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Behaviors of box-shape steel reinforced concrete composite beam

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Abstract. Experimental studies on the behaviors of box-shape steel reinforced concrete (SRC) composite beams were conducted. Seven 1:3 scale model composite beams were tested to failure. Each of the beams was simply supported at the ends and two concentrated loads were applied at the one-third span and two-thirds span respectively. Experimental results indicate that the flexural strength can be enhanced when the ratio of flexural reinforcements and flange thickness of the shape steel are increased; the shear strength is enhanced with increase of web thickness of the shape steel. Insignificant effects of concrete in the box-shape steel are found on improving the flexural strength and shear strength of the box-shape SRC composite beams, thus concrete inside the box-shape steel can be saved, and the weight of the SRC beams can be decreased. Shear studs can strengthen the connection and co-work effects between the shape steel and the concrete and enhance the shear strength, but stud design for the composite beams should be further improved. Formulas for flexural and shear strength of the composite beams are proposed, and the calculated results are in good agreement with the experimental results. In general, the box-shape SRC composite beam is a kind of ductile member, and suitable for extensive engineering application.

Keywords: steel reinforced concrete (SRC); experimental study; ultimate strength; box-shape steel; composite beam.

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1. Introduction

Composite beams, such as steel reinforced concrete (SRC) composite beams, have been widely

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used in high-rise buildings, long span buildings, highway bridges, etc. The advantages of composite structure are that 30% to 50% weight of steel can be saved; on a static ultimate load basis, an increase in the overload capacity over that of a non-composite beam can be obtained; under a given load, a reduction in structure depth with consequent savings in embankment costs for bridges or story height in buildings can be achieved.

With the above advantages, both theoretical and experimental studies have been carried out in the past to investigate the behavior of SRC composite I-beams. Nakamura and Narita (2003), Elnashai *et al*. (1991), Kindmann and Bergmann (1993) studied the strength and analytical methods of partially encased composite I-girders as bridge girders, bending and shear tests showed that the bending strength of the partially encased girder model is 2.08 times higher and the shear strength is 2.98 times higher than the conventional steel I-girder model. Subedi and Baglin (1999, 2001), Subedi (1989, 1990) carried out experimental work on the behaviors of plate reinforced concrete beams. Such kinds of beams were proved to be a viable alternative to conventional shear reinforcement, and encased plate construction allowed reduced sections for high strength shear beams, leading to greater flexibility in design and can simplify construction in areas of congestion, but shear failure can not be avoided still. Mergulhao *et al.* (1998) studied the composite structures of profiles filled with reinforced concrete as a solution for structural elements submitted to fire situations. Ye and Fang (2000), Ye *et al.* (1999) studied the behaviors of steel reinforce concrete (SRC) composite beams, and the calculating methods of flexural strength of SRC composite beams. Caughey and Scott (1929) proposed a practical design method of SRC beams and studied the effects of concrete enclosed outside shape steel on strength of SRC beams. Chapman and Balakrishnan (1964), Yam and Chapman (1968) conducted experimental researches on co-work effect of SRC composite beams. Cai *et al.* (2002), Dai *et al.* (2003) carried out experimental researches on mechanical behaviors of composite deep beams and their application in transfer structures in tall buildings. And some design methods for SRC composite beam have been developed in different countries, such as Specification for Design of Steel Reinforced Concrete Structures (YB9082-97) by the China Ministry of Metallurgy (1998), which is based on the principle of superposition, that is the bearing capacities of the shape steel and the concrete part of one section are determined separately and then added to each other; the Technical Specification for Steel Reinforced Concrete Composite Structures (JGJ138-2001) by Ministry of Construction of China (2002), which is based on the theory of reinforced concrete structures, the co-work effect of the shape steel and the concrete are fully considered; Manual of Steel Construction, Load and Resistance Factor Design (LRFD) by the American Institute of Steel Construction (1992), Building Code Requirements for Reinforced Concrete (ACI 318) by the American Concrete Institute (1989), Composite structures (ESSC) by London and New York (1981), Design of Composite Steel and Concrete Structures (Eurocode 4) by the European Committee for Standardization (1992), Steel, Concrete and Composite Bridges (BS5400) by the British Standards Institution (1979), in which theory of steel structures is always adopted.

However, when the SRC composite beams are applied to story height structures, such as transfer structures in tall buildings or long span bridges, the weights of concrete parts of SRC beams are very huge, and it is difficult to install the beams. According to normally used I-steel reinforced concrete composite beam, two web plates are placed at the ends of the flange plates, then box-shape steel is formed, schematically shown in Fig. 1. By employing box-shape steel, the integral stiffness of the composite beam is enhanced and the cross section of the composite beam is decreased; concrete in the box-shape steel can be removed, the weight of the composite beam can be cut down,

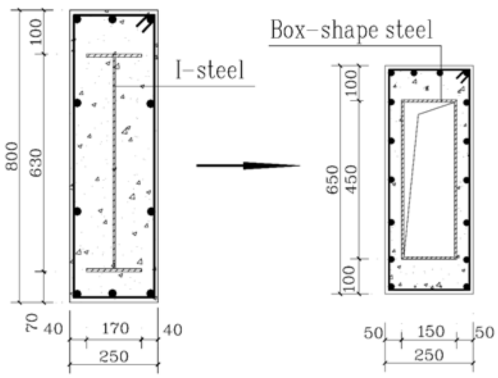


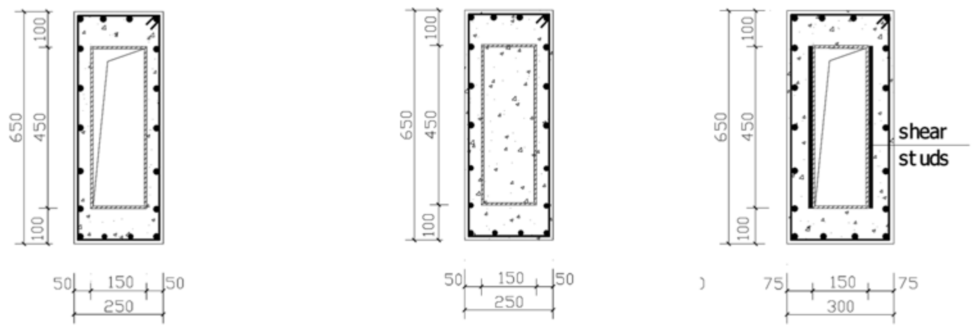
Fig. 1 Schematic of development of box-shape SRC composite beam

and then the installation become more easily. Therefore, box-shape SRC composite beams are developed and applied to the transfer structures in a high-rise building in Guangzhou, P.R. China. Experimental researches on the behaviors of box-shape SRC composite beams are conducted to study the behaviors of the new developed composite beam. Seven simply supported composite model beams are tested to failure under static concentrated loading applied on the axis of the beam. The parameters of the box-shape steel and reinforcements of the composite beams were varied within the range that might be contemplated for design purposes. The behaviors of the beams were observed. Additionally, the design method of the composite beams are studied, and the calculating equations of flexural strength and shear strength are proposed, the calculated results are in good agreement with the experimental results.

2. Experimental investigation

2.1 Details of test specimens

Seven 1:3 scale box-shape SRC composite beams designated as KL1 to KL7 were tested. The typical geometry and detailed reinforcements of the specimens are shown in Fig. 2 and Table 1. The



(a) Specimens KL1, KL3 and KL6 (b) Specimens KL4, KL5 (c) Specimens KL2 and KL7

Fig. 2 Details of test specimens

Table 1 Dimension and reinforcement of the specimens

Specimens	KL1	KL2	KL3	KL4	KL5	KL6	KL7
Dimension of cross section (mm × mm)	250 × 650	300 × 650	250 × 650	250 × 650	250 × 650	250 × 650	300 × 650
Top reinforcement	4ϕ 12	4ϕ 16	4ϕ 16	4ϕ 16	4ϕ 16	4ϕ 16	4ϕ 22
Bottom reinforcement	4ϕ 12	4ϕ 16	4ϕ 16	4ϕ 16	4ϕ 16	4ϕ 16	4ϕ 22
Thickness of shape steel (mm)	6	6	6	4	8	4	8
Ratio of reinforcement	0.3%	0.4%	0.5%	0.5%	0.5%	0.5%	0.8%
Stirrup	ϕ8@100	ϕ8@100	ϕ8@100	ϕ8@100	ϕ8@100	ϕ8@100	ϕ8@100
Web reinforcement	ϕ12@100	ϕ12@100	ϕ12@100	ϕ12@100	ϕ12@100	ϕ12@100	ϕ12@100
If hollow in the box-shape steel	Hollow	Hollow	Hollow	Concrete filled	Concrete filled	Hollow	Hollow

Table 2 Material properties of specimens (MPa)

Specimens	KL1	KL2	KL3	KL4	KL5	KL6	KL7
Yield strength of reinforcing bar	353.1	375.9	375.9	375.9	375.9	375.9	373.0
Ultimate strength of reinforcing bar	520.8	560.3	560.3	560.3	560.3	560.3	540.8
Yield strength of shape steel	321.9	321.9	321.9	292.4	317.9	292.4	317.9
Ultimate strength of shape steel	460.7	460.7	460.7	419.8	457.4	419.8	457.4
Cubic compressive strength of concrete	28.4	33.7	30.6	32.8	34.1	34.3	31.5

material properties of concrete, reinforcing bars and steel are summarized in Table 2. Each of the specimens is 3.5 m long, and simply supported on a span of 3.3 m. The widths of the beams are 0.25 m and 0.3 m, and the height is 0.65 m. The box-shaped steel embedded in the beams are made of Q235 steel, the width is 150 mm, the height is 450 mm and the thickness are 4 mm, 6 mm and 8 mm respectively. For specimens KL4 and KL5, the box-shape steel are filled with concrete, for other specimens, the box-shape steel are hollow inside, as shown in Fig. 2.

The shear studs are used to enhance the bonding behaviors between shape steels and concrete for specimens KL2 and KL7. The shear studs are made of 25 mm diameter and 50 mm long reinforcing bars and welded onto the sidewall of the shape steel by a space of 300 mm, as shown in Fig. 2(c).

Parameters such as the thickness of the shape steel, the ratio of top and bottom reinforcements, the shear studs, and hollow or not in the box-shape steel are varied, as shown in Table 1, and the fundamental mechanical behaviors of the beams and co-work effects between concrete and shape steel are studied.

2.2 Test setup, instrumentation and test procedure

Two 1000 kN hydraulic jacks were mounted on the top of the beam in one-third span and two-thirds span along the length of the specimens. The test setup is shown in Fig. 3. Instrumentations were provided by means of electromechanical dial indicators for measurements of vertical

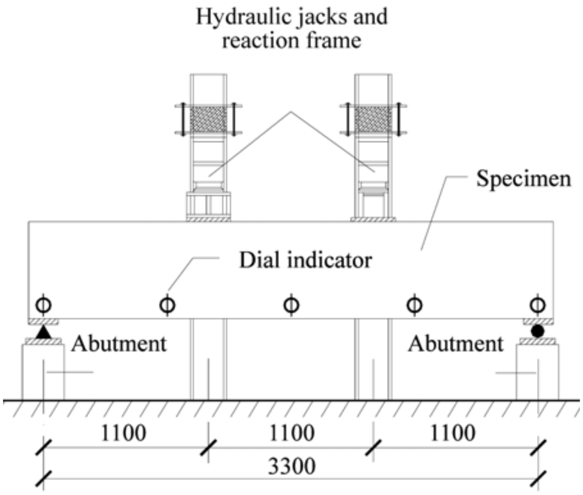


Fig. 3 Test setup and instrumentation (mm)

deflections along the length of the specimen, and wire strain gauges for measurements of steel and concrete strains and slips between concrete and shape steel. Fig. 3 shows the locations of electromechanical dial gauges for the specimens. The readings from these strain gauges were recorded using a PORTABLE DATA LOGGER TDS-302 connected to a personal computer. The load-displacement plot displayed by the computer enabled the yielding of the steel and the onset of failure of the specimen to be monitored.

The specimens were loaded under monotonically increasing vertical concentrated loads. The load was applied to the specimen in increments, ten percent of the theoretical ultimate load. At every load increment, the strain gauge readings and displacements from transducers were recorded, the box-shape steel was examined for yielding and the surface of concrete was carefully inspected for the development of cracks. Close observations were made to locate the first crack, and the corresponding load was marked. Testing was terminated when significant crushing of the concrete had occurred or the deflection became excessively large with excessive crack widths. The ultimate load and mode of failure were recorded for each specimen. After the specimen failed, the loading system and transducers were removed, and additional cracks were marked.

3. Results and discussion

3.1 Load-deformation relationship and failure mode

Because of different parameters of the specimens, for convenience to discussion, the relative load values (P/P_u) are used in Fig. 4 and Figs. 6-8.

The procedure of failure of the specimens can basically be described as follows. Generally, the flexural crack appears firstly at the mid-span for all the specimens when the load is approximately 12% of the test ultimate load, the widths of the cracks are about 0.05-0.1 mm. Splitting sounds are heard clearly and cracks along the border of the shape steel and concrete at the ends of the beam turn up when the load is approximately 60% P_u, meanwhile slips between the shape steel and

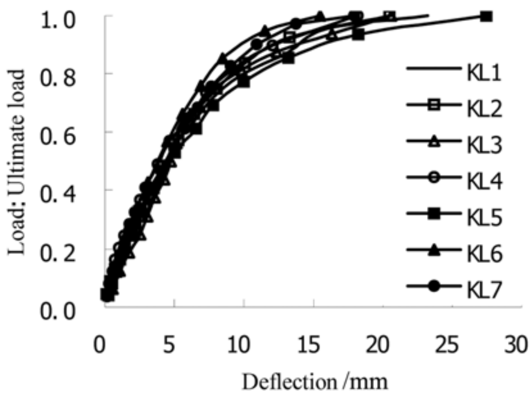


Fig. 4 Curves of load versus deflection at mid-span

(a) (b) (c)

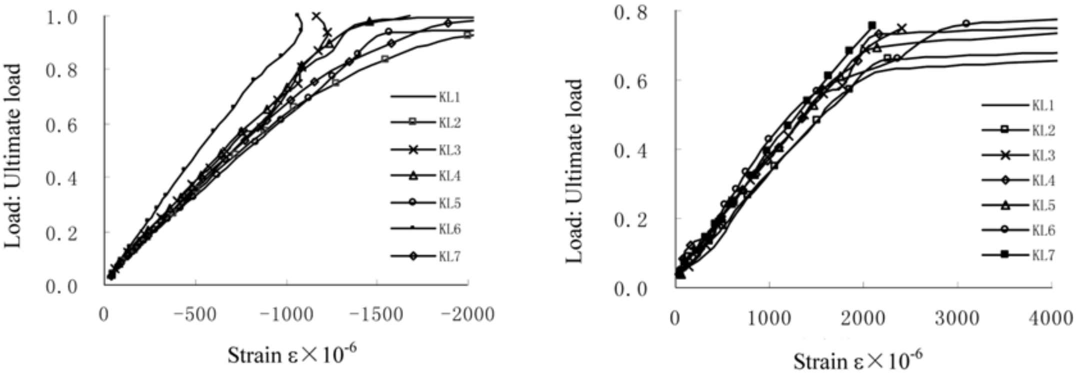
Fig. 5 Modes of failure of the specimens

concrete occur. Diagonal cracks increase significantly, especially for specimens KL1, KL3 and KL6 that are without concrete filled into shape steel and without shear studs. Beyond this load level, the shape steels begin to yield and cracks develop slowly until failure. Curves of test load versus mid-span deflection are presented in Fig. 4. With increase of deflection, the load keep increasing until failure, all the beams present good ductility.

There exist three modes of failure. One is buckling failure of the box-shape steel, the typical specimen is KL6, as shown in Fig. 5(a). For KL6, the thickness of the shape steel is just 4 mm and the shape steel is hollow inside, the specimen fails earlier than other specimens due to the buckling of the box-shape steel. The second one is flexural failure, typical specimens are KL4 and KL5, where the shape steels are filled with concrete inside. The last one is shearing failure, and typical specimens are KL1, KL2, KL3 and KL7, as shown in Fig. 5(b), in which there arise longitudinal cracks on the top of the specimens KL2 and KL7, as shown in Fig. 5(c).

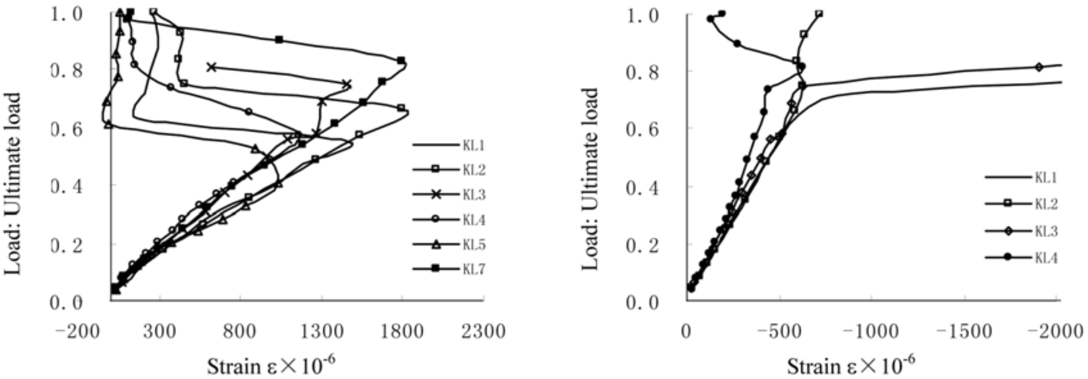
3.2 Strains of reinforcing bars, shape steel and stirrups

Figs. 6(a) and (b) show respectively the strains of the top and bottom reinforcing bars versus loads in the mid-span of the specimens. Generally, the top reinforcing bars do not yield until the



(a) Strain of top reinforcing bars in the mid-span (b) Strain of bottom reinforcing bars in the mid-span

Fig. 6 Strains of reinforcing bars in specimens



(a) Strain of bottom flange of shape steel in the mid-span (b) Strain of top flange of shape steel in the mid-span

Fig. 7 Strains of shape steels in specimens

beam fail; the bottom reinforcing bars yield when the load reaches to about 70%~75% P_u for specimens KL1~KL3; for specimens KL4, KL5 and KL7, the yielding loads are about 80% P_u; and for KL6, shape steel buckles and the bottom reinforcing bars yield earlier at 43% P_u.

Fig. 7(a) shows the strains of bottom flanges of shape steels in the mid-span, the flanges of all specimens do not yield, and the strains decrease rapidly when the load is about 70% P_u. The reason is mainly because of the poor bonding effects between the shape steel and the concrete, where good quality of construction along the bottom of the beam is always difficult to be obtained, the phenomenon should be paid more attention in practical projects. Fig. 7(b) shows the strains of top flanges of shape steels versus loads in the mid-span of specimens KL1~4. For specimens KL1 and KL3, hollow inside shape steels and without shear studs, the top flange strains of the shape steels increase rapidly, then the top flanges yield when the load reaches to 70% P_u. At this state, slips between shape steels and concrete happen and stresses redistribute in the beams, parts of loads originally undertaken by shape steels are transferred to reinforced concrete section part, thus after the load stage, tensile reinforcing bars begin to yield. Further experiments should be carried out on the characteristics of the stress redistribution and the mechanism of slip between shape steel and

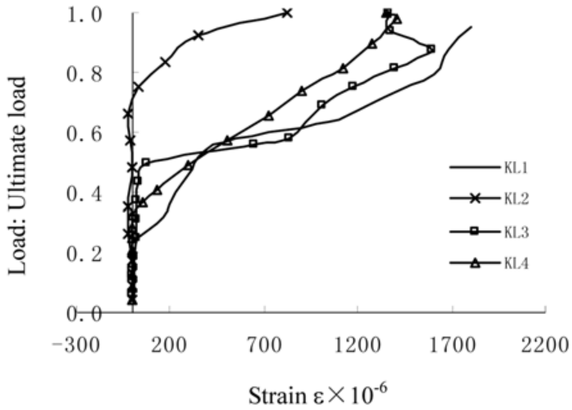


Fig. 8 Strain of stirrups in the middle point of shear-flexural region

concrete. Therefore, according to Fig. 6 and Fig. 7, bearing capacity of beams and co-work effects can be enhanced by increasing the ratio of reinforcements, thickness of shape steel and arranging shear studs.

Fig. 8 shows the strains of stirrups at the middle point of the shear-flexural region of specimens KL1~KL4. For KL2 with shear studs, the strains of the stirrup lag significantly behind that of other specimens without shear studs, obviously the web of the shape steel undertakes most of the shear forces. But for those specimens without shear studs, such as KL1, KL3 and KL4, the stirrups yield much earlier than stirrups of KL2 do, in which the stirrups of KL4 with concrete filled shape steel yield a little later than those of KL1 and KL2. Compared with reinforcing bars, stirrups of all beams yield earlier. Therefore, shear studs are the most effective measure to strengthen the co-work effects between shape steels and concrete, and enhance the shear strength; concrete in the shape steel has much minor effects.

3.3 Effects of parameters

Table 3 shows the cracking load and the ultimate load of specimens KL1 to KL7. Comparing specimen KL1 with KL3, whose experimental parameters are same except the ratio of flexural reinforcements, it is clear from Table 3 that the cracking load and the ultimate load of KL3 are

Table 3 Cracking load and ultimate load of specimens KL1~KL7

Specimens	Cracking load of initial flexural crack (kN)	Cracking load of initial shear crack (kN)	Ultimate load (kN)	Modes of failure
KL1	69	139	583	Shearing
KL2	102	136	774	Shearing
KL3	79	158	634	Shearing
KL4	68	181	554	Flexural
KL5	102	273	838	Flexural
KL6	68	158	477	Buckling of shape steel
KL7	102	171	947	Shearing

enhanced by increasing the ratio of flexural reinforcements compared with specimen KL1. The flexural reinforcement is an important factor affecting the strength of the box-shape SRC composite beam.

The ratio of shape steel is another effective factor affecting the ultimate strength of the box-shape SRC composite beam. Took specimens KL4 and KL5 for example, which have same experimental parameters except the thickness of shape steel, the thickness of KL5 is 2 mm larger than that of KL4. It indicated that with the increase of the ratio of shape steel, the cracking load and the ultimate strength are significantly increased, as shown in Table 3.

Comparing the specimen KL2 with KL3, shear studs are welded on the side plate of the shape steel for KL2, and the width of KL2 is 50 mm larger than that of KL3 to meet the requirement of covering thickness of concrete. Results detailed in Table 3 show that the cracking loads and the ultimate load of KL2 are significantly increased by arranging shear studs, even if the ratio of reinforcement of KL2 is smaller than that of KL3. Therefore, the shear stud is an effective element to improve the co-work effects between the concrete and the shape steel. However, the researches of the relationship of shear studs and ultimate strength of composite beams should be further conducted.

Concrete inside the shape steel is another important factor for box-shape SRC composite beams. For specimen KL4, the shape steel is filled with concrete, while it is hollow for specimen KL6. From Table 3, the cracking load of flexural cracks of KL4 and KL6 is same, but the shear cracking load and ultimate load of KL4 are higher than those of KL6. Thus when the shape steels are much thinner, concrete inside the shape steel can effectively prevent the shape steel from buckling. But when buckling failure of shape steel can be avoided, for example it suggests that the thickness of the shape steel should be larger than 4 mm, concrete inside the shape steel can be removed and the weight of the beams can be greatly be cut down.

Compared with parameters, such as ratio of reinforcements, ratio of shape steel and shear studs, concrete has minor effects on enhancing the shear strength and strengthening co-work between shape steels and concrete, but the integrity and failure mode of beams with concrete filled into the shape steel, such as KL4 and KL5, are indeed superior to others, for flexural failure occurs only in those two beams.

4. Calculation of ultimate strength

4.1 Comparison of experimental strength and calculating strength by codes

Some design methods (Subedi 1990, Mergulhao *et al.* 1998, Ye and Fang 2000, Ye *et al*. 1999, Caughey and Scott 1929, Chapman and Balakrishnan 1964, Yam and Chapman 1968) for the SRC beam have been developed in different countries. For calculating the flexural strength, the design methods are based on the two concepts. One is based on the principle of the superposition. That is the strength of the shape steel part and the reinforced concrete part of one section are determined separately and then added to each other. The other is based on the calculating theory of reinforced concrete structures, in which co-work effect of the shape steel and the concrete is considered. For calculating the shear strength, the design methods are based on the principle of the superposition.

The comparison between the experimental strength and the calculating strength by typical code (YB9082-97, JGJ138-2001) is shown in Table 4 and Table 5, in which M_1 and V_1 are calculated

Table 4 Comparison of calculating flexural strength and experimental strength

Specimen	M_u (kN·m)	M_1 (kN·m)	M_2 (kN·m)	M_1/M_u	M_2/M_u
KL1	641.3	352.2	515.6	0.55	0.80
KL2	851.4	434.9	641.9	0.51	0.75
KL3	697.4	434.9	605.8	0.62	0.87
KL4	609.4	335.3	528.9	0.55	0.87
KL5	921.8	511.0	844.5	0.55	0.92
KL7	1041.7	664.7	866.8	0.64	0.83

Table 5 Comparison of calculating shear strength and experimental strength

Specimen	V_u (kN)	V_1 (kN)	V_2 (kN)	V_3 (kN)	V_1/V_u	V_2/V_u	V_3/V_u
KL1	583	869	829	596	1.49	1.42	1.02
KL2	774	1446	1066	760	1.87	1.38	0.98
KL3	634	936	839	606	1.48	1.32	0.96
KL4	554	1088	790	720	1.96	1.43	1.30
KL5	838	1778	1183	1027	2.12	1.41	1.23
KL6	477	941	643	502	1.97	1.35	1.05
KL7	947	1351	1216	838	1.43	1.28	0.89

based on the superposition principle (YB9082-97); M_2 and V_2 are calculated based on the calculation theory of reinforced concrete structures (JGJ138-2001); M_u and V_u are the experimental strength. It can be seen that the flexural strengths are underestimated by the method based on the superposition principle, for specimens KL4 and KL5, the calculated values are about 55 percent of tested values. These are mainly because the co-work effect of the shape steel and the concrete is not considered in the method based on the superposition principle. However, co-work effects of the concrete and the shape steel are considered in the Specifications (JGJ138-2001), therefore the flexural strengths M_2 based on the code are much reasonable, which are about 90 percent averagely of actual flexural strength, and are in reasonable agreement with the experimental results. Although both methods are suitable for I-shape SRC beams, only the method of Specifications (JGJ138-2001) is more suited for box-shape SRC composite beams and should be abided by in the engineering design of box-shape SRC composite beams.

The shear strengths V_u are overestimated by the two methods. Both methods are suitable for I-steel SRC beams, while are not suited for calculating shear strength of box-shape SRC composite beams. This is because the co-work effects of the composite beams are worse than those of I-shape SRC beams. Therefore, the equations for I-shape SRC beams proposed in the Specification should be revised for extensive application of composite beams, which will be discussed in the next section.

4.2 Calculation of shear strength

The experimental results show that many of the mechanical properties of this type of box-shape SRC composite beams are consistent with those of conventional I-shape SRC beams. The calculating methods for I-shape SRC beams are used for reference to deduce the methods for the evaluation of the shear strength of box-shape SRC composite beams.

For calculation of shear strength, principle of superposition is adopted by both Specification for Steel Reinforced Concrete Composite Structures (JGJ138-2001) and Specification for Design of Steel Reinforced Concrete Structures (YB9082-97). The shear strength of composite beams is the sum of that of concrete, shape steel and stirrups. Based on the calculating equations of shear strength of I-shape SRC beams provided in the Specifications and experimental results, the calculating equations of shear strength of box-shape SRC composite beams are proposed.

The calculating shear strength of I-shape SRC beams under distributed loads and concentrated loads are written in Eqs. (1) and (2), respectively, which can be found in the specification (JGJ138-2001).

$$V = \frac{1}{\gamma_{RE}}\left[0.06f_c A_0 + 0.8f_{yv}\frac{A_{sv}}{s}h_0 + 0.58f_a t_{tw} h_w\right] \tag{1}$$

$$V = \frac{1}{\gamma_{RE}}\left[\frac{0.06}{\lambda + 1.5}f_c A_0 + 0.8f_{yv}\frac{Asv}{s}h_0 + \frac{0.58}{\lambda}f_a t_{tw} h_w\right] \tag{2}$$

in which V is shear strength of the composite beam; A_0 is the area of cross section of concrete beam from the resultant point of tensile flange of shape steel and tensile reinforcing bars to the top edge of cross section; t_{tw} is the total width of web of shape steel, for box-shape steel, $t_{tw} = 2t_w$; h_w is the height of web of shape steel; f_{yv} is tensile design strength of stirrups; f_a is tensile strength of shape steel; A_{sv} is the area of stirrups at the same cross section; s is the space of stirrups; λ is shear span ratio of composite beam, $\lambda = a/h_0$, a is the distance from calculating cross section to the abutment, h_0 is the distance from the top edge of the cross section to the centroid of tensile reinforcing bars.

Based on the discussions mentioned above, the co-work effects of the box-shape steel and concrete should be considered in the proposed equations. As one trying, the co-work effects are supposed as the effects of shear span ratio and non-uniform of shear stress of web of shape steel for box-shape SRC composite beams.

For box-shape SRC composite beams under distributed loads, calculating equations of shear strength can be written as:

$$V = \frac{1}{\gamma_{RE}}\left[0.06f_c A_0 + 0.8f_{yv}\frac{A_{sv}}{s}h_0 + 0.58\beta f_a t_{tw} h_w\right] \tag{3}$$

For box-shape SRC composite beams under concentrated loads, the equation is written as:

$$V = \frac{1}{\gamma_{RE}}\left[\frac{0.06}{\lambda_1 + 1.5}f_c A_0 + 0.8f_{yv}\frac{Asv}{s}h_0 + \frac{0.58}{\lambda_2}\beta f_a t_{tw} h_w\right] \tag{4}$$

In the equations, shear span ratio λ of composite beam is revised to consider the effects of shear span ratio of the concrete beam and the shape steel respectively, so shear span ratio of the concrete beam λ_1 and shear span ratio of the shape steel λ_2 are introduced. For composite beams with concrete filled shape steel, $\lambda_1 = \lambda_2 = a/h_0$, for beams with hollow shape steel, $\lambda_1 = a/h_0$ and $\lambda_2 = a/h_a$, h_a is the height of the shape steel. And another parameter β, coefficient of non-uniform of shear stress of web of shape steel, is introduced. According to the theory of mechanics, β can be defined as:

$$\beta = \frac{1-(1-\phi_1)\phi_2^2}{1-\phi_2^2+\phi_1\phi_2^2} \tag{5}$$

in which $\phi_1 = t_{tw}/b_f$ and $\phi_2 = h_w/h_f$; b_f is width of flange of shape steel; h_f is the height of shape steel. The lower limit value of β is 0.66.

Table 5 gives the comparison between calculating shear strength and experimental results of specimens, in which V_3 is shear strengths calculated by Eqs. (3)-(5) proposed. It is clear that the actual shear strengths V_u of specimens KL1~7 are much smaller than those (V_1 and V_2) calculated by equations of the Specifications. The shear strengths V_1 calculated by Specification (YB9082-97), which adopts equations of normal reinforced concrete beams, is far too larger than the experimental shear strengths. The maximum calculating shear strength is more than 2 times experimental shear strength. The main reason is that the effects of shear span ratio of the shape steel are not included in the equations adopted by the Specification, while the shear span ratio is an important factor for shear strength of beams, especially for those deep beams, which may be with full story height, and so are the composite beams in the experiments. The shear strengths V_2 calculated by Specification (JGJ138-2001) are still much different from the actual shear strengths, which are about 1.4 times actual shear strengths, because of not considering the effects of non-uniform of shear stress of web of shape steel. Therefore the theoretical values based on the Specification are significantly unsafe for the box-shape SRC composite beams.

The effects of both shear span and non-uniform behaviors of shear stress of web of shape steel are considered in Eqs. (3)-(5), calculated results are around 1.0 times experimental shear strengths, which are in reasonable agreement with the test results, shown in Table 5. The revised equations proposed are more superior to equations in the Specification (YB9082-97, JGJ138-2001), and more suitable for calculating shear strength of box-shape SRC composite beams.

5. Conclusions

The experimental results of the box-shape SRC composite beams are described, and the influences of ratio of reinforcements, ratio of shape steel and shear studs on the strength of composite beams are discussed. The following conclusions are drawn based on the results.

(1) The box-shape SRC composite beam displays the advantages of the shape steel beam and steel-concrete composite sections.

(2) The steel section can effectively prevent shear cracks in concrete from propagating rapidly. The larger ratio of the shape steel and reinforcements, the higher the cracking load and the ultimate strength.

(3) Shear studs could strengthen the co-work effects of the shape steel and the concrete and enhance the shear strength. Filling concrete in the box-shape steel can prevent the too early failing of specimens due to the buckling of the box-shape steel and increase the ultimate load.

(4) Equations of I-steel reinforced concrete composite beams of both Specifications (JGJ138-2001) and (YB9082-97) are not suitable for calculating shear strength of the box-shape SRC composite beams, and equations of the Specification (JGJ138-2001) are more suitable for calculating flexural strength of the box-shape SRC composite beams.

(5) Equations for the shear strength of the box-shape SRC composite beams are proposed based on the Specifications and experimental results. The results calculated by proposed equations are in good agreement with the experimental ones.
(6) The research mentioned above is a preliminary study on the box-shape SRC composite beam. Further experimental and analytical research works are needed to investigate the behavior of the beam. For example, the suggested equations should be examined for their rationality and perfected, measures and details should be put forward to prevent the buckling of box-shape steel and to assure the ductile flexural failure happened prior to other failure, and so on.

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Notation

A, A_0	: Area of cross section of concrete beam (initial, effective)
A_{sv}	: Area of cross section of stirrups
b_f	: Flange width of shape steel
f_a	: Tensile strength of shape steel
f_{yv}	: Tensile design strength of stirrups
h_a	: Height of the shape steel
h_f	: Height of shape steel
h_0	: Effective height of cross section
h_w	: Web height of shape steel
P_u	: Ultimate test load
t_{tw}	: Total width of web of shape steel
V	: Shear strength of the composite beam
λ	: Shear span ratio
β	: Coefficient of non-uniform of shear stress