



OPEN Experimental study on flexural behavior of bonded steel-concrete composite beams

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To address the limitations of mechanical shear connectors, adhesives are used in this research as shear connectors of steel-concrete composite beams (SCCBs). Several groups of bending tests were conducted to compare the flexural behavior of bonded and mechanical SCCBs. Moreover, the results show that the failure modes of the bonded SCCBs mainly include yielding of the bottom flange of the I-beam and the cracking of the concrete bottom surface, local detachment between the two bonding surfaces and the crushing of the concrete slab at the top surface. The rigidity of the bonded SCCB is higher than that of the mechanical one. In addition, the ultimate load of the bonded SCCB connected by 6 mm thick epoxy resin is the highest, which is about 16.8% higher than that of mechanical one. Furthermore, increasing the adhesive layer's thickness can improve the adhesive performance to a certain extent. Thus, it is suggested that the adhesive thickness should exceed 4 mm, and 6 mm is the optimal. In addition, as local detachment of the adhesive layer occurred in this test, further research can be carried out to avoid such damage.

Keywords Bonded steel-concrete composite beams, Four-point bending test, Failure modes, Flexural rigidity, Ultimate load

SCCB is a structural member that is composed of steel-concrete in the same cross-section, and realizes the combination of steel and concrete through shear connectors. Owing to the benefits in terms of mechanical properties, construction performance and economy, SCCBs have been widely adopted and continuously developed and innovated. Since the 1950s, composite bridges have been developed rapidly. Composite beams have been applied in bridges ranging from short- and medium- span bridges with spans of 20 ~ 25 m to cable-stayed bridges with spans of nearly 1,000 m¹. The overall performance of composite beams should be ensured by the effective transmission of longitudinal shearing force between steel and concrete. However, only the natural bonding between steel and concrete surfaces is insufficient to meet the requirements of longitudinal shear force transmission. Therefore, the application of shear connectors between the steel and concrete is an essential measure, as well as the key to ensuring the overall performance and collaborative action of SCCB²⁻⁴. Mechanical shear connectors are most widely adopted in SCCB, i.e., steel and concrete are connected by mechanical interlocking mechanisms⁵.

The common mechanical shear connectors⁶ include studs, structural steels, bent-up bars, etc. However, the shear area of a mechanical shear connector is usually small, thus resulting in a higher degree of stress concentration on steel girders and concrete slabs. This will induce cracks in concrete slabs, even the crushing of concrete on the rear side of shear connectors, as shown in Fig. 1⁷⁻⁹. Moreover, mechanical shear connectors need to be embedded in the concrete slab, which means that a certain thickness is required for concrete slab to ensure the connection effect. Therefore, it is very unfavorable to reduce the dead weight of SCCB⁵. As the most important and highly developed joining methods, welding is widely used for the connection between steel beams and mechanical shear connectors. Simultaneously, the heat input will affect the material properties of the shear connectors¹⁰. Mechanical shear connectors are mostly metal ones, and they are easily corroded during service life, thus affecting the durability of structure. Besides, the corrosion will affect the fatigue life¹¹⁻¹⁴.

Since the 1960s, scholars¹⁵ have begun to explore new shear connectors, among which the utilization of organic adhesives as shear connectors to replace the metal shear connectors is the most pioneering attempt¹⁶.

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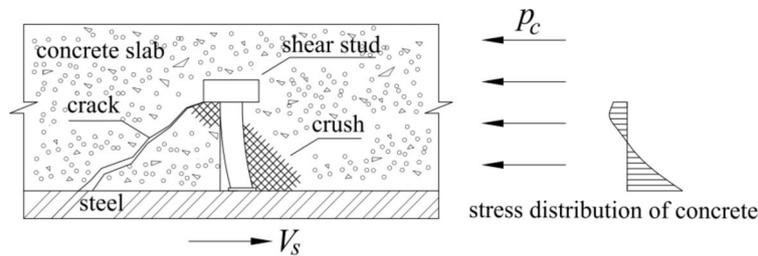


Fig. 1. Mechanical shear connectors destroy the integrity of concrete slabs⁹.

Year of publication	Authors	Concrete slab		I-beam height/mm	Span /mm	Adhesive materials
		Thickness /mm	Width /mm			
2007	Bouazaoui ²⁷	70	350	220	3300	Epoxy resin & Polyurethane (PU)
2013	Souici ¹⁹	55	350	200	3250	A mixture of epoxy resin and silicon dioxide
2011	Jurkiewicz ¹⁸	100	300	220	4000	A mixture of epoxy resin and silicon dioxide
2014	Jurkiewicz ²²	80	400	160	4000	A mixture of epoxy resin and silicon dioxide
2008	Bouazaoui ¹⁷	140	800	420	8500	A mixture of epoxy resin and silicon dioxide

Table 1. Statistics of experimental studies on bonded SCCB.

When the bonded shear connector is properly designed, the SCCB with a bonded shear connector has similar behaviors as the SCCB with a mechanical connector^{17,18}. However, the shear stiffness of the former is better than that of the latter^{17,19}. Compared with mechanical shear connector, the bonded shear connector can reduce the crack risk of concrete slab²⁰, in addition, the SCCBs with a bonded shear connector make the assembly construction more convenient^{20–22}, and it has good fatigue performance¹⁴. Some scholars studied the shear capacity of bonded shear connector by push-out test. The research by Kumar et al.²³, shows that the failure mode will convert from the adhesive mode of failure to a cohesive mode of failure with the increase in the thickness of the adhesive layer, the shear capacity does not increase monotonically with the adhesive layer's thickness, and the researcher proposed an optimal thickness in his research. Moreover, the performance of the bonded shear connector is affected by the nature of adhesive and the strength of concrete²⁴. The shear capacity of adhesive is greater than the strength of concrete to assure structural performance²⁵. However, improving the performance of the two materials may be beneficial to improving the overall structural performance²⁶. Bouazaoui et al.²⁷ found that the epoxy performs as a rigid shear connector between the steel and the concrete, preventing any slip, by comparison, the polyurethane is a flexible shear connector. Besides, the impact of nonuniform distribution of adhesive layer thickness is not important for the shear capacity. In addition to the above parameters, the research shows that the performance of bonded shear connector is affected by other parameters, such as the bonding area, the thickness of the concrete slab and the surface treatment^{28,29}. Moreover, the grooves/abutments in the interface between the concrete and steel seemed to be very efficient in improving the shear capacity, but they did not significantly increase the load-bearing capacity of composite beams³⁰. Zhan et al.³¹ predicted the ultimate shear strength of bonded shear connectors through push-out tests, which provides a certain experimental and theoretical basis for the design of SCCB.

To study the structural behavior of adhesives as the shear connectors of SCCB, the experimental research on bonded SCCBs is the most effective and direct research method. Although most of the adhesives used in existing researches are made of epoxy resins, there are great differences in the properties of different types of epoxy resins produced by different manufacturers in different countries. In this paper, epoxy resins and magnesium phosphate cement (MPC) manufactured in China with better durability are adopted, and the behavior of composite beams with adhesives as shear connectors is studied through tests. In addition, bonded shear connectors pose much less restrictions on the concrete slab's thickness than the mechanical ones, so the thickness of the concrete slab designed by each research team tends to decrease.

This paper will focus on the investigation and discussion of the steel-thin concrete slab composite beams, and evaluate the flexural behavior of bonded SCCBs. Mechanical performance tests were conducted using the SCCBs as the research object, in which two connection modes, the mechanical one and bonded one were adopted. Taking into consideration the effect of adhesive type and thickness, the failure mode and the ultimate load of SCCBs were compared and analyzed, so as to investigate the effect of two kinds of shear connectors on SCCBs with concrete slabs of different thicknesses.

Experimental program

Test specimens

To study the flexural performance of SCCBs, seven SCCBs were fabricated and subjected to four-point bending tests. Table 1 provides a review of previous experimental studies on bonded SCCBs. It is shown that when

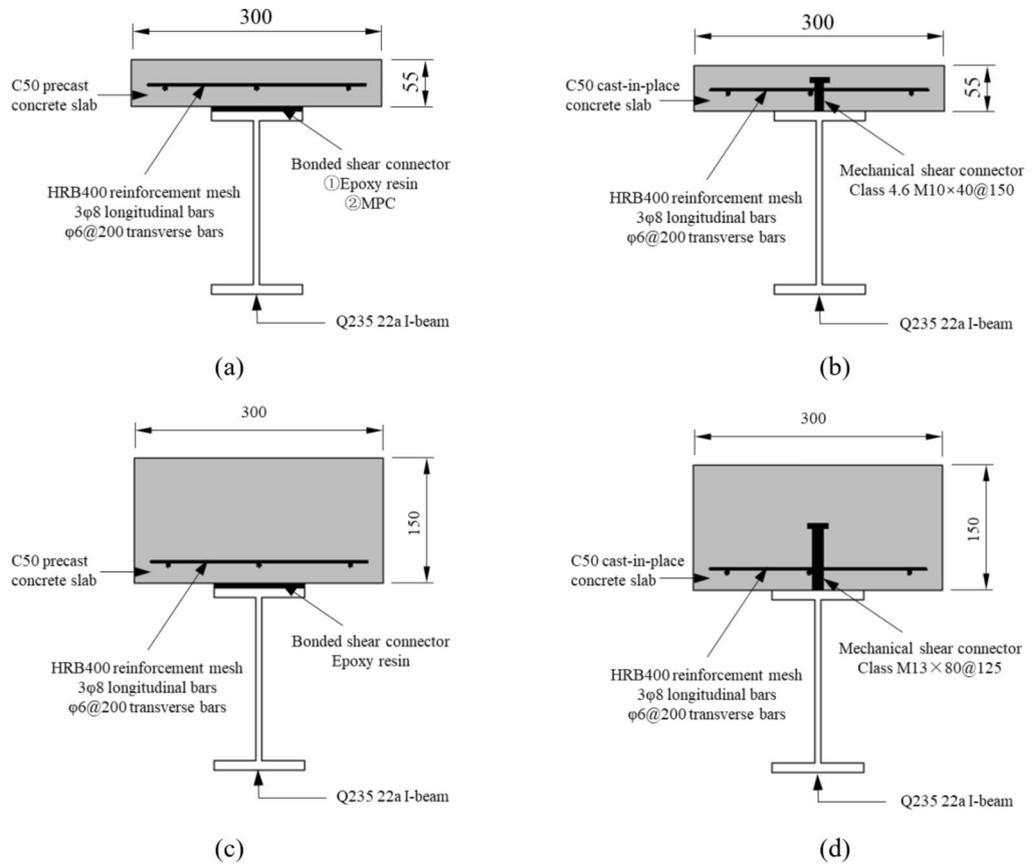


Fig. 2. Specimen dimensions (/mm).

Specimen No.	Shear connectors		Thickness of the thin concrete slab h_c /mm	Cross-section forms as shown in Fig. 2
	Types	Specification		
JL55-2	Epoxy resin	2 mm	55	(a)
JL55-4	Epoxy resin	4 mm	55	(a)
JL55-6	Epoxy resin	6 mm	55	(a)
ML55-2	Magnesium phosphate cement (MPC)	2 mm	55	(a)
JL150-2	Epoxy resin	2 mm	150	(c)
SL55-10	Stud	Class 4.6 M10×40@150	55	(b)
SL150-13	Stud	Class 4.6 M13×80@125	150	(d)

Table 2. Parameters of test specimens.

designing the SCCB tests, various scholars tend to reduce the thickness of the concrete deck. In this work, a smaller value of thickness was adopted for the concrete slab to study the flexural behavior of steel-thin concrete slab beams.

The dimensions of the specimen are shown in Fig. 2: the length of the beam is 3300 mm; the calculated span is 3000 mm; the bearing position has been strengthened and widened; the height of the 22a I-beam is 220 mm; the width of the flange is 110 mm; the concrete slab is 300 mm wide; the thicknesses of the concrete slabs are 55 mm and 150 mm; each concrete slab is equipped with 3φ8 longitudinal bars with a spacing of 110 mm, as well as φ6@200 transverse bars. The parameters of the specimens are listed in Table 2.

The stud-connected SCCBs are cast-in-situ concrete slabs, and the headed studs and the steel beam are depicted in Fig. 3. Formworks cannot be removed until the concrete reaches certain strength. The concrete formwork is shown in Fig. 4. After the concrete has been cured for 28 days, the bonding surfaces of the I-beam and concrete slab were first ground by a sander, then cleaned with absolute ethyl alcohol and bonded by the adhesive, and left to stand for 14 days before being formally loaded. The manufacturing process of bonded SCCBs is shown in Fig. 5.



Fig. 3. Stud shear connectorsFigure.



Fig. 4. Concrete formwork.

Material properties

The major materials of SCCBs are steel and concrete. The concrete used in this test is C50 grade. The steel beam is made of Q235 grade steel, and a 22a I-beam shape is adopted. The longitudinal reinforcement bars of concrete slab are of HRB400 grade, and a diameter of 8 mm. The transverse reinforcement bars of the concrete slab are of HRB400 grade, and the diameter is 6 mm. According to relevant codes, the properties of concrete and steel were tested, and the material properties are shown in Tables 3 and 4.

Shear connectors adopted in this test are studs and adhesives, representing mechanical and bonded shear connectors respectively. Studs used in this test comprise two types, namely the Class 4.6 M10 × 40 small studs and M13 × 80 large studs. To study the performance of different adhesives, two adhesives are used in this test. The first one is epoxy resin with high bonding strength, which is constituted of Fasten concrete bonding structural adhesives FAV111A and FAV111B through a mixing ratio of 2:1, with a compressive strength of 80.9 MPa and an elastic modulus of 5110 MPa. The second one is magnesium phosphate cement (MPC) with good durability, which is made up of dead burned magnesium oxide (M), ammonium dihydrogen phosphate (ADP), borax (B) and water (W) as raw materials according to the mixing ratio shown in Table 5.

Test procedure

The structural performance of SCCB was studied through the four-point bending test. Each test beam was equipped with displacement and strain testing devices. Five displacement sensors were arranged at four equal-division points in the length direction of the beam to test deflection (as shown in Fig. 6). Concrete and steel strain gauges were respectively fixed in the middle of the span in the height direction of the SCCBs to test the strain in mid-span. The layout of mid-span strain gauges is shown in Fig. 7.

In this test, jacks were applied to impose the loading, which is shown in Figs. 6 and 8. The step loading method was adopted, with a preload of 20kN and a loading duration of 5 min. At the elastic stage, the load increment per level was 6kN, and the loading step duration was 30s. When the rigidity of the SCCB started to change, the load increment was altered into 2kN until the specimen was damaged.

Test results and discussion

Failure modes

The following two types of SCCBs exhibited different test phenomena during the whole loading process:

- (1) Mechanical SCCBs.

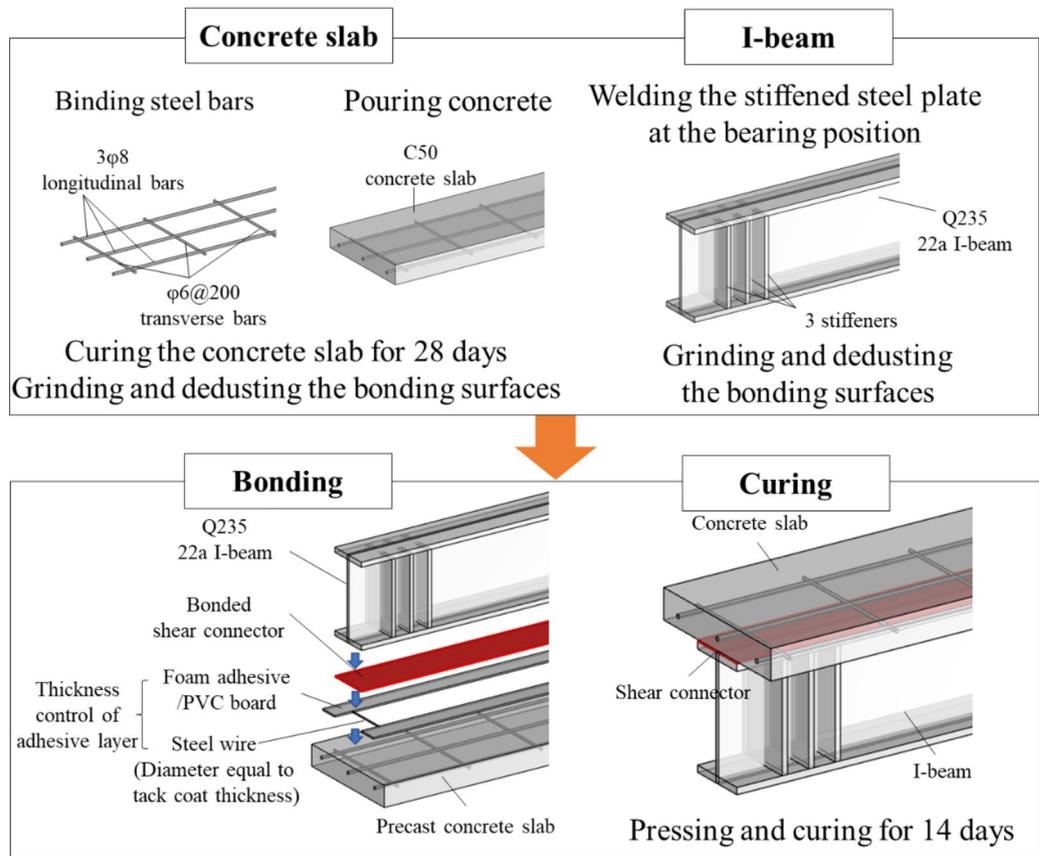


Fig. 5. Manufacturing process of bonded SCCB specimens.

Cube compressive strength f_{cc}/MPa	Axial compressive strength f_{cp}/MPa	Elastic modulus E_c/MPa	Splitting tensile strength f_{ts}/MPa
49.2	50.7	2.84×10^4	6.86

Table 3. Concrete properties.

Specification	Yield strength f_s/MPa	Elastic modulus E_s/MPa
Steel bars with diameter of 8 mm	507	1.96×10^5
Steel bars with diameter of 6 mm	694	1.96×10^5
I-beam	257	1.94×10^5

Table 4. Steel properties.

Name	M	ADP	B	W
Amount /kg/m ³	1404.89	468.30	196.68	234.15

Table 5. Mixing ratio of MPC.

As the load increased gradually, the slip between concrete and steel increased in the mechanical SCCB with headed studs as shear connectors. In the later stages of loading, the deflection growth rate significantly increased, and the connection between the concrete slab and the I-beam weakened. The ultimate failure mode was characterized by the yielding of the I-beam bottom flange and concrete slab cracks, as demonstrated in Fig. 9(a). It is noteworthy that in the mechanical steel-concrete composite beams with thin concrete slabs

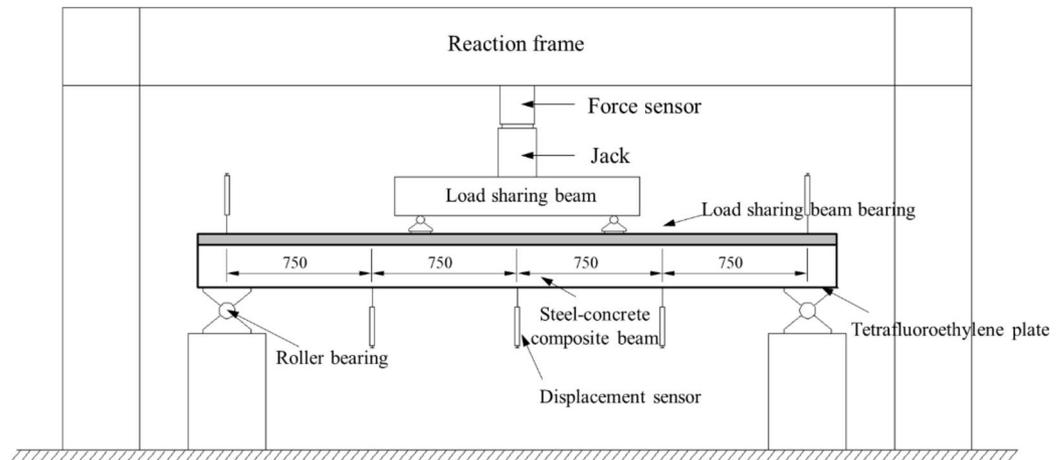


Fig. 6. Loading (/mm).

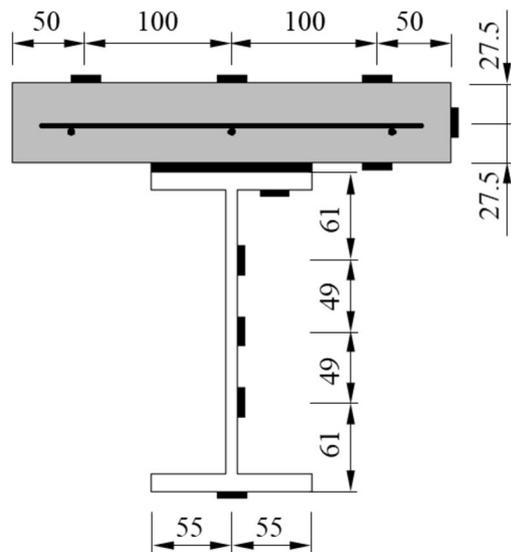


Fig. 7. Layout of strain gauges in mid-span cross-section (/mm).

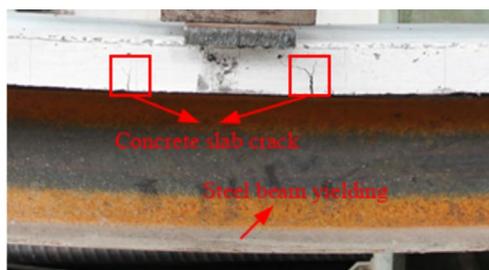
(55 mm thickness), oblique cracks appeared at the concrete end and longitudinal cracks also developed at the concrete top surface, according to Fig. 9(b) and Fig. 9(c).

The bonded SCCBs using epoxy resin and magnesium phosphate cement (MPC) as shear connectors exhibit two distinct failure modes. The first mode is characterized by partial detachment of the concrete slab from the steel I-beam during the later stages of loading, as demonstrated in Fig. 10(a) and Fig. 10(b). Subsequently, intermittent and slight debonding occurred when the loading continued. After the bonding surface of the steel was partially detached from the concrete slab, the loading continued until the bottom flange of the I-beam yielded, accompanied by cracking of the bottom surface of the concrete slab. The final failure mode was characterized by the yielding of the I-beam bottom flange and the cracking of the concrete slab, as shown in Fig. 10(c). The second mode manifested as the steel and concrete were well connected without any detachment during the whole loading process, and the failure mode showed as the yielding of the I-beam bottom flange and the crushing of the concrete top surface, as shown in Fig. 10(d).

Significantly, cracks appeared at the end of the concrete slab and longitudinal cracks formed on the top surface of the concrete slab, when a stud was used as the shear connector in a 55 mm-thick concrete slab. This phenomenon may be caused by the large concentrated stress generated in the concrete during the shear force transmission by the stud. However, the bonded SCCB did not exhibit any signs of such cracks. In addition, both the yielding of the bottom flange of steel I-beam and the crushing of the concrete top surface occurred together only in bonded SCCB when the thickness of the concrete slab was 55 mm, which indicates that the strength of both steel and concrete had been fully exerted. Therefore, in SCCBs with reduced concrete slab thickness, effective bonded shear connectors outperform mechanical shear connectors, which give full play to the load-bearing capacity of the steel and concrete.



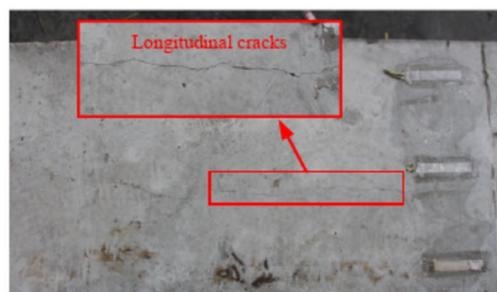
Fig. 8. On-site test photos.



(a) Concrete slab crack and steel beam yielding



(b) Concrete beam end crack



(c) Longitudinal cracks at the top surface of the concrete

Fig. 9. Mechanical SCCB failure modes.

Load-displacement behaviour

Load-displacement characteristics

Figure 11(a) presents the load-displacement curves of all test specimens in this study. The curves can be classified into two distinct types: Type I exhibits a sequential progression of linear segment-nonlinear segment-yield segment, while Type II demonstrates a zig-zag segment between the linear and nonlinear segments. The key distinction between these curve types lies in the presence of the zig-zag segment. When the adhesive connector does not fail, the concrete slab will not crack and remains under compression (e.g., JL55-6). However, when the adhesive connector fails, the bottom edge of the concrete slab is under compression, and the upper edge of the concrete slab is under tension. As the load increases, the bottom edge of the concrete slab will crack, this bond failure and concrete slab cracking cause stiffness reduction, and the stiffness changed presents a zig-zag in the load-displacement curve (e.g., JL55-2). This stage can be defined as the adhesive connector failure and

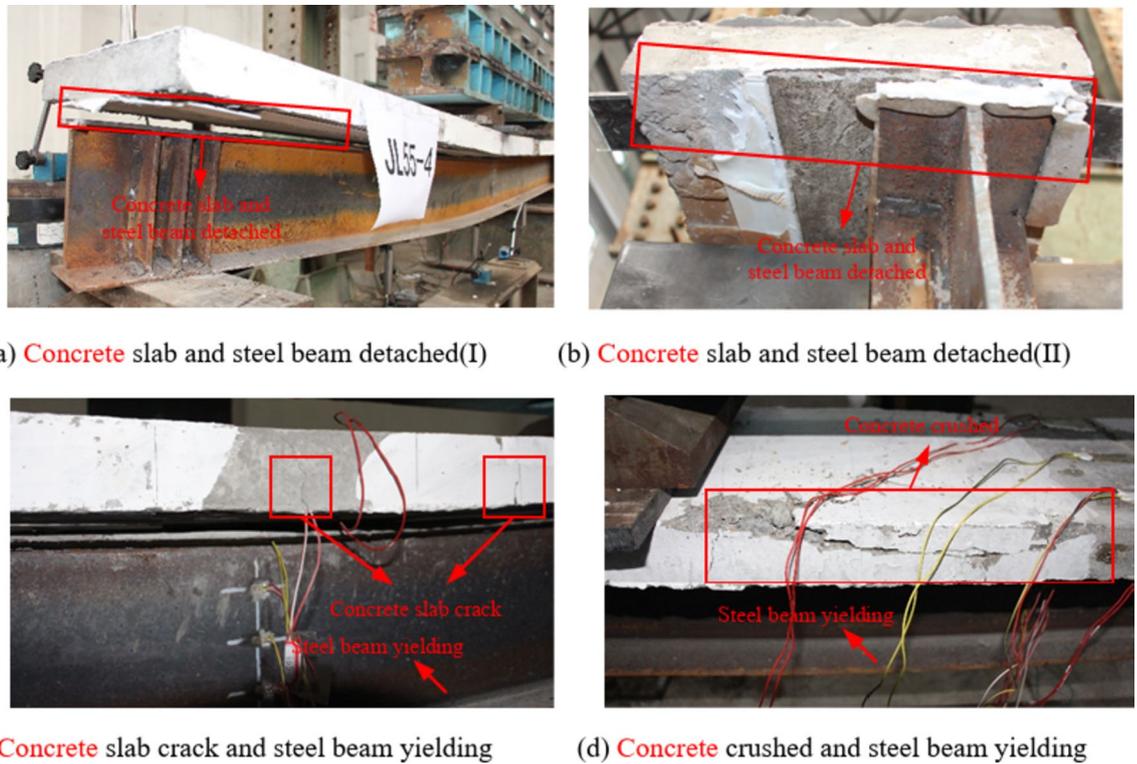


Fig. 10. Bonded SCCB failure modes.

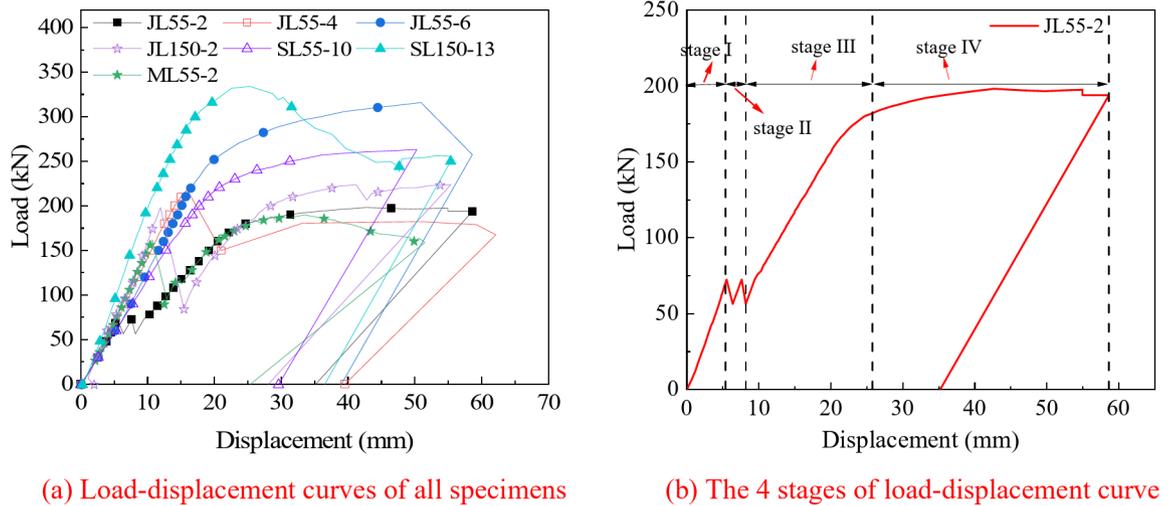


Fig. 11. Load-displacement curves.

concrete cracking phase, it should be emphasized that this zig-zag curve pattern only appears when the adhesives connector first failure. Therefore, through the observation of the whole test process, the load-displacement curve could be separated into 4 stages in the bonded SCCB test process, as illustrated in Fig. 11(b). The 4 stages are as follows: (I) elastic stage, (II) adhesives connector failure and concrete slab cracking stage, (III) hardening stage, and (IV) failure stage. The relationship of the load and displacement exhibited a linear in stage I when the load is small. As the load continues to increase, the concrete deck detaches from the steel I-beam, and the adhesive connector partially fails, it can be considered the stage II begins. In the stage III, the SCCB can still work, but the relationship of the load and displacement is nonlinear. In this stage, the steel beam yields, and the concrete slab cracks or is crushed, leading to the SCCB being damaged. It is noteworthy that the stage II is not observed in the test of SCCBs with mechanical connectors.

Effect of connector type

The load-displacement curves of composite beams with different types of connectors are shown in Fig. 12. As can be seen from the Fig. 12(a), during the stage I, all load-displacement curves exhibit an elastic state, the slopes of all the composite beams are close to each other, indicating that the stiffness of these beams is similar, i.e., the steel and concrete are well connected. During the stage II, the adhesive thicknesses of 2 mm and 4 mm are damaged by the partial detachment between the concrete and steel bonding surfaces. The slope of the load-displacement curve dramatically decreases when the bonding surface of the steel is partly detached from the concrete, as shown in Fig. 12(a), indicating that the bending stiffness of the composite beams decreases. When the loading continues after the local detachment, the ultimate loads of the adhesive thicknesses with 2 mm and 4 mm are similar, which are about 190 kN.

When the concrete slab thickness in both specimen JL55-6 and SL55-10 is 55 mm, and the concrete slab has not been separated from the I-beam during the whole loading process. Under the excellent bonding conditions, the bonded SCCB exhibits a higher peak load (315 kN) compared to the mechanically connected one (263 kN). Moreover, the deflection of the bonded SCCB is lower than the mechanical one under the same load as the load is increased, and it indicates that the rigidity of the bonded SCCBs has a better performance. It is interesting to note that the bonded SCCBs obviously perform better than mechanical ones with a certain thickness of adhesive layer. Therefore, it is entirely feasible to adopt epoxy resin as the shear connector of SCCBs when the concrete slab using “thin-slab”.

The load-displacement curves of specimen SL150-13 and JL150-2 were compared as shown in Fig. 12(b). When the thickness of concrete slab is 150 mm of the SCCB, the load-bearing capacity of SCCB with an adhesive connector is decreased by 32.9% compared with that of the mechanical one. It mainly due to the steel beam and concrete slab have been detached during loading. Significantly, the ultimate strength of SCCB with an adhesive connector is 315 kN, and that with a mechanical connector is 334 kN, the ultimate bearing capacities of both are very close. Therefore, a conclusion can be drawn that the application of epoxy resin in thin concrete slab of composite beams can achieve the same effect as that in thick concrete slab of mechanical composite beams.

Effect of adhesive thickness

When the thickness of the concrete slab in the SCCB is 55 mm, the load-displacement curves of SCCBs with different thicknesses of epoxy resin as shear connectors are shown as Fig. 13. When the thicknesses of epoxy resin are 2 mm and 4 mm, local detachment between the two bonding surfaces occurred in the SCCB, with corresponding loads of 72 kN and 218 kN respectively. However, local detachment does not occur on the bonding surface of the epoxy resin adhesive layer with 6 mm thick during the entire loading process. Thus, it follows that as the thickness of the epoxy resin adhesive layer increases, the load for local detachment between the two bonding surfaces gradually increases, and the adhesive connector performance also gradually improves. According to the experimental results in this paper, it is suggested that the thickness of the adhesive layer should exceed 4 mm, and 6 mm is the optimal.

Effect of adhesive type

As shown in Fig. 14, the load-displacement curves of the bonded SCCBs with magnesium phosphate cement (MPC) and epoxy resin as shear connectors were compared. In these two SCCBs, the thickness of epoxy resin and MPC shear connectors are the same, that is, 2 mm. Local detachment occurred between the steel beam and concrete slab in both SCCBs. The load for local detachment of the SCCB with epoxy resin as the shear connector is 72 kN, while that of MPC is 162 kN. Both the SCCBs can continue to bear load after the local detachment occurs, and the subsequent load-displacement curves of the SCCB with epoxy resin as the shear connector are consistent with that of the MPC one, and their ultimate loads are close. Hence, the MPC shear connector with a

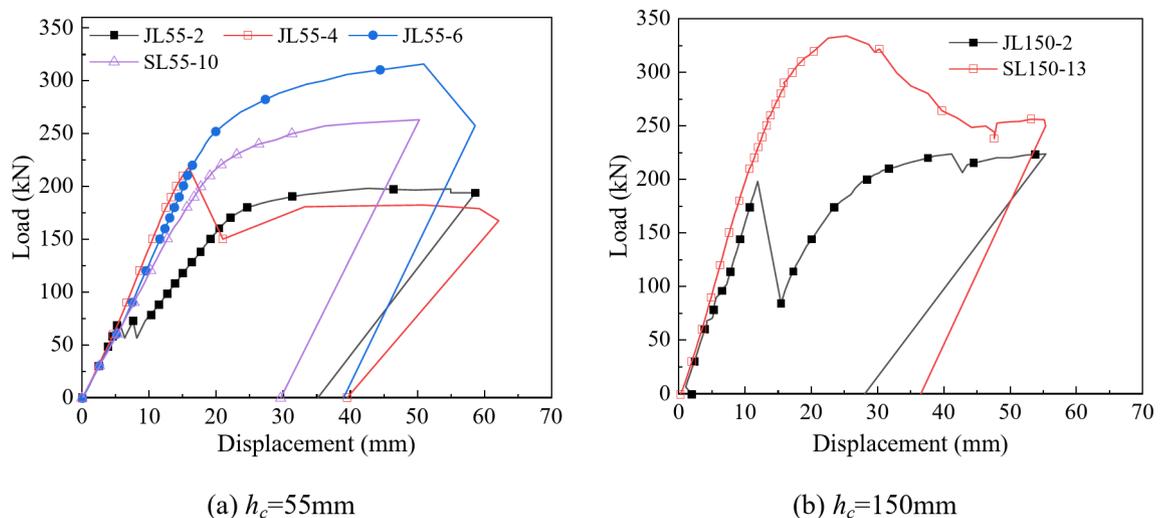


Fig. 12. Load-displacement curves of different connector type.

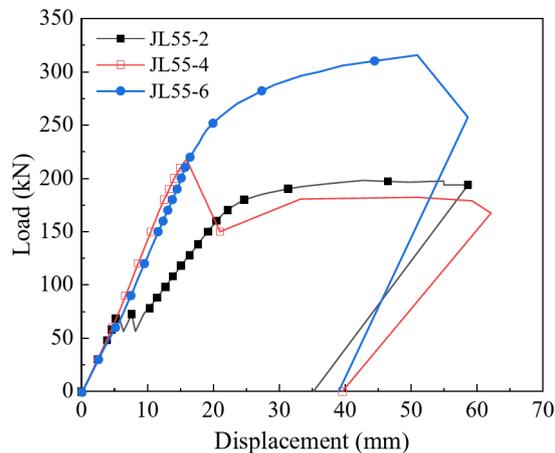


Fig. 13. Load-displacement curves of different adhesive thickness.

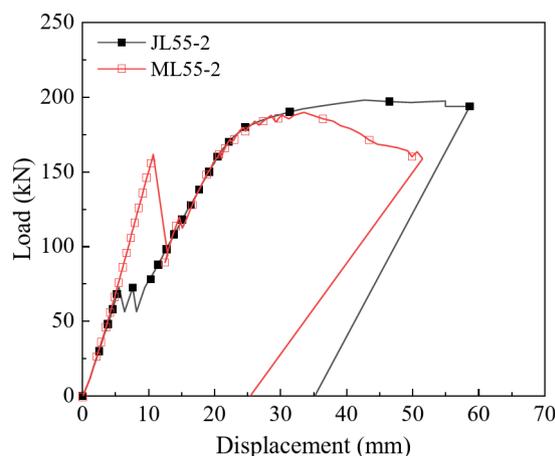


Fig. 14. Load-displacement curves of different adhesive type.

thickness of 2 mm performs slightly better than the epoxy resin shear connector with the same thickness, which may be related to their different material properties and construction technologies. Due to limited space, no further comparison is provided here. Further discussion should be based on the premise that the beams have no local detachment between the concrete slab and steel beam.

Effect of concrete slab thickness

When the shear connectors are made of epoxy resin with a thickness of 2 mm, the load-displacement curves of two bonded SCCBs with different concrete slab thicknesses were compared as shown in Fig. 15(a). Both beams showed local detachment of the adhesive layer. The load for local detachment with a concrete slab thickness of 55 mm is 72 kN, and that with a concrete slab thickness of 150 mm is 198 kN. The ultimate load-bearing capacity of the two SCCBs were close to each other. Hence, it can be concluded that epoxy resin performs well in SCCBs with thick slabs. The load-displacement curves of two mechanical SCCBs with different concrete slab thicknesses were compared as shown in Fig. 15(a) and Fig. 15(b). With the increase of concrete slab thickness, the rigidity and bearing capacity of the SCCBs increased greatly. To sum up, when the shear connectors are adhesive or stud, the increase in thickness of concrete slab is beneficial for improving the performance of SCCBs.

Load-strain response

Taking the JL55-6 as example, the load-strain response of the bonded SCCB is depicted in Fig. 16(a). The strain is approximately linearly distributed along the beam height when the load does not exceed 180 kN, and the neutral axis, as shown in Table 6, is between 190 mm and 200 mm with minimal variation. As the load increases, the strain distribution becomes nonlinear. Significantly, the strain distribution exhibits a sudden change at the junction of the concrete slab and steel beam, but the strains in both the concrete slab and steel beam is approximately linearly distributed. The neutral axis is between 209 mm and 218 mm which are shown in Table 6. According to the variations in the neutral axis and strain distribution, it can be found that the bonding layer was

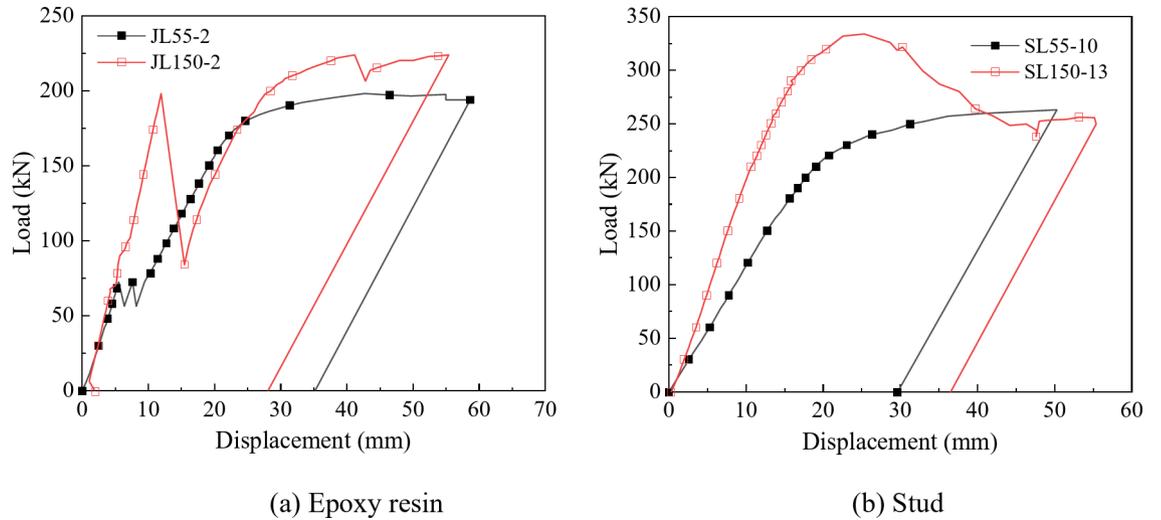


Fig. 15. Load-displacement curves of different concrete slab thickness.

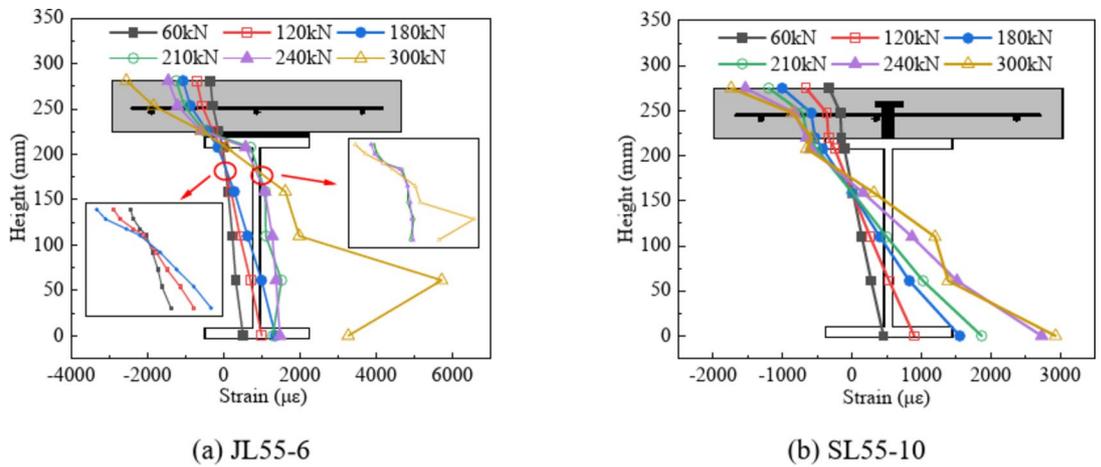


Fig. 16. Strain distribution at the elastic stage.

Load/kN	60	120	180	210	240	300
Height of neutral axis (JL55-6)/mm	200.37	192.84	190.22	218.19	216.66	209.47
Height of neutral axis (SL55-10)/mm	164.95	160.12	158.85	159.69	169.36	174.79
Maximum compressive stress (JL55-6)/µε	-354.65	-709.32	-1066.99	-1246.94	-1454.41	-2554.96
Maximum compressive stress (SL55-10)/µε	-327.92	-664.78	-1004.58	-1198.64	-1536.12	-1741.26

Table 6. Height of neutral axis.

damaged while the load was between 180kN and 210kN, nevertheless, there is still a reliable connection between the concrete slab and the steel beam.

As an example, the load-strain response of SL55-10 mechanical SCCB is shown in Fig. 16(b). Throughout the entire loading process, the strain is approximately linearly distributed along the beam height direction, and the height of the neutral axis remains relatively constant when the load does not exceed 240kN (shown in Table 6). As the load increases, the height of the neutral axis rises gradually, indicating a good co-working between the concrete slab and steel beam.

As shown in Table 6, the neutral axis height of the bonded SCCB is higher than that of the mechanical one when the load does not exceed 180kN. For example, at a load of 60 kN, the neutral axis height of JL55-6 is approximately 200 mm, while that of SL55-10 is approximately 165 mm. This demonstrates that in bonded SCCBs with the same cross-section, JL55-6 exhibits a neutral axis height approximately 35 mm higher than that of SL55-10. The bond strength between steel and concrete is higher in bonded SCCBs, and the rigidity of

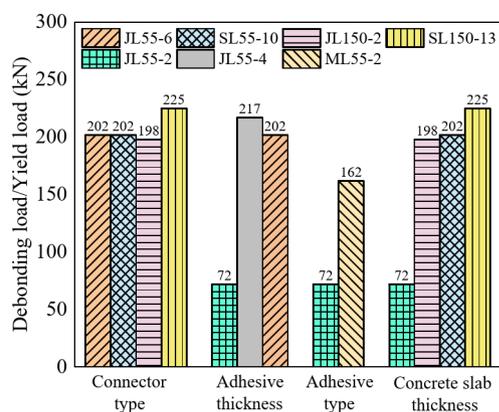


Fig. 17. Comparison of debonding load/ultimate load and yield load at the elastic stage

Specimen No.	Debonding loads/Yield loads /kN	Ultimate load /kN	Test phenomena
JL55-2	72	198	(a) Steel yielding; (b) Concrete cracking; (c) Adhesive detachment
JL55-4	217	217	(a) Steel yielding; (b) Concrete cracking; (c) Adhesive detachment
JL55-6	202	316	(a) Steel yielding; (b) Concrete crushing
ML55-2	162	190	(a) Steel yielding; (b) Concrete cracking; (c) Adhesive detachment
JL150-2	198	224	(a) Steel yielding; (b) Concrete cracking; (c) Adhesive detachment
SL55-10	202	263	(a) Steel yielding; (b) Concrete cracking; (c) Cracks at concrete end; (d) Longitudinal cracks in the concrete
SL150-13	225	334	(a) Steel yielding; (b) Concrete cracking

Table 7. Ultimate load statistics. Note: When the SCCB with bonded connectors (except JL55-6), the second column of the table is Debonding loads; When the composite beam with Stud connectors (include JL55-6), the second column of the table is Yield loads.

the SCCB is greater than that of mechanical SCCBs. Therefore, the deformation of the bonded SCCB is smaller than that of the mechanical one under the same load, which is consistent with the experimental result that the deflection of JL55-6 is smaller than that of SL55-10 under the same load.

The SCCB enters the elastic-plastic stage as the load steadily increases, the bottom flange of the I-beam yields, and the neutral axis gradually moves upward. Through the comparison of strain distribution between the two beams at this elastic-plastic stage, the maximum load borne by the I-beam in specimen JL55-6 is larger than that of the mechanical one, as shown in Table 6. It was demonstrated that the advantages of steel and concrete in mechanical properties can be fully exerted in specimen JL55-6, which aligns more closely with the original design purpose of composite structures. Therefore, the bearing capacity of the bonded SCCB is significantly higher than that of the mechanical one.

Ultimate load

Figure 17 presents the debonding load of bonded SCCB and yield load of mechanical composite beams. When the concrete slab thickness is 55 mm, the yield load of bonded SCCB is equal to that of the mechanical one, while the concrete slab thickness is 150 mm, the debonding load of bonded composite beam is 12% less than the yield load of the mechanical one, it's important to note that debonding between the concrete slab and steel beam occurred before the concrete slab crushing, as shown in Table 7. For different adhesive layer thicknesses, debonding occurred at 2 mm and 4 mm adhesive layers, with the debonding load of bonded SCCB being higher than that of mechanical one. In contrast, the bonded SCCB with adhesive layer thicknesses of 6 mm is intact. Therefore, a thicker adhesive layer is beneficial to promote debonding load.

Figure 18 presents the ultimate load of mechanical SCCB. When the concrete slab thickness is 55 mm, the ultimate load of bonded SCCB is about 20% higher than that of the mechanical one. However, when the concrete slab thickness is 150 mm, the ultimate load of bonded SCCB becomes lower than that of the mechanical one. It should be emphasized that the concrete slab and the steel beam were detached before the concrete slab was crushed. This phenomenon demonstrates that under the excellent bonding condition, the ultimate load of the bonded SCCB is higher than that of the mechanical one. Hence, this type of epoxy resin shows potential as an effective bonded shear connector in SCCB. When the adhesive layer thicknesses are different, the ultimate loads for adhesive layer thicknesses of 2 mm and 4 mm are 198kN and 217kN respectively, which account for 62.7% and 68.7% of the ultimate load (316kN) observed with epoxy resin adhesive layer of 6 mm, respectively. Therefore, it can be observed that the ultimate load of the SCCB gradually improves with the increase of adhesive layer thickness. The ultimate loads for epoxy resin and MPC are very close, it indicates that the ultimate load

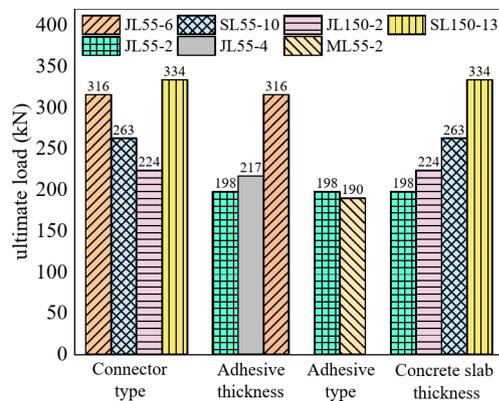


Fig. 18. Comparison of ultimate load.

is not sensitive to the adhesive type. As the concrete slab increases, the ultimate load with a stud connector increases, although that of the bonded connector also increases. However, the failure mode of all components is adhesive detachment. Significantly, when the concrete slab thickness is 150 mm, the ultimate load of the mechanical composite beam is 334kN, while the ultimate load of the bonded SCCB with a 55 mm concrete slab is 316kN, the former is only 5.7% higher than the latter, this indicates that a thinner concrete slab can be used for a bonded SCCB.

Conclusions

In this paper, the four-point bending test was conducted to study the flexural performance of the bonded and mechanical SCCBs. The following conclusions can be drawn:

(1) The failure modes of the bonded SCCBs can be categorized into two primary types, the first type involves the yielding of the I-beam bottom flange and cracking of the concrete bottom surface. While the second type is characterized by local detachment between the two bonding surfaces and the crushing of the concrete top surface. The local detachment at the bonding surfaces belongs to brittle failure, which should be avoided as much as possible.

(2) Under the excellent bonding condition, the rigidity of bonded SCCBs can be better than that of the mechanical one under the same load. Besides, the bearing capacity of the bonded SCCBs is higher than that of the mechanical SCCBs. This is due to the bonding between the steel and concrete in the SCCB enables its material properties to be completely used.

(3) The mechanical SCCBs' bearing capacity will be significantly decreased by reducing the thickness of the concrete slab, which will result in cracks caused by the slip of shear connectors at the end of the concrete slab, as well as longitudinal beam cracks on the concrete top surface. However, there are greater advantages to using epoxy resin as the shear connector of SCCBs when the concrete slab is used as a 'thin-slab', since reducing the concrete slab thickness will not adversely affect the ultimate bearing capacity of the bonded SCCB.

(4) The adhesive performance of epoxy resin gradually improves as the thickness of the adhesive layer increases. Increasing the thickness of the adhesive layer can improve the performance of the bonded SCCB to a certain extent. This paper suggests that the thickness of the adhesive layer should exceed 4 mm, and 6 mm is the optimal thickness.

(5) The primary difference between bonded SCCB and mechanical SCCB lies in their shear connectors, which leads to different methods for predicting their mechanical properties. Experimental results show that the failure mechanisms of bonded SCCB are more complex, and the key to predicting their mechanical properties depends on simulating the adhesive shear connectors. Therefore, in the framework of Finite Element Analysis, future research can focus on developing cohesive models to account for the progressive failure process of the adhesive shear connectors, thereby achieving the prediction of the mechanical properties of bonded SCCB. Additionally, predicting the residual bearing capacity after local adhesive shear connector failure is also a valuable field of study. It can be argued that predicting the performance of bonded SCCB is more challenging compared with mechanical SCCB, and further research is needed to improve the theories for predicting their performance.

Data availability

The data of this study are available within the article. The models or code generated or used during the study are available from the corresponding author by request.

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Author contributions

J.H.S. wrote the main manuscript text. J.H.S. analyzed the results. H.J.J. and L.Z. conducted the experiment. W.F.H. and T.M.M. checked the main manuscript text. Y.H.S. Drew the graphs. All authors reviewed and edited the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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