OF MATERIAL'S MECHANICAL PROPERTIES

In the proposed floor system, the Q235B profiled steel sheet with a concrete strength of C30 was used. The average compressive strength of fine aggregate concrete in slab measured 31.8MPa and the compressive strength of SIKA structural adhesive was 50.3MPa. However, the elasticity modulus of structural adhesive was about 1/10 of that of concrete. The test results concerning other major material's mechanical properties are shown in Table.4 (see section: supplementary material).

3.3. LOADING SCHEME

As for the design requirements of the floor prototype structure, it is regulated by China code[18] that the structure must basically remain stable and intact in case of the rare 7-degree seismic load (the designed seismic accelerated speed is 0.1g). Based on this design goal, the control load in the floor test should be determined by equivalent static method [19]. That's to say, the horizontal force applied on the plane 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 load. Because the surface load of the floor prototype structure is 13.3 kN/m^2, the horizontal applied force on the floor plane under the action of strong seismic loads is defined as F_w=1618kN. In the specimen set, resemblance constant of load is I_p=1/9 and the horizontal control load in the test is 180 kN.

According to structural layouts and loading conditions of specimens, the loading process was completed by the mode shown in Fig.7. The top floor of different specimens was investigated and the way of 3-point loading was employed to the top floor plane of different specimens. That's to say, loads were applied at 1axis×B axis, 1 axis×C axis and 1 axis×D axis in the parallel direction (parallel to the slab seams) or at A axis×2 axis, A axis×3 axis and A axis×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, 500kN jack was placed at each

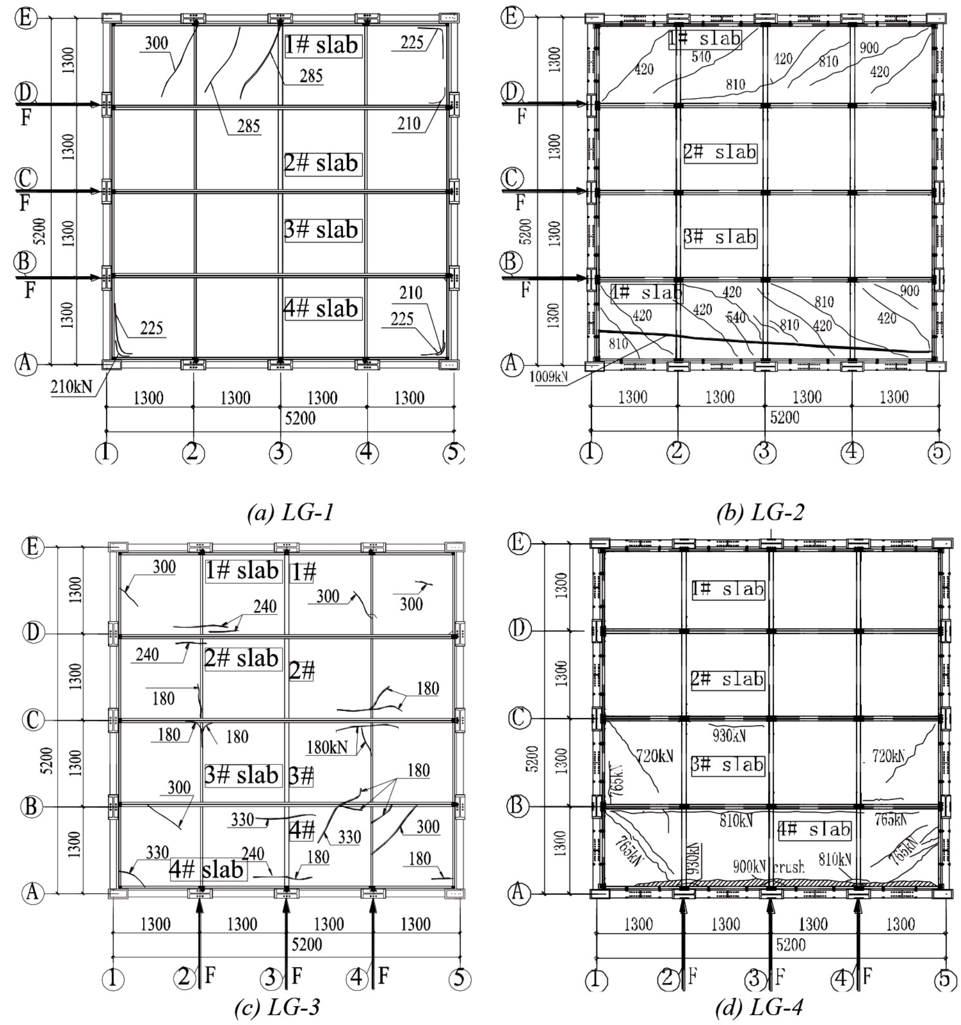


Fig. 11: Distribution of cracks on the slabs of different specimens

loading point so as to apply the horizontal load in the monotonous mode. At each point, loads increased by 10kN every time until the failure of specimens. The self-balancing loading device in the test is shown in Fig.9 (see section: supplementary material).

3.4. LAYOUT OF MONITORING POINT AND CORRESPONDING MEASUREMENT

The test mainly measured different load levels and the corresponding in-plane displacement of the floor system. Layout of displacement transducers for different specimens is shown in Fig.10 (see section: supplementary material).

Moreover, in the course of test, the occurrence and development of cracks on concrete slab of all specimens were recorded in real time.

4. RESULTS AND DISCUSSION

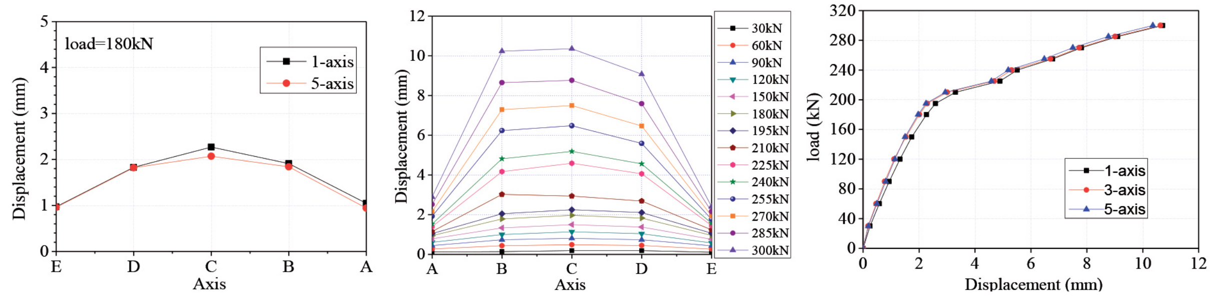
4.1. FAILURE CHARACTERISTICS OF FLOOR SYSTEM

The occurrence and development of cracks on concrete slab of the prefabricated floor system under the action of horizontal load can reflect the overall properties of the floor system visually. Crack extension and distribution on specimens under different load levels are presented in Fig.11. Typical crack extensions on specimens are displayed in Fig.12 (see section: supplementary material). The initial horizontal cracking loads of LG-1~LG-4 are 210kN, 420kN, 180kN and 720kN, respectively. Compared with the designed horizontal load (180kN) of the floor systems corresponding to the load in case of the strong earthquake, the cracking loads of all specimens are no lower than 180kN.

It can be seen from Fig.11 that three cracks on LG-1 extend from the slab-column connection on both sides of the floor system to the loading point, which basically corresponds to the overall bending deformation state of the floor system. However, cracks mainly appear at edges of major slabs, presenting irregular dotted distribution. On the contrary, the cracks on LG-2 generally show regular distribution. They all extend from the slab-column connection on both sides of the floor system to the loading point, which corresponds to the overall bending deformation state of the floor system. These phenomena verify the good overall properties of the new prefabricated composite flow systems under the action of parallel loads. Moreover, the integrality of type-II floor system (LG-2) is significantly superior to that of the type-I floor system (LG-1).

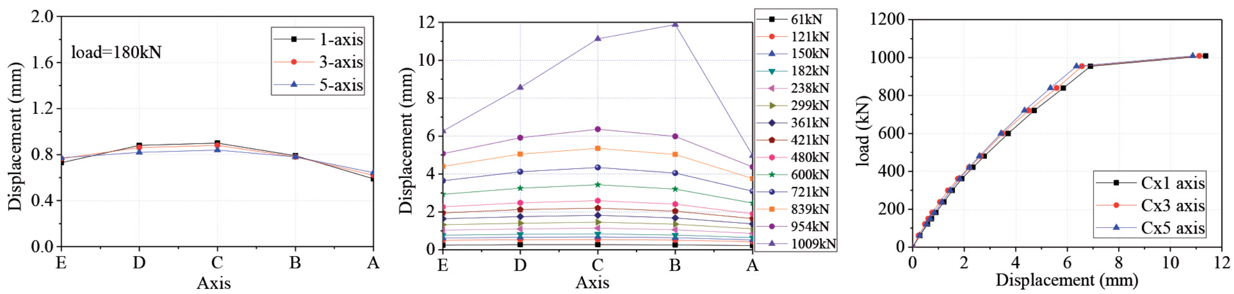
Cracks firstly occurred on the slab seam of LG-3. In early stage, the cracks mainly concentrated at the slab unit in the vicinity of the loading end. With the increase of horizontal load, cracks extend toward the slab unit that is farther away from the loading end. Cracks in different slab units basically extend toward the slab-slab connection in the inclined pattern, showing dotted failure characteristics. According to the overall occurrence and development of cracks on LG-3, all assembly units are bended independently in all floor systems, indicating the general property of LG-3. On LG-4, cracks mainly extend from slab-column connection on both sides of the floor system to the loading point, accompanied with the cracks parallel to the slab seams. However, these cracks parallel to the slab seams are only distributed on two major slabs adjacent to the loading side. This implies that the upper concrete of two other major slabs bears a small load. This can be explained as follows. Because the elasticity modulus of structural adhesive is only 1/10 of that of the concrete, there's uncoordinated deformation between the structural adhesive and the concrete slab. However, the response of the type-II floor system (LG-4) is better than that of the type-I floor system (LG-3).

Type-II floor systems (LG-2 and LG-4) developed overall stress failure of concrete. The cracks on the floor systems of type-I (LG-1 and LG-3) present the dotted failure characteristics. In other words, the slab concrete is characterized by local failure. Comparatively speaking, the overall property of type-II prefabricated integral floor system is apparently superior to that of type-I floor system, but the horizontal integrality is superior to the transverse integrality.



(a) (b) (c)

Fig. 14: The horizontal displacement parallel to the slab seam for the top chord of truss beam (LG-1). (a)Comparison between horizontal displacements at 1-axis (near-loading axis) and 5-axis (far-loading axis) under the designed horizontal loads. (b) Horizontal displacement distribution curve of 5-axis (far-loading axis) under different horizontal load levels. (c) Load-displacement curve at different measuring points of C-axis



(a) (b) (c)

Fig. 15: The horizontal displacement parallel to the slab seam for the top chord of truss beam(LG-2). (a) Comparison between horizontal displacements at 1-axis (near-loading axis) and 5-axis (far-loading axis) under the designed horizontal loads. (b) Horizontal displacement distribution curve of 1-axis (far end) under different horizontal load levels. (c) Load-displacement curve at different measuring points of C axis

The relative deformations at both sides of slab-slab connection when the load is parallel to the slab seam (LG-1 and LG-2) are presented in Fig.13 (see section: supplementary material). Even when the horizontal load is lower than the designed value (180kN), the slab-slab connection of LG-1 begins to develop relative slippage. When the horizontal load reaches the designed value, the average relative slippage at measuring points of LG-1 reaches 0.16mm. The horizontal dislocation at the slab-slab connection of LG-2 is nearly zero when the total horizontal load is lower than 600kN, which indicates that the shear capacity at connection increases greatly after the structural adhesives are poured into the slab seams.

4.2. DEFORMATION BEHAVIOUR OF FLOOR SYSTEMS

The deformations of the second floor and the adjacent frame columns below the second floor in all specimens are investigated in detail. The deformations of the second floor of LG-1~LG-4 were recorded, as shown in Fig.14, Fig.15, Fig.16 (supplementary material) and Fig.17 (supplementary material), respectively. Moreover, the horizontal displacements of floor systems at the near and far loading 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 axes of all specimens under different horizontal load levels was further analyzed.

The deformation characteristics of all specimens are displayed in Fig.14~Fig.17. 1) When the in-plane horizontal load of all specimens is lower than the cracking load, the floor deformation is basically shown as a symmetric pattern and there exists an obvious linear section in the load-displacement curve at measuring points on the middle axis. 2) The load-displacement curve at measuring points on the middle axis of type-I floor systems (LG-1 and LG-3) shows an evident turning point when the horizontal load approaches the cracking load, followed by continuous increase of the load-displacement curve. The load-displacement curve of type-II floor systems (LG-2 and LG-4) is kept linear throughout the loading process, without any evident turning point. 3) As far as the truss beam of LG-3 is concerned, its overall deformation at the near loading end is apparently different from that at the far loading end which shows a parabola distribution. It can be revealed from the analysis that the local buckling of truss beam on the floor close to the loading end is the main factor that gives rise to the overall deformation. For the truss beam of LG-4, its overall deformation at the near loading end is consistent with that at the far loading end which shows a parabola distribution. This indicates that the integrality of the type-II floor systems is strengthened significantly by means of pouring structural adhesives into the slab seams.

Comparisons of horizontal displacements on the near-loading axis and far-loading axis for different floor systems are shown in Fig.14(a), Fig.15(a), Fig.16(a) and Fig.17(a), respectively. The overall deformations of the loaded floors under the designed horizontal load (180kN) equivalent to the strong earthquake are listed in Table.5. The maximum relative deformation of floor refers to the difference between the average middle-span displacement on the axis perpendicular to the floor and the average displacement on both sides. The average lateral displacement of the lower adjacent lateral resistance structure refers to the average of the horizontal displacement of the four frame corner columns at the elevation of the second floor.

The maximum relative deformation of the floor is the basic parameter that determines the floor rigidity. For example, ASTM E455-2011 [20] determines the shear stiffness of the floor by measuring the maximum relative deformation. The data of the near-loading axis are used to calculate the shear stiffness in this study. Based on a contrastive analysis on displacement of floor specimens, it can be found that under the perpendicular loads, the maximum relative deformation of type-I floor system is 5.3 times that of type-II floor system, likewise, under the parallel loads, the maximum relative deformation of type-I floor system is 3.4 times that of type-II floor system, which reflects that the shear rigidity of type-I floor system is far smaller than that of the type-II floor system.

Based on the concept of equivalent shear stiffness in Reference [1], the equivalent shear stiffness (k_e) of the proposed new prefabricated composite floor system can be determined according to the equation (2):

$$k_e = F/\Delta` \qquad (2)$$

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 horizontal load. According to the evaluation method of floor stiffness that is reported by ASTM2126-11[21], $0.4F_{max}$ and the maximum relative horizontal displacement of the floor system are used. In this paper, F_{max} was the designed horizontal load (180kN) equivalent to the 7-degree strong earthquake. The equivalent shear stiffness of floor system is calculated according to equation (2). The corresponding results are listed in Table 5.

It can be seen from the average lateral displacement of the lower adjacent lateral resistance structure (Table 5) that the average lateral displacement of the lower adjacent lateral resistance structure of LG-3 (perpendicular to the slab seam) is about 1.5 times that of LG-1 (parallel to the slab seam), and similarly, the the average lateral displacement of the lower adjacent lateral resistance structure of LG-4 (perpendicular to the slab seam) is about 1.5 times that of LG-2 (parallel to the slab seam). This is because the lateral stiffness of the box-shaped corner column (strong axis) parallel to the slab seam is greater than that perpendicular to the slab seam and the truss section (rigidity) of specimens parallel to the slab seam is greater than that perpendicular to the slab seam. Given the same loading process, the average lateral displacement of the lower adjacent lateral resistance structure of type-II floor system is about 50% that of type-I floor system, indicating that the overall later rigidity of type-II floor system is about twice that of the type-I floor system.

4.3. EVALUATION OF IN-PLANE RIGIDITY OF THE NEW FLOOR

Rigidity refers to the ability of the floor to distribute and transmit the horizontal force and coordinate the deformation of the surrounding lateral resistance components under the horizontal load. Generally, it can be classified as three types: rigid, flexible and semi-rigid floor. It has been pointed out in the literature [22] that the rigidity of the floor is not only related to the in-plane stiffness of the floor itself, but also to the stiffness and distribution of the lateral resistance components. That is to say, the rigidity of the floor is a relative concept, and its analysis and evaluation should not only be based on the stiffness of the floor, but also be based on the stiffness of the corresponding lateral resistance structure. The existing seismic codes for buildings in the United States (ASCE41-13) [23] clearly define the classification of the rigidity of the floor. The classification method is based on the ratio of the maximum relative displacement in the floor plane to the average lateral displacement of the lower adjacent lateral resistance structure (Fig. 18 see section: supplementary material). When the evaluation index λ_{ASCE}=MRD/ADLS<0.5, the floor is defined as a rigid floor; when λ_{ASCE}=MRD/ADLS>2.0, the floor is rated as a flexible floor; and when 0.5≤ λ_{ASCE}=MRD/ADLS≤2.0, the floor is rated as a semi-rigid floor.

Table 5 shows the values of the in-plane rigidity evaluation index for the new prefabricated composite floor proposed in this paper based on US specification. According to the rigidity evaluation index ASCE shown in Table 5, the evaluation index of the I-type prefabricated composite floor is greater than 0.5 and less than 2. According to the evaluation criteria of ASCE41-13, the type I prefabricated composite floor can be judged as a semi-rigid floor. The evaluation index of the Type II prefabricated composite floor is less than 0.5. According to the evaluation criteria of ASCE41-13, the Type II perfabricated composite floor can be judged as a rigid floor. It manifests that the reinforcement measures (e.g. pouring structural adhesives into the major slab seam and setting a post-cast stripe between floor and frame beam) can significantly improve the mechanical properties of the new floor system, and the floor is transformed from a semi-rigid floor to a rigid floor.

5. CONCLUSION

In order to improve the in-plane mechanical properties of the prefabricated floor system, a new truss composite floor system applicable to long-span structure was proposed based on the experimental study. Unidirectional loading tests were carried out on four floor models. Failure characteristics, in-plane equivalent shear stiffness and deformation behaviour of the new floor system proposed in this study were analyzed further. In addition, key attentions were also paid to the influence of reinforcement measures (e.g. pouring structural adhesives in main slab seams and setting post-cast stripe between the floor and frame columns) on in-plane stiffness and integrality of the floor. According to the

Floor number	Maximum relative deformation of floor (mm)		Equivalent shear rigidity (kN/m)	Average lateral displacement of the lower adjacent lateral resistance structure ADLS (mm)	Rigidity evaluation index based on US specification λ_{ASCE}	Evaluation results of floor rigidity
	Near-loading axis	Far-loading axis				
LG-1 Type -I (parallel to the slab seam)	1.262	1.02	142631	1.36	0.93	Semi-rigid floor
LG-2 Type –II (parallel to the slab seam)	0.24	0.13	750000	0.71	0.34	Rigid floor
LG-3 Type -I (perpendicular to the slab seam)	1.265	0.38	142292	2.03	0.62	Semi-rigid floor
LG-4 Type-II (perpendicular to the slab seam)	0.37	0.10	486486	1.04	0.36	Rigid floor

Table. 5: Displacements of each loaded floor under the designed horizontal load

observations and measurements from these tests, the following conclusions could be drawn.

(1) Under the action of in-plane horizontal load, cracking loads of all four specimens are no smaller than the designed horizontal load of floor in response to the regulated 7-degree rare strong earthquake.

(2) The integrality of floor systems parallel to the slab seams is better than that perpendicular to slab seams. The overall lateral rigidity of floor systems parallel to the slab seams is greater than that perpendicular to the slab seams. It is suggested that the cross-sectional form of the corner post can be changed so that the lateral stiffness value along two directions are relatively close.

(3) Reinforcement measures for the new floor systems, such as pouring structural adhesives in major slab seams and setting post-cast stripe between the floor and frame columns, can effectively improve the in-plane mechanical properties of the floor system. Cracks on the concrete slab evolve from irregular local dotted distribution to significant linear distribution. The corresponding cracking load of the concrete slab increases by 2~4 times. Likewise, the in-plane equivalent shear rigidity increases by 3.4~5.3 times. The overall lateral stiffness of the floor system increases by 2 times. In a word, the in-plane rigidity and overall properties of the floor system are strengthened significantly.

(4) Pouring structural adhesives into the major slab seam and setting a post-cast stripe between floor and frame beam can significantly improve the mechanical properties of the new floor system, and the floor is transformed from a semi-rigid floor to a rigid floor.

The new long-span prefabricated floor system proposed in this study can meet the design requirements of horizontal loads (equivalent to 7-degree rare strong earthquake). The reinforced prefabricated integral floor system is superior to the fully prefabricated floor system in terms of mechanical properties. The test and analysis results can provide references for the popularization and application of similar prefabricated truss composite floor system. In future studies, it should be taken into consideration that the materials possessing the similar elasticity modulus with concrete can be chosen to fill the slab seams. At the same time, it is possible to test the seismic performance of the new floor system proposed in the study through the quasi-static experiment in the future study.

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SUPPLEMENTARY MATERIAL

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