

Experimental study on box shape steel reinforced concrete beam

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Abstract: Experimental study on the fundamental behavior of box shape steel reinforced concrete (SRC) beams was conducted. Seven 1:3 scale model SRC beams were tested to failure. The experimental results indicate that the flexural strength increases with the increase of the ratio of flexural reinforcement and the thickness of flange of the shape steel; the shear strength increases with the increase in the thickness of the web of the shape steel. Concrete filled in the box shape steel can prevent the early failure of specimens due to the buckling of the box shape steel, and increase the ultimate load. Measures should be made to strengthen the connection and co-work between the shape steel and the concrete. Formulae 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 beam is a kind of ductile member, and it is suitable for extensive engineering application.

Key words: steel reinforced concrete (SRC); experimental study; ultimate strength; box shape steel

Composite beams, such as steel reinforced concrete (SRC) beams, have been widely used in high-rise and long span buildings. They have also been used extensively in the construction of modern buildings and highway bridges. Both theoretical and experimental studies^[1-7] have been conducted in the past to investigate the behavior of I-shape SRC beams, and some design methods have been developed in different countries^[8-14]. However, few studies have been published on the behavior of box shape SRC beams and no specified design method and construction are given in the published specifications. In this paper, experimental investigation on box shape SRC beams, which was applied to the transfer structures in a high-rise building in Guangzhou, was conducted under static concentrated loads. The fundamental mechanical behaviors and performances of co-work of concrete and shape steel under different constructions are studied.

1 Experimental Investigation

Seven 1:3 scale box shape SRC beams designated as KL1 to KL7 were tested. The typical geometry and detail reinforcements of the specimens are shown in Fig. 1 and Tab. 1. The material properties of concrete, reinforcing bars and steel are summarized in Tab. 2. The shear studs (25 mm in diameter, 50 mm in length,

300 mm in space) were used to enhance the bond behaviors between shape steels and concrete for specimens KL2 and KL7.

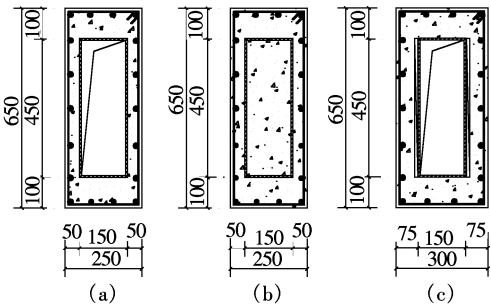


Fig. 1 Details of specimens. (a) KL1, KL3 and KL6; (b) KL4 and KL5; (c) KL2 and KL7

The test setup is shown in Fig. 2. Instrumentations were provided by means of electromechanical dial indicators for measurements of vertical deflections along the length of the specimen, and wire strain gauges for measurements of steel and concrete strains and the slip between the concrete and the shape steel. The specimens were loaded under monotonically increasing vertical concentrated loads.

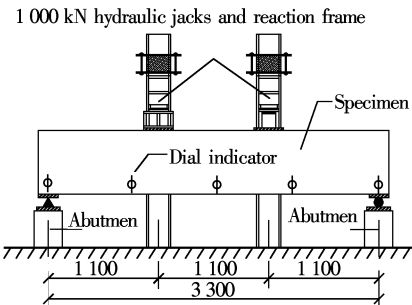


Fig. 2 Test setup and instrumentation (unit: mm)

Received 2005-03-31.

Foundation items: The Natural Science Foundation of Guangdong Province (No. 020965), the Natural Science Foundation of Construction Committee of Guangzhou (No. 9915), the Natural Science Foundation of South China University of Technology (No. E5304300).

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Tab.1 Dimension and reinforcement of specimens

Specimen	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	4φ12	4φ16	4φ16	4φ16	4φ16	4φ16	4φ22
Bottom reinforcement	4φ12	4φ16	4φ16	4φ16	4φ16	4φ16	4φ22
Thickness of shape steel/mm	6	6	6	4	8	4	8
Ratio of reinforcements/%	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
Box shape steel	Hollow	Hollow	Hollow	Concrete filled	Concrete filled	Hollow	Hollow

Tab.2 Material properties of specimens

Specimen	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

2 Results and Discussion

2.1 Load-deformation relationship and failure mode

Because of different parameters of the specimens, for convenience of discussion, the relative load values P/P_u are used in the following figures.

The procedure of failure of the specimens can basically be described as follows. The flexural crack appeared first at the mid-span for all the specimens when the load was approximately 12% of the test ultimate load, the width of cracks was about 0.05 to 0.1mm. Splitting sounds were heard clearly when the load was approximately 60% of the test ultimate load. Slips between the shape steel and concrete occurred, and cracks arose at the border of the shape steel and concrete at the end of the beam. A significant increase in diagonal cracks occurred along the two sides of the specimens, especially for specimens KL1, KL3 and KL6 with hollow shape steel and specimens without shear studs. Beyond this load level, the shape steel began to yield and cracks developed stably and slowly until failure. Curves of test load versus mid-span deflection are presented in Fig. 3, which shows that good

ductility can be obtained by adopting the box shape SRC beam.

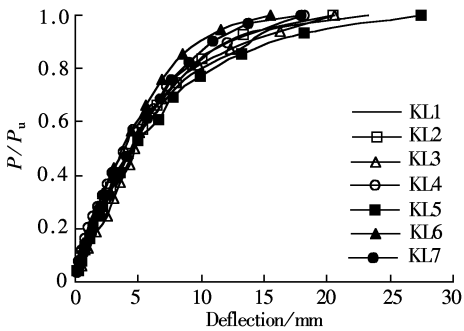


Fig.3 Curves of load versus deflection at mid-span

There exist three modes of failure. One is buckling failure of the box shape steel, the typical specimen is KL6, as shown in Fig. 4(a); the second one is flexural failure, such as KL4 and KL5 with concrete filled shape steel; the last is shearing failure after the yielding of tensile reinforcing bars, such as KL1, KL2, KL3 and KL7, as shown in Fig. 4(b), in which longitudinal cracks occurred on the top of the specimens KL2 and KL7, as shown in Fig. 4(c).

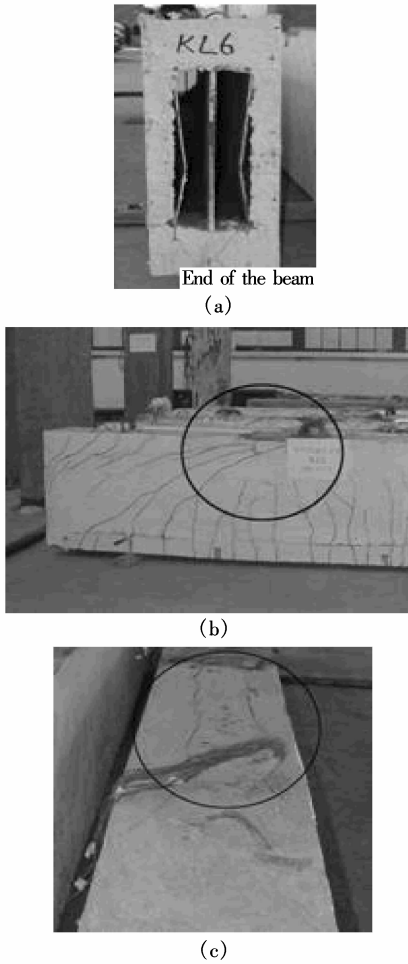


Fig. 4 Modes of failure of specimens

2.2 Strains of reinforcing bars, shape steel and stirrups

Figs. 5(a) and (b) show respectively the strains of the top and bottom reinforcing bars in the mid-span of the specimens. Generally, the top reinforcing bars do not yield until the beam fails, while the bottom reinforcing bars yield when the load reaches 70% of the ultimate load.

It can be observed from Fig. 6(a), for the specimens KL2 and KL7 with shear studs the strains of the bottom flange of shape steels in the mid-span of specimens can reach their yield strain, but the strains of other specimens cannot do so. The strains of all specimens decrease rapidly when the load is about 70% of the ultimate load. The reason is mainly because of the poor bonding effects between the shape steel and the concrete, although the shear studs have some effects on bonding performances. Along the bottom of the beam, good quality of construction is always difficult to obtain. More attention should be paid to this in practical projects. Fig. 6(b) shows the strains of the top flange of shape steels in the mid-span of specimens

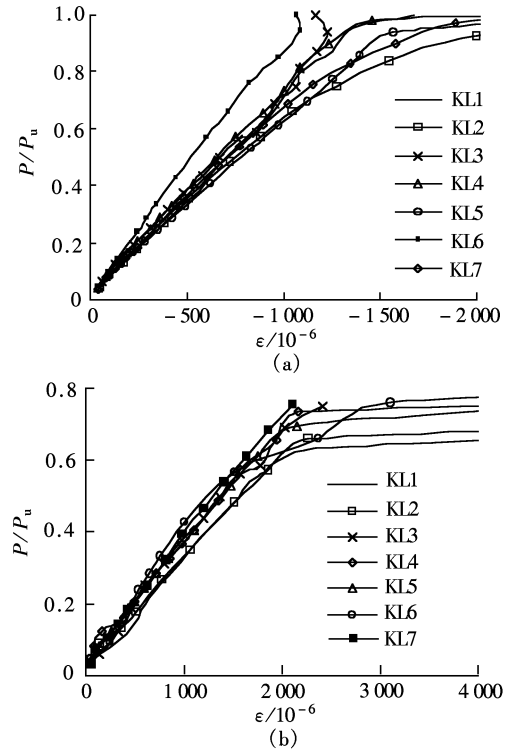


Fig. 5 Strains of reinforcing bars in specimens. (a) Strain of top reinforcing bars in the mid-span; (b) Strain of bottom reinforcing bars in the mid-span

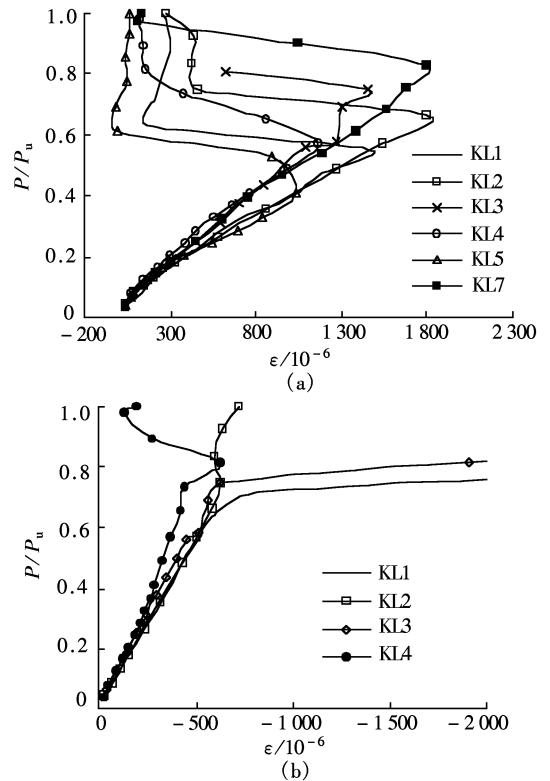


Fig. 6 Strains of shape steels in specimens. (a) Strain of bottom flange of shape steel in the mid-span; (b) Strain of top flange of shape steel in the mid-span

KL1 to KL4. The strains of the top flange of shape steels of KL1 and KL3, with hollow shape steel and

without any shear studs, increase rapidly, and then the members yield when the load reaches 70% of the ultimate load. This demonstrates that after the slip between the shape steel and the concrete occurs, stresses redistribute in the beams.

Fig. 7 shows the strains of the middle point of stirrups in the shear-flexural region. The strains of the stirrups of KL2 with shear studs lag significantly behind that of other specimens without shear studs, the shear is mainly undertaken by the web plate of the shape steel. But for specimens without shear studs, the stirrups yield much earlier than the top or bottom reinforcing bars in the mid-span. Thus shear studs streng-

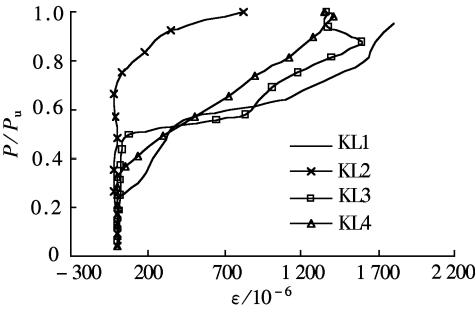


Fig. 7 Strain of stirrups in the middle point of shear-flexural region

then the co-work effects of the shape steel and the concrete, and they are useful for enhancing the shear strength. The difference of co-work effects between the specimens with hollow shape steel and with concrete filled shape steel is not clear.

2.3 Effects of parameters

Tab. 3 shows the cracking load and the ultimate load of specimens. For specimens KL1 and KL3, experimental parameters are the same except for the ratio of flexural reinforcements. When the tensile reinforcing bars yield, the load is 350.4 kN for KL1 and 456.8 kN for KL3. Obviously, the cracking load and the flexural strength of the beam are significantly enhanced by increasing the ratio of flexural reinforcements. Thus the flexural reinforcement is an important factor affecting the flexural strength of the box shape SRC beam. For specimen KL4 filled with concrete and KL6 with hollow shape steel, the cracking load of flexural cracks is the same, but the shear cracking load and ultimate load of KL4 are higher than those of KL6, which proves that the concrete filled in the box shape steel can effectively prevent the specimens failure from buckling of the shape steel and enhance the shear cracking load and ultimate load.

Tab. 3 Cracking load and ultimate load of specimens KL1 to KL7

Specimen	Cracking load of initial flexural crack/kN	Cracking load of initial shear crack/kN	Ultimate load/kN	Mode 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

* Loading was too fast, and the shear crack did not inspect on time.

The ratio of shape steel is another effective factor to affect the ultimate strength of the box shape SRC beam. For KL4 and KL5, where only the thickness of KL5 is 4 mm larger than that of KL4, with the increase of the ratio of shape steel, the cracking load and the ultimate load increase significantly. Specimens KL2 and KL3 were compared. For KL2 shear studs are welded, and the width of KL2 is 50 mm larger than that of KL3 to meet the requirement of covering thickness of concrete. The ultimate load of KL2 is much larger than that of KL3, even if the contribution of the larger amount of concrete is deducted. This can be approximately calculated by the equations in the code^[8,9]. Thus the shear stud is an effective element to improve the effect of co-work between the concrete and the shape steel.

3 Calculation of Ultimate Strength

3.1 Comparison of experimental strength and calculating strength by codes

The design methods of the flexural strength are based on two concepts. One is based on the principle of the superposition^[8], the other is based on the calculating theory of reinforced concrete structures^[9]. For calculating the shear strength, the design methods are based on the principle of the superposition. The comparison between the experimental strength and the calculation strength by typical code^[8,9] is shown in Tab. 4 and Tab. 5, in which M_1 and V_1 are calculated based on the superposition principle^[8]; M_2 and V_2 are calculated based on the calculation theory of reinforced concrete structures^[9]; M_u and V_u are the experimental strengths. The flexural strengths are underestimated

by the superposition method. For specimens KL4 and KL5, the calculated values are about 55% of tested values. Obviously, the co-work effect between the shape steel and the concrete is not considered. On the contrary, the flexural strengths M_2 are much more reasonable, amounting to about 90%, on average, of actual flexural strength, in which co-work effects between the concrete and the shape steel are considered. However, the shear strengths V_u are overestimated by the two methods, which are suitable for I-steel SRC beams. Therefore, the equations should be revised for extensive application of composite beams, which will

be discussed in the next section.

Tab. 4 Comparison between calculating flexural strength and experimental strength

Specimen	$M_u / (\text{kN} \cdot \text{m})$	$M_1 / (\text{kN} \cdot \text{m})$	$M_2 / (\text{kN} \cdot \text{m})$	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

Note: For KL1 to KL3 and KL7, M is just for reference. (Although the tensile reinforcing bars yield before shear failure occurs, M does not reach the flexural strength.)

Tab. 5 Comparison between calculating shear strength and experimental strength

Specimen	V_u / kN	V_1 / kN	V_2 / kN	V / kN	V_1 / V_u	V_2 / V_u	V / 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

Note: For KL4 and KL5, V is just for reference. (Flexural failure occurs, V does not reach the shear strength.)

3.2 Calculation of shear strength

Based on the calculating equations of I-shape SRC beams provided in the specifications (JGJ138—2001)^[9] and experimental results, the calculating equations of shear strength of box shape SRC beams are proposed. The co-work effects between the box shape steel and concrete are supposed as the effects of shear span ratio and non-uniform of web shear stress. When under distributed loads, the calculation equation of shear strength can be written as

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

When under concentrated loads, Eq. (1) is written as

$$V = \frac{1}{\gamma_{RE}} \left(\frac{0.06}{\lambda_1 + 1.5} f_c A_0 + 0.8f_{yv} \frac{A_{sv}}{s} h_0 + \frac{0.58}{\lambda_2} \beta_f f_a t_{tw} h_w \right) \quad (2)$$

where V is the shear strength; $A_0 = bh_0$, b is the width of the cross section, h_0 is the distance 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 web width of shape steel, for box shape steel, $t_{tw} = 2t_w$; h_w is the web height of shape steel; f_{yv} is the tensile design strength of stirrups; f_a is the tensile strength of shape steel; A_{sv} is the area of stirrups at the same cross section; s is the space of stirrups. The shear span ratio of the concrete beam λ_1 and the 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 $\lambda_2 = a/h_a$, a is the distance from calculating cross section to the abutment, h_a is the height of the shape steel. And another parameter β , coefficient of non-uniform of web shear stress of shape steel, is introduced. According to the theory of mechanics, β can be defined as

$$\beta = \frac{1 - (1 - \phi_1)\phi_2^2}{1 - \phi_2^2 + \phi_1\phi_2^2} \quad (3)$$

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

Tab.5 gives the comparison between calculating shear strength and experimental results of specimens, in which V are shear strengths calculated by proposed Eqs. (1) to (3). The actual shear strengths V_u of specimens KL1 to KL7 are much smaller than those (V_1 and V_2) calculated by equations of the specifications. The effects of both shear span and non-uniformity of web shear stress of shape steel are considered in Eqs. (1) to (3). Calculated results are around 0.9 to 1.3 times of experimental shear strengths, which are in reasonable agreement with the test results. Thus the revised equations are more superior to equations in the specification^[8,9], and more suitable for calculating shear strength of box shape SRC beams.

4 Conclusion

The box shape SRC beam displays the advantages of the shape steel beam and steel-concrete com-

posite sections. The steel section can effectively prevent shear cracks from propagating rapidly. The larger ratio of the shape steel and reinforcements is, the higher the cracking load and ultimate strength are. Shear studs can 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 box shape from buckling and increase the ultimate load.

Equations of the specification (JGJ138—2001) are used for calculating flexural strength of the box shape SRC beams, and equations for the shear strength are proposed. The results are in good agreement with the experimental ones.

The research mentioned above is a preliminary study on the box shape SRC beam. Further experimental and analytical research work is needed to investigate the behavior of the beam. For example, the suggested equations should be examined for their rationality and perfection, measures and details should be put forward to prevent the buckling of box shape steel and to assure the ductile flexural failure happening prior to other failure, and so on.

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箱形型钢混凝土梁的试验研究

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摘要:以 7 根 1:3 模型梁为研究对象, 试验研究箱形型钢混凝土 (SRC) 梁的性能. 试验结果表明, 箱形 SRC 梁的抗弯强度随纵筋配筋率和型钢翼缘板厚度的增大而提高, 剪切强度随型钢腹板的厚度增大而提高. 箱形型钢内浇注混凝土不但可避免型钢屈曲破坏而且还可提高梁的极限荷载. 型钢和混凝土间的连接需要改善以加强混凝土和型钢的共同工作作用. 给出了箱形 SRC 组合梁的抗弯承载力和抗剪承载力计算公式, 计算结果和试验结果吻合良好. 箱形 SRC 组合梁是一种延性构件, 适用于工程实践应用.

关键词:型钢混凝土 (SRC); 试验研究; 极限强度; 箱形型钢

中图分类号: TU398