Experimental Study On Hysteretic Behavior of Concrete Filled Square CFRP Steel Tubular Beam-Column

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Experimental study on hysteretic behavior of concrete filled Square CFRP steel tubular Beam-Column

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Abstract: In order to study the hysteretic behavior of concrete filled square CFRP steel tubular
Beam-Column under different influence factors, 12 specimens were designed, and the failure
mode, middle section lateral force-deflection($P-\Delta$) curve, middle section bending
moment-curvature($M-\phi$) curve and middle section deflection-deformation($\Delta-\Delta'$) curve were
studied. Axial compression ratio and longitudinal CFRP reinforcement coefficient as influencing
factors, the effects of axial compression ratio and longitudinal CFRP reinforcement coefficient on
 $P-\Delta$ skeleton curve, $M-\phi$ skeleton curve, strength and stiffness degradation, ductility, cumulative

energy consumption and other indexes were studied; the $P-\Delta$ curve and deformation mode of the specimens were simulated by ABAQUS, and the effects of axial compression ratio, slenderness ratio and other main parameters on the hysteretic performance of the members were studied. The test results show that CFRP has good lateral restraint and longitudinal reinforcement effect on CFST, and the local buckling of CFST is delayed. The $P-\Delta$ curve and $M-\phi$ curve of all specimens are full. In addition, the steel tube and CFRP have good synergy in both longitudinal and transverse directions. The change of axial compression ratio and longitudinal CFRP reinforcement coefficient has no significant effect on the strength degradation. The increase of axial compression ratio and longitudinal CFRP reinforcement coefficient can improve the flexural capacity and stiffness of the specimens, and slow down the stiffness degradation, but reduce the ductility and cumulative energy consumption of the specimens. The finite element software ABAQUS is used to simulate the $P-\Delta$ curve and deformation mode of specimens. It is found that the simulation results are in good agreement with the experimental results. Based on the model analysis of the main parameters, it is found that the increase of steel yield strength and CFRP layers can improve the bearing capacity of the specimens, and the axial compression ratio has the most significant effect on the specimens.

Key words: Square CFRP concrete filled steel tube; Middle section lateral force-deflection curve; Hysteretic behavior; Finite element simulation

1 Introduction and research significance"

In recent years, earthquakes are more and more widespread in the world. The distribution of seismic zones is not uniform, but they are widely distributed. Some scholars have carried out extensive and in-depth research on the seismic design of building structures, and the earthquakes have caused huge economic losses and casualties. To deal with the threat of earthquake disaster to buildings, the research on hysteretic behavior of building structures is more and more extensive [1-2]. Nowadays, the most commonly used composite structure is steel-concrete composite structure. It is a composite structure composed of steel and concrete, which mainly uses the advantages of compressive performance of concrete and tensile performance of steel [3-4]. This composite structure is not only convenient for construction, but also saves a lot of materials, so as to achieve the goals of reducing the cost, reducing the weight of components and shortening the construction period. Therefore, the steel-concrete composite structure is widely used in practical engineering[5].

Liu Y et al. [6] carried out the torsion tests of 16 circular CFRP concrete filled steel tubes. The results show that the failure modes of the specimens bonded with longitudinal CFRP and circumferential CFRP are different. Ling ZG et al. [7] carried out experimental research and finite element theoretical analysis on torsion performance of 18 CFRP square section

concrete-filled steel tubular members. The results show that the steel tube and CFRP can work together, and the deformation of the component approximately conforms to the plane section assumption. Han LH et al. [8] deduced the axial force torque correlation equation of concrete filled steel tubular members, described the moment torque correlation equation, and analyzed the whole process of such specimens. Tao et al. found that square CFRP-CFST specimens' bearing capacity was reduced significantly after fire damage, while concrete-filled CFRP-steel tube specimens' fire resistance was better than that of ordinary concrete-filled steel tube specimens [9-10]. In practical application, members often also bear hysteretic loads, such as wind and earthquake load[10-11].

In view of this, 12 groups of square CFRP concrete-filled steel tubular specimens are designed in this paper. Referring to the hysteretic test of concrete-filled steel tubular, the failure mode, $P-\Delta$ curve, $M-\phi$ curve and $\Delta-\Delta'$ curve of each group of specimens are studied. The axial compression ratio and longitudinal CFRP reinforcement coefficient are taken as the influencing factors to study their influence on $P-\Delta$ skeleton curve and $M-\phi$ skeleton curve. ABAQUS is used to simulate the $P-\Delta$ curve and deformation mode of the specimens. On this basis, the influence of axial compression ratio, slenderness ratio and other main parameters on the hysteretic performance of the member is studied, so as to provide some theoretical reference for engineering

practice.

2 Raw material performance and experimental design

2.1 Performance of raw materials

(1) Steel

Cold-formed steel tubes were used for the S-CF-CFRP-ST specimens, in which the inner chamfer radius at the bending angle was 5mm. The steel tubes' material properties are shown in Table 1.

Table 1 The material properties of steel tube used in experiment

Section	f_y/MPa	f_u/MPa	E_s/GPa	$\varepsilon_{sy}/\mu\varepsilon$	ν_s	$\varepsilon' / \%$
Square	298	425	199	2502	0.28	27

(2) Concrete

Portland cement with a strength grade of 42.5 was used in the experiment. Medium coarse sand was used as fine aggregate. The particle size of the coarse aggregate gravel was 5~15mm, and a water reducer with 1% cement weight was added. The specific ratio of the concrete is shown in Table 2.

Table2 Specific ratio of concrete kg/m^3

Cement	Water	Fine Aggregate	Coarse Aggregate
--------	-------	----------------	------------------

490	171.5	661.5	1078
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After 28 days of standard curing, the concrete cube's compressive strength (f_{cu}) was 47.8MPa and the elastic modulus (E_c) was 34.6GPa. The cube's compressive strength was 77.7MPa during the hysteretic test.

(3) CFRP and viscose

Carbon fiber fabric is a unidirectional fabric woven with carbon fiber made in China. Its main properties are shown in Table 3.

The adhesive and base adhesive are building structural adhesives produced by China Institute of construction science and technology in the test.

Table 3 Basic Performance Parameters of CFRP

Thickness of single layer (mm)	Weight (g/m ³)	Elongation at break(%)	Tensile strength of monofilament (GPa)
0.111	200	2.1	4.9

2.2 Experimental design

A total of twelve S-CF-CFRP-ST specimens was designed, and their hysteretic behavior was tested. The main parameters included the axial compression ratio (n), and strengthening factor of longitudinal CFRP (η). n is defined by the following equation:

$$n = N_0 / N_{u, cr} \quad (1)$$

In which: N_0 is the axial compression applied to the specimens.

The specimens' calculated length (L) was 2000mm. The steel tube's outer length (B_s) was 140mm. The tube's wall thickness (t_s) was 4mm, and the number of transverse CFRP layers (m_t) was 1, where m_l was the number of longitudinal CFRP layers, and Δ_y was the specimens' displacement in the yield state. All specimens' specific parameters are shown in Table 4.

Table 4 The parameters of S-CF-CFRP-ST specimens with hysteretic behavior

Order	Number	n	m_l /layers	η	N_0 /KN	Δ_y /mm
1	A0	0	0	0	0	16.1
2	A1	0	1	0.17	0	14.1
3	A2	0	2	0.34	0	14.1
4	B0	0.2	0	0	263	10.1
5	B1	0.2	1	0.17	268	11.1
6	B2	0.2	2	0.34	273	14.1
7	C0	0.4	0	0	526	9.1
8	C1	0.4	1	0.17	536	9.1

9	C2	0.4	2	0.34	546	8.1
10	D0	0.6	0	0	789	5.1
11	D1	0.6	1	0.17	804	7.1
12	D2	0.6	2	0.34	819	8.1

CFRP's adhesion is extremely important to the experimental results. It is necessary to ensure that the steel tube is hooped by the longitudinal CFRP in the preparation process, so that it can maintain the cooperation with the steel tube. In addition, the longitudinal CFRP was hooped by transverse CFRP to avoid premature stripping of the longitudinal CFRP [12].

The experiment was carried out at the Structural Engineering Laboratory. The loading equipment in the experiment is shown in Fig. 1.

111

112 **Fig. 1** Loading equipment of hysteretic performance test of S-CF-CFRP-ST specimens

113 Before the experiment, the specimens were placed horizontally and hinged at both ends. The
114 axial loading (1250KN) was exerted by the actuator of Electro-hydraulic Servo-system that
115 was installed horizontally. At the same time, the cyclic loading (500KN) was exerted by the
116 actuator that was installed vertically in the midsection. The actuator was connected to the
117 specimens through a rigid fixture. To avoid the specimen's instability during loading, a set of
118 4-piece lateral support devices was designed, which were installed at two quarter points of the
119 specimen, respectively. The sliding plate was arranged on the side of the equipment, which
120 contacted the specimen to ensure its unimpeded vertical movement in the plane during the
121 loading process. The lateral support was connected rigidly with the ground anchor.

122 The method to control loading-displacement was used in the experiment [13]. In the initial
123 stage of the experiment, the loading was controlled and classified. The specimens were loaded
124 at $0.25P_{uc}$ (P_{uc} is defined as the estimated lateral bearing capacity), $0.5P_{uc}$, and $0.7P_{uc}$,
125 respectively, and each stage loading was circulated for 2 times. Thereafter, displacement
126 control and step loading were adopted, and the specimens were loaded with 1.0, 1.5, 2.0, 3.0,
127 5.0, 7.0, and $8.0\Delta y$. The loading of the first three levels was cycled 3 times, and that of the
128 other levels was cycled 2 times, where $\Delta y = P_{uc}/K_{0.7}$ and $K_{0.7}$ is the secant stiffness of the $P-\Delta$
129 skeleton curve at $0.7P_{uc}$. The criteria for termination of the experiment were set that P dropped

to 50% of the peak loading; the displacement ductility coefficient reached 8, and the displacement was close to the range of the actuator.

In the process of the test, P and Δ were collected directly by the INV-306D intelligent signal acquisition system, which was connected to the vertical actuator of Electro-hydraulic Servo-system, and the P - Δ curves were drawn at the same time. N_θ and Δ' were collected directly by the INV-306D intelligent signal acquisition system, which was connected to the horizontal actuator of Electro-hydraulic Servo-system. The deflection was measured at two quarter points close to the two supports. One transverse and one longitudinal strain gauge were pasted on the top and bottom outermost edges of the steel tube's midsection, respectively, and one transverse and one longitudinal strain gauge were also pasted on the top and bottom outermost edges of the CFRP's midsection to measure the strain.

3 Test results and analysis

3.1 Test phenomena

During the $1\Delta_y \sim 2\Delta_y$ period, some tiny cracks appeared between the transverse CFRPs in the longitudinal tensile zone near the midsection. With the increase in displacement, the cracks continued to expand from the upper and lower edges to the neutral axis, and some new cracks

also appeared. Thereafter, the axial compression ratio affected the experimental phenomenon greatly.

When the specimens with a small axial compression ratio ($n \leq 0.2$) were loaded to $3\Delta_y$, a slight deformation occurred in the compression area near the midsection. With unloading and reverse loading, the convex deformation flattened again, and the increases in the convex deformation were proportional to the increase in displacement. At this time, the transverse CFRP at the bending angle began to fracture sporadically. When they were loaded to $5\Delta_y$, the convex deformation developed significantly and the sound of the CFRP splitting could be heard. At this time, a large number of transverse CFRPs fractured at the bending angle, and then the longitudinal CFRPs also fractured, as shown in Fig. 2(a). When loaded to $7\Delta_y \sim 8\Delta_y$, a large number of them fractured, and finally, the steel tube was destroyed. In the specimens without longitudinal CFRP, when the deflection was large during the later stage of loading, a large number of transverse CFRPs fractured at the bending angle, and finally, the steel tube was destroyed swiftly, as shown in Fig. 2(b).

161 (a) Longitudinal CFRP of A1 (b) Transverse CFRP and steel tube of A0

162 **Figure 2.** Fracture of CFRP of specimens with a small axial compression ratio

163 When the specimens with a large axial compression ratio ($n \geq 0.4$) were loaded to $3\Delta_y$, a slight
164 deformation occurred in the compression zone near the midsection. When loaded to $5\Delta_y$, the
165 deformation developed significantly, and at this time, the transverse and longitudinal CFRP at
166 the bending angle fractured gradually, as shown in Fig. 3(a). When loaded to $7\Delta_y$, a large
167 number of transverse and longitudinal CFRP fractured at the bending angle with a continuous
168 crackling sound. When loaded to $8\Delta_y$, obvious convex deformation occurred in the tube's
169 midsection. The experimental results of specimens without longitudinal CFRP were the same
170 as those of specimens with a small axial compression ratio. When the deflection was large at
171 the end of loading, many transverse CFRP fractured at the bending angle, as shown in Fig.
172 3(b).

173

174 (a) C1 test results

(b) C0 test results

175 **Fig 3.** CFRP fracture and steel tube failure of specimens with a large axial compression ratio

Figs. 4(a) and 4(b) separately show the failure status of the steel tube and concrete in S-CF-CFRP-ST specimens with $n=0.2$, $n=0.6$. The figures show that as the axial compression ratio increased, the extent of the damage to the steel tube and concrete decreased. Because the concrete is confined by the CFRP and steel tube, the plastic filling showed good performance.

(a) The failure status of the steel tube and concrete in specimen with $n=0.2$

(b) The failure status of the steel tube and concrete in specimen with $n=0.6$

Figure 4. Failure of specimens with different axial compression ratio

In general, as the η and n increased, the extent of the specimen's damage decreased. Fig. 5 shows the hysteretic behavior of the S-CF-CFRP-ST specimens after loading.

Figure 5. Hysteretic behavior of the S-CF-CFRP-ST specimens after loading.

3.2 The curve of $P-\Delta$

3.2.1 The hysteresis curve of $P-\Delta$

Fig. 6 shows the S-CF-CFRP-ST specimens' $P-\Delta$ curves when $m_1=1$. It can be seen that the specimens' hysteretic curves were relatively full. During the initial stage of loading, the specimens were in the elastic stage, and the hysteretic curves changed linearly. After the yielding stage was reached, the residual deformation was inversely proportional to the stiffness. In the process of unloading to reverse loading, the stiffness did not change obviously. During the final stage of loading, the S-CF-CFRP-ST specimens' bearing capacity decreased gradually.

(a) $P-\Delta$ curve of A1

(b) $P-\Delta$ curve of B1

(c) $P-\Delta$ curve of C1

(d) $P-\Delta$ curve of D1

Figure 6. $P-\Delta$ curves of specimens with $m_1=1$

3.2.2 Skeleton curve of $P-\Delta$

Figs. 7 (a) and 7 (b), respectively, show the S-CF-CFRP-ST specimens' $P-\Delta$ skeleton curves, which are related to the axial compression ratio (n) and strengthening factor of longitudinal CFRP (η). It can be seen that as the n increased, both the specimens' stiffness in the elastic

stage and their lateral bearing capacity decreased, and the curves showed a descending section during the later stage of loading. As the η increased, the specimens' bearing capacity increased, while the stiffness remained unchanged in the elastic stage.

Figure 7. Effect of n and η on P - Δ skeleton curves

3.3 M - ϕ skeleton curve

Figure 8 shows the deflection curve shape of the most representative A2 specimen. In this paper, the curvature and bending moment of the middle section of the specimen are calculated by formula (2) and (3), respectively:

$$\phi = \pi^2 \frac{u_m}{L^2} \quad (2)$$

$$M = PL/4 + N_0 \square \quad (3)$$

213 where: ϕ is the curvature of the middle section, u_m is the deflection of the middle section, L is
 214 the calculated length of the specimen, M is the bending moment of the middle section, P is the
 215 lateral bearing capacity, and N_0 is the axial force.

Fig. 8 Deflection curve of A2 specimen

3.3.1 M - ϕ hysteresis curve

(a) M - ϕ curve of A0

(b) M - ϕ curve of B0

(c) $M-\phi$ curve of C0

(d) $M-\phi$ curve of D0

Fig. 9 $M-\phi$ curve of partial specimens

It can be seen from Fig.9 that the $M-\phi$ hysteretic curves of specimens are shuttle shaped, and there is no obvious pinch phenomenon. When the force control is adopted at the initial stage of loading, the deformation of the specimen is elastic deformation, When the displacement control is adopted, the component produces a less obvious "Bauhinia" effect.

3.3.2 $M-\phi$ skeleton curve

(a) $\eta=0.17$ specimens

(b) $n=0.2$ specimens

Fig. 10 Effect of axial compression ratio and longitudinal CFRP reinforcement coefficient on

$M-\phi$ skeleton curve of specimens

Fig. 10 shows the influence of axial compression ratio η and longitudinal CFRP reinforcement coefficient on the $M-\phi$ skeleton curve of specimens hysteretic behavior. It can be seen that the increase of axial compression ratio and longitudinal CFRP reinforcement coefficient

can improve the bending capacity of the specimens, and the change of axial compression ratio is more sensitive to the bending capacity of the specimens.

3.4 Deformation of axial direction

Figures 11 (a) ~ (d) show the lateral deflection axial deformation (Δ - Δ') curves of four groups specimens with different axial compression ratios. For A2 specimens without axial compression ratio, it can be found that Δ' increases with the increase of Δ at the initial stage of loading. Δ' decreases with the increase of Δ at the later stage of loading. For B2, C2 and D2 specimens with axial compression ratio, Δ' increases with the increase of Δ .

(a)axial deformation of A2 specimen

(b)axial deformation of B2 specimen

(c)axial deformation of C2 specimen

(d)axial deformation of D2 specimen

Fig. 11 Δ - Δ' curves of partially specimens

3.5 Strain relationship

3.5.1 Strain of steel tube and CFRP

In order to ensure the accuracy of the test results, the transverse strain curves (P - ε_t curves) of steel tube and CFRP at two test points of A1 group specimens are taken, as shown in Fig. 12 (a) and Fig. 12 (b). Similarly, the longitudinal strain curve (P - ε_l curve) at the same two test points of

group A2 are taken, as shown in Fig. 12 (c) and Fig. 12 (d). ε_{st} and ε_{cft} are the transverse strains of steel tube and CFRP. ε_{sl} and ε_{cfl} are the longitudinal strains of steel tube and CFRP. It can be seen from Figure 12 that the transverse and longitudinal strains of steel tube and CFRP are consistent, which indicates that under the action of hysteretic force, steel tube and CFRP can keep cooperation in both transverse and longitudinal directions.

(a) P- ε_t curve of A1 specimen at point 1

(b) P- ε_t curve of A1 specimen at point 2

(c) P- ε_l curve of A2 specimen at point 1

(d) P- ε_l curve of A2 specimen at point 2

Fig. 12 P- ε_t and P- ε_l curves of steel tube and CFRP at two test points

3.5.2 Comparison of transverse and longitudinal strain of steel tube

Fig. 13 is the comparison curve (P - ε_s curve) of transverse and longitudinal strain of steel tube.

It can be seen from Figure 13 that the longitudinal strain ε_{sl} and transverse strain ε_{st} of each group of specimens at the same point are different. When they are subjected to longitudinal tension, they

are subjected to transverse compression at the same time.

(a) P - ε_s curve of A2 specimen

(b) P - ε_s curve of D1 specimen

Fig.13 P - ε_s curves of partially specimens

4. Analysis of main indicators

4.1 Strength degradation

According to the method of reference[7], the strength degradation coefficient λ_{ji} is determined. Figure 14 shows the strength degradation of the specimen. It is obvious from Figure 15 that the strength degradation of the specimen is not obvious.

(a) $\eta=0$ specimens

(b) $\eta=0.157$ specimens

(c) $\eta=0.314$ specimens

Fig.14 Strength degradation of specimens

4.2 Stiffness degradation

262 The stiffness EI of each cycle was determined according to the method of reference [11]. Figs.
263 15 (a) and (b) show the effects of axial compression ratio and longitudinal CFRP reinforcement
264 coefficient on the stiffness degradation of specimens, respectively, where $EI_{\Delta=0}$ is the initial
265 stiffness of the specimens. It can be seen from Figure 15 that the increase of axial compression
266 ratio can delay the stiffness degradation of the specimen. In addition, the increase of longitudinal
267 CFRP reinforcement coefficient can delay the stiffness degradation of the specimen.

268 **Fig. 15** Effect of axial compression ratio and longitudinal CFRP reinforcement coefficient on
269 stiffness degradation of specimens

270 4.3 Displacement ductility factor

271 The ductility of the specimen is calculated by the following displacement ductility coefficient μ :

$$272 \mu = \frac{\Delta_u}{\Delta_y} \quad (4)$$

273 where, Δ_u is the corresponding displacement when the load on the skeleton line decreases by 15%.

The comparison of the ductility coefficient of each group of specimens is shown in Fig. 16. Since the load of $n = 0$ specimen does not drop to 85% of its peak bearing capacity at the end of the test, it is impossible to determine its ductility coefficient, which is taken as a larger value in comparison. It can be seen from Figure 16 that, in terms of the overall trend, the increase of axial compression ratio and longitudinal CFRP reinforcement coefficient will reduce the ductility of the specimen. The reason is that the larger the axial compression ratio and the longitudinal CFRP reinforcement coefficient, the more the failure mode of the specimen tends to the brittle failure mode of the concrete being crushed.

Fig. 16 Comparison of specimens' displacement ductility coefficient □

4.4 Cumulative energy consumption and energy dissipation

Fig. 17 (a) and Fig. 17 (b) respectively show the influence of axial compression ratio and longitudinal CFRP reinforcement coefficient on the cumulative energy dissipation E of specimens [14-15]. It can be seen that the increase of axial compression ratio will reduce the

288 energy dissipation capacity of the specimens, which is due to the poor ductility of the specimens
 289 with large axial compression ratio. The residual bearing capacity of the specimens with large axial
 290 compression ratio is lower than that of the specimens with small axial compression ratio. In
 291 addition, the increase of longitudinal CFRP reinforcement coefficient can improve the energy
 292 dissipation capacity of the specimens.

Fig. 17 Effect of axial compression ratio and longitudinal CFRP reinforcement coefficient on
 cumulative energy dissipation

293 According to the method of reference [14-15], the energy dissipation coefficient η is determined.
 294 Figure 18 shows the relationship between energy dissipation coefficient and displacement of
 295 $\eta=0.34$ specimen in the last cycle of each load level. It can be seen from the figure that when the
 296 specimen yields, the energy dissipation coefficient of the specimen with axial compression ratio is

greater than that of the specimen without axial compression ratio, which indicates that the axial compression ratio is beneficial to the seismic performance of the specimen within a certain range.

Fig.18 Effect of n on energy dissipation of specimens

5 Finite element simulation

5.1 Stress strain relationship of materials

In the process of using ABAUQS finite element modeling, steel tube adopts the mixed hardening model provided by ABAUQS software, and concrete adopts the plastic damage model provided by ABAUQS finite element software. Both of them adopt the stress-strain relationship provided by reference[16-21]. The parameters are determined as follows: the tensile plastic damage parameter b_t is 0.6~0.8, the compressive plastic damage parameter b_c is 0.6~0.8; the tensile stiffness recovery coefficient ω_t is 0, and the compressive stiffness recovery coefficient ω_c is 0.4~0.95 according to the different axial compression ratio.

5.2 Finite element calculation model

The element selection, mesh generation and interface model treatment method of specimens are consistent with those of CFST members. Figure 19 shows the boundary conditions for the finite element simulation of specimens.

Fig. 19 Boundary conditions for the specimens' finite element simulation

According to the symmetry of the geometry and boundary conditions of the component, the quarter model of the actual component is taken for analysis, and the symmetrical constraint conditions are imposed on the symmetry plane of the calculation model. The boundary condition is that the surface load is applied on the end plate and the lateral hysteretic force is applied on the middle section. In order to ensure that the loading mode is consistent with that in the test process, the loading-displacement control mode is adopted.

5.3 Comparison of finite element simulation and test results

Fig. 20 and Fig. 21 show the comparison between the simulation results and the test results of $P-\Delta$ curve and $P-\Delta$ skeleton curve of partially S-CF-CFRP-ST specimens, respectively. Fig. 22 (a)

and Fig. 22 (b) show the actual failure modes and the finite element simulation failure modes of the steel tube in the specimens, respectively. Fig. 23 (a) and Fig. 23 (b) show the failure modes of concrete in specimens and those of finite element simulation, respectively. It can be seen that the simulation results are in good agreement with the experimental results. The test results of each group are basically consistent with the finite element simulation results, which shows that the simulation results of the established model are in good agreement with the actual test results.

(a) A1 specimen

(b) B1 specimen

(c) C1 specimen

(d) D1 specimen

336

Fig. 20 Comparison of simulation results and experimental results of

337

P- Δ curves of partially specimens

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339

Fig. 21 Comparison of simulation results and experimental results of

340

P- Δ skeleton curves of partially specimens

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342

343

(a) Test result (b) FE result

Fig.22 Failure modes of steel tube with middle section

(a) Test result

(b) FE result

Fig.23 Failure modes of concrete with middle section

6 Parameter analysis

Axial compression ratio, slenderness ratio, number of CFRP layers, steel yield strength, concrete strength and steel ratio are the main indexes to evaluate the performance of S-CF-CFRP-ST specimens, which have significant influence on the skeleton curve of members with compression bending hysteretic behavior. Therefore, a typical example is used to analyze the influence of the above parameters on the $p-\Delta$ skeleton curve of members.

6.1 Influence of axial compression ratio n and slenderness ratio λ

Figure 24 shows the effect of axial compression ratio on the $P-\Delta$ skeleton curve of members. It can be seen that with the increase of n , the bearing capacity and the stiffness of the elastic stage of the member decrease significantly. The shape of the curve also has obvious changes: when $n=0$, there is no descending segment in the $P-\Delta$ skeleton curve. With the increase of n , the second-order effect of axial force is more obvious, and the descending segment appears in the curve, and the

amplitude of the descending segment increases. Effect of λ on P - Δ skeleton curve of specimens is

shown in Figure 25. It can be seen that the bearing capacity and the stiffness of the elastic stage of

the member decrease significantly with the increase of λ and the shape of the curve also has

obvious changes: the stability coefficient decreases with the increase of λ and the second-order

effect caused by the constant axial force is more obvious.

Fig.24 Effect of n on P - Δ skeleton curve of specimens

Fig.25 Effect of λ on P - Δ skeleton curve of specimens

6.2 Effect of CFRP layers

Figure 26 shows the effect of the number of longitudinal CFRP layers on the P - Δ skeleton

curve of members. It can be seen that with the increase of m_l , the shape of the skeleton curve and

the stiffness of the elastic stage are basically unchanged, and the bearing capacity of the member

is slightly improved. Figure 27 shows the effect of the number of transverse CFRP layers on the

P - Δ skeleton curve of members. It can be seen that with the increase of m_t , the shape of the

skeleton curve and the stiffness of the elastic stage have no obvious changes, and the bearing

capacity of the member increases slightly.

Fig.26 Effect of m_1 on P - Δ skeleton curve of

specimens

Fig.27 Effect of m_t on P - Δ skeleton curve of

specimens

6.3 Influence of steel yield strength and concrete strength

Figure 28 shows the effect of steel yield strength on the P - Δ skeleton curve of members. It

can be seen that with the increase of f_y , the shape of the skeleton curve and the stiffness of the

elastic stage are basically unchanged, and the bearing capacity of the component is improved.

Figure 29 shows the effect of concrete strength on the P - Δ skeleton curve of members. It can be

seen that with the increase of f_{cu} , the shape of skeleton curve and the stiffness of elastic stage are

basically unchanged, and the bearing capacity of members is slightly improved.

Fig.28 Effect of f_y on P - Δ skeleton curve of

Fig.29 Effect of f_{cu} on P - Δ skeleton curve of

7 Conclusion

(1) CFRP has a good lateral restraint and longitudinal strengthening effect on CFST, and the local buckling of steel tube is delayed. The $P-\Delta$ curve and $M-\phi$ curve of the specimen are full, showing good hysteretic behavior, and the deflection curve of the specimen is approximate to sine half wave curve, and the steel tube and CFRP can keep cooperation in both longitudinal and transverse directions.

(2) The increase of axial compression ratio and longitudinal CFRP reinforcement coefficient can improve the flexural capacity and stiffness of the specimens, and decrease the rate of stiffness degradation, but the ductility and cumulative energy consumption of the specimens were reduced. The axial compression ratio is beneficial to the seismic performance of the specimens in a certain range. During the loading process, the strength of each group of specimens has a certain degradation trend.

(3) ABAQUS can be used to simulate the load-deformation curves and deformation modes of members. The $P-\Delta$ hysteretic curves of members established by ABAQUS can be used to analyze the stress distribution of the components of members, and the simulation results are in good agreement with the experimental results.

(4) The results of parametric analysis show that the increase of steel yield strength and steel ratio can significantly improve the bearing capacity of members, and the increase of concrete strength and CFRP layers can only slightly improve the bearing capacity. With the increase of slenderness ratio or axial compression ratio, the bearing capacity and elastic stiffness of the members decrease significantly, while the shape of load-deformation curve also has obvious change.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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