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Improvement of a Truss-Reinforced, Half-Concrete Slab Floor System for Construction Sustainability

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Abstract: The truss-reinforced half-concrete slab has been widely used in prefabricated construction all over the world. It has become the most widely used prefabricated component form in China. However, its construction cost is higher than using the conventional construction method. To improve the half slab floor system, it is essential to have a comprehensive understanding of the truss-reinforced half slab's structural performance over its complete loading history. Six experimental tests on such slabs were carried out. Three of them were reinforced with a steel bar truss (SBT) and the other three with a steel tube/bar truss (STBT). The steel tube in an STBT was grouted. The results show that when the specimen is damaged, the grouted steel tube does not undergo out-of-plane or in-plane buckling, and its force performance is good when compared to the steel bar in SBT. Compared with the SBT-reinforced slab specimens, the load characteristic values of the STBT-reinforced slabs were significantly improved, and the slabs had greater initial stiffness and resistance to deformation. Due to the fact that good structural performance of the steel tube was observed, after having studied the half slab component design, a dry, prefabricated, STBT-reinforced half slab system that can reduce the volume of concrete and amount of steel used in the present slab system is proposed. The proposed system has the advantages of allowing easier construction, cost reduction, and reuse of the components afterward to make the prefabrication construction more sustainable.

Keywords: precast concrete slab; steel tube; truss-reinforced slab; bearing capacity



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1. Introduction

From the perspective of the worldwide development of prefabricated buildings, researchers and practitioners generally agree upon the facts that prefabrication improves the speed of construction on site; the quality and accuracy in manufacturing; the efficiency of materials; and worker safety, while limiting the environmental impacts of construction, such as construction waste and CO₂ emissions and causing less disturbances to the building site's neighbors by minimizing on-site noise and dust [1–9]. It has gotten an increasing amount of momentum over the last few decades as a way to promote sustainable construction [10]. Although it is arguable that low cost is the advantage of prefabricated concrete buildings, when all the cost factors are considered, there are essentially no countries in the world where the cost of prefabricated construction is much lower than that of cast-in-place concrete buildings. Asamoah et al. [11] analyzed cost estimating of the structural frame by considering cast-in-place and precast concrete slabs and columns, respectively. Their study indicated that precast concrete slabs were on average 23.22% cheaper than the cast-in-place concrete elements, and precast columns were on average 21.4% cheaper than cast-in-place concrete columns. Dineshkumar and Kathirvel [8] performed a comparative study on prefabrication construction with the cast in-situ construction of double story residential buildings in India. Their findings indicated that the prefabrication construction cost for individual double story residential buildings is 13% more than the conventional construction in this case. At the same time, the prefabricated parts were easy to work with, and the project's duration was reduced by 63 days when compared to the conventional. Nanyama et al. [12] studied the construction costs of two projects in India. Project

1 was a 36,000 sq. ft. residential project and project 2 was a luxury project consisting of a 4500 sq. ft. villa. The cost comparison shows that the precast building was 16% more expensive than the conventional building for project 1 and 29% more than the conventional building for project 2. Karthikeyan et al. [13] studied a G + 7 story housing board colony building in India to compare the costs of precast and in-situ construction. The cost of prefabricated construction was 6% less than conventional construction. Vinoth Kumar and Nagavinothini [6] conducted a comparative study on the prefabrication and the conventional construction of a single story residential building. They revealed that the total duration of the project could be reduced up to 42.5% with the adoption of prefabrication technology. The comparison also showed that the total cost of the prefabricated construction was 20% more than the conventional method of construction. With the acceleration of the Chinese national housing industrialization process, prefabricated building structures have developed rapidly. However, the cost of prefabricated concrete buildings in China is much higher than that of cast-in-place buildings. Mao et al. [14] applied a multiple-case study method to conduct an in-depth analysis on expenditure items of implementing OSC (off-site construction) against conventional construction methods in China. Their findings validated that the total cost of implementing OSC or semi-OSC techniques is significantly higher than that for conventional construction methods. The major expenses are incurred from processes such as prefabricated component production, transportation, and design consultancy. Hong et al. [15] established a cost-benefit analysis framework to explore the basic cost composition of prefabrication and examined the effect of adopting prefabrication from the total costs of eight real building projects. Results showed that the concrete and steel used in the typical prefabricated components were responsible for 26% to 60% of the total cost, followed by labor cost (17–30%) and transportation (10%). The cost of prefabricated buildings was proven to be 26.3% to 72.1% higher than that of conventional buildings and is highly linearly correlated with the prefabrication rate. Jiang et al. [16] studied the constraints on the promotion of prefabricated construction in China. In their findings, four influential factors were presented: industry chain, cost, social climate and public opinion, and risk. Mao et al. [17] investigated the major factors inhibiting the adoption of OSC in the Chinese construction market from the developer's perspective. They identified 18 critical factors, which can be grouped into five categories, namely, government regulations and policies, technological innovation, industry supply chain, cost, and market demand. It is doubtless that cost is considered one of the key issues by the researchers and practitioners in the development of prefabrication construction. If the cost of construction with the prefabrication technology were lower than with the conventional method, the construction industry would have been eager to fully adopt this technology. It is fair to say that the cost of construction with this technology is still higher than via conventional construction. However, prefabrication has become increasingly popular and widely promoted. Murali et al. [18], through a comprehensive review of relevant literature, observed that prefabricated construction systems have become increasingly popular and widely promoted due to their potential to improve the construction environment, quality, and productivity. According to Jiang et al. [16], there are three variables in the "cost" factor: high initial cost, high employee training cost, and higher average cost compared to traditional buildings. The last variable includes the transportation cost of components and modules to the site, design costs, component costs, and additional procurement costs. From the perspective of structural design, component costs are our main concern. Thus, it is important for us to reexamine and improve the precast components used in the prefabricated buildings to make them more cost effective. This study reviews precast components with a focus on floor components.

The floor system occupies a large proportion in the entire structure. The use of prefabricated slabs can reduce the workload of the construction site support formwork and save labor and turnover materials and requires less wet work. Prefabricated slabs include prefabricated truss-reinforced half slabs (also known as lattice slab or filigran slab), prefabricated prestressed half slabs, prefabricated ribbed prestressed half slabs (also known

as PK panels), prefabricated solid slabs, prefabricated hollow core slabs, prefabricated half balconies, and fully prefabricated balconies. Among them, the truss-reinforced half slabs have become the most widely used prefabricated component form [19–24].

The half slab floor system consists of a series of truss-reinforced concrete slabs with a cast-in-place reinforced concrete topping. It is a universal system of reinforced concrete slab that is used all over the world. The half slabs are prefabricated in the factory and are made up of thin reinforced concrete slabs, which are part of the complete reinforced concrete floor and have a thickness between 40 and 75 mm. The research on half slabs can be grouped into six categories:

- (1) truss-reinforced half slabs [25,26];
- (2) prestressed half slabs [27,28];
- (3) truss-reinforced prestressed half slabs [29–33];
- (4) light weight concrete half slabs [34–36];
- (5) ribbed half slabs [37,38]; and
- (6) hollow core slabs [22,39].

Additionally, strengthening precast concrete slabs with high-performance concrete or textile-reinforced concrete has been studied [40–42].

During the development of half slabs, there have been load bearing problems in the construction stage, such as a large thickness of the precast slabs and many supports under the slab [25,43]. To solve the problems under construction loading, the top chord of the steel bar truss (SBT) was replaced using a steel tube, and the tube may be filled with high-strength grouting material [26]. Additionally, an STB or steel tube/bar truss (STBT) has been used in prestressed half slabs [29,30].

Zhou et al. [29] studied the short-term stiffness of a steel STBT-reinforced prestressed half slab through the bending of four half slabs. Experiments have deduced the short-term stiffness calculation formula of the steel tube truss during construction. Yu et al. [30] tested the bending performance of eight STBT-reinforced prestressed half slabs with densely spliced joints, analyzed the overall working performance of the joints, and put forward the calculation formula of the prestressing direction stiffness influence coefficient. Hou et al. [26] carried out a static load test on two grouted STBT concrete reinforced half slabs. Through research on deformation performance and crack distribution, it was shown that the composite slab has good ductility performance. Liu et al. [31] conducted a comparative test between the SBT-reinforced prestressed half slab and the precast bottom slab. The results show that the steel truss can significantly improve the load bearing capacity of the floor slab and improve the performance of the bottom slab and the composite layer. The upper chord moment calculation formula has been established. As can be seen, the above research on the load bearing capacity and joint connection of the half slab floor system can solve the construction problems encountered, its main objective is to improve its structural performance. However, this may give us some insights that can be used to improve the truss-reinforced half slab system. In addition to the above research areas, there are studies on half slab construction productivity [5,9,44,45], but we hardly see any research on how to improve the current half slab design or innovative half slab design ideas that can really cut down construction costs.

In this study, the most used truss-reinforced half slabs are studied. Both the SBT-reinforced half slab and the STBT-reinforced half slab are considered. The steel tube is filled with high-strength grouting material. In order to improve the half slab floor system, it is essential to have a comprehensive understanding of truss-reinforced half slab structural performance throughout its complete loading history. Each one of the test specimens will be loaded from zero load to maximum load so that the mechanical performance of the components used in the slab can be examined and its load bearing capacity and ductility can be understood. Experimental results will provide the initial basis for improving the half slab floor system. The objectives of this study were as follows:

- (1) to perform an experimental study on the structural performance of STBT- versus SBT-reinforced half slabs to understand the impacts of using the steel tubes in the half slab;
- (2) to study why precast half-concrete slabs cost more than traditional cast-in-place slabs by comparing their component designs; and
- (3) to propose a new cost-effective half slab floor system that is more environmentally friendly and labor friendly based on the above two objectives.

2. Experimental Description

2.1. Specimen Design and Production

According to the current Chinese national standard “Specifications for Design of Concrete Structures (GB 50010-2010)” [46], truss-reinforced concrete half slabs should be used for half slabs with a span greater than 3 m and prestressed concrete precast slabs should be used for half slabs with a span greater than 6 m. The loading performances of prefabricated STBT-reinforced half slabs with three different spans, 3.9, 4.8, and 5.7 m, were studied (between 3 and 6 m), and comparative tests of SBT-reinforced slabs with the same reinforcement in the slab were carried out to analyze the failure mode, crack distribution, and load bearing performance of each slab. In the experiment, six prefabricated truss-reinforced half slab specimens were designed, as shown in Figures 1 and 2. In order to compare the mechanical performances of SBT and STBT under different loading stages, the specimens were divided into two groups, respectively, the SBT-reinforced half slabs (the specimen numbers were SBT-3, SBT-4, and SBT-5) and the grouted STBT-reinforced half slabs (specimen numbers were STBT-3, STBT-4, and STBT-5). The cross-sectional size of each test specimen was the same, 600 mm × 60 mm. The positive bending moment reinforcement of each slab (concrete cast bottom chord members) was five Ø10 threaded steel bars; the negative bending moment reinforcement (visible top chord members) of the SBT-reinforced half slab was two Ø10 threaded steel bars. The negative bending moment reinforcement (visible top chord members) of the STBT-reinforced half slab was the two D20 steel pipes filled with high-strength grouting material. Based on the principle of equal strength replacement, the calculated compressive bearing capacity of a Ø10 steel bar is close to that of a grouted steel pipe used with an outer diameter of 20 mm and a thickness of 2 mm. The diagonals between the top and lower members were Ø10 threaded steel bars arranged in double rows. The main parameter of each test specimen was the half slab length: 4100, 5000, or 5900 mm. A distance of 100 mm was reserved at both ends of the loading area. The dimensions and parameters of each test specimen are shown in Table 1.

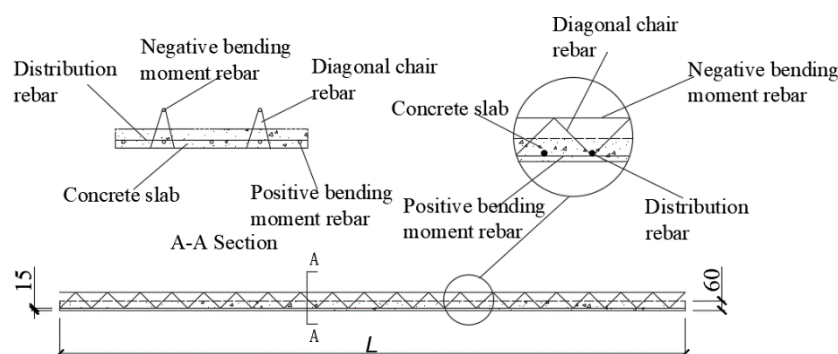


Figure 1. Bar-reinforced half slab diagram.

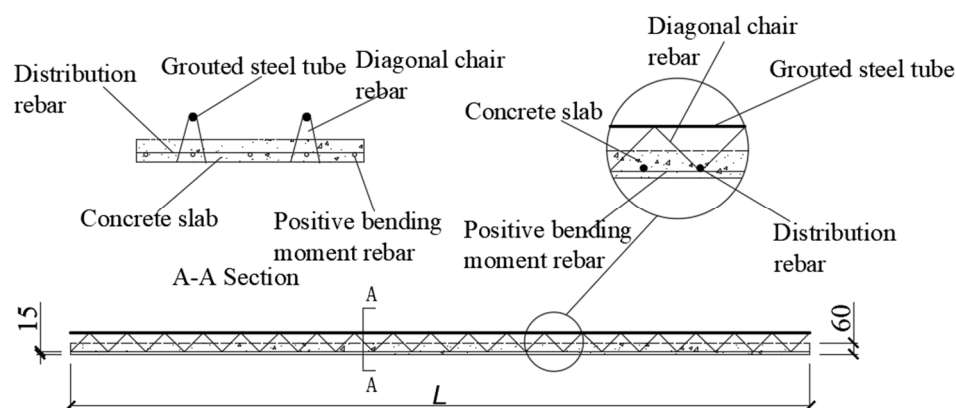


Figure 2. Tube/bar-reinforced half slab diagram.

Table 1. Basic parameters of specimens.

Specimen Number	Positive Reinforcement	Negative Reinforcement	Cross Section (mm)	Span (mm)
SBT-3	5 Ø10	2 Ø10	600 × 60	3900
SBT-4	5 Ø10	2 Ø10	600 × 60	4800
SBT-5	5 Ø10	2 Ø10	600 × 60	5700
STBT-3	5 Ø10	2 D20 Tube	600 × 60	3900
STBT-4	5 Ø10	2 D20 Tube	600 × 60	4800
STBT-5	5 Ø10	2 D20 Tube	600 × 60	5700

SBT, steel bar truss; STBT, steel tube/bar truss.

2.2. Material Properties

Each half slab was made of commercial concrete with a strength grade of C30 (30 MPa concrete strength), and each steel tube was poured with a special grouting material (CGMJM-VIII) to have a strength grade of 80 MPa. During the production of each specimen, a concrete cube test block with a side length of 100 mm and a grouting cuboid test block with a size of 160 mm × 40 mm × 40 mm were cured under the same conditions as the test specimen. The axial compressive strength, f_{cu} , of concrete and grouting is shown in Table 2. The steel bar grade used in the test specimen was HRB400, and the steel pipe adopted was a round steel pipe with a strength grade of Q235. The measured mechanical properties of the steel pipe and the steel bar are shown in Table 3. The test methods of the material properties in this research were implemented in accordance with the “Specifications for Design of Concrete Structures” (GB50010-2010) and the “Design Standards for Steel Structures” (GB50017-2017).

Table 2. The material’s compressive strength (measured).

Material	Grouting	Concrete
Compressive strength, f_{cu} (MPa)	63.6	41.2

Table 3. The mechanical properties of reinforcing steel.

Steel Type	Yield Strength, f_{cu} (MPa)	Yield Strain, $\epsilon_y \times 10^{-6}$	Tensile Strength, f_t (MPa)	Modulus of Elasticity, E_s (MPa)
Ø10 Bar	422	2087	530	2.0×10^5
D20 Tube	325	1923	634	1.7×10^5

2.3. Loading Device and Measurement

The test loading device is shown in Figure 3. The test specimen was a simply supported floor slab with one end (support A) as a rolling bearing and the other end (support B) as a sliding bearing. The measurements included the strain of the steel, the deflection and deformation of the slab along the span direction, the distribution of the slab cracks, and the development of changes. The steel strain included the positive bending moment bar strain and negative moment bar strain at the mid-span.

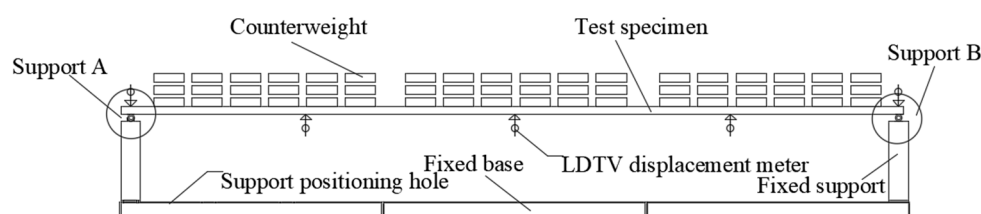


Figure 3. Experimental loading device setup.

2.4. Loading Scheme and Procedure

The crack load, q_{cr} , and ultimate load, q_u , of each specimen were calculated before the tests. All calculations were based on the measured strength. Before the concrete cracks, the control load of each loading level was measured as 0.3, 0.6, 0.9, and $1.2q_{cr}$. If the concrete was not cracked, the loading was increased by $0.1q_{cr}$ according to the control load of each level. After the concrete cracked, the control load of the loading level was 0.3, 0.4, 0.5, 0.6, 0.9, or $1.0q_u$. During the loading, we observed the strain change of the positive bending moment bar and recorded the bar yield load.

Each specimen was loaded with a uniform distribution of counterweight blocks, and the mass of a single counterweight block was 10 kg. The loading design takes full account of the deflection deformation caused by self-weight and loads according to the control load; the loading process divided the slab into three loading units along the span, and according to the load situation at each level, the counterweight block was evenly arranged in each loading unit. Before the concrete cracked, three counterweight blocks were applied to each loading level; after the concrete cracking, six counterweight blocks were applied to each loading level. When the mid-span deflection reached $1/50$ of the span or the maximum crack at the bottom of the plate reached 3 mm, the loading was terminated.

3. Test Results and Analysis

3.1. Crack Development and Failure Mode

The failure processes and failure modes of all test pieces were similar, as they were typical bending failures. Figure 4 shows the pictures of the six test specimens when they were loaded to their respective limits. For STBT-4, when loaded to 1.2 kN/m , the concrete under the slab 0.5 m from the mid-span cracked. As the load continued, cracks appeared in the concrete on the left and right sides of the slab at a distance of 0.1 m from the mid-span, and the cracks extended and penetrated. After the test piece reached a stable state, the side concrete cracked 0.1 and 0.5 m from the middle of the span. The widths of the concrete cracks measured by a crack meter were 0.019 and 0.033 mm, respectively. When loaded to 1.5 kN/m , the concrete on the bottom surface of the slab at a distance of 0.7 m from the mid-span position cracked and formed a through crack extending to the side. The width of the concrete crack was 0.033 mm. At this time, the widths of the concrete cracks at 0.1 and 0.5 m from the middle of the span were 0.036 and 0.052 mm, respectively. At 1.9 kN/m , cracks appeared on the bottom surface of the concrete at 0.9 and 0.8 m from the middle of the span, and the crack width was 0.019 mm. At this time, the maximum crack width at 0.5 m from the middle of the span was 0.074 mm. When loading to 2.3 kN/m , multiple cracks were formed on the bottom and sides of the slab. The cracks were mainly concentrated at 1.5 m on the left and right sides of the middle span, and the distribution

was relatively uniform along the span direction. At this time, the maximum crack width at 0.1 m from the middle span was 0.095 mm. When loaded to 5.7 kN/m, the mid-span deflection suddenly increased to 159 mm (approximately $L/300$), and the width of the side crack on the slab reached 0.6 mm.

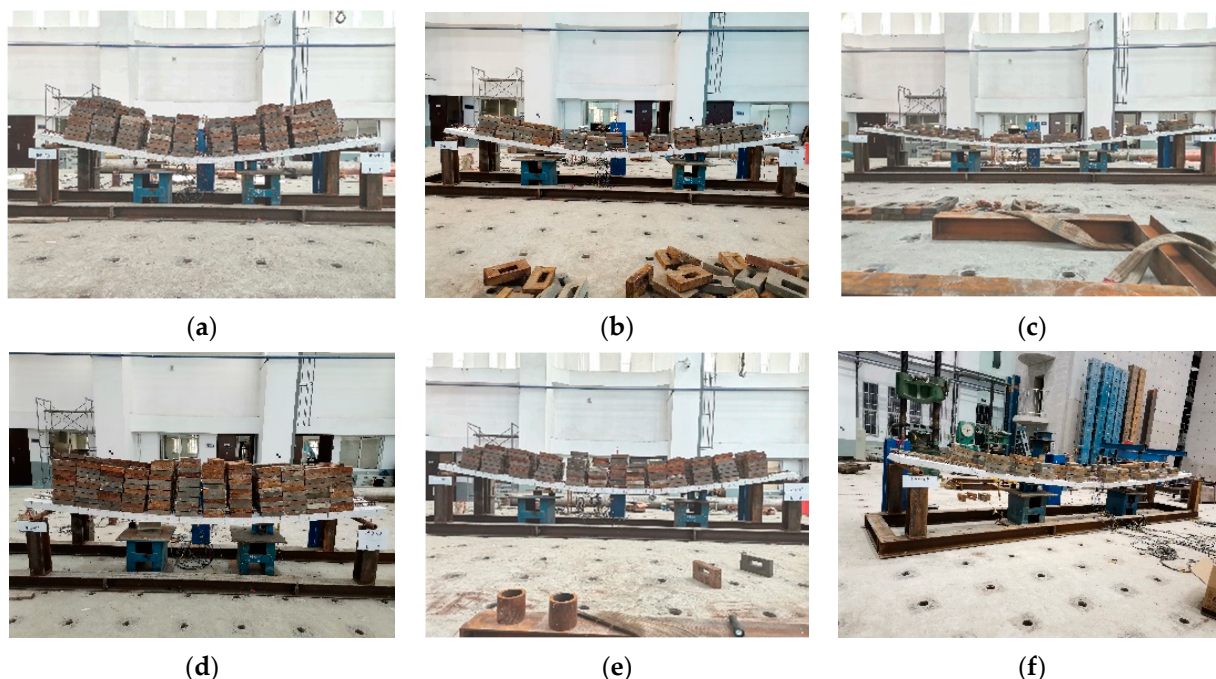


Figure 4. Loading pictures of test slab specimens: (a) SBT-3; (b) SBT-4; (c) SBT-5; (d) STBT-3; (e) STBT-4; and (f) STBT-5.

The loading test result showed that during the loading process of the STBT-reinforced half slab specimens, the compressive steel tube did not undergo any buckling. Namely, Figure 5a shows “no local failure.” However, all of the SBT-reinforced specimens experienced in-plane buckling, as shown in Figure 5b, and/or out-of-plane buckling of the compressive steel bars, as shown in Figure 5c.

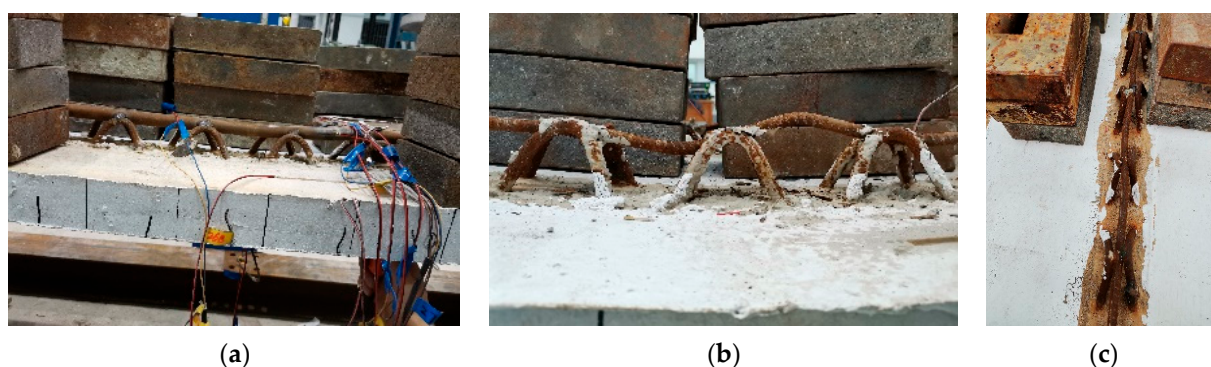


Figure 5. Local failure modes of compressive members: (a) steel tube—no local failure; (b) rebar in-plane buckling; and (c) rebar out-of-plane buckling.

3.2. Load Deformation Curves

Figure 6 reveals the load–deflection curves of the half slabs, where the abscissa is the mid-span deflection change, Δ ; the ordinate is the applied local linear load, q . The black arrow in the figure is the crack point, and the black circle is the yield point of the bottom truss steel bar. Rebar buckling did not happen for steel tube/bar truss-reinforced

specimens, but it did happen for steel bar truss-reinforced specimens (DHB-R3, DHB-R4, DHB-R5) after the compressive steel bar had yielded. The buckling points (in green) are shown in Figure 6a.

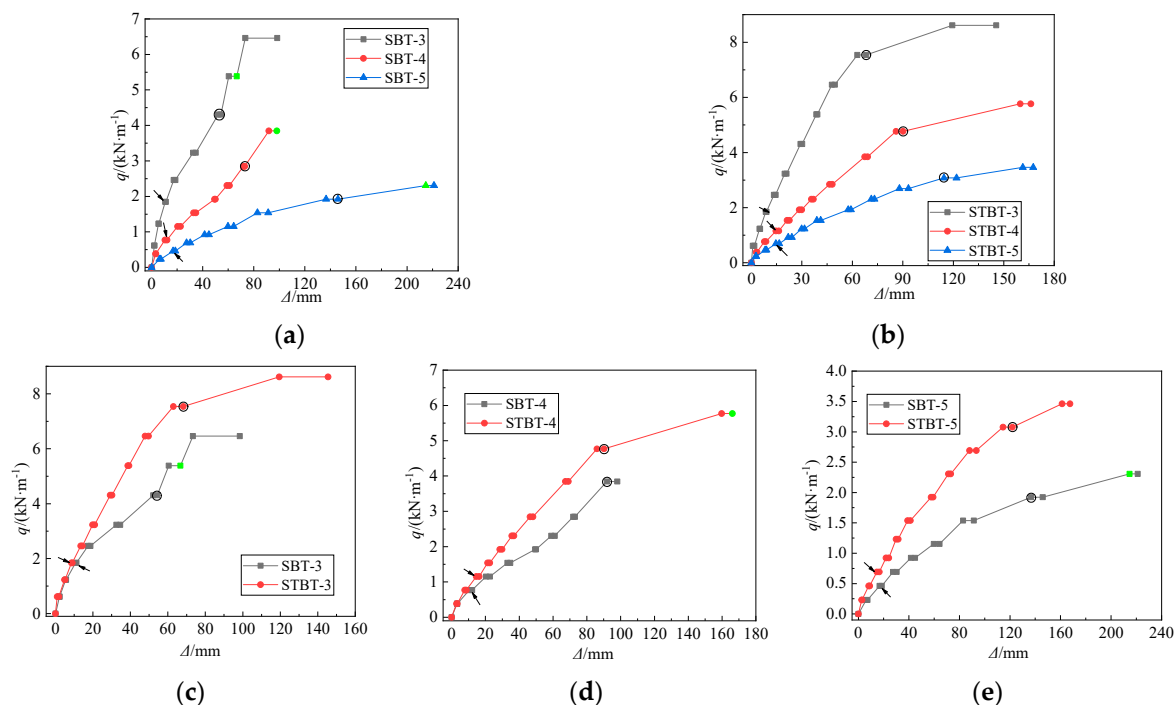


Figure 6. Load–deformation curves of test specimens: (a) steel bar-reinforced half slabs; (b) steel tube/bar-reinforced half slabs; (c) L = 3.9 m slab specimens; (d) L = 4.8 m slab specimens; and (e) L = 5.7 m slab specimens.

It can be seen from Figure 6a,b that under the same form of reinforcement, when the half slabs with different spans cracked (the first crack appeared at the bottom of the slab), the mid-span deflections were the same, and the range of variation was 11.2–18.5 mm. When the steel bar in the half slabs with different spans yielded, the mid-span deflection increased with the increase of the span. The measured value of the load characteristic value of each specimen is shown in Table 4. For the steel bar truss slab specimen, when the span increased from 3.9 to 5.7 m, the deflection increased by 69.2% and 58.8%, respectively. For the steel tube/bar truss slab specimen, when the span increased from 3.9 to 5.7 m, the deflection increased by 32.1% and 27%, respectively. When the span is increases by 46%, the mid-span deflection will increase by 169% or 67.9%, respectively, when the steel in the steel truss slab or the steel tube/bar truss slab yields. Therefore, the steel tube/bar truss is recommended for the large span half slab.

Table 4. Measured values of load and deflection.

Slab	Crack			Yield		Maximum		
	Mid-Span Deflection, Δ_{cr}/mm	Load (kN)	Measured Value/Calculated Value	Mid-Span Deflection, Δ_{cr}/mm	Load (kN)	Mid-Span Deflection, Δ_{cr}/mm	Load (kN)	Measured Value/Calculated Value
SBT-3	11.2	1.9	0.86	54.3	4.3	73.4	6.5	0.76
SBT-4	12.1	0.8	0.64	91.9	3.8	98.1	3.8	0.70
SBT-5	18.6	0.5	0.77	145.9	1.9	221.1	2.3	0.64
STBT-3	8.9	1.8	0.82	68.2	7.5	145.5	8.9	1.03
STBT-4	16.3	1.2	1.00	90.1	4.8	166.1	5.8	1.07
STBT-5	16.5	0.7	1.17	114.5	3.1	167.5	3.5	0.97

Figure 6c–e shows the load–deformation comparison curves of the half slab with different truss layouts of the same span. It can be seen that when the half slabs of different truss layouts crack and yield, the mid-span deflection and deformation are basically the same. The load bearing performance of the steel tube/bar truss–reinforced specimen does not decrease after yielding, and its load bearing capacity safety reserve is large. Figure 6c–e shows the load–deformation comparison curves of the half slabs with different layouts of the same span. It can be seen that compared with the SBT-reinforced half slabs, the initial stiffness of the concrete-filled steel tube half slabs (the stiffness before the concrete cracks) was significantly improved, indicating that the STBT-reinforced half slab has better resistance to deformation during the construction stage; after yielding, the bearing performance of the concrete-filled steel tube truss floor did not decrease.

3.3. Steel Strain Curves

Figure 7 shows the change curves of the strain–load of the steel bar and steel tube for the test specimens. A horizontal dotted line in the figure shows the position of the measured yield strain of the steel bar or steel tube. It can be seen that, with the exception of SBT-5, the strain values of the tensile steel bars in the slab specimens and the compressive truss bars or steel tubes reached the yield strain. The main reason for SBT-5's compressive steel bar not yielding is that the welding of the local diagonal bars and the steel bar was damaged, which caused the lateral deformation of the diagonal bars.

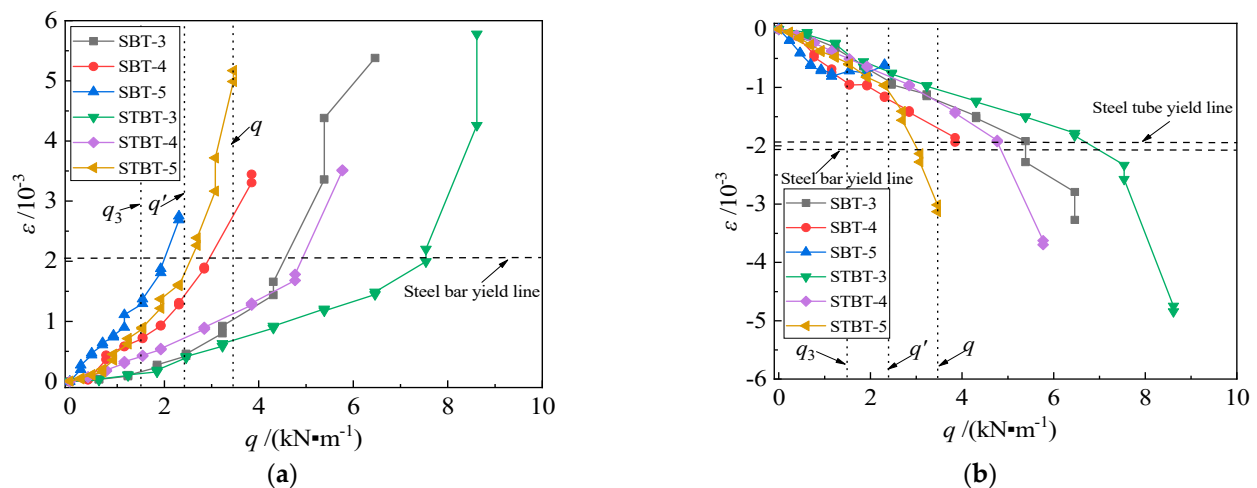


Figure 7. Steel strains: (a) tensile steel strains and (b) compressive steel strains.

The load during the construction phase, q_3 , can be calculated as follows [46,47]:

$$q_3 = Q_k + G_{k3}$$

where Q_k is the live load during construction, which can take a larger value in different specifications, which was $Q_k = 1.5 \text{ kN/m}^2$; G_{k3} is the self-weight of the cast-in-place concrete layer— $G_{k3} = 0.86 \text{ kN/m}$. We calculated that $q_3 = 1.76 \text{ kN/m}$. The position is marked by the q_3 vertical dotted line in Figure 7. All test pieces of steel bar and steel tube did not reach yield, indicating that, for the prefabricated steel tube/bar–reinforced half slabs with spans from 3.9 to 5.7 m, the load bearing performance met the load requirements under construction loading without temporary supports.

According to the calculation [42,43] of the applied load design value of the half slab bearing uniformly distributed load:

$$q = q_1 + q_2, \text{ where } q_1 = \gamma_0 \gamma_G G_{k1}, q_2 = \gamma_0 (\gamma_G G_{k2} + \gamma_Q Q_k)$$

where γ_0 is the structural importance coefficient— $\gamma_0 = 1$; γ_G is the permanent load distribution factor— $\gamma_G = 1.2$; γ_Q is the variable load distribution factor— $\gamma_Q = 1.4$; G_{k1} is the standard value of slab self-weight (assuming a 6 cm thick concrete topping)— $G_{k1} = 1.728 \text{ kN/m}^2$; G_{k2} is the standard value of surface layer and ceiling weights— $G_{k2} = 1 \text{ kN/m}^2$; Q_k is the variable load standard value— $Q_k = 2.0 \text{ kN/m}^2$.

It was calculated that $q = 3.4368 \text{ kN/m}$. The position is marked by the q vertical dotted line in Figure 7. It can be seen that the tensile steel bars in SBT-4, SBT-5, and STBT-5 and the compressive steel tube in STBT-5 yielded (the compressive steel bar welding in SBT-5 was damaged earlier), indicating that the amount of steel used in the steel bar or tube should be increased for slabs with a larger span in order to meet the load requirements under construction loading and the actual applied load without temporary supports. In general, the load bearing performance of the steel tube/bar truss-reinforced specimen was much better than that of steel bar truss-reinforced specimen. However, the above analysis assumed that there was no composite behavior between the topping concrete layer and the bottom precast half slab.

3.4. Load Bearing Capacity

The measured values of load are shown in Table 4. It can be seen that as the span increased, the crack load, yield load, and maximum load all decreased. For the steel bar truss specimen, when the span was increased to 3.9 or 5.7 m, the crack load was reduced by 57.9% or 37.5%, the yield load was reduced by 13.2% or 50%, and the maximum load was reduced by 41.5% or 39.5%, respectively. For the steel tube/bar truss specimen, when the span was increased by 3.9 or 5.7 m, and the crack load was reduced by 33.3% or 41.7%, the yield load was reduced by 36% or 35.4%, and the maximum load was reduced by 34.8% or 39.7%, respectively.

When compared with the steel bar truss-reinforced specimens under the same span, the average values of crack load, yield load, and maximum load of the steel tube/bar truss-reinforced specimens increased by 28.2%, 54.6%, and 47.2%, respectively. Therefore, the use of a steel tube/bar truss instead of a steel bar truss significantly improved the load bearing performance of the prefabricated half-concrete slab.

For the steel bar truss-reinforced half slab specimen, the average value of the ratio of the crack load to the calculated value was 0.76, the variance was 0.11, the average of the ratio of the maximum load to the calculated value was 0.7, and the variance was 0.06; for the steel tube/bar truss-reinforced half slab specimens, the average ratio of the measured value of the crack load to the calculated value was 1.0, the variance was 0.18, the average of the ratio of the measured maximum load to the calculated value was 1.02, and the variance was 0.05. Therefore, it is not appropriate to consider the compressive effect of the bar truss reinforcement when the steel bar truss-reinforced half slab with thin concrete thickness is used in the load calculation of the building in use. For the prefabricated steel tube/bar truss-reinforced half slab with thin concrete, the compressive effect of the steel tube should be considered in the load calculation of the building in use.

4. Half Slab System Improvement and Discussion

Prefabricated buildings are an important development direction for the transformation and upgrading of the Chinese national construction industry, but the high cost of precast concrete is the main reason for the high construction and installation costs of prefabricated concrete structure residential projects. The more precast concrete is used in a building, the more it costs. Hong et al. found that the cost of prefabricated buildings is 26.3% to 72.1% higher than that of conventional buildings and is highly linearly correlated with the prefabrication rate [15]. From the perspective of real estate developers, it is a difficult problem faced by most of them not only to meet the requirements of the national or local construction administrative departments for the prefabrication rate or assembly rate but also to effectively control the costs of project construction and installation. However, from the perspective of a structural designer, it is essential to understand why precast

concrete buildings cost more than traditional cast-in-place buildings by comparing their component designs.

4.1. Cost Assessment of Half Slabs

The reasons for the increased cost of a truss-reinforced half-concrete slab can be found in Article 6.6 of the Technical Regulations for Precast Concrete Structures [48]. It states that (1) the prefabricated thickness of the half slab should not be less than 6 cm; (2) a half slab with a span greater than 3 m should be a truss-reinforced half-concrete slab; (3) the diameter of the truss steel chord should not be less than 8 mm, the diameter of web bars should not be less than 4 mm; and (4) the shear-resistant structural steel bars set between the prefabricated slab of the half slab and the post-cast concrete laminated layer should adopt the shape of footrest stirrups, the spacing should not be greater than 400 mm, and the diameter of the steel bars should not be less than 6 mm. If the precast structure adopts truss-reinforced half slabs, the emphasis is on the “truss.” There is no need to use more steel bars because the cast-in-place structure basically does not require a truss. According to the current national standard “Code for Design of Concrete Structures (GB 50010-2010),” the thickness of the precast half slab should not be less than 60 mm, and the thickness of the top layer of post-poured concrete should not be less than 60 mm. The thickness of the half slab is at least 6 cm. If the cast-in-place layer of no less than 6 cm is added, the thickness is at least 12 cm. If it is a cast-in-place floor slab, the minimum thickness is 10 cm, and the concrete’s material cost increases by 20%. As the thickness of the floor slab of prefabricated buildings increases, the amount of steel reinforcement and the corresponding floor slab weight both increase. To offset the influence of its weight, the corresponding beams and columns must increase in volume, which leads to high costs.

The introduction of the reinforced truss increases the rigidity and bearing capacity of the prefabricated components. In the construction stage, the deformation of the prefabricated half bottom plate is reduced, which can reduce the support, simplify the operation process, and reduce the labor intensity of the workers. However, in order to meet the pre-buried requirements of the water, electricity, and air-conditioning pipelines, it is necessary to arrange a cast-in-place layer of more than 70 mm, which increases the total thickness of the prefabricated half slab floor by 20–30 mm compared with the cast-in-place slab, which increases the weight of the floor and increases the cost of beams, walls, columns, and foundations. In addition, there will be manufacturing errors in the reserved water, electricity, and air-conditioning pipelines, which will bring great troubles to on-site construction.

Prefabricated building planning was introduced in China in 2015 and fully promoted in 2016. The developments since then indicate that the cost of prefabricated concrete buildings in China is higher than that of cast-in-place buildings. The main cost increase comes from the precast concrete volume increase and the increase in the amount of steel brought about by precast concrete, and the main cost reduction comes from the lack of on-site formwork and lack of plastering. In order to make the components of the prefabricated building cost effective, it is essential to improve the design of the components so that the precast concrete volume and steel used in each component can be reduced.

4.2. Proposed Slab System

Xie et al. [49] studied the importance–performance analysis of the sustainability of prefabricated buildings in Guangzhou, China. They found that “construction cost” and “product quality” are considered high-importance but low-performance items, which need to be focused on, and measures need to be taken to promote improvement. Murali and Sambath [9], in their study on prefabrication as a solution to improve the productivity of the construction industry in Tamilnadu, India, found that one of the difficulties of prefabrication is the development type not being appropriate. The present prefabricated half slab floor system uses more concrete and steel than the conventional construction method. In addition, it also has a new pouring system, so it is not a very effective and efficient system. When considering not only how to reduce the concrete volume and amount

of steel in the present system but also how to improve and obtain a complete prefabricated floor system by brainstorming, the concepts to improve the present prefabricated truss-reinforced half slab floor system are summarized as follows:

- (1) As the steel tube used in the truss has good structural performance, it can be used effectively to resist the tensile force in the precast slab.
- (2) To reduce the concrete volume in the half slab floor system, the cast-in-place concrete topping layer (at least 60 mm thick) needs to be replaced by a light board subfloor resting on the steel tubes. Thus, this design concept changes the present wet–dry half slab floor system into a completely dry system and the amount of steel in the cast-in-place layer can be reduced.
- (3) The steel trusses are used to support the light subfloor, which is placed on the steel tubes. The subfloor can be made of plywood, OSB (oriented strand board), a precast concrete panel, or green material certified board. The open space between the subfloor and the precast slab has electrical wiring, plumbing, heat insulation, and sound insulation materials and other built-in services.
- (4) Since the light subfloor rests on the steel tubes, it is better to use square or rectangular tubes.

Based on the above concepts, a dry prefabricated half slab floor system is proposed. Figure 8a shows the traditional half slab floor system. The conceptual design of the proposed system is shown in Figure 8b. Figure 9 shows the 3D diagram of the proposed system. In order to realize the proposed system, a lot of studies, both experimental and theoretical, need to be done in the future.

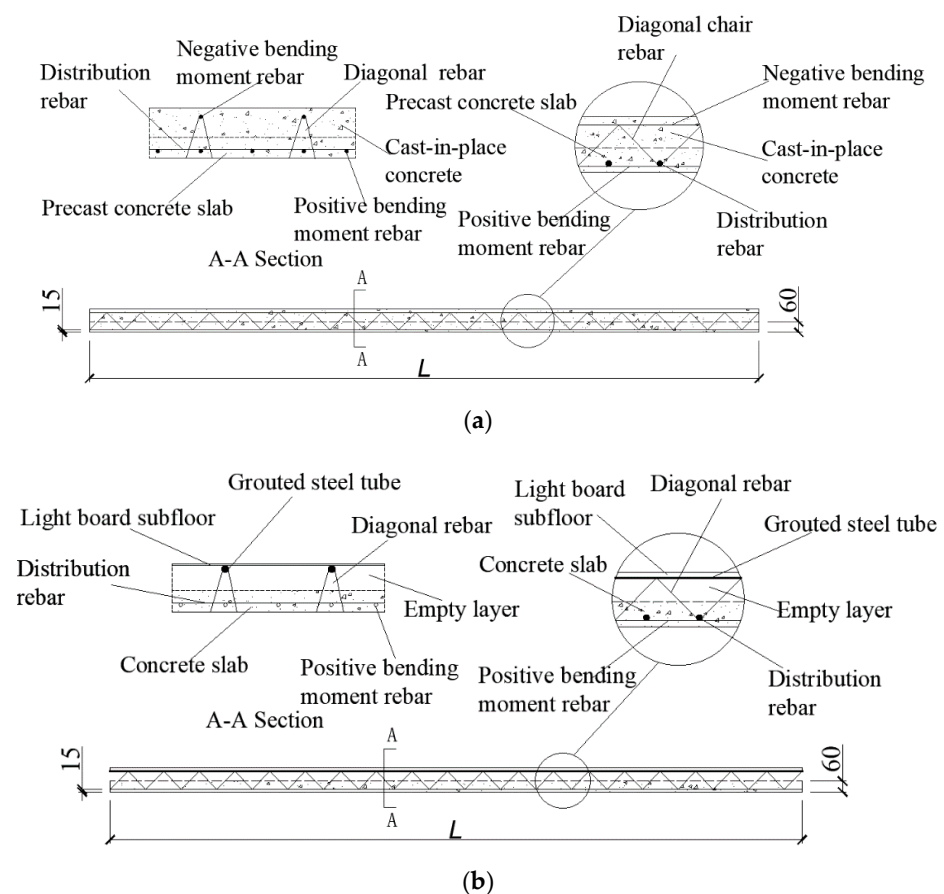


Figure 8. Traditional half slab floor system vs. proposed half slab floor system: (a) bar truss-reinforced half slab with a cast-in-place concrete topping and (b) tube/bar truss-reinforced half slab with a light board subfloor.

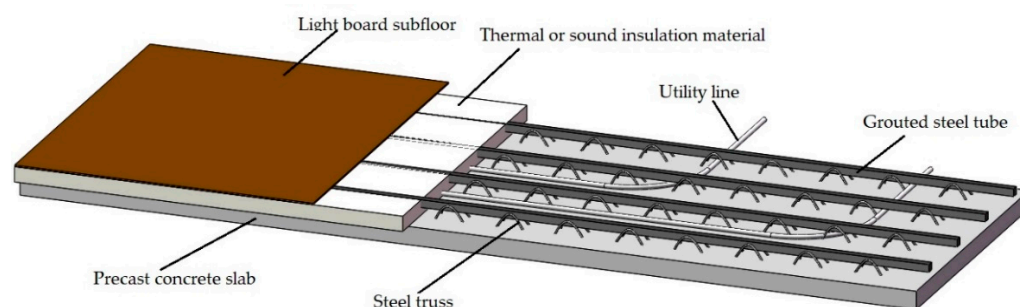


Figure 9. A 3D diagram of the proposed half slab floor system.

It is interesting to see the impact of the self-weight reduction on the steel strains in Figure 7. Without the topping concrete layer (assume 6 cm thickness), it is calculated that $q = 3.4368 \text{ kN/m}$ will reduce to $q' = 2.40 \text{ kN/m}$. The position is marked by the q' vertical dotted line in Figure 7. It can be seen that, except for the SBT-5 slab steel bar that yielded, the rest of the test pieces of steel bar or steel tube did not yield, indicating that for a prefabricated steel tube/bar-reinforced half slab with a span of 5.7 m, its load bearing performance can meet the load requirements under construction loading and actual applied load without temporary supports.

5. Conclusions

The conclusions of this study are as follows:

- (1) The failure mode of the prefabricated STBT-reinforced half slab was typical bending failure. The bending cracks were mainly distributed within 3 m of the middle span, and the cracks were evenly distributed. When the final failure occurred, the steel tube did not have out-of-plane and/or in-plane buckling, and its mechanical performance was better than the compressive steel bar in the SBT-reinforced half slab.
- (2) For the three spans adopted in the experiment, with the increase of the span, the crack load, yield load, and maximum load of the prefabricated truss-reinforced half slab were reduced. Compared with the SBT-reinforced specimens, the load characteristic values of the STBT-reinforced specimens were significantly improved. Therefore, a steel tube truss can be used instead of a steel bar truss to improve the load bearing capacity of the prefabricated steel truss-reinforced half slab.
- (3) The prefabricated STBT-reinforced half slab had greater initial stiffness and resistance to deformation when compared to the SBT-reinforced half slab. Therefore, we recommended using the STBT form for the prefabricated half slab with a larger span.
- (4) Due to the fact that good structural performance of the steel tube was observed, after having studied the half slab component design, a dry prefabricated steel tube/bar truss-reinforced half slab system that can reduce the concrete volume and steel amount used in the present slab system was proposed.

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