

## Research Article

# Experimental Study and Numerical Simulation on Mechanical Properties of the Bottom Plate in the Assembled Composite Slab with Additional Steel Trusses

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The composite slab with steel trusses is composed of precast bottom plate and cast-in-place concrete. In engineering applications, cracks often appear in the bottom plate before casting the upper concrete, which even leads to the failure of the composite slab. To improve the crack resistance of the slab, a composite slab with additional steel trusses is proposed; that is, on the basis of the original longitudinal steel trusses, the transverse steel trusses are added. Static test and numerical analysis were carried out on the bottom plate of the new type of composite slab with the additional transverse steel trusses. The experimental and analytical results show that the load level of the plate with additional steel trusses can be increased by 33% under the normal service limit state; the deflection of the plate is significantly reduced and the crack development is effectively controlled, which illustrates that the new type of composite slab can improve the bearing capacity, increase the bending stiffness, and enhance the crack resistance effectively.

## 1. Preface

The composite slab with steel trusses has been widely used in prefabricated buildings, and it is composed of precast bottom plate and cast-in-place upper concrete [1].

The precast bottom plate is produced in the factory, transported to the construction site for installation, and then used as the formwork for casting the upper concrete so that the composite slab is formed, as shown in Figure 1.

Many experts and scholars have carried out the study on the properties of composite plates with steel trusses [2–9] and have achieved some results. Lu et al. [10] analyzed the dynamic behavior and serviceability of a new type of U-shaped steel-concrete composite floor slab. Huang et al. [11] carried out the experimental study on flexural behavior of lightweight multiribbed composite slabs. Wu et al. [12] studied the shear capacity of open sandwich steel plate-concrete composite slab by experiment and analysis. Nam

et al. [13] and Hanus et al. [14] presented a kind of composite concrete slab with the FRP bottom plate. Zhang et al. [15] carried out loading tests on the steel trusses composite slabs with close joints on the side and obtained the conclusion that the stiffness of the slab belt perpendicular to the splicing seam is slightly lower than that in the parallel direction. Li et al. [16] tested the flexural behavior of four different types of steel trusses composite slabs, and the results showed that the deflection is the controlling factor of the slab design.

The above research results provide valuable experimental data and research materials for exploring the mechanical properties of steel trusses composite slabs and provide theoretical basis and experimental support for the optimization and popularization of composite slabs.

Existing research studies mainly focus on the overall mechanical properties of the composite slabs, while there is relatively little research on the mechanical properties of the bottom plate serving as formwork.



FIGURE 1: The composite slab with steel trusses.

In fact, in the engineering application, it is often found that the bottom plate cracks before field installation, especially the wide plate, resulting in the composite slab failing to be used. To solve this problem, a type of composite slab with additional steel trusses is proposed; that is, on the basis of the original longitudinal steel trusses, the transverse steel trusses is added perpendicular to the direction of the original trusses, as shown in Figure 2.

To investigate the effect of the additional transverse steel trusses on the mechanical performance and cracking state of the bottom plate, the static loading test and numerical simulation analysis were carried out for the plates with additional steel trusses and the traditional plate with one-way steel trusses.

## 2. Mechanical Property Test

**2.1. Test Preparation and Process.** Three bottom plates with different forms were made by experiment to study the mechanical properties and cracking characteristics contrastively, which serial numbers are DHB1, DHB2, and DHB3. The first plate, DHB1, is the bottom plate of B90 composite slab with one-way steel trusses, which is commonly used in the design atlas “reinforced concrete composite slab with steel trusses” (15G366-1). On the basis of DHB1, the second plate DHB2 is added with three additional transverse steel trusses to form a new type of plate with two-way steel trusses. The thickness of the third plate DHB3 is reduced by 20 mm on the basis of DHB2. The dimensions of the three plates are all 4200 mm × 2400 mm, the thickness of DHB1 and DHB2 is 60 mm, and the thickness of DHB3 is 40 mm. The longitudinal and transverse reinforcement in the bottom plate are HRB400 with 8 mm diameter per 200 mm, the upper chord member of the longitudinal trusses is HRB400 with 10 mm diameter, the lower chord member is HRB400 with 8 mm diameter, and the web member is HPB235 with 6 mm diameter. The length of the additional transverse steel trusses is 2300 mm, the upper chord member is HRB400, with 10 mm diameter, and the web member is HPB235 with 6 mm diameter, with no lower chord. C25 concrete is used in the plates, and the thickness of the concrete cover is 15 mm. The specific sizes of the three plates, DHB1, DHB2, and DHB3, are shown in Table 1, and the test plates are shown in Figure 3.

To be consistent with the actual engineering, the bottom of each plate is supported by 6 points. A wooden cushion block is placed at each point. The block size is 200 mm × 100 mm × 100 mm. The distance between the block and the edge of the plate is 200 mm, and the spacing of the blocks is 1900 mm, as shown in Figure 4. The positions of the displacement meter and strain gauge are also shown in Figure 4.

The load was applied step by step with an increment of 0.12 kN/m<sup>2</sup>, and a load holding time of 5 min for each level. The midspan deflection was recorded with the load increasing, and the development of cracks in the bottom of the plates was observed and marked. The ZBL-F800 comprehensive crack tester was used for observing cracks, with a range of 0–6 mm and an accuracy of ±0.01 mm, as shown in Figure 5.

Considering the safety of the full-scale test, this test is not a destructive test; the serviceability limit state was taken as the comparison state of the plates. According to the specification of the deflection limiting value and the maximum crack width of the plate, one of the following conditions is satisfied, and the plate is considered to reach the serviceability limit state: (1) the midspan deflection reaches 9 mm and (2) the maximum crack width is 0.2 mm.

**2.2. Test Data and Analysis.** The uniformly distributed load is applied on the plate, increasing step by step, and the load of each step is set at 0.12 kN/m<sup>2</sup>.

For plate DHB1, when loading to level 5 (0.6 kN/m<sup>2</sup>), tiny cracks began to appear in the bottom of the plate, with the length of about 600 mm and the width of 0.02 mm. When loading up to level 12 (1.44 kN/m<sup>2</sup>), the cracks on the edge of the bottom were connected with the midspan cracks to form continuous cracks. When loading to level 15 (1.8 kN/m<sup>2</sup>), a 0.2 mm crack appeared in midspan; it is considered to reach the serviceability limit state, and the plate cracks of DHB1 are shown in Figure 6.

For plate DHB2, when loading to level 12 (1.44 kN/m<sup>2</sup>), tiny cracks began to appear in the bottom of the plate, with the length of about 500 mm and the width of 0.02 mm. When loading up to level 15 (1.8 kN/m<sup>2</sup>), cracks appeared on both left and right sides of the plate. When loading to level 17 (2.04 kN/m<sup>2</sup>), long cracks appeared in midspan, with about 1100 mm in length. When loading to level 20 (2.4 kN/m<sup>2</sup>), a 0.2 mm crack appeared in midspan; it is considered to reach the serviceability limit state, and the plate cracks of DHB2 are shown in Figure 7.

For plate DHB3, when loading to level 5 (0.6 kN/m<sup>2</sup>), tiny cracks began to appear in the bottom of the plate, with the length of about 300 mm and the width of 0.01 mm. When loading up to level 7 (0.84 kN/m<sup>2</sup>), long cracks appeared in midspan. When loading up to level 12 (1.44 kN/m<sup>2</sup>), the cracks on the edge of the bottom were connected with the midspan cracks to form continuous cracks. When loading to level 14 (1.68 kN/m<sup>2</sup>), a 0.2 mm crack appeared in midspan; it is considered to reach the serviceability limit state, and the plate cracks of DHB3 are shown in Figure 8.

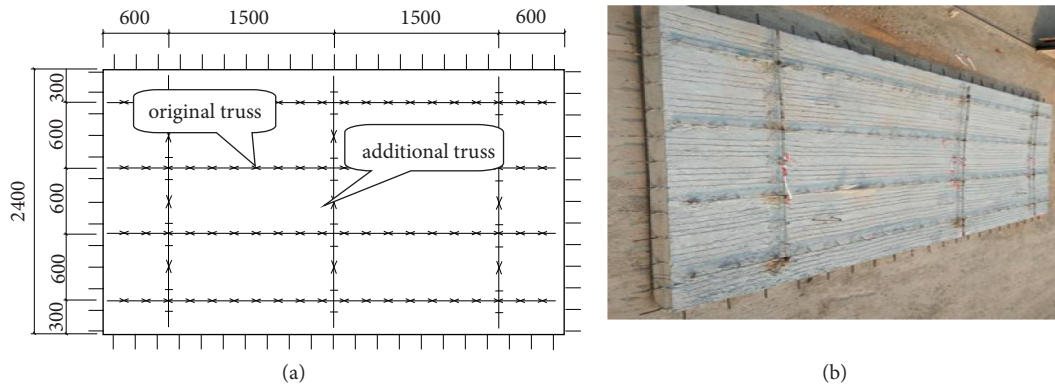


FIGURE 2: The new type of composite slab with additional steel trusses. (a) Diagrammatic sketch (mm). (b) Engineering photo.

TABLE 1: The specific sizes of the plates.

Plate number	Truss type	Plan view size (mm)	Thickness (mm)
DHB1	One-way steel trusses	4200 × 2400	60
DHB2	Two-way steel trusses	4200 × 2400	60
DHB3	Two-way steel trusses	4200 × 2400	40

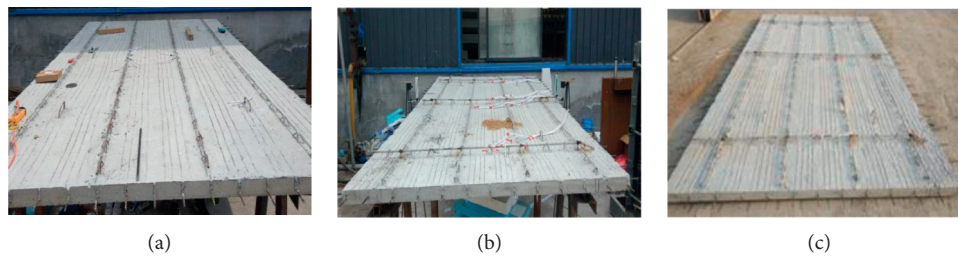


FIGURE 3: The test plates. (a) DHB1. (b) DHB2. (c) DHB3.

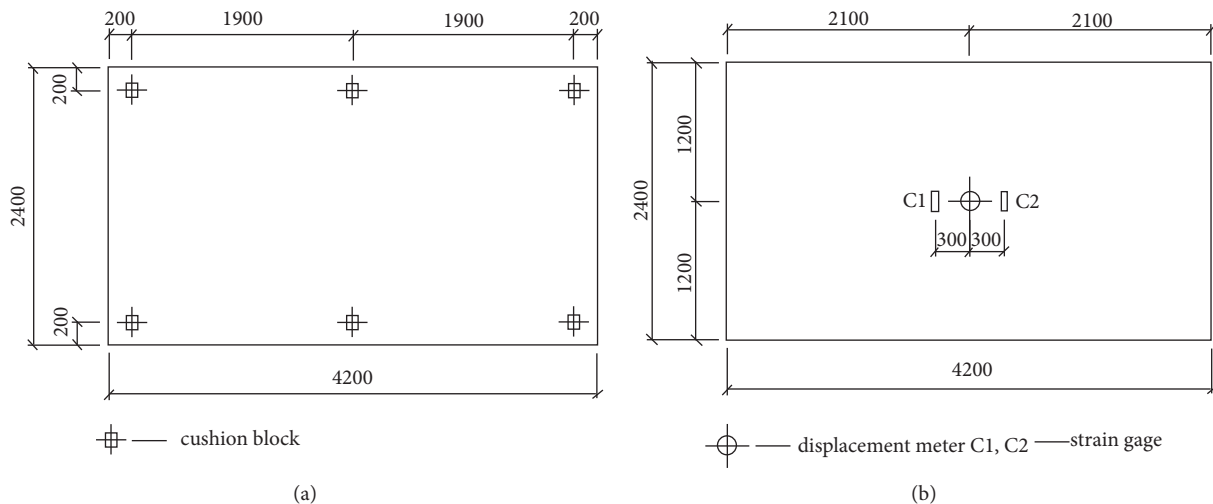


FIGURE 4: The positions of (a) cushion block position (mm) and (b) displacement meter and strain gage position (mm).

It can be seen from the above test that, for DHB1 and DHB2 with the same thickness of 60 mm, DHB2 added the lateral additional steel trusses, which load was increased by 33% compared with DHB1 in the serviceability

limit state. Compared with DHB1, DHB3 added lateral additional steel trusses, and its thickness was reduced from 60 mm to 40 mm. In the case of the bottom plate thickness decreased by 20 mm, the crack development law



FIGURE 5: Comprehensive crack tester. (a) Tester. (b) Testing process.



FIGURE 6: The plate cracks of DHB1.

and the load serviceability limit state of both were very close. The above indicates that the two-way steel trusses can effectively improve the bearing capacity and control the cracks, as well as reduce the plate thickness.

The reason for the crack of the bottom plate is that its thickness is small before pouring the upper concrete, which leads to the insufficient transverse flexural stiffness and further leads to the crack of the bottom slab. Additional steel trusses are added in the short span direction to form two-way trusses, it can be shown from the test that the two-way trusses can increase the stiffness and effectively control the crack development of the plate.

Figure 9 shows the load-deflection contrastive curves of DHB1, DHB2, and DHB3.

It can be seen from the curves in Figure 9 that the development trend of midspan deflection is consistent in the three plates.

At the initial stage of loading, the deflection varied with the load slightly; then, with further increasing of the load, the deflection increased significantly. As shown in Figure 9, under the same load, the deflection values of DHB3 with two-way steel trusses 40 mm thickness are very similar to those of DHB1 with one-way steel trusses 60 mm thickness, while those of DHB2 with two-way steel trusses 60 mm thickness is significantly smaller. The deflection value of DHB2 is about 50% of that of the other two plates in its serviceability limit state. It is further indicated that the setting of the additional transverse steel trusses can significantly improve the stiffness of the plate.

### 3. Numerical Simulation

The finite element software ABAQUS [17, 18] was used to analyze the above test process, and the mechanical properties parameters were inputted according to the material performance test. That is, the yield strength of steel bars with diameters of 10, 8, and 6 are 450 MPa, 420 MPa, and 320 MPa, respectively. The damage parameters and plastic strains [19] of concrete in compression are given in Table 2.

The bottom plate model is established and meshing is carried out. The mesh size has a certain influence on the calculation accuracy, so the mesh division of the plate is as dense as possible to maintain high calculation accuracy. The entire floor is divided into 14,000 units; the finite element model of the two-way steel trusses plate is shown in Figure 10 (the one-way steel trusses' plate has only longitudinal steel trusses).

The six points of support were set according to the test conditions, and the finite element model after loading is shown in Figure 11.

Load is applied step by step, the load-deflection curves comparing the calculated values with the test values and the cloud chart of the three plates DHB1, DHB2, and DHB3 are shown in Figures 12–14, respectively.

By comparing the three plates with different trusses forms and thicknesses, it can be found that the calculated values of the deflection have the same development trend with the experimental values, and the two results are in good agreement.

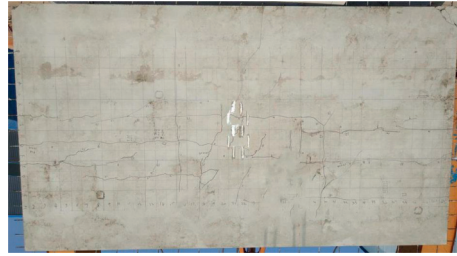


FIGURE 7: The plate cracks of DHB2.



FIGURE 8: The plate cracks of DHB3.

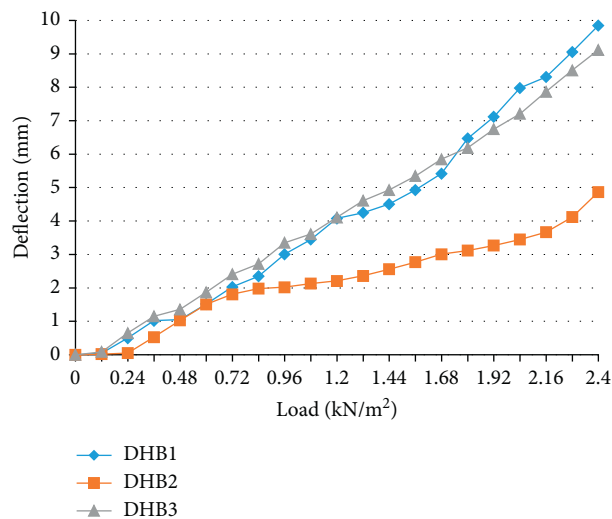


FIGURE 9: The load-deflection contrastive curves of DHB1, DHB2, and DHB3.

TABLE 2: The stress-plastic strain properties of concrete in compression.

Stress (MPa)	Plastic strain	Damage parameter
11.781	0.000	0.000
23.562	0.001	0.139
22.337	0.002	0.387
19.277	0.003	0.543
16.431	0.004	0.647
14.122	0.005	0.719
12.293	0.006	0.771
10.839	0.007	0.810
9.666	0.008	0.839
8.706	0.009	0.862
7.909	0.011	0.880
7.239	0.012	0.895
6.668	0.013	0.907
6.177	0.014	0.917

TABLE 2: Continued.

Stress (MPa)	Plastic strain	Damage parameter
5.750	0.015	0.926
5.377	0.016	0.933
5.047	0.017	0.939
4.754	0.018	0.944
4.492	0.019	0.949
4.256	0.020	0.953
4.043	0.021	0.957
3.850	0.022	0.960
3.673	0.023	0.963
3.512	0.024	0.965
3.364	0.025	0.967

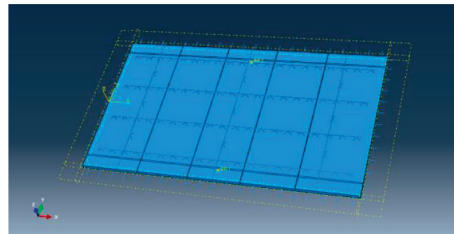


FIGURE 10: Finite element model of the two-way steel trusses' plate.

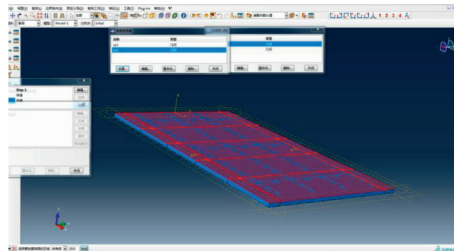


FIGURE 11: Loading model.

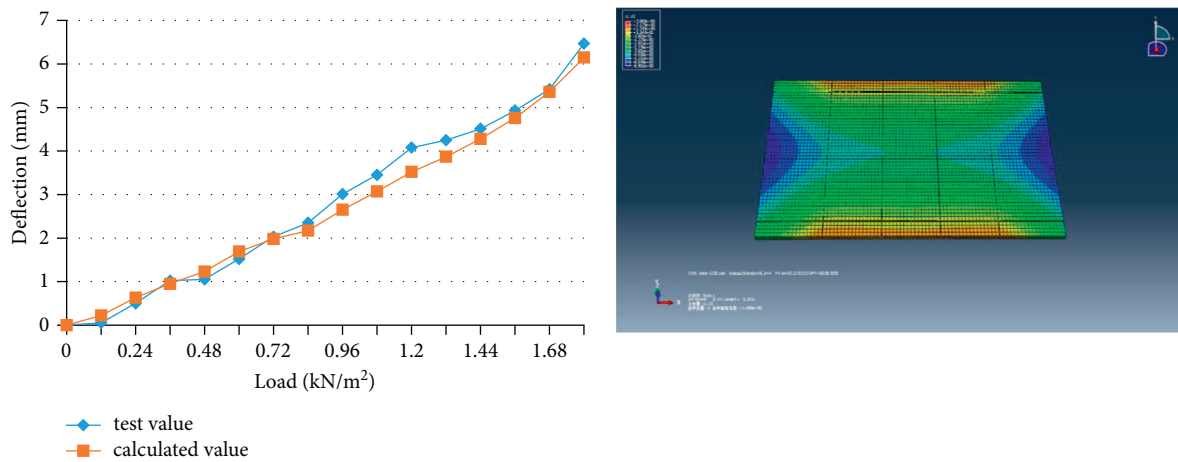


FIGURE 12: The deflection of DHB1. (a) Load-deflection curves. (b) Cloud chart.

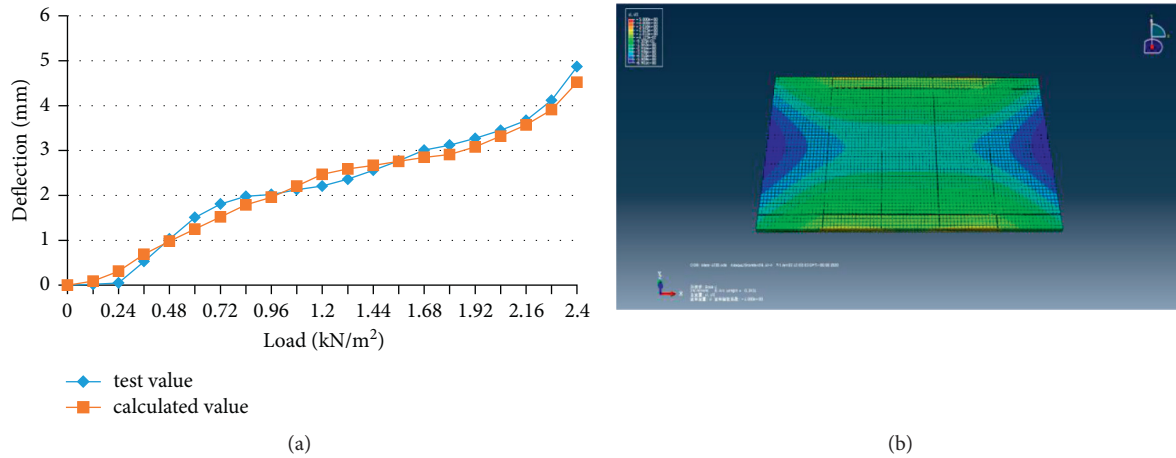


FIGURE 13: The deflection of DHB2. (a) Load-deflection curves. (b) Cloud chart.

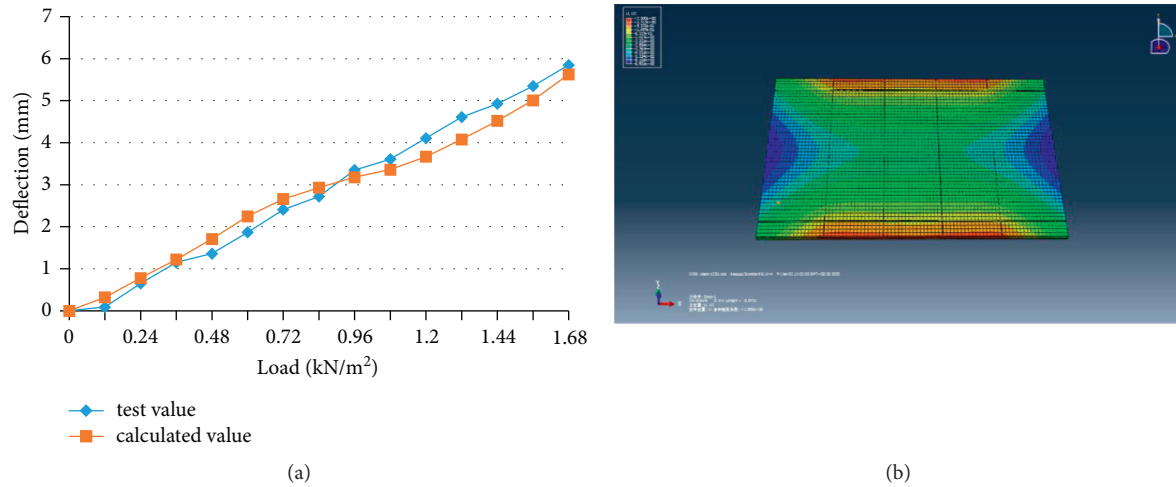


FIGURE 14: The deflection of DHB3. (a) Load-deflection curves. (b) Cloud chart.

Under the same load, the calculated value of deflection is relatively small because there is a slip phenomenon of reinforcement in the test, which is not considered in the process of calculation so that the calculated value is smaller than the experimental value.

#### 4. Conclusion

Based on the experimental research and numerical simulation of three plates with different trusses' forms and thicknesses, the following conclusions are obtained:

- (1) The transverse additional steel trusses are beneficial to the improvement of the crack resistance and the integral stiffness of the plate.
- (2) The load in the serviceability limit state can be increased greatly for the plate with additional transverse steel trusses. For the research object in this paper, this value is increased by 33%.
- (3) The plate with smaller thickness with additional transverse steel trusses can achieve similar stiffness

and cracking performance as the thick plate of one-way steel trusses. For the object studied in this paper, the thickness can be reduced by 20 mm.

- (4) The finite element analysis is in good agreement with the test, which indicates the correctness of the finite element model and analysis method and provides the basis for more parameter simulation in the future.
- (5) The spacing of the additional transverse steel trusses has a certain influence on the stiffness and cracking performance of the plate. The reasonable spacing will be further studied in the follow-up work.

#### Data Availability

The data supporting the results of this study are available from the corresponding author by request.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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