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Experimental Study on Flexural Behavior of Assembled U-shaped Steel–Concrete Composite Beams

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Abstract

The open U-shaped beam section of the traditional U-shaped steel–concrete composite beam has limited restriction on internal concrate, and formwork cast-in-place on the upper concrete slab is required on site, leading to a low assembly rate. A novel assembled U-shaped steel–concrete composite beam is proposed to strengthen the restriction of the lower U-shaped steel and improve its assembly rate. In accordance with the connection mode between the lower box beam and the upper floor slab, six full-scale simply supported specimens were designed considering the single and combined arrangement of three types of shear connectors: joint bar, truss, and stud. A destructive loading test was carried out under positive bending moment to compare and analyze the bending capacity, load-displacement curve, failure model, and strain distribution law of new members with different types of shear connectors. Results show that the U-shaped steel and concrete in the composite beam exhibit good synergistic effect, which can effectively avoid the overall instability and local buckling failure of the U-shaped steel. Under the action of positive bending moment, stress can be roughly divided into three stages: elasticity (0–0.7 P_u), weak elasticity (0.7–0.9 P_u), and elastoplasticity. The ultimate failure mode of composite beam members with shear connectors without studs is a ductile failure, whereas that with an arrangement of stud shear connectors is a plastic failure. The ultimate load of the member with truss welded to steel beam+joint bar (5-TJ) can increase by 11.5% and 33.3% compared with that with joint bar (1-J) and steel truss (2-T), respectively, thereby effectively improving the flexural behavior of the novel assembled U-shaped steel–concrete composite beam. Meanwhile, the member presents a strong ductility deformation capacity, and the ductility coefficient reaches 4.22. This shear connector form is excellent for this new type of member. The study provides a good reference for selecting shear connectors in the design of assembled composite beams.

Keywords: Assembled composite beam, Steel–concrete, Flexural behavior, Failure mode, Experimental study

1. Introduction

Assembled buildings have the characteristics of quick construction, high production efficiency, material saving, and improved labor production environment, thereby effectively realizing building industrialization, energy saving, and emission reduction. This condition conforms to the development direction of building and housing industrialization [1-2]. A U-shaped steel–concrete composite beam, as an important mechanical component in the assembled building structure, has various advantages, such as high stiffness, high bearing capacity, small section size, and good seismic performance. It has attracted the attention of researchers in China and foreign countries and has been widely used in practical projects [3-4].

However, for the traditional U-shaped steel–concrete composite beam, angle steel or studs are arranged at the interface between the U-shaped steel beam and the concrete floor slab as shear connectors, and then the concrete is poured into the open U-shaped steel to form the rib and concrete floor slab of the composite beam. The U-shaped steel beam and the concrete floor slab form a cooperative whole through the interface bonding stress and the shear connectors. The cross section of the open U-shaped beam has limited restriction on its internal concrete, and the U-shaped steel beam itself is prone to buckling or sliding with internal concrete when it is damaged [5]. At the same time, the traditional concrete floor slab on the upper part of composite beams usually adopts cast-in-place, and formwork support is required on site, which is not conducive to the assembly. This condition results in a challenging application of U-shaped steel-concrete composite beams in prefabricated buildings.

Scholars have attempted to use different methods to enhance the restraint of the open U-shaped beam section on internal concrete and improve the synergy effect[6-9]. However, the cast-in-place steel–concrete composite beam in the form of on-site formwork support still failed to effectively solve the problem of bulging of the U-shaped steel or sliding of internal concrete [7-9]. Therefore, improving the assembly rate of U-shaped steel–concrete composite beams and limiting the buckling of U-shaped steel or sliding of internal concrete are urgent problems to be solved to realize the wide application of this type of composite beams in prefabricated buildings.

This study proposed a novel assembled U-shaped steel–concrete composite beam composed of a closed box beam and reinforced truss floor slab, and then explored its flexural performance under positive bending moments through full-scale experiments. The study results provide a reference for the design of such new members.

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2. State of the art

Studies on steel–concrete composite beams are abundant in China and foreign countries, and have been widely used in practical engineering.

For the calculation and design theory of composite beams, Oehlers [10] carried out experiments on the shear and bending behavior of thin-walled steel–concrete composite beams as early as 1993, and pointed out that side-wall steel plates can improve shear strength without reducing the ductility of members. Bradford [11] studied the slip effect between U-shaped steel and concrete in cold-formed thin-walled U-shaped steel–concrete composite beams, the bending performance, and the local buckling performance of steel plates. The experimental results show that the concrete inside U-shaped steel can effectively improve the buckling performance of steel plates, enhancing the overall stability and bearing capacity of composite beams. Ban [12] put forward a method to calculate the stiffness of steel–concrete composite beams with different steel strengths. Nie [13] developed a calculation method of section stiffness of composite beams considering slip effect through experiments and obtained the additional curvature and deflection with slip effect parameters by theoretical study. Shu [2] proposed an assembled tenon–mortise composite beam considering the saving of technology and materials of shear connectors, carried out experimental and theoretical studies of its flexural performance, and obtained the corresponding midspan deflection calculation formula. The studies of Kemp [14] and Tong [15] showed that the traditional steel–concrete composite beam is unstable and damaged under negative bending moments. The ratio of web height to thickness and beam width should be controlled to enhance the bearing capacity and rotation capacity of the composite beam. Yang [16] found that filling concrete in the negative bending moment area can restrain the concave of the web, but it cannot avoid convex buckling. Xiao [17] and Chen [18] put forward a calculation method of the ultimate bending capacity of steel-encased concrete composite beams through static experimental study and theoretical analysis. They not only considered the difference between the full shear connection and the partial shear connection of steel-encased concrete composite beams, but also included the relationship of the nonlinear neutral axis between outer steel and encased concrete. The study results have also been successfully applied to practical projects. However, the shear connectors of the externally wrapped U-shaped steel–concrete composite beam are studs with a complicated constructional detail and require large welding; the construction quality is also unstable.

For the study and development of new forms of composite beams and shear connectors, Patel [19] introduced a detachable assembled composite beam. The lower component is an I-shaped beam, and the upper component is a profiled steel plate–concrete slab, which can be directly connected by embedded bolts. The composite beam can be applied to assembled structures. However, in the I-shaped beam, the embedded bolts are used as shear connectors, which are difficult to construct, and the shear performance is uncertain. Ariel [20] proposed two types of shear connectors, namely, embedded shear connectors and self-tapping shear connectors, and the shear connection performance of which is studied through push-out tests of thin-walled steel and concrete. The results show that self-tapping shear connectors are suitable for thin steel plates with thickness under 2 mm. Cao [21] studied the high-strength everted U-shaped encased steel–concrete composite beam. The high-strength concrete and U-shaped steel were connected by shear studs, and shear stirrups were arranged in the concrete inside the U-shaped beam. The results indicate that the integrity is good, but the everted U-shaped clad steel is not a closed section. Zhang [22] designed a novel inverted U-shaped steel–clad concrete composite beam, and the shear connector was a welded-free steel plate. The flexural performance of the continuous beam was tested and studied. However, the upper panel reinforcement of the beam needs to pass through the U-shaped steel plate, and the construction is complicated. Keo [23] proposed a welding angle steel on the everted steel flange of an everted U-shaped clad steel as a shear connector. The results demonstrate that the connector has a good performance, but the steel consumption of the angle is large. Zhou [7] and Liu [8-9] welded continuous Z-shaped steel bars on the flange of the inverted U-shaped steel–clad beam to form a closed section and arranged U-shaped stirrups in the beams to act as shear connectors. The test results show that the composite beams have good overall working performance, but the slip between the lower U-shaped steel and the internal concrete or the buckling of steel plates still exists during the test, indicating that the U-shaped steel has a limited restraint on the internal concrete. Kim [23] developed a novel U-shaped steel–concrete composite beam, which had two Z-shaped thin-walled steel plates bolted to C-shaped thin-walled steel plates, and then conducted a bending test. However, there is a bolt slip during the stress process. Zhao [5] put forward a new type of U-shaped steel-concrete composite beam, and the two weak surfaces of flange–web interface and steel–concrete interface were enhanced with joint bars to improve the integrity and fully maximize the natural advantages of U-shaped steel–concrete composite beams. The mechanical performance and design method were also thoroughly studied. However, the upper concrete floor slab still requires on-site formwork cast-in-place, whose assembly rate is low.

These studies focus on the steel–concrete composite beams whose upper concrete floor slabs are traditional cast-in-place slabs, which cannot adapt to the development trend of building assembly. The lower ribs of composite beams mostly adopt a U-shaped steel with internal or external openings. Although some scholars [6-9] have put forward different methods to enhance the restraint effect of the open U-shaped beam section on the internal concrete to enhance the synergy, they failed to effectively avoid the buckling of the U-shaped steel or the slip between the U-shaped steel and the internal concrete [7-9]. Moreover, studies on improving the assembly rate of the upper floor slab and adopting a closed form of the lower rib of composite beams are few. Therefore, a novel assembled U-shaped steel–concrete composite beam composed of a closed box beam and reinforced truss floor slab is proposed in the present study. The positive bending moment tests of six full-scale members were carried out to discuss the influence of the single and combined arrangement of three types of shear connectors, namely, joint bar, truss, and stud, on their flexural performance, such as ultimate bearing capacity, failure mode, and strain distribution law. The results can provide references for the design of shear connectors and practical engineering application for this new type of members.

The remainder of this study is structured as follows. Section 3 discusses the composition of assembled U-shaped steel–concrete composite beam and introduces the test in detail. In Section 4, the failure modes, load–deflection curves, and strain distribution laws of members with different shear connectors are compared and analyzed, and the failure modes of assembled U-shaped steel–concrete composite beams are summarized. Finally, Section 5 summarizes this study and draws relevant conclusions.

3. Methodology

3.1 Composition of assembled U-shaped steel-concrete composite beam

The composition of assembled U-shaped steel–concrete composite beams is shown in Fig. 1. The lower part of the composite beam is a cold-formed thin-walled box beam. Regular waist-shaped holes are set in the box beam, and a steel bar truss deck is used in the upper floor slab. Shear connectors are arranged between the box beam and the floor slab to improve the cooperative working performance between the beam and the slab.

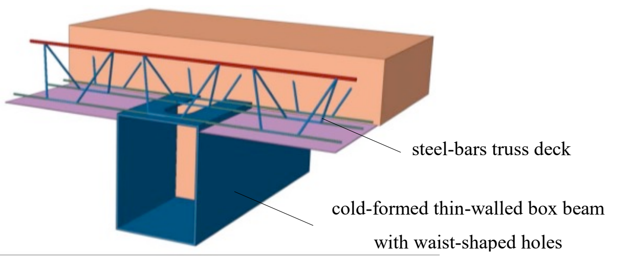


Fig. 1. Assembled U-shaped steel–concrete composite beam

Compared with the traditional open U-shaped steel–concrete composite beam, the box beam with regular waist holes can strengthen its restraint on the concrete inside the beam and improve the overall stability of the composite beam. Cold-formed thin-walled box beams and steel bar truss decks can be prefabricated in the factory, which has high industrial production accuracy and can save steel consumption. They are assembled on site, and concrete is poured uniformly to realize the integration of assembly, thereby reducing the workload of on-site formwork support for traditional composite beams and improving the construction speed and the assembly rate of the entire structure.

3.2 Specimen design and fabrication

In this experiment, six specimens were made, and the cross-sectional geometry and detailed structure of composite beam specimens are shown in Fig. 2. The cross section of the composite beam specimen is T-shaped, the total beam length L=3000 mm, and the effective loading length L_0=2800 mm. The width of the T-beam at the bottom is b=150 mm, and the width of the cast-in-place concrete slab at the top is B=1050 mm. The thickness of the concrete slab t_f=120 mm, the height of the U-shaped steel beam h=300 mm, and the total height of the T-shaped beam H=400 mm (the steel truss sinks 15 mm). The thickness of the U-shaped box girder t_w=4 mm, and the thickness of the plate protective layer a=15 mm. Pin diameter d_t=13 mm, and stud height h_t=65 mm. The concrete strength grade of C35, Q355B steel plate, and HRB400 steel bar are used.

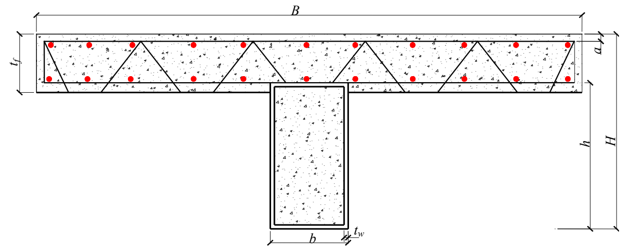


Fig. 2. Schematic of sectional dimensions of assembled U-shaped steel–concrete composite beams

The shear connectors in the specimens are set as joint bar [9], truss, stud, and their mutual combination. Table 1 lists the number of each specimen and the specific parameters for the arrangement of shear connectors. “J” indicates that the shear connectors of composite beams are joint bar, “T” indicates truss, and “S” indicates studs. “(T+S)” indicates truss and studs, and “(T+J)” indicates truss and joint bar. The upper part of the joint bar is suspended from the steel bar on the upper steel bar truss decks of the slab, and the lower part extends into the box beam by half height (150 mm). The layout of shear connectors in each specimen is shown in Fig. 3.

Table 1. Parameters of Composite Beam

Specimen number	Shear connector form			Remarks
	Joint bar	Truss	Studs	
1-J	●			Full span layout C 8@120
2-T		●		Lower chord of the steel bar truss is welded to the upper flange of the box beam
3-S			●	Full-span lay of studs M13@120
4-TS		●	●	Full-span layout of studsM13@240
5-TJ	●	●		Full-span layout of joint bar C 8@240
6-TJ	●	●		Full-span layout of joint bar C 8@120

Note: The black point indicates that the specimen adopted this type of shear connector.

Fig. 3. Layout of shear connectors in each specimen

3.3 Mechanical properties of specimen materials

The thickness of each plate of the box beam is 4 mm. According to Fig. 4, the sample of box beam is processed into standard tensile specimens and tested. The material properties of the tensile specimens are shown in Table 2.

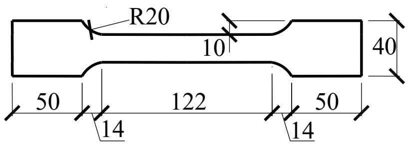


Fig. 4. Dimension of steel tensile specimen

Table 2. Test results of material properties of the steel plate

Name	Measured value (mm)	Yield strength f_y (MPa)	Ultimate strength f_u (MPa)	Modulus of elasticity E_s (Mpa)
4 mm steel plate	4.0	381	541	2.06×10^5

The reinforcing bars in the steel bar decks are C 8 and C 16, and the tensile test results of the reinforcing bars are shown in Table 3. C35 concrete is used for the composite beam. After curing several cube blocks and prism blocks when the specimens are poured under the same conditions for 28 days, the cube compressive strength of three blocks in each group is measured according to *Standard for Test Methods of Mechanical Properties of Ordinary Concrete* (GB/T 50081-2002). The concrete material properties are given in Table 4.

Table 3. Test results of the material properties of steel bars

Diameter (mm)	Yield strength f_y (MPa)	Ultimate strength f_u (MPa)	Modulus of elasticity E_s (Mpa)
8	300	468	2.0×10^5
16	428	577	2.0×10^5

Table 4. Test results of the material properties of concretes

Ultimate bearing capacity of cube(kN)	Compressive strength of cube f_{cu} (Mpa)	Modulus of elasticity E_c (Mpa)
880	38.6	----
856		
870		

3.4 Test equipment

This experiment is a static load test of simply supported assembled U-shaped steel–concrete composite beam. The actual loading device is shown in Fig. 5. A self-balancing reaction frame is used. A hydraulic jack with a range of 150t is used for loading, and two-point loading is realized by setting a distribution beam at the loading end of the jack.

3.5 Loading system and measuring scheme

Preloading is conducted prior to the formal loading. In formal loading, the specimens are first loaded in accordance with the 20 kN grade difference before 70% of the yield load. After that, they are then loaded in accordance with the 10 kN grade difference. When the ultimate load is reached, it is continuously loaded until the member is destroyed (the load drops to 85% of the ultimate load or the deformation is too large to continue loading). Each grade of loading lasts for 5 minutes, and the experimental phenomena are observed.

Fig. 5. Actual loading device of composite beam

The arrangement of displacement meters in the experiment is shown in Fig. 6, where DT1 and DT5 are used to measure the settlement of the bearing, and DT2, DT3, and DT4 measure the deflection at the midspan and loading point. DT7 and DT8 are used to measure the relative slip between concrete and steel plate. DT6 and DT9 measure the relative slip between the U-shaped steel beam and the concrete in the beam.

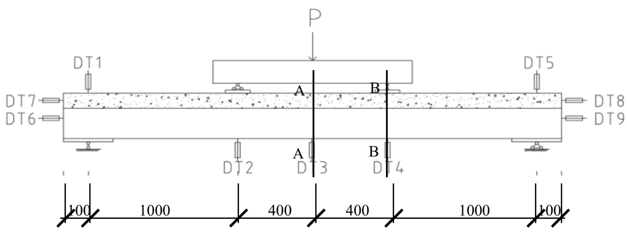


Fig. 6. Arrangement of displacement meters

The arrangement of strain gauges (H) on the surface of concrete floor slab is shown in Fig. 7. The strain gauge arrangement (S) of the reinforcement bars in the concrete floor slab is shown in Fig. 8. Meanwhile, strain gauges are arranged unilaterally and arranged on the upper reinforcement of the floor slab. Fig. 9 shows the arrangement of the strain gauges in different cross sections.

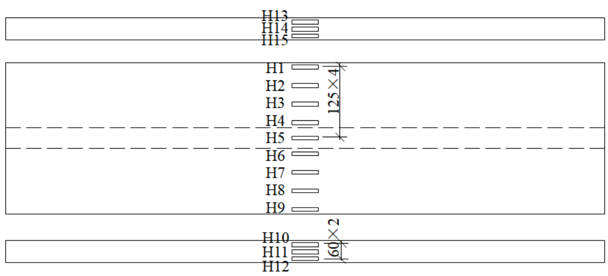


Fig. 7. Arrangement of strain gauges on the surface of concrete floor slab

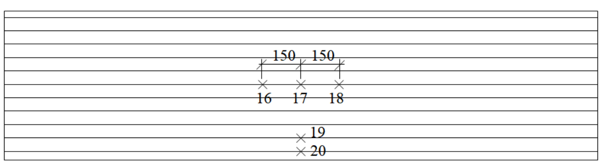
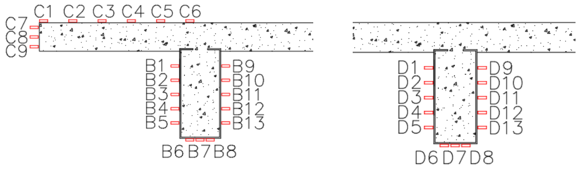


Fig. 8. Arrangement of strain gauges of the reinforcement bars in the floor slab



(a) (b)

Fig. 9. Arrangement of the strain gauges in different cross sections.(a) Cross section A-A. (b) Cross section B-B

4. Result Analysis and Discussion

4.1 Experiment phenomenon

The experimental phenomena observed during the loading process of each specimen in the test can be roughly divided into two categories in accordance with the different types of shear connectors. One category contains studs, namely, specimens 3-S and 4-TS. The other category includes the remaining specimens, which do not contain studs.

In each category, the test phenomena of specimens are similar, but with different ultimate load value and deformation, because the specific shear connectors in each specimen are different. Here, the two categories of test phenomena are described with specimen 2-T and specimen 4-TS as examples.

When specimen 2-T is loaded to 280 kN, cracks appear in the concrete floor slab. When loaded to 360 kN, a dislocation of the concrete slab and the composite beam is found at the right end. Subsequently, the lateral cracks of the concrete floor slab at the midspan and the loading point of the composite beam develop upwards. The staggered slip between the concrete floor slab and the composite beam develops. After loading to 500 kN, the load remains unchanged, and the midspan deflection increases rapidly. The maximum deflection is 89.2 mm, reaching $1/31.4L$. The slip between the concrete floor slab and the U-shaped steel increases. When the staggered crack at the right end is 27.71 mm, the upper concrete floor slab is finally crushed into a through crack, which can no longer bear the load. The test is ended, and the maximum width of the crack is obtained at 14.0 mm.

When specimen 4-TS is loaded to 460 kN, the concrete floor slab cracks. After loading to 600 kN, with the sudden abnormal sound of the specimen, the load suddenly decreases to 480 kN, and the concrete floor slab and the composite beam are evidently dislocated at the right end. As the load is maintained at approximately 470 kN, the bending deformation of the specimen becomes evident, and the midspan deflection increases rapidly. The maximum deflection of the composite beam is 78.8 mm, reaching $1/35.5L$. Moreover, the slip between the concrete slab and the U-shaped steel increases. When the dislocation crack is up to 24.12 mm, the upper concrete floor slab is finally crushed into a through crack, and the maximum width of the crack is 8.0 mm. The load decreases, and the test is ended.

The deformation and failure states of the two categories of specimens during loading are compared, and the result shows that the load of the members with studs as shear connectors decreases during loading, and an abnormal sound is observed. Fig. 10 shows the deformation and failure of specimen 4-TS during loading. During the test, no bulging of the steel plates of box beam or relative sliding between the box beam and its inner concrete was observed.

Fig. 10. Failure phenomenon of specimen 4-TS during loading. (a) Before loading.(b) Evident bending of the specimen after loading. (c) Crack of concrete floor slab at loading point. (d) Evident staggered slip at the right end of the specimen. (e) Through crack of the concrete panel at loading point. (f) Final failure mode of the specimen

4.2 Load displacement curve

Fig. 11 shows the measured displacement curve of the midspan load of each specimen during the entire loading process. The load–midspan deflection curves of the specimen without studs are smooth, continuous, and has no evident abrupt change, showing excellent interaction between the steel and the concrete because of the constraint of the external steel-clad beam on the internal concrete. These findings indicate that all specimens have an excellent elasto-plasticity property, good ductility, and deformation performance. However, the load–midspan deflection curves of the specimens with studs as shear connectors in the other category, exhibit a sudden drop. This condition is mainly due to the brittle failure of stud shear connectors at the maximum load, resulting in a sudden decline in bearing capacity.

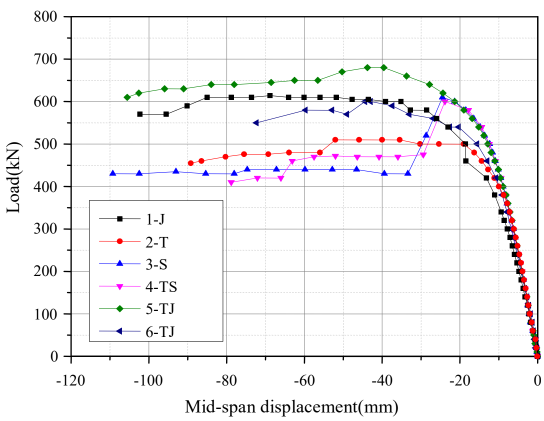


Fig. 11. Load–midspan displacement curves of each specimen

Comparatively, the ultimate load of specimen 2-T is the smallest, followed by specimen 1-J, specimen 3-S, specimen 4-TS, and specimen 6-TJ, and the ultimate load of specimen 5-TJ is the largest. This finding demonstrates that the composite form of steel bar truss is welded to the box beam and joint bar (specimen 5-TJ) as the shear connector has the highest bearing capacity. The ultimate load is increased by 11.5% and 33.3% compared with that of only joint bar (1-J) and only steel bar truss (2-T), respectively. Hence, the flexural capacity of the novel assembled U-shaped steel–concrete composite beam is effectively improved. At the same time, the deformation of the member is remarkable, showing that it has a strong deformation ability, and the ductility coefficient reaches 4.22. Therefore, the combined form of steel bar truss welded to box beam and joint bar can be recommended as the shear connector of the novel assembled U-shaped steel–concrete composite beam members. In addition, the smaller space of the joint bar does not necessarily indicate better performance, and a reasonable spacing is required to achieve its best effect.

The curve in Fig. 12 shows no slip between the box beam and the concrete floor slab of each specimen when the load is small. When the load increases to a certain value, an evident slip occurs. Similarly, due to the high shear stiffness of the studs and their brittle failure, the slip of the specimens with studs as shear connectors suddenly changes when the load reaches the maximum, showing brittle failure characteristics. However, the slip of other specimens is large during the complete loading process, showing ductile failure characteristics.

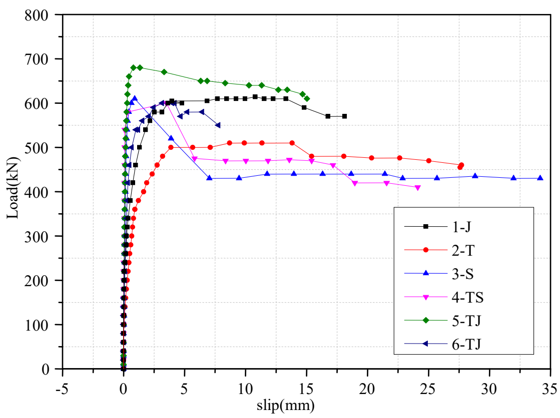
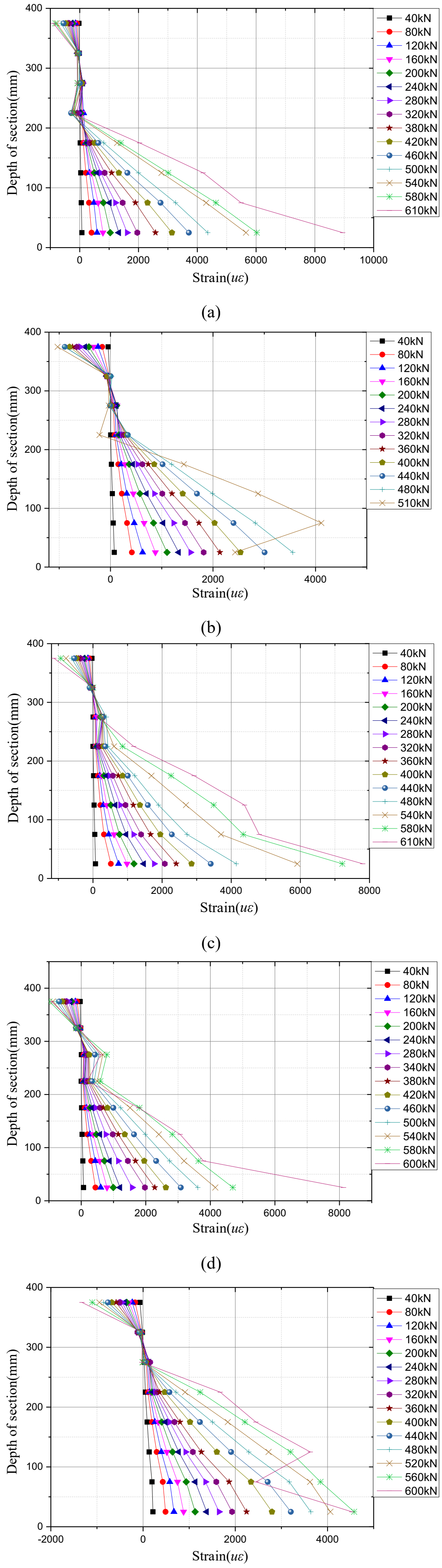
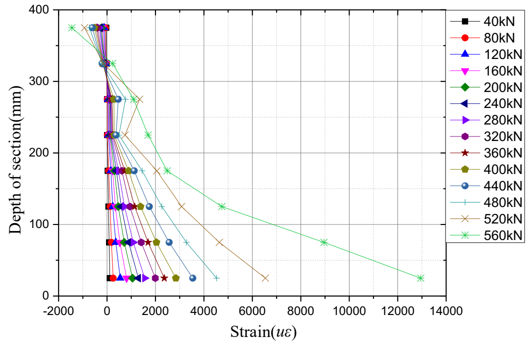


Fig. 12. Load-slip curves of each specimen

4.3 Strain distribution of midspan section along height

The strain distribution of the midspan section of each specimen along the beam height is shown in Fig. 13. The strain of each specimen is basically linearly distributed along the height at the initial stage of loading. The beam section is nearly consistent with the plane cross-section assumption. This finding indicates that the lower box beam and the upper concrete floor slab can bear load synergistically, and their composite effect is good. When the specimen bears a large load, slip strain occurs at the interface between the clad steel box beam and the concrete floor slab. As the load increases, the neutral axis in the section moves up gradually, the steel beam is in tension, whereas the concrete is in compression. Thus, the different materials can be used sufficiently. The strain distribution of the clad box beam is no longer linear at this time. However, only one neutral axis is found in this section, indicating a composite effect between the box beam and the concrete floor slab.





(f)

Fig. 13. Strain distribution of the midspan section of each specimen. (a) Specimen 1-J. (b) Specimen 2-T. (c) Specimen 3-S. (d) Specimen 4-TS. (e) Specimen 5-TJ. (f) Specimen 6-TJ

4.4 Failure mode

Based on the deformation and failure process and the stress–strain distribution law of the above specimens during the complete loading process, the failure modes of the novel assembled U-shaped steel-concrete composite beams can be divided into two categories according to the different shear connector types.

The ultimate failure form of each non-stud specimen is the same as that of an ideally reinforced beam. They are all bending failures on normal sections, that is, the concrete in the compression area reaches the compressive strain limit and is then crushed. Meanwhile, the box beam has been stretched to yield before the specimens can experience a long deformation process from yield to final failure. The specimens present good ductility, which can be defined as a ductile failure mode.

Furthermore, the entire bending failure process of non-stud specimens can be divided into the three stages according to the law of the load–midspan deflection curve in the complete loading process of each specimen: when the applied load is less than 70% of the ultimate load (P_u), the load–midspan deflection curve changes linearly. Thus, this stage (0–70% P_u) can be regarded as an elastic stage. When the load is approximately (70%–90%) P_u, the slope of the curve decreases, indicating that the stiffness of the member starts to decrease. Hence, this zone can be considered a weak elastic working stage. When the box beam is yielded, the midspan deflection increased rapidly, but the load did not decrease immediately. When the bearing capacity decreased to 85% P_u, a large deformation is observed, indicating an elastic–plastic working stage.

Although the specimens with studs can also finally reach the state of concrete crushing in the compression zone and box beam yielding in the tension zone, the brittle failure of the shear studs can evidently decrease the bearing capacity of the specimens during the loading process. For example, the reduction rate of specimen 3-S reaches 30%, and the dropping trend is rapid. Therefore, this study defines it as a brittle failure mode. Similar to the non-stud specimen, the entire bending failure process of the specimens with studs can be divided into the three stages, but the bearing capacity suddenly decreases in the elastic–plastic working stage.

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5. Conclusions

An assembled U-shaped steel–concrete composite beam is proposed to improve the assembly rate of the steel–concrete composite beam and enhance the synergistic effect of lower U-shaped steel beam and concrete. The effects of different shear connectors on flexural behavior were compared through the experimental study of the flexural behavior of the composite beams with different types of shear connectors. The possible failure modes of composite beams were analyzed, and some suggestions on selecting shear connectors for the novel composite beams were recommended. Finally, the following conclusions could be drawn:

(1) Filling concrete in the box beam can enhance the overall and local stability of the steel plate, which can avoid the overall and local buckling of the box beam.

(2) The failure modes of the presented assembled U-shaped steel–concrete composite beams can be divided into two categories according to whether they adopt studs as connectors. The failure mode of the composite beams without studs as shear connectors is the same as that of the ideally reinforced beams. It presents good ductility, which can be defined as a ductile failure mode. When studs act as shear connectors, the brittle failure can lead to an evident reduction of the bearing capacity of composite beams, referred to as a plastic failure.

(3) The loading process of composite beam members can be roughly divided into three stress stages under the action of positive bending moment: elastic working stage (0–0.7 P_u), weak elastic working stage (0.7–0.9 P_u), and elastic–plastic working stage.

(4) The combined form of steel bar truss welded on the box beam and joint bar (5-TJ) can improve the ultimate load by 11.5% and 33.3%, respectively, compared with only joint bar (1-J) and only steel bar truss (2-T), thereby effectively improving the flexural capacity of the novel assembled U-shaped steel–concrete composite beam. Meanwhile, the ductility coefficient of the member reaches 4.22, and the ductile deformation capacity is also remarkable. However, a reasonable spacing is found between joint bars to achieve the best enhancing effect.

This study explored the influence of different shear connectors on the positive bending behavior of the novel assembled U-shaped steel–concrete composite beams through experimental method, and the possible failure modes of the composite beams under different shear connector types were obtained. Some suggestions on selecting shear connectors in the novel composite beams were presented, thereby providing references for the design and practical engineering application of such new composite beams. Although this study cannot fully reveal the bending characteristics of the composite beams due to the limited amounts of specimens, the test can provide experimental verification for further studying the mechanical performance by finite element analysis.

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