Experimental study of axial compression on new types of CFST column-RC beam joints after the low-cycle reversed loading test

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Abstract. In this paper, the axial compression tests were carried out on the concrete filled steel tube (CFST) column-reinforced concrete (RC) beam joints connected by steel plates and studs after the low-cycle reversed loading test. The failure mode, steel tube strain and ultimate bearing capacity of new types joints were discussed under axial compression load. The comparative study with the specimen of CFST column was conducted. The results showed that new types CFST column-RC beam joints maintain good axial compression performance after the low-cycle reversed test loading at the beam ends. The specimens were designed following the principle of “strong column-weak beam”. The low-cycle reversed loading had little effect on the axial bearing capacity of the CFST column, but the damaged RC beams of the joints had certain influence on the failure mode of the columns under axial compression.

1. Introduction
Concrete filled steel tube (CFST) columns have superior loading capacity, seismic capacity, and good construction performance [1,2]. A lot of engineering experience shows that the axial compression members used CFST structures could reduce the self-weight by 50% and save 50% consumption of concrete when the steel consumption is as the same as that of the reinforced concrete structures. CFST structures can save 50% steel consumption comparing with steel structures under the same bearing capacity, and its economic performance is outstanding [3]. In recent years, CFST columns have been widely used in high-rise buildings [4-7]. The joint is always an important part of the structure to promote structural technologies, as well as the CFST structure. The application of CFST columns in engineering projects are mostly connected with steel beams. The use of CFST column-RC beam joints is relatively less due to the complex construction work of the joint or hard to form a rigid connection. The CFST column-RC beam joints have received little attention compared with CFST column-steel beam joints [8,9].

A single beam joint with steel rebars piercing the column is proposed in the technical code of China (GB50936-2014) for CFST structures [10]. Small round holes were made on the steel tube to pass through the longitudinal rebars of the beam. The inner or outer sectional steel pipes are welded to strengthen the column weakened by the openings. In this paper, based on this single beam joint
proposed in the code, two connection methods for the CFST column-RC beam are studied: a vertical steel plate and studs, and a U-shaped steel plate and studs. The schematic diagram is shown in Figure 1. The joints designed have advantage such as clear force transmission, good integrity, reduced material consumption, and convenient construction. The results of low-cycle reversed load test showed that the CFST column-RC beam joints connected by plate-studs have good seismic performance [11]. However, the compressive behavior of the joints is not clear after the low-cycle reversed test. Therefore, the axial compression tests were carried out on the specimens experienced the low-cycle reversed test loaded at the ends of the beam. Compared with the axial compression test of corresponding CFST column, the axial compression performances were analyzed.

![Figure 1. Schematic diagram of the new types joints: (a) Vertical steel plate-studs connection; (b) U-shaped steel plate-studs connection.](image)

2. Overview of the tests
Three specimens were designed for the test, namely JD-1, JD-2 and Z0 respectively. JD-1 and JD-2 were jointed as specimens. JD-1 joint was connected by vertical plate and studs, JD-2 joint was connected by U-shaped plate and studs. Small round holes were opened on the steel tube with a diameter of 1.2d, where d is the diameter of the corresponding longitudinal rebar. Attached steel pipes were welded on the outside of the opening area to reinforce the steel tube. The longitudinal rebars of the beam pass through the holes opened in the steel tube and keep continuous. Z0 is CFST column specimen, which is identical with the column in the JD-1 and JD-2. The sectional dimensions and reinforcement details of the specimens are shown in Figure 2. Table 1 presents the main parameters of each specimen. The strength grade used in all the steel plates and steel tubes is Q345, and in all of the rebars is HRB400. ML15 grade studs were used for plate-studs connections. For all the beams, concrete grade is C35 (based on the Chinese design code [12]) and for all the columns is C50. The tested mechanical properties of the steel and concrete used in this test are listed in Table 2 and Table 3.
Figure 2. Sectional dimensions and reinforcement details of specimens: (a) JD-1; (b) Section for the beam of JD-1/JD-2; (c) JD-2; (d) Z0.

Table 1. Parameters of specimens.

| Specimen no. | Column section size [mm] | Column height H [mm] | Reinforced steel pipe [mm] (b × h × t) | Beam section size [mm] | Reinforcement in beam | Configuration of the beam–column connection |
|--------------|--------------------------|----------------------|--------------------------------------|------------------------|-----------------------|---------------------------------------------|
| JD-1         | 610 × 10                 | 2440                 | 402 × 219 × 10                       | 300 × 700              | Longitudinal bar top: 3C25 + 2C20 | Vertical steel plate and studs            |
| JD-2         | 610 × 10                 | 2440                 | 402 × 180 × 10                       | 300 × 700              | Bottom: 4C25 Stirrup: 3C10@100 | U-shaped steel plate and studs            |
| Z0           | 610 × 10                 | 2440                 | —                                    | —                      | —                      | —                                           |
Table 2. Material properties of steel.

| Material      | Diameter (thickness) [mm] | Material grade | Yield strength $f_y$ (MPa) | Ultimate strength $f_u$ (MPa) | Elongation A [%] | Elastic modulus $E_s$ (MPa) |
|---------------|---------------------------|----------------|---------------------------|-------------------------------|------------------|-----------------------------|
| Rebar         | 10                        | HPB400         | 413                       | 607                           | 22.06            | $1.8 \times 10^5$           |
|               | 20                        | HRB400         | 430                       | 559                           | 20.13            | $2.0 \times 10^5$           |
|               | 25                        | HRB400         | 436                       | 608                           | 19.93            | $2.0 \times 10^5$           |
| Steel plate   | 4                         | Q345           | 395                       | 530                           | 19.03            | $2.1 \times 10^5$           |
|               | 6                         | Q345           | 409                       | 539                           | 22.90            | $2.0 \times 10^5$           |
| Steel tube    | 10                        | Q345           | 423                       | 569                           | 16.17            | $2.0 \times 10^5$           |
| Stud          | 13                        | ML15           | 339                       | 456                           | 15.38            | --                          |
|               | 16                        | ML15           | 340                       | 457                           | 15.40            | --                          |

Table 3. Material properties of concrete.

| Strength grade | Axial compressive strength $f_c$ (MPa) | Axial tensile strength $f_t$ (MPa) | Elastic modulus $E_c$ (MPa) |
|----------------|----------------------------------------|-----------------------------------|-----------------------------|
| C35            | 29.2                                   | 2.48                              | $3.34 \times 10^4$          |
| C50            | 52.1                                   | 3.35                              | $3.78 \times 10^4$          |

According to the technical code for CFST structures [10] and the code for design of concrete structures [12], the design values of bending and shear capacity of the beam and column were calculated respectively. The design values were checked and listed in Table 4. The results show that the joints satisfied the seismic design principle “strong column and weak beam, strong shear and weak bending”.

Table 4. Checking results of bearing capacity of each specimen.

| Check          | Bending capacity ratio | Shear capacity ratio |
|----------------|------------------------|----------------------|
| CFST column/beam | $M_{c0} / M_b$ | $V_{ca} / V_{cb}$ |
| CFST column     | $V_{c0} / V_{cb}$ | $V_{ca} / V_{cb}$ |

$V_{ca} = L / L_c$ where $L$ is the distance from the loading point to the end of the beam;

$V_{ca} = H_c / H_c$ where $H_c$ is the distance from the end of the column to the outside of the core area of the joint; and the values in parentheses are the results calculated with the longitudinal bar of the beam section under tension.

The joint specimens JD-1 and JD-2 showed good seismic performance in the low-cycle reversed load tests which were loading at the end of the beam. Figure 3 shows the load–displacement curves of the loading point at the end of the north beam. After the low-cycle reversed loading, the damage of the beam of JD-1 happened at the area distanced about 350mm (at the outer edge of the vertical plate) from the junction of beam and column, and JD-2 at the outer edge area of U-shaped steel plate. Figure 4 shows the failure model of the joints [11].
Both the axial compression and low-cycle reversed load tests were carried out on 40000kN multi-function electro-hydraulic servo test system. The loading device is shown in Figure 5. After the low-cycle reversed loading test of the joint specimens, the loading devices supplied on the end of the beam were removed to set the restrained beam end free. And then the axial compression test was carried out. The axial deformations of the specimens were measured by the LVDT displacement meter. The measuring range is 3/4H in the middle of the specimen, which H is the height of the specimen. The strain gauges were pasted on the wall of the steel tubes to monitor the strain. The measuring points are shown in Figure 5(c).

**Figure 3.** Load–displacement curves of specimens (N): (a) JD-1; (b) JD-2.

**Figure 4.** Failure modes of specimens: (a) JD-1; (b) JD-2.

**Figure 5.** Test setup: (a) Low-cyclic reversed loading test; (b) Axial compression test; (c) Strain measuring point.
3. Test results and discussion

3.1. Failure process and failure model of the axial compression test
In the initial stage of loading, all the specimens did not change obviously. As the load increased, the deformation increased gradually within the range of 3/4H. For the specimen JD-1, the upper part of the core area of the steel tube was compressed and expanded, and the steel tube below the cover plate was slightly buckled. For specimen JD-2, the upper steel tube of the diagonal line of U-shaped steel plate at the end of the beams was inclined to bulge. The steel tube below the core area was slightly bulged and the region of the steel tube within a range of 10cm from the cover plate was buckled around. For specimen Z0, the top of the column was buckled obviously. The upper part of the steel tube was deformed by compression, and obvious oblique deformation under the top of the column on the east side was observed. The steel tube around upper part of the underside reinforced plate was compressed and buckled. Figure 6 shows the failure mode of each specimen.

![Figure 6](image_url)

**Figure 6.** Axial compression test figure model of each specimen: (a) JD-1; (b) JD-2; (c) Z0.

3.2. Load-displacement relationship
Figure 7 shows the load-displacement curves of each specimen. The displacement is the vertical deformation of the range within 3/4H in the middle of the specimen. As it can be seen from the curves of the specimens, there are three stages from loading to failure: elastic stage, plastic stage and failure stage. In the elastic stage, the load-displacement curves are basically linear, and the stiffness of all the specimens is basically the same in the elastic stage. With the increase of the load, the load-displacement curve increases slowly and presents a non-linear state. All the specimens reached the peak loading capacity shortly after the steel tube yielded. After that, the bearing capacity decreased. The load dropped to 85% of the peak load is defined as the ultimate load. The yield point of each specimen is determined by the equal energy method. Test values of feature points of each specimen are listed in Table 5.
Figure 7. Load-deformation: (a) JD-1; (b) JD-2; (c) Z0; (d) Load-deformation curves comparison.

Table 5. Test values of feature points of specimens.

| Specimen no. | Yield Displacement /mm | Peak Load /kN | Peak Displacement /mm | Ultimate Load /kN | Ultimate Displacement /mm | Ultimate Load /kN |
|--------------|-----------------------|--------------|-----------------------|------------------|---------------------------|------------------|
| JD-1         | 3.4                   | 21407.3      | 5.0                   | 24298.1          | 24.8                      | 20653.4          |
| JD-2         | 4.1                   | 22409.7      | 6.3                   | 24572.1          | 10.0                      | 20886.3          |
| Z0           | 5.5                   | 23683.2      | 7.9                   | 25632.2          | 13.2                      | 21787.4          |

3.3. strain analysis of the steel tube

Figure 8(a) shows the vertical strain of the measuring point G5 (in Figure 5(c)), which is in the above of the upside reinforced plate. The strains of the three specimens in the elastic stage of the measuring point G5 show the similarity. Before reaching the yielding strain, the strain growth rates of the three specimens are not significantly different.

Figure 8(b) shows the vertical strain of the measuring point G3, which is at the center of the steel pipe column core area. At the initial stage of loading, the strain growth rate of Z0 specimens at the same location is higher than that of the rest specimens. As the load increases, the strain growth rate of JD-1 and JD-2 at G3 increases, but it does not reach yielding point during the whole loading process. After Z0 reaches the peak bearing capacity, the strain at G3 measuring point continuously increase. Finally, the steel tube is buckled at this measuring point, while the deformation of JD-1 and JD-2 specimens at this location isn’t obvious, which is consistent with the test phenomenon.
3.4. Axial bearing capacity calculation

The axial bearing capacity of CFST column was calculated according to the commonly used design codes of CFST in various countries, including CECS 28-2012 [13], GB50936-2014 [10], ANSI/AISC 360-10 [14] and EN 1994-1-1(2004) [15]. The calculation formulas and results of axial capacity of CFST column in the corresponding specifications are listed in Table 6. The test columns are the steel tube with openings and reinforced with steel plates. The axial bearing capacity of the CFST column without openings was calculated by the codes of various countries. The axial bearing capacity calculated by the Chinese codes is greater than the test values, while that calculated by the foreign codes are less than the test values. The main reason is that the Chinese codes take the restraint effect of steel tube into account of concrete, therefore the concrete strength is improved. While in the foreign codes, the bearing capacity of steel and concrete are calculated respectively, and then add the two parts together. In this case, the strength of the concrete is considered as plain concrete, or reduced the strength to a certain extent. Therefore, the calculation result is relatively smaller.

Table 6. Calculation of axial bearing capacity of circular steel tube concrete in various countries.

| Serial number | Code                  | Code formulae                                                                 | Calculation of axial bearing capacity/ kN |
|---------------|-----------------------|-------------------------------------------------------------------------------|------------------------------------------|
| (1)           | CECS 28-2012, GB 50936-2014 | \(0.5 < \theta \leq [\theta], N_a = 0.9 f_c A_s (1+\alpha \theta); \) \(\alpha = 2\) (When the concrete grade is below C50 take 2, otherwise take 1.8), \(\theta = A_f f_c / A_s f_c\); | 27163.8                               |
| (2)           | GB 50936-2014         | \(N_a = f_c A_s + f_c A_r (1.212+8B\theta+C\theta^2), B=0.176f_c/213 + 0.974, C=-0.104f_c/14.4+0.031\) | 28047.5                               |
| (3)           | ANSI/AISC 360-10      | \(N_a = f_c A_s + C f_c A_r, C=0.95\)                                       | 21494.2                               |
| (4)           | EN 1994-1-1(2004)     | \(N_a = f_c A_s + 0.55 f_c A_r\) For circular column, 0.85 is replaced by 1.0. | 22206.1                               |

4. Conclusion

The new types CFST column-RC beam joints JD-1 and JD-2 exhibit good axial compression performance after subjected to the low-cycle reversed loading test. The bearing capacity is basically the same as that of the specimen column which has not subjected to the low-cycle reversed loading test.

The failure modes of the joints JD-1 and JD-2 are different from the CFST column, since there are RC beams on the left and right side of the core area of the joint. The JD-1 failure mode is compressive expansion of the part above the core area. The final failure mode of the JD-2 is mainly oblique shearing pattern. The failure mode of CSFT column specimen Z0 is mainly caused by steel tube buckling in the core area.
According to the codes of various countries, the axial bearing capacity of ordinary CFST columns is calculated. The test values are slightly lower than the calculated values of the domestic codes, but higher than those of the foreign codes. The calculation formula for the new type of reinforced CFST columns with openings needs to be further studied.

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