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Experimental study on through-beam connection system for concrete filled steel tube column-RC beam

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Abstract. A new through-beam connection system for a concrete filled steel tube column to RC beam is proposed. In this connection, there are openings on the steel tube while the reinforced concrete beams are continuous in the joint zone. The moment and shear force at the beam ends can be transferred to column by continuous rebar and concrete. The weakening of the axial load and shear bearing capacity due to the opening of the steel tube can be compensated by strengthening steel tube at joint zone. Using this connection, construction of the joint can be made more convenient since welding and hole drilling in situ can be avoided. Axial compression and reversed cyclic loading tests on specimens were carried out to evaluate performance of the new beam-column connection. Load-deflection performance, typical failure modes, stress and strain distributions, and the energy dissipation capacity were obtained. The experimental results showed that the new connection have good bearing capacity, superior ductility and energy dissipation capacity by effectively strengthen the steel tube at joint zone. According to the test and analysis results, some suggestions were proposed to design method of this new connection.

Keywords: concrete filled steel tube; RC beam; connections; experiment; capacity

1. Introduction

Concrete filled steel tubes (CFSTs), as an economical type of column, have been developed for several decades due to their advantages over either pure steel or pure reinforced concrete members. The inner concrete of CFST enhances the stability of the tube, while the tube causes the core concrete to be in a triaxial stress state, and, thus, induces a confinement effect. With the increasing number of applications of CFSTs, more attention was paid on safety and economical design for beam-column connections. Many studies have been done on beam-column connections, including steel beam-CFST column connection and RC beam-CFST column connections. Schneider and Alostaz (1998) studied the experimental and analytical behavior of two types of connection details, namely, through-column and through-beam connections. The through-column connections utilize stiffeners to connect steel beams to CFST columns, while for through-beam connections, the beams directly pass through the panel zone or use other embedded elements to enhance the connection. Test results showed that through-beam connections had better seismic performance.

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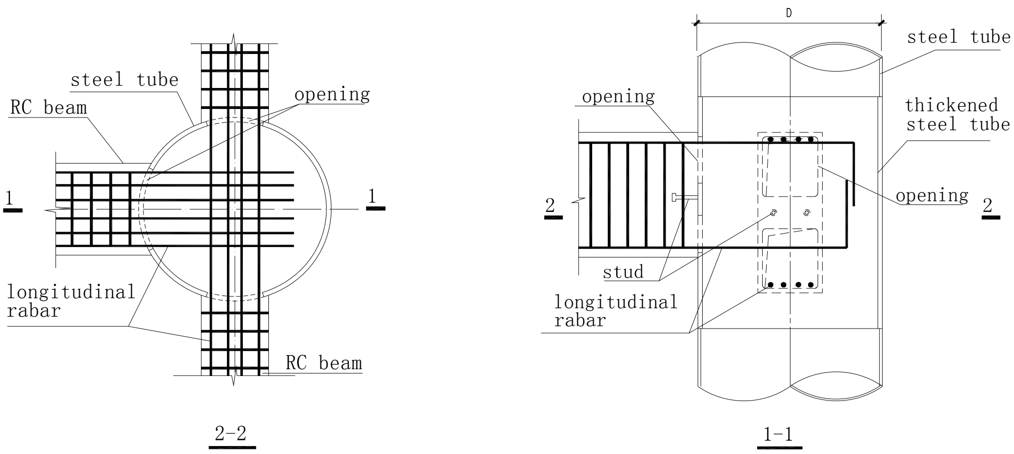
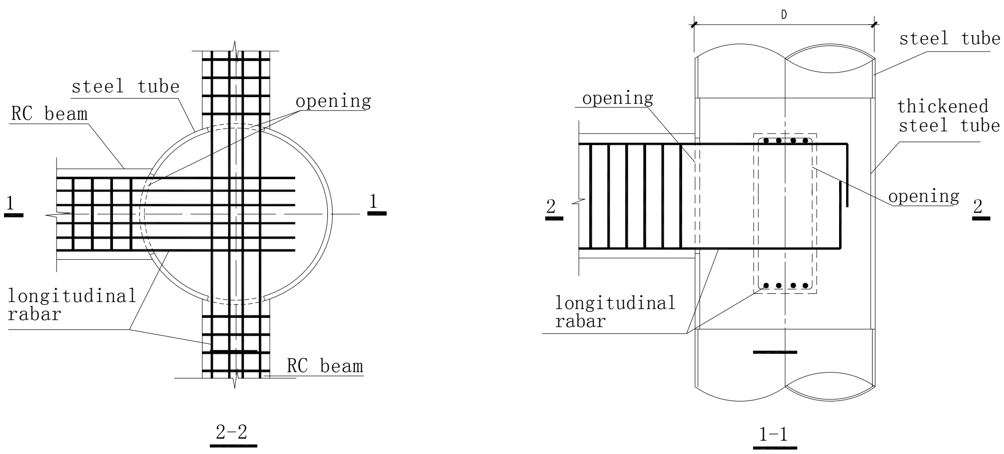
However, these connections may cause difficulties in field construction due to the complex fabrication in the panel zone and the fact that welding or hole drilling on site cannot be avoided. Azizinamini and Elremaily (2001) gave the design provisions for another type of the through-beam connections between the steel beams and the CFST columns. Cheng and Chung (2003) performed the research to achieve a better performance of through-column connections where the welded components were proven again to be critical, since all specimens failed due to the fracture of welds. A study on CFST column to H-beam welded connections, which are reinforced externally with T-shape stiffeners at the junction of the column and beam, was proposed by Kang *et al*. (2001) and Shin *et al*. (2004). Their test results demonstrated that an increased stiffener length was more effective than an increase in the area of penetrated elements for both strength and stiffness. Shin *et al*. (2008) carried out cyclic loading tests on seven square concrete-filled tube column-to-beam connections specimens which were reinforced with T-shaped stiffeners attached to the beam flanges. Ductility capacity of all the specimens exceeds the requirements for special moment frame connections in the AISC seismic provisions. The tapered horizontal stiffener elements, RBS cutouts and the horizontal stiffener holes were effective in reducing the stress concentration at the tip of the horizontal element. Ricles *et al*. (2004) carried out experimental study on ten full-scale moment resisting connections of square concrete filled steel tube columns and wide flange steel girders under simulated seismic loading conditions. The results show that split-tee connections and extended-tee connections with tapered tee flanges provide adequate cyclic joint stiffness and strength for a weak beam–strong CFT column system, and therefore offer a viable alternative to connections with diaphragms for seismic resistant design. Wu *et al*. (2005) proposed a new design of bolted connections for CFST columns, and established a mechanical model to calculate the stiffness, the yielding, and the ultimate shear strength of the panel zone. Wang *et al*. (2009) conducted experimental program for bolted moment connection joints of circular or square concrete filled steel tubular (CFST) columns and H-shaped steel beams using high-strength blind bolts. The results show that the proposed blind bolted connection, which behaves in a semi-rigid and partial strength manner according to the EC3 specification, displays reasonable strength, stiffness and enough ductility. Li and Han (2011) proposed a FEA model and investigated the failure mode and mechanism of the concrete-filled steel tubular (CFST) column to steel beam joint with a reinforced concrete (RC) slab under cyclic loading by stress analysis. Suggestions for design were proposed based on analysis results.

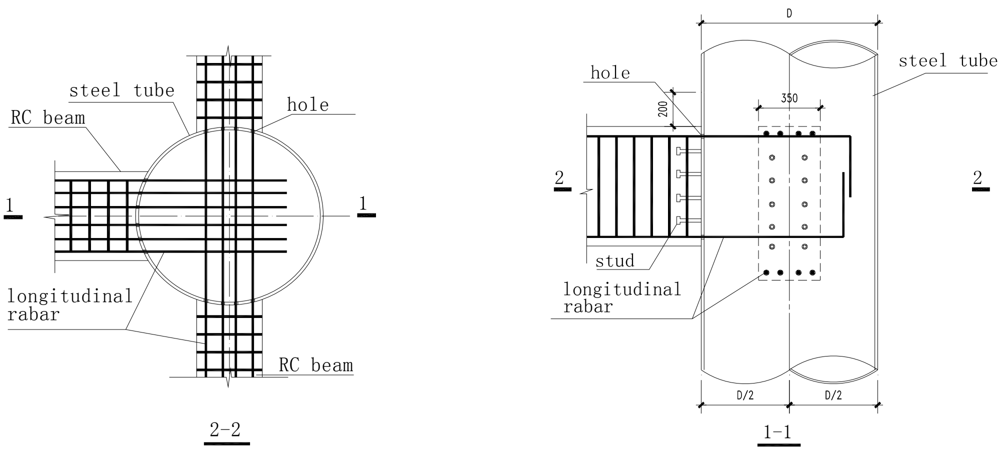
Nie *et al*. (2008a, b) studied the experimental and analytical behavior of a new connection system for CFST columns and RC beams, in which the steel tube is interrupted while the reinforced concrete beams are continuous in the joint zone. Multiple lateral hoops that constitute the stiffening ring are used to confine the core concrete in the connection zone. The axial compression tests and the reversed cyclic loading tests were conducted. Further theoretical analysis was carried out. The results showed that the effective confinement can be achieved by the stiffening ring, and an excellent axial bearing capacity can be obtained, as well as a superior ductility and energy dissipation capacity. Yao *et al*. (2008) studied the behavior of inner joint of concrete filled steel tube column - RC ring beam and proposed some suggestions for design of RC ring beam connection. Qian and Jiang (2009) conducted tests on three RC beam - composite steel tube confined concrete column joint specimens under cyclic loads at the beam cantilever ends. Zhang *et al*. (2012) introduced a new type of connections — ring beam joints with a discontinuous outer tube between the concrete-filled twin steel tubes (CFTSTs) columns and reinforced concrete (RC) beams. Four beam-column assemblage specimens were tested subjected to cyclic loads. The test results show that the joints with good aseismatic behavior can easily achieve the anti-seismic



(a) Details of joint A



(b) Details of joint B



(c) Details of joint C

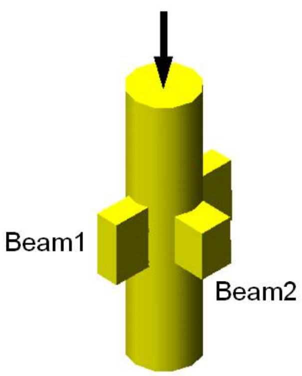
Fig. 1 Illustration of the through-beam connection system design principles, namely "strong column-weak beam" and "strong joint-weak member". Chen *et al*. (2012) carried out numerical simulation by OPENSEES on CFST column-beam joint with the column tube discontinuous in joint zone. The results indicate that models with higher reinforcement ratio of the beams will result in joint failure under cyclic reverse loading, and their load-displacement curves are pinched and ultimate bearing capacity would not increase while strength degradation and stiffness degradation would appear obviously.

However, new connection system and further study is required for the CFST columns – RC beams connection due to difficulty to arrange the longitudinal steel bars in the beams and the transferring of moments and shear forces at the beam ends.

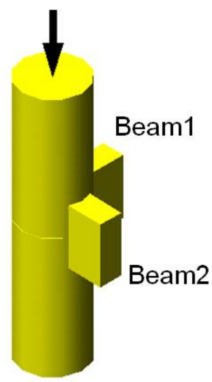
2. Description of new connection system

Since the through-beam connection shows a good performance, as reported in the literature, this paper proposed a new connection system for CFST composite column and RC beams, which can be considered as a typical through-beam connection. There are openings on the steel tube while the reinforced concrete beams are continuous at the joint zone. The transfer of moment and shear force at the beam ends can be ensured by continuous rebar and concrete, the weakening of the axial load and shear bearing capacity due to the opening of the steel tube can be compensated by strengthening steel tube at joint zone. Using this connection, construction of the joint can be made more convenient since welding and hole drilling in situ can be avoided.

In order to investigate the mechanical behavior and seismic performance, both monotonic and reversed cyclic loading experiments were conducted for this new connection system at China Academy of Building Research. Two types of joint A and B with different manners of openings on steel tube were designed and tested, as shown in Fig. 1. For joint A, there is a big opening on steel tube at joint zone and the RC beam cross through the opening directly, as show in Fig. 1(a). For joint B, there are two small openings on steel tube at joint zone and the top and bottom reinforcement of RC beam cross through the two openings respectively, as show in Fig. 2(b). For both joint A and B, thickness of steel tube at joint zone is 1.5 times of column to compensate the



(a) Side column



(b) Corner column

Fig. 2 Type of axial compression specimens weakening due to the openings. For joint B, some studs were welded on outside of steel tube between two openings for shear transmission. In order to compare performance of the new connection with normal connection, joint C was also tested. For joint C, many little holes were drilled on the steel tube at joint zone and each bar of RC beam cross through these holes respectively, as show in Fig. 1(c). Some studs were welded on outside of steel tube at joint zone to bear shear force of beam.

The effects on the axial load bearing capacity due to different joint details were investigated in the axial compression loading tests. Moreover, more consideration was focused on the connection's ductility, energy dissipation capacity, and hysteretic behavior for seismic resistance, which were evaluated in the reversed cyclic loading tests.

3. Axial compression loading test

3.1 Specimens

The specimens with details of joint type A, B and C shown in Fig. 1 were designed. Both side columns connected with three beam and corner column connected with two beams were considered as shown in Fig. 2. All specimens were listed in Table 1. For all specimens, column height is 1000 mm, steel tube diameter is 312 mm and thickness is 5 mm. Beam 1 and beam 2 has rectangular section of 109 mm × 281 mm and 156 mm × 219 mm, respectively. The steel cages were fabricated and the concrete was cast in the lab while the steel tubes were provided by the manufacturer. All the specimens were cured under standard conditions in the lab until the concrete design strength was achieved. Each time when pouring concrete, four concrete specimens were prepared and cured under the same conditions in order to obtain reliable material properties that were shown in Table 1. The material properties of steel tube were shown in Table 2.

3.2 Test setup and load procedure

The experiments were conducted under a servo hydraulic machine with a capacity of 10,000 kN in static loading, as shown in Fig. 3. The strain gages for steel were preset to measure the axial and hoop strains of steel tube of joint zone and column. Displacement transducers were preset to measure the axial compression deformation of column and joint zone.

Table 1 Axial compression specimens

Symbol	Joint detail	Column position	Tested cube compression strength of concrete in column $f_{cu,m}$ / MPa
Z – As	A	Side	58.3
Z – Ac	A	corner	43.9
Z – Bs	B	Side	58.3
Z – Cs	C	Side	58.3

Table 2 Steel material properties

Part	Thickness	Yield strength (MPa)	Ultimate strength (MPa)
Steel tube for column	5.43 mm	316.5	439.0
Steel tube for joint zone	7.73 mm	342.6	505.3

Fig. 3 Experimental setup for axial compression test

Table 3 Axial compression capacity and failure mode of specimens

Specimen symbol	P_u (kN)	[N] (kN)	P_u / [N]	Failure mode
Z – As	5400	5521	0.98	Steel tube buckled above joint zone
Z – Ac	5100	5118	1.00	
Z – Bs	5100	5521	0.92	
Z – Cs	6400	5521	1.16	

3.3 Test results

The maximum axial compression capacity and failure mode are summarized for each specimen in Table 3, where P_u is tested maximum axial compression capacity, [N] is the calculated axial compression capacity of column according to the method in Chinese code as below

$$[N] = 0.9 A_c f_c (1 + \alpha \frac{A_a f_a}{A_c f_c}) \tag{1}$$

where A_c is area of concrete, f_c is characteristic strength of concrete and $f_c = 0.76 f_{cu,m}$, A_a is area of steel tube, f_a is yield strength of steel. $f_{cu,m}$ and f_a are shown in Table 2. $\alpha = 1.8$ when $f_{cu,m} > 50$ MPa,

$\alpha = 1.8$ when $f_{cu,m} < 50$ MPa.

The test results are approximately accordant with calculated results.

For all specimens, the steel tube above joint zone yield firstly. Then the load increased slowly until the steel tube buckled and tore out. No failure happened at joint zone. Fig. 4 showed the failure mode of all the specimens.

Z – As Z – Ac Z – Bs Z – Cs

Fig. 4 Failure mode of axial compression specimens

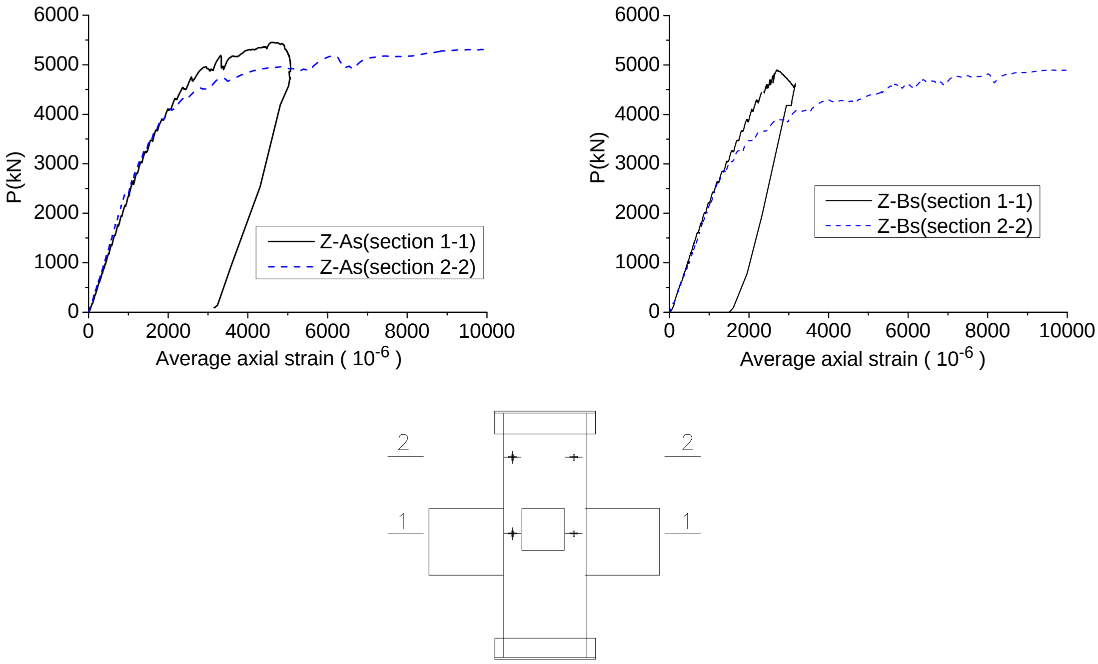


Fig. 5 Load-strain curves of steel tube at column and joint zone

Fig. 5 shows the load-strain curves of steel tube at column (Section 2.2) and joint zone (Section 1.1), respectively for specimen Z – As and Z – Bs. The strain values were obtained from the average results of four gages around the tube section. The yielding happened firstly at Section 2.2 and strain of steel tube at joint zone was far less than that of column at ultimate state. It is verified again that the safety of this new beam-column system can be assured; therefore, the “strong joints” design can be achieved at least in this monotonic compression loading case by increasing thickness of steel tube with openings.

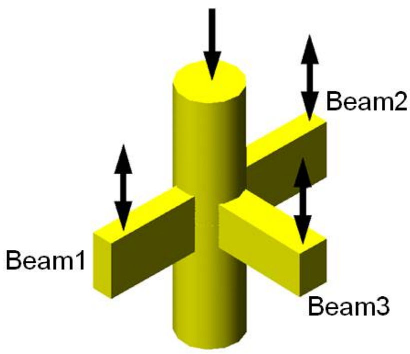
4. Reversed cyclic loading tests on beam-column moment connection

4.1 Specimens

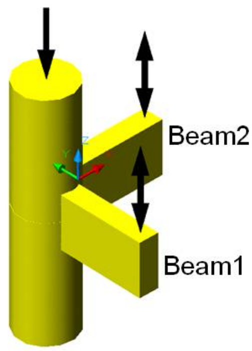
In addition to the axial compressive properties of this new connection system, the seismic performance and energy dissipation capacity of this system were also investigated. The specimens with details of joint type A, B and C shown in Fig. 1 were designed. Both side columns connected with three beam and corner column connected with two beams were considered as shown in Fig. 6. All specimens were listed in Table 4. For all specimens, height of column is 1000 mm, dimension of steel tube section is 312-5 mm. Axial compressive ratio is 0.7. The RC beams are through the joint, with section dimensions of 150 × 350 mm for Beam1 and Beam2, 156 × 219 mm for Beam3. The material properties of concrete were listed in Table 4 and material properties of steel were same with axial compression specimens as shown in Table 2.

4.2 Test setup and load procedure

The experiments were conducted in a self-equilibrating reaction frame with one hydraulic jack (capacity of 5000 kN) on the top of the column, applying an axial compressive force to the design value that is controlled by the axial compressive ratio, two (for corner column) or three (for side column) load actuators (capacity of 1000 kN) at the ends of the beams for exerting cyclic forces. The ends of the column were pinned, while the beams had free ends where load cells were located,



(a) Side column



(b) Corner column

Fig. 6 Type of reversed cyclic loading test specimens

Table 4 Reversed cyclic loading test specimens

Specimen symbol	Joint detail	Column position	number	Tested cube compression strength of concrete for column /MPa	Tested cube compression strength of concrete for beam /MPa
J – As	A	Side	2	58.3	43.9
J – Ac	A	corner	2	43.9	43.3
J – Bs	B	Side	2	58.3	43.9
J – Cs	C	Side	2	58.3	43.9

Fig. 7 Experimental setup for cyclic tests of side column specimens

as shown in Fig. 7. At the beginning of the test, the axial force was directly applied on the top of the column up to the design value and kept constant to simulate the static load. Considering the difficulty in applying the vertical and horizontal loads simultaneously to the column, vertical cyclic loads were applied at the beam ends. The two actuators located on the ends of the beams acted at the same time to achieve the reversed loads to simulate the story displacement due to horizontal loading.

Since the hysteretic behavior was not obvious in the early stage, the load steps were taken as 25%, 50%, 75%, 85%, and 100% of the yielding load of the RC beam and were repeated once at first. After the yielding load was reached, the load steps were controlled by the displacement as the multiples of the yielding displacement at the beam end. Besides the measurement positions, as introduced in the axial compression loading test, the displacement at the beam ends, the strains at typical positions of the beams, as well as the strains at the steel bars of the beams were measured.

4.3 Test results

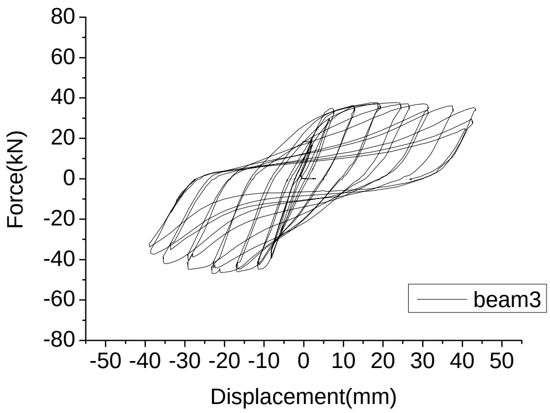
The performances of specimens with different joint details during testing were similar. After applying the axial force, no cracks or buckling were observed. Keeping the axial loads stable, the reversed cyclic forces at the beam ends were applied until the failure happened. Cracks were found at top and bottom surface of beams at the ends connected with column where the moment is the

Fig. 8 Bending failure at beam end

Fig. 9 Concrete of joint zone after testing

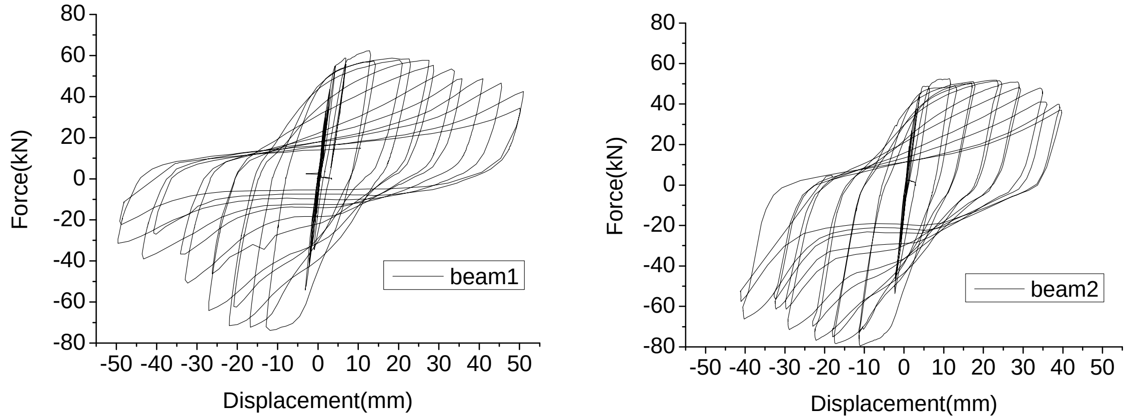
maximum. The cracks developed with increasing of loads until bending failure happened at beam ends. All specimens had a similar bending failure mode due to the same design of the beams (see Fig. 8). The yield of the beam was followed by the propagation of cracks at the end of the beam, while the joints and columns kept a stable status. After testing the steel tube at joint zone were taken away and no cracks or crush can be found on concrete of joint zone (see Fig. 9). The axial and hoop strains of the steel tube at joint zone almost keep elastic during testing. The design concepts of ‘strong column, weak beam’ and ‘strong joints’ were achieved for all types of joints even with openings on steel tube.

For specimen J – As and J – Bs, longitudinal rebar at bottom of Beam1 and Beam2 began to slip after yielding and maximum value of slip was about 2 cm. The reason is that smooth rebar with no rib on surface was adopted in the beams and there were no vertical rebar and stirrup in the joint zone. The bond between rebar and concrete is not enough. Therefore, when adopting this new connection system, deformed rebar should be adopted for beam and it is better to take some measures, such as longer anchor length, anchor hook or mechanical anchor setup, to ensure the anchor of beam’s longitudinal rebar in the joint zone.

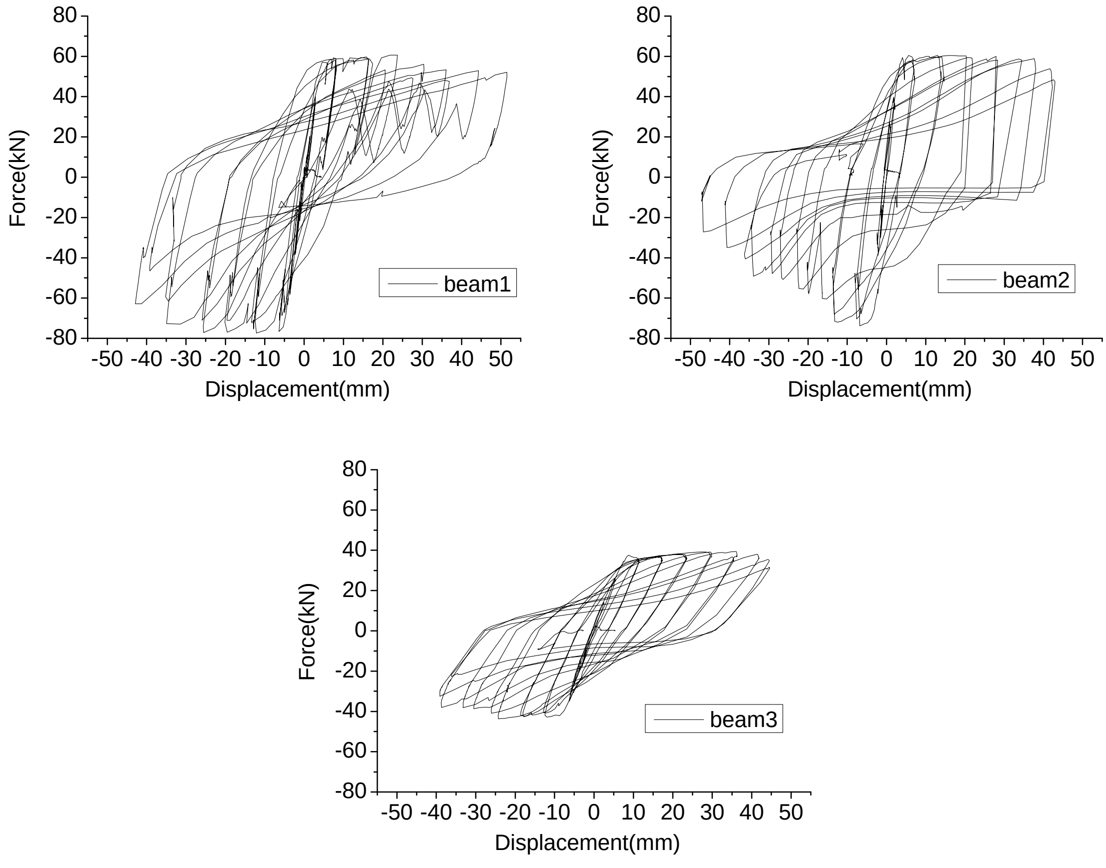


(a) Load-displacement response curves for specimens J – As

Fig. 10 Load-displacement response curves for specimens

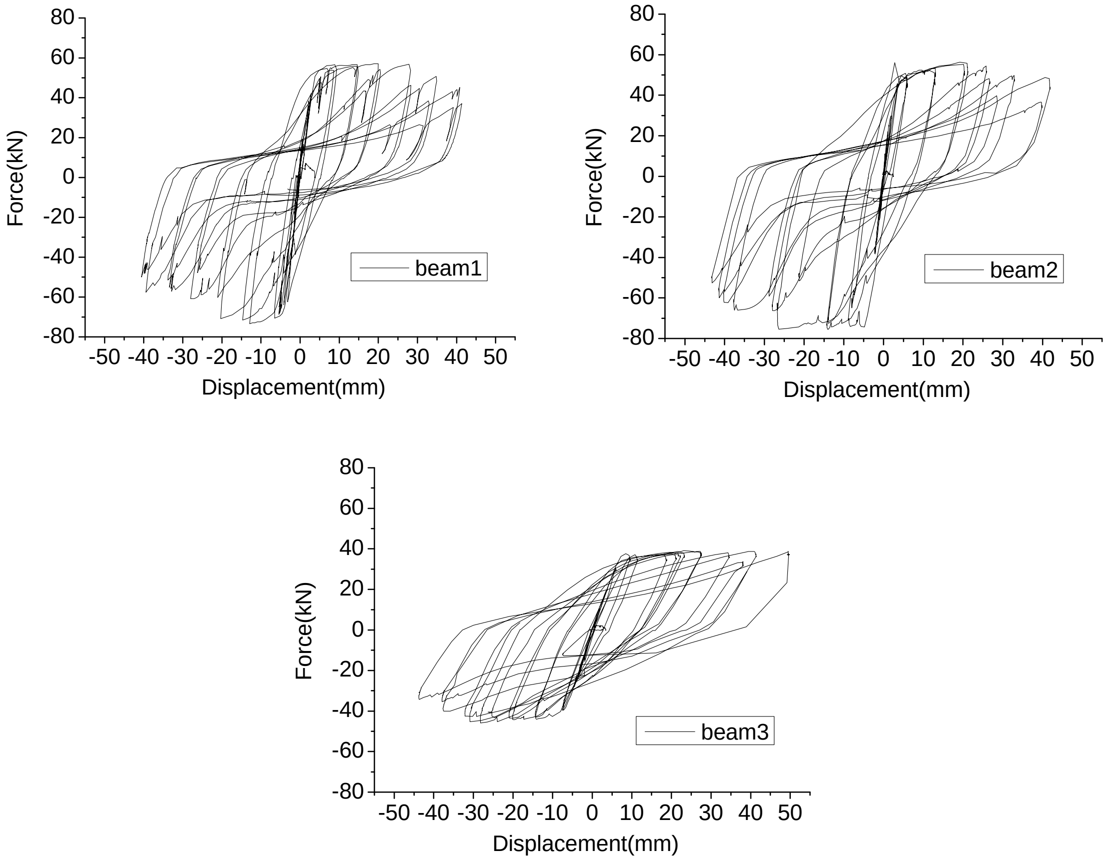


(b) Load-displacement response curves for specimens J-Ac



(c) Load-displacement response curves for specimens J-Bs

Fig. 10 Continued



(d) Load-displacement response curves for specimens J-Cs

Fig. 10 Continued

The full hysteretic response curves of the four specimens can be seen in Fig. 10, where the vertical axis shows the force at the beam ends, and the horizontal axis shows the displacements of the beam ends. Since the area under the hysteretic loop indicates the energy dissipation in each cycle, these plots give a visual representation of the energy dissipation. The majority of the energy was dissipated through the flexural yielding at the plastic hinge generated by the loading at the beam ends. After the yielding and the concrete spalling on the beam's upper surface, the stiffness decreased rapidly, as shown in the displacement controlled loop, and there was no further increase of strength. No failures resulted from the joints, even with different joint details. The design requirements as "strong joints" could be achieved, and the plastic hinges formed at the beam ends near the connection.

The load-displacement envelope curve of Beam1 for the four specimens can be seen in Fig. 11. The curves of four specimens were almost overlapping. The area under the full load-displacement envelopes indicates the energy that could be dissipated by the specimen before failure. All the tested specimens had excellent deformation capacity and energy dissipation capacity.

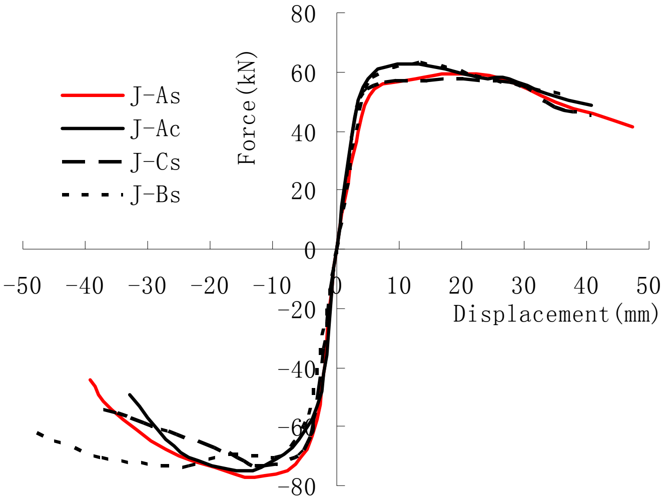


Fig. 11 Load-displacement envelope curve of beam1 for the four specimens

The load capacity and displacement ductility is summarized in Table 5. The ductility is taken as the ratio between the displacement at 85% maximum load and the yield displacement. The results showed that the joint with openings on steel tube have similar capacity, ductility with that of joint without openings on steel tube.

Table 5 The load capacity and displacement ductility of specimens

Specimens symbol	Beam symbol	Moment capacity of beam end /kN.m				Yield displacement /mm		Ultimate displacement /mm		Ductility	
		Test result		Calculated result							
		Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
J – As	1	59.5	77.1	37.9	65.2	5.5	4.0	34.1	28.4	6.2	7.1
	2	55.9	80.3	37.9	65.2	5.2	4.6	45.4	38.4	8.7	8.3
	3	37.2	46.4	27.9	38.2	6.7	9.7	38.0	36.9	5.7	3.8
J – Ac	1	62.1	73.8	37.9	65.2	4.8	4.3	32.7	27.6	6.8	6.4
	2	52.2	79.5	37.9	65.2	4.7	3.4	36.3	30.1	7.7	8.9
J – Cs	1	56.5	73.4	37.9	65.2	3.8	4.8	35.4	25.8	9.3	5.4
	2	55.7	75.6	37.9	65.2	3.8	4.4	40.9	38.1	10.8	8.7
	3	39.1	45.9	27.9	38.2	7.4	8.3	39.9	38.5	5.4	4.6
J – Bs	1	63.2	73.4	37.9	65.2	5.1	5.5	33.6	47.8	6.6	8.7
	2	59.3	76.4	37.9	65.2	3.5	4.6	37.2	34.1	10.6	7.4
	3	37.9	45.4	27.9	38.2	6.5	5.8	30.8	25.7	4.7	4.4

5. Conclusions

A new connection system between the RC beam and CFST composite column was proposed, in which there are openings on steel tube for the through-beam connection. The axial compression tests and the reversed cyclic loading tests were conducted and some conclusions can be drawn below:

- The loss of confinement due to the openings of the steel tube can be fully compensated by strengthening steel tube at joint zone. The “strong joints” design can be achieved in this compression loading case by increasing thickness of steel tube with openings.
- All specimens had a similar bending failure mode in cyclic loading tests. The design concept of ‘strong column, weak beam’ and ‘strong joints’ was achieved for all types of joint even with openings on steel tube. The joint with openings on steel tube have similar capacity, ductility with that of joint without openings on steel tube.
- The new through-beam connections between the CFST composite column and RC beams, exhibited good safety and reliability even until the beam were totally damaged. Enough energy dissipation capacity and ductility can be obtained for this system, which is used for both side columns and corner columns.
- When adopting this new connection system, deformed rebar should be adopted for beam and it is better to take some measures, such as longer anchor length, anchor hook or mechanical anchor setup, to ensure the anchor of beam’s longitudinal rebar in the joint zone.

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