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Eccentrically compressive behaviour of RC square short columns reinforced with a new composite method

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Abstract. A new composite reinforced method, namely self-compacting concrete filled circular CFRP-steel jacketing, was proposed in this paper. Experimental tests on eight RC square short columns reinforced with the new composite reinforced method and four RC square short columns reinforced with CFS jackets were conducted to investigate their eccentrically compressive behaviour. Nine reinforced columns were subjected to eccentrically compressive loading, while three reinforced columns were subjected to axial compressive loading as reference. The parameters investigated herein were the eccentricity of the compressive loading and the layer of CFRP. Subsequently, the failure mode, ultimate load, deformation and strain of these reinforced columns were discussed. Their failure modes included the excessive bending deformation, serious buckling of steel jackets, crush of concrete and fracture of CFRP. Moreover, these reinforced columns exhibited a ductile failure globally. Both the eccentricity of the compressive loading and the layer of CFRP had a significant effect on the eccentrically compressive behaviour of reinforced columns. Finally, formulae for the evaluation of the ultimate load of reinforced columns were proposed. The theoretical formulae based on the ultimate equilibrium theory provided an effective, acceptable and safe method for designers to calculate the ultimate load of reinforced columns under eccentrically compressive loading.

Keywords: new composite reinforced method; eccentrically compressive behaviour; experimental tests; theoretical formulae

1. Introduction

Due to the advantages of abundant raw material, good global behaviour, high economic efficiency, etc., reinforced concrete (RC) structures have been widely used in civil engineering buildings. As a basic load-bearing member, square short columns play an important role in the design of RC structures. However, due to the following reasons, the bearing capacity and ductility of existing RC square short columns may not satisfy design requirements. (1) The long-term exposure of RC structures to adverse environmental conditions could lead to durability problems, including the physical aging, concrete carbonation and corrosion of reinforcement bars. (2) The fault design, improper construction, additional loads, structural modification and change of using function could result in the insufficient bearing capacity of existing RC columns. (3) After the natural disasters of the earthquake, wind, fire, snow, etc., existing RC structures should be rehabilitated. (4) The improvement of design standards and safety reserves. The demolition and reconstruction of weak existing RC structures could cause enormous economic losses obviously. On the contrary, the reinforcement and rehabilitation of weak existing RC structures are the effective methods to meet the sustainable social and economic development. As a result, more and more attentions have been attracted to the development of the reinforced method of existing RC structures. Recently, three commonly used reinforced methods, involving the RC jacketing, fiber-reinforced polymer (FRP) jacketing and concrete filled steel (CFS) jacketing, have been developed.

The RC jacketing is a simple, cheap and effective method for the reinforcement and rehabilitation of existing RC columns. This method could implement by casting a RC jacket around existing columns. Therefore, their bearing capacity, stiffness and ductility could improve by means of the enlargement of the transverse cross section and the addition of the longitudinal and transverse reinforcement. Lots of researchers have studied the reinforcement effect of the RC jacketing method. Vandoros and Dritsos (2008) carried out an experimental study on the seismic performance of RC columns strengthened with three alternative methods of the concrete jacketing, and a significant strength and stiffness increase was observed. The bond strength between RC jackets and original RC columns could influence the reinforcement effect significantly. According to the experimental and theoretical study, Elbakry and Tarabia (2016) found that the surface roughness of the substrate concrete and the stirrup are the main factors affecting the bond strength. Dubey and Kumar (2016) adopted self-compacting concrete jackets to retrofit RC cylindrical columns and indicated that the axial load carrying capacity of the retrofitted confined columns improved, because the compressive strength of the confined

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concrete enhanced by the confinement effect. Minafo *et al*. (Minafo 2015, Minafo and Papia 2016, Minafo *et al*. 2016) studied the concrete softening effects on the axial capacity of RC jacketed circular columns and proposed a simplified analytical method to estimate the strength and ductility of RC jacketed columns.

FRP is widely used in the construction industry because of its high tensile strength, low weight, good durability and rapid construction. Reinforcing and rehabilitating RC columns by wrapping FRP has become a popular technique in civil engineering (Quiertant and Clement 2011). The FRP jacket could confine the transverse deformation of RC columns effectively, leading to the improvement of the ultimate compressive strength and ductility of existing RC columns. Wang *et al*. (2011) and Wu *et al*. (2011) conducted a systematic study on the compressive behaviour of high-strength concrete square columns reinforced with aramid FRP jackets and discussed the influence of the concrete strength, thickness of FRP jackets and form of FRP wrapping. They indicated that the strength and ductility of reinforced high strength concrete square columns can be enhanced by the confinement of external aramid FRP jackets. In real RC structures, the biaxial bending is always generated. Hence, Rahai and Akbarpour (2014) carried out an experimental investigation on rectangular RC columns strengthened with CFRP composites under axial load and biaxial bending. To investigate the different interface response of RC columns with different composite materials, Achillopoulou *et al*. (2016) studied transfer mechanisms from concrete elements to strengthening materials (carbon FRP, glass FRP, textile reinforced mortars and near surface mounted bars) through analytical models. The current study focuses on the seismic performance of RC columns reinforced with FRP jackets (Shin *et al*. 2016). Juntanalikit *et al*. (2016) and Wang *et al*. (2017) indicated that by means of CFRP jacketing, the ductility, energy dissipation capacity, shear strength and displacement capacity improved significantly.

Compared with traditional RC columns, CFS tube columns have a better mechanical behaviour, including strength, stiffness, ductility and seismic response (Huang *et al*. 2016, Hua *et al*. 2014). Based on CFS tube columns, the reinforced method of CFS jacketing for existing RC columns is developed. Moreover, the CFS jacketing has been one of the most common techniques adopted for the reinforcement and rehabilitation of existing members recently. Jiang *et al*. (2017) indicated that the primary merits of the CFS jacketing include an ease and rapidness of construction and an improvement of the impact property and load-bearing capacity of existing members. Sezen and Miller (2011) investigated the axial compressive behaviour of RC columns reinforced with RC jackets, FRP jackets and CFS jackets, respectively. The experimental results showed that the CFS jacketing is the most effective method to increase the axial strength and stiffness of RC columns. Considering the parameters of the recycled coarse aggregate replacement ratio, concrete strength, steel jacket thickness, preloading level and load eccentricity, He *et al*. (2016, 2017) studied the compressive behaviour of steel-jacket retrofitted RC columns systematically.

Although all the aforementioned reinforced methods could effectively increase the mechanical behaviour of RC columns, some shortcomings of each reinforced method need to be identified. For the RC jacketing, the stress and strain between original and new concretes are always discontinuous, leading to their poor cooperative work. Moreover, the reinforced method of the RC jacketing will create a larger size of RC columns, limiting the use space of structures. For the FRP jacketing, RC columns reinforced with FRP jackets always exhibit a brittle failure. In addition, the cost of CFRP is high, making it less competitive. For the CFS jacketing, when a structure requires a higher load-bearing capacity, the thicker steel tube should be adopted, improving the supply requirements and construction difficulty. Therefore, a new composite reinforced method, namely self-compacting concrete filled circular CFRP-steel jacketing, was proposed in this paper.

This paper is aimed to investigate the behaviour of RC square short columns reinforced with self-compacting concrete filled circular CFRP-steel jackets under eccentrically compressive loading. A detailed description of the new composite reinforced method was presented firstly. To study the reinforcement effect of this new composite reinforced method, an experimental program on twelve reinforced square short columns was conducted. The parameters of the eccentricity of the compressive loading and the layer of CFRP was considered. Moreover, the failure mode, ultimate load, deformation and strain were also discussed. In addition, to predict the ultimate load of reinforced columns, the theoretical formulae based on the ultimate equilibrium theory were proposed and estimated. The achievements of this paper could have an important theoretical meaning and were of great help to the application and development of this new composite reinforced method.

2. New composite reinforced method

The new composite reinforced method not only combines the advantages of the FRP and CFS jacketing methods, but also remedies their shortcomings. The construction of the new composite reinforced method for

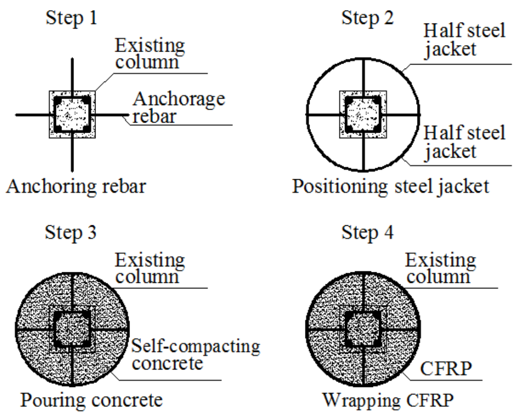


Fig. 1 Construction of the new composite reinforced method

existing RC columns could be divided into four steps, as shown in Fig. 1. Firstly, the anchorage rebar with 8 mm nominal diameter needs to be anchored at the positions which are 20 mm away from the top and bottom ends of existing columns. The dimensions of the anchorage rebar should match the size of existing columns and steel jackets. With the help of the anchorage rebar, on the one hand, existing columns could be placed at the center of steel jackets; on the other hand, the bond strength between original and new concretes improves. Subsequently, two half steel jackets manufactured in advance are positioned around existing columns. Two half steel jackets are assembled by weld. Due to the confinement effect of steel jackets, the core concrete is in triaxial compression stress state, leading to the improvement of the ultimate compressive strength. To connect existing columns and steel jackets tightly, the self-compacting concrete is poured into the gap between them. The curing period of the self-compacting concrete is 28 days. With the support of the self-compacting concrete, the stability of steel jackets enhances. Finally, CFRP is wrapped around steel jackets. In order to adhere CFRP to steel jackets tightly, the rust of steel jackets should be cleaned and the resin should be daubed uniformly onto the surface of steel jackets. With the help of CFRP jackets, the confinement effect could enhance and the thickness of steel jackets could reduce. The primary merits of existing RC columns reinforced with the new composite reinforced method include better mechanical behaviour of load-bearing capacity, ductility, durability, seismic response, impact property and ease and rapidness of construction. However, the study on the new composite reinforced method is limited, which greatly obstructs the development and application of this new composite reinforced method. Thereby, this paper presented a systematic investigation on the reinforcement effect of the new composite reinforced method.

3. Experimental program

An experimental program on the behaviour of RC square short columns reinforced with self-compacting concrete filled circular CFRP-steel jackets under eccentrically compressive loading was carried out. The main purposes of this experimental program were listed as follows:

(1) Assessing the reinforcement effect of this new composite reinforced method for existing RC square short columns under eccentrically compressive loading.
(2) Understanding the failure mode and mechanism of reinforced columns.
(3) Discussing the influence of the eccentricity of the compressive loading and the layer of CFRP on the behaviour of reinforced columns.

The achievements could provide the references for the practical engineering.

3.1 Specimens

A series of tests on twelve reinforced square short columns was performed. Eight columns were reinforced with the new composite reinforced method, while four columns were reinforced with CFS jackets as reference. All the existing square short columns had the same cross-section of 150 mm × 150 mm, and the same length of 800 mm. Considering the influence of the construction period and long-term environmental conditions, the concrete of C20 strength grade was selected for these existing square short columns. These existing square short columns had four longitudinal bars with 12 mm nominal diameter. The strength grade of longitudinal bars was HRB335 (the nominal yield strength is 335 MPa) and the concrete cover thickness of longitudinal bars was 20 mm. Stirrups with 6 mm nominal diameter and 150 mm spacing were adopted. The spacing of stirrups was 100 mm at the ends of existing square short columns. The thickness, diameter and length of steel jackets were 3 mm, 273 mm and 800 mm, respectively. Self-compacting concrete of C40 strength grade was adopted to fill the gap between existing columns and steel jackets. CFRP is wrapped around steel jackets and its overlapping length was 100 mm. Two key parameters were varied in the experimental program. The first parameter was the eccentricity e_0 of compressive loading. Four kinds of eccentricities of compressive loading, including e_0 = 0 mm, 20 mm, 40 mm and 60 mm, were applied to reinforced columns. The second parameter was the layer m of CFRP. Three kinds of layers of CFRP, including m = 0, 1 and 2, were bonded on reinforced columns. The dimensions and detailed information of reinforced columns are shown in Fig. 2 and Table 1. Concise symbols were assigned to these reinforced columns for an explicit understanding. "A" represents the CFS jacketing method; "B" represents the new composite reinforced method; "M" represents the layer of CFRP and "E" represents the eccentricity of the compressive loading.

3.2 Materials

Ordinary concrete of C20 strength grade and self-compacting concrete of C40 strength grade were selected as the material for the existing column and filled concrete, respectively. The mix proportions of these concretes are shown in Table 2. To obtain the mechanical properties of these concretes, six concrete cubes with the dimensions of

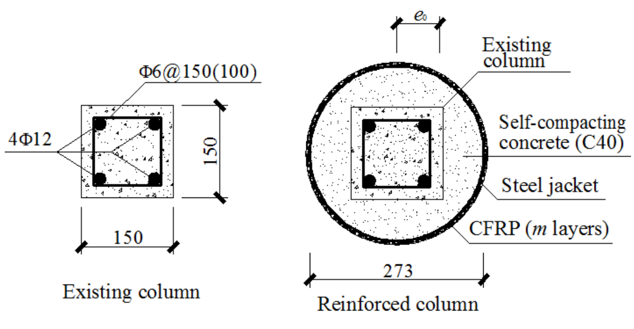


Fig. 2 Dimensions of reinforced columns

Table 1 Detailed information of reinforced columns

No.	e_0 / mm	m	N_u / kN	α	β	N_{uT} / kN	N_{uT} / N_u
A-M0-E0	0	0	2899		1.000	2703	0.932
A-M0-E20	20	0	2190		0.756	2054	0.938
A-M0-E40	40	0	1850		0.637	1692	0.915
A-M0-E60	60	0	1700		0.587	1442	0.848
B-M1-E0	0	1	3400	117.28%	1.000	3168	0.932
B-M1-E20	20	1	2550	116.44%	0.751	2421	0.949
B-M1-E40	40	1	2120	114.59%	0.623	1995	0.941
B-M1-E60	60	1	1980	116.47%	0.583	1699	0.858
B-M2-E0	0	2	4100	141.43%	1.000	3759	0.917
B-M2-E20	20	2	3040	138.81%	0.742	2887	0.950
B-M2-E40	40	2	2600	140.54%	0.636	2379	0.915
B-M2-E60	60	2	2350	138.23%	0.573	2027	0.862

Table 2 Mix proportions of concrete

Concrete	Cement	Fine aggregate	Coarse aggregate	Water	Water reducing agent	Bloating agent	Fly ash
C20	1.000	3.454	5.202	0.710	0.000	0.000	0.000
C40	1.000	2.205	1.928	0.472	0.004	0.139	0.250

Table 3 Material properties

Material	$f_{cu,0}$ / MPa	f_y / MPa	f_u / MPa	ε_u / $\times10^{-6}$	Material
C20 concrete	22.4	—	—	—	C20 concrete
C40 concrete	43	—	—	—	C40 concrete
HRB335 rebar	—	450	620	—	HRB335 rebar
Q235 steel	—	359	467	—	Q235 steel
CFW200	—	—	3012	1.28×10^5	CFW200

150 mm × 150 mm × 150 mm were designed. Three of them were constructed from C20 concrete, and the other three were constructed from C40 concrete. The curing period of these concrete cubes was 28 days. According to the requirements of Chinese standard of ordinary concrete (GB/T 50081-2002), compressive concrete cube tests were conducted. The measured compressive strength $f_{cu,0}$ of these concrete cubes is shown in Table 3.

Steel jackets were manufactured from Q235 steel (the nominal yield strength is 235 MPa), and longitudinal bars were manufactured from HRB335 rebar (the nominal yield strength is 335 MPa). Tensile coupons were cut directly and randomly from these steel jackets and longitudinal bars. In order to determine the mechanical properties of Q235 steel and HRB335 rebar, tensile coupon tests were conducted in accordance to the requirements of Chinese standard of metallic materials (GB/T 228-2002). The measured yield strength f_y and ultimate strength f_u of Q235 steel and HRB335 rebar are shown in Table 3.

The material model of CFRP was CFW200. The thickness of CFRP was 0.167 mm. Its tensile strength f_u and ultimate strain ε_u were tested based on the requirements of Chinese standard of orientation fiber reinforced polymer matrix composite materials (GB/T 3354-1999), as listed in Table 3.

3.3 Strain and displacement measurements

To measure the strain of steel jackets, longitudinal bars and CFRP jackets, the deformation of reinforced columns and the load, the strain gauge, the linear variable differential transducer (LVDT) and the force transducer were used, as shown in Fig. 3. These measuring points could be classified into five categories:

(1) The load was monitored by a force transducer between reinforced columns and a pressure device.
(2) For the out-of-bending plane of reinforced columns, two vertical LVDTs (D1 and D2) were located between the ends of reinforced columns to measure the longitudinal deformation. For the in-bending plane of reinforced columns, three horizontal LVDTs (D3 ~ D5) were located at the 1/4, 1/2 and 3/4 positions along the length of reinforced columns to measure the lateral deformation. According to the longitudinal and lateral deformation, the axial stiffness and bending stiffness of reinforced columns and the confinement effect of CFS jackets and CFRP jackets could be assessed.
(3) Four groups of hoop and longitudinal strain gauges (S1~S4) were placed at the middle of steel jackets to measure the strain distribution. The longitudinal strain gauges could be used to monitor eccentric

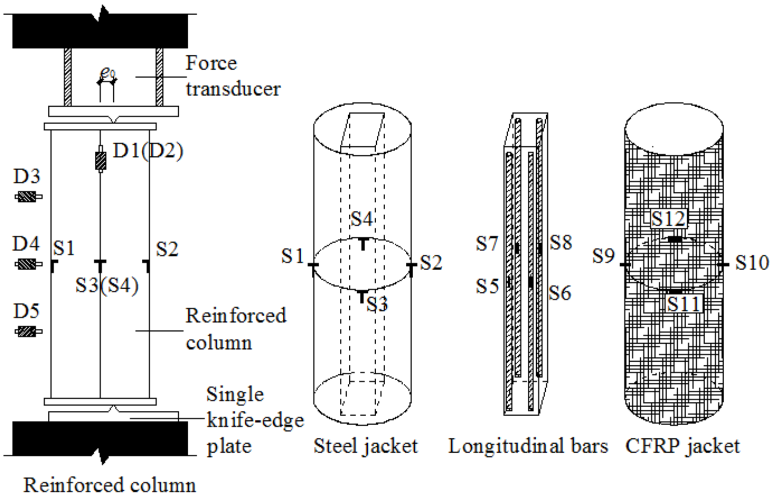


Fig. 3 Strain and displacement measurements

Fig. 4 Test device and procedure

action.

(4) Four longitudinal strain gauges (S5~S8) were placed at the middle of longitudinal bars. On the basis of the longitudinal strain of longitudinal bars, the stress state of existing columns could be estimated.

(5) Four hoop strain gauges (S9~S12) were placed at the middle of CFRP jackets to observe the hoop strain. The hoop strain could monitor the working state of CFRP jackets.

3.4 Test devices and procedure

A 5000kN pressure testing machine was adopted for the experimental study on behaviour of RC square short columns reinforced with self-compacting concrete filled circular CFRP-steel jackets under eccentrically compressive loading. All the reinforced columns were installed in the same test setup, as shown in Fig. 4. Two single knife-edge plates were placed at two ends of reinforced columns respectively to enable reinforced columns to rotate freely. Eccentrically compressive loading was applied through adjusting the position of two single knife-edge plates.

After the installation of each reinforced column and measuring equipment, the test equipment was checked by trial loading at 2~3 times. A preload which is 10%~20% of the ultimate load was performed to ensure that these reinforced columns and the test equipment were working properly and the eccentrically compressive loading was applied correctly. The ultimate load was estimated initially according to the code “Technical code for concrete filled steel tubular structures” (GB 50936-2014). As everything was examined, the tests were started. The increment of compressive loading was 1/15 of the ultimate load per minute when reinforced columns were in the elastic phase. For each loading level, the compressive loading needed to last 3 minutes to record the stable data. The test was conducted under force control at the beginning of the loading process. When the behaviour of reinforced columns was close to the ultimate state, the test control was changed to displacement control until the load reduced to about 80% of the ultimate load. At that time, a large deformation and failure of reinforced columns occurred. Hence, the test should be stopped.

4. Test phenomena and failure modes

The test phenomena of reinforced columns almost went through five phases. (1) At the beginning of the loading process, the deformation of reinforced columns was inconspicuous, signifying the elastic phase. (2) When the load increased to about 60% of the ultimate load, the fracture sound of CFRP and the crush sound of concretes occurred. (3) When the load increased to about 80% of the ultimate load, for reinforced columns under axial compressive loading, buckling occurred at the bottom of steel jackets and developed toward to their middle; for reinforced columns under eccentrically compressive loading, buckling occurred at the middle of steel jackets and CFRP fractured at the corresponding position. (4) When the load increased close to the ultimate load, for reinforced columns under axial compressive loading, the steel jacket buckled obviously and CFRP fractured at the buckled position; for reinforced columns under eccentrically compressive loading, great bending deformation appeared, CFRP fractured at the middle of reinforced columns in the compressive region. (5) When the load decreased to about

(a) A-M0-E0

(b) A-M0-E20

(c) A-M0-E40

(d) A-M0-E60

(e) B-M1-E0

(f) B-M1-E20

(g) B-M1-E40

(h) B-M1-E60

(i) B-M2-E0

(j) B-M2-E20

(k) B-M2-E40

(l) B-M2-E60

Fig. 5 Failure modes

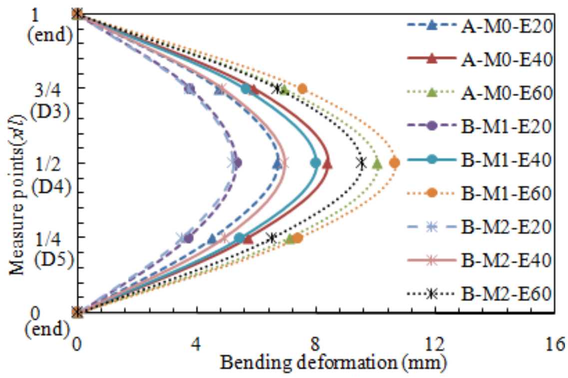


Fig. 6 Final bending deformation

85% of the ultimate load, for reinforced columns under axial compressive loading, the local buckling of steel jackets was seriously; for reinforced columns under eccentrically compressive loading, the bending deformation was excessive, accompanied with the serious buckling of steel jackets in the compressive region. At that time, the concrete crushed and CFRP fractured, meaning that reinforced columns could not sustain the load any more. It is found that these reinforced columns had a post bearing and deformation capacity after the ultimate load. Thereby,


Fig. 7 Crack of the concrete

these reinforced columns exhibited a ductile failure globally.

The failure modes and final bending deformation of reinforced columns are shown in Figs. 5 and 6, respectively. For reinforced columns under axial compressive loading, these reinforced columns exhibited the convex buckling failure at their middle. The buckling deformation of columns reinforced with CFS jackets was larger obviously than that reinforced with the new composite reinforced method. For reinforced columns under eccentrically compressive loading, great bending deformation appeared when reinforced columns failed. The shape of the bending

(a) Compressive region (b) Tensile region

Fig. 8 Fracture of CFRP

deformation was similar to the half wave of the sine curve. Moreover, the bending deformation increased with the increase of the eccentricity of the compressive loading or the decrease of the layer of CFRP. The main reason might be that CFRP jackets made a contribution to theconfinement effect, limiting the buckling of steel jackets and the deformation of reinforced columns. The crush of the concrete at the ends of reinforced columns is shown in Fig. 7. A crack ran through ordinary and self-compacting concretes, implying a good bond behaviour between them. CFRP fractured and dropped seriously in the compressive region, while CFRP connected well with steel jackets in the tensile region, as shown in Fig. 8.

5. Test results and discussion

The ultimate load, deformation and strain of reinforced columns were measured and discussed in this test.

5.1 Ultimate loads

The ultimate load N_u of reinforced columns obtained from the test is shown in Table 1 and Fig. 9. To discuss the influence of the parameters on the ultimate load of reinforced columns, the enhancement factor α for the CFRP effect and the reduction factor β for the eccentricity effect were defined, and they could be calculated by Eqs. (1) and (2), where $N_{u,new}$ represents the ultimate load of columns reinforced with the new composite reinforced method; $N_{u,CFS}$ represents the ultimate load of corresponding

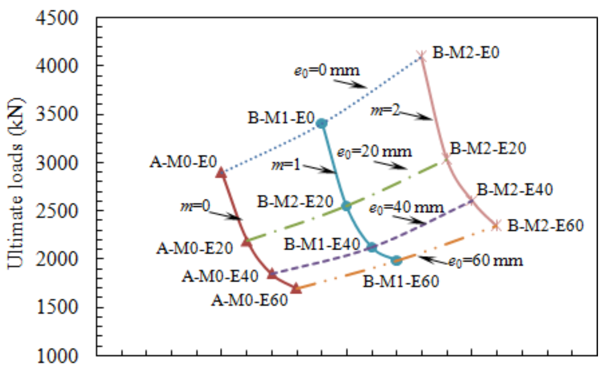


Fig. 9 Ultimate loads

columns reinforced with CFS jackets; $N_{u,ec}$ represents the ultimate load of reinforced columns under eccentrically compressive loading and $N_{u,ax}$ represents the ultimate load of reinforced columns under axial compressive loading. It is found that the ultimate load of reinforced columns was primary influenced by the eccentricity e_0 of compressive loading and the layer m of CFRP. (1) Regarding reinforced columns which only differed in the eccentricity e_0 of compressive loading, the ultimate load decreased significantly with the increase of the eccentricity e_0 of compressive loading. Moreover, their effects were similar. The ultimate load decreased by 25%, 37% and 42% averagely, when the eccentricity e_0 of compressive loading was 20 mm, 40 mm and 60 mm. (2) For reinforced columns which only differed in the layer m of CFRP, the ultimate load increased significantly with the increase of the layer m of CFRP. When m = 1, the ultimate load improved by 16.2% averagely; and when m = 2, the ultimate load improved by 39.8% averagely. Since the CFRP jackets enhanced the confinement effect evidently, the ultimate load of reinforced columns improved.

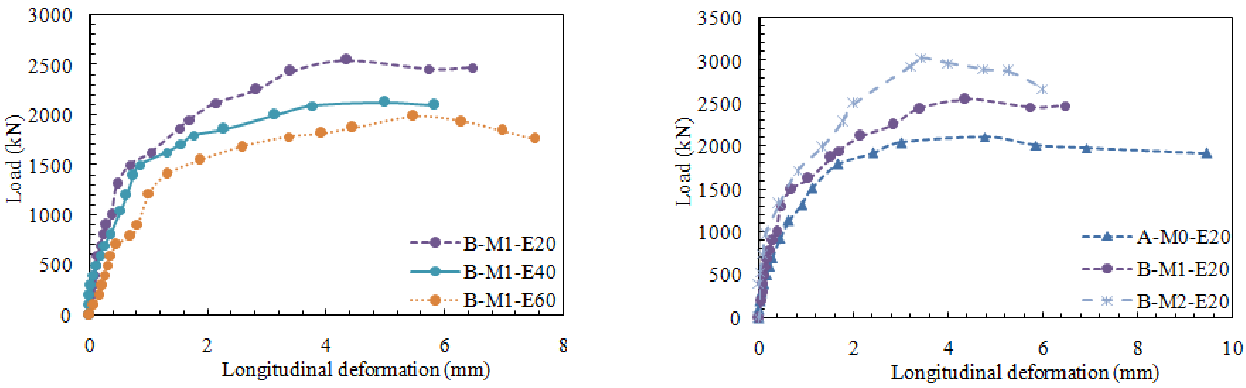
$$\alpha = \frac{N_{u,new}}{N_{u,CFS}} \times 100\% \tag{1}$$

$$\beta = \frac{N_{u,ec}}{N_{u,ax}} \times 100\% \tag{2}$$

5.2 Load-longitudinal deformation curves

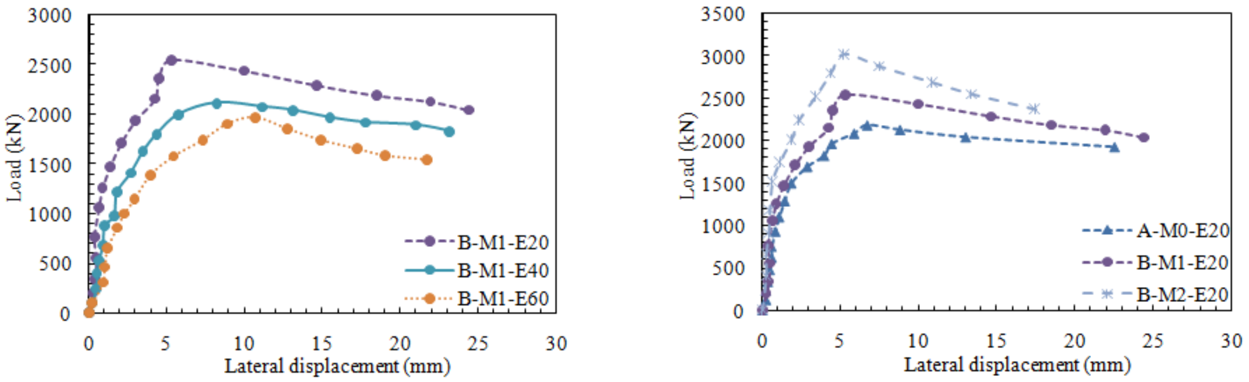
According to the longitudinal deformation measured by the LVDTs D1 and D2, the load-longitudinal deformation curves were obtained. The load-longitudinal deformation curves of all the reinforced columns were similar. Meanwhile, the influence of the eccentricity and the layer of CFRP on the load-longitudinal deformation curves was similar. Therefore, Fig. 10 plotted the load-longitudinal deformation curves of partial reinforced columns with the different eccentricities of the compressive loading and different layers of CFRP. Generally, during the loading process, these load-longitudinal deformation curves approximately went through three phases. At the beginning of the loading process, these curves ascended almost linearly initially, and the longitudinal deformation was very small. As the load increased continuously, the longitudinal deformation increased rapidly, followed by a non-linear behaviour. After the ultimate load, a slowly descending response could be observed, implying a good ductility and post-bearing capacity of reinforced columns. According to the comparison of these load-longitudinal deformation curves, it could be found that:

(1) The eccentricity of the compressive loading had a significant effect on the load-longitudinal deformation curve. As the eccentricity of the compressive loading increased, the bending moment increased, leading to the reduction of the compressive region and confinement effect of the CFRP-steel jacket. Hence, the axial stiffness of



(a) Influence of the eccentricity of the compressive loading (b) Influence of the layer of CFRP

Fig. 10 Load-longitudinal deformation curves



(a) Influence of the eccentricity of the compressive loading (b) Influence of the layer of CFRP

Fig. 11 Load-lateral displacement curves

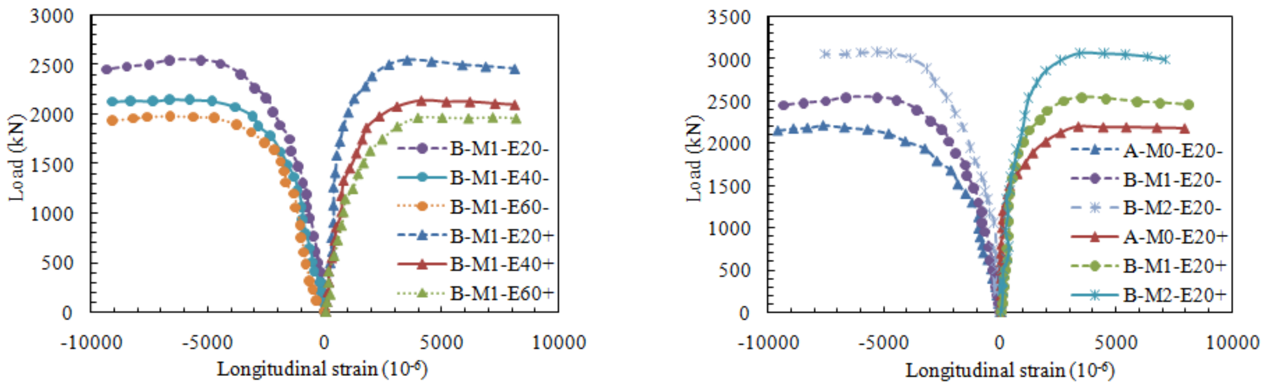
reinforced columns decreased and the longitudinal deformation increased. The longitudinal deformation at the ultimate load increased with the increase of the eccentricity of the compressive loading. After the ultimate load, the load-longitudinal deformation curve of reinforced columns with large eccentricity of compressive loading descended more rapidly than that with small eccentricity of compressive loading. This result implied that the increase of the eccentricity of the compressive loading could decrease the ductility of reinforced columns.

(2) The layer of CFRP influenced the load-longitudinal deformation curve greatly. As the layer of CFRP increased, the axial stiffness increased, accompanied with the decrease of the longitudinal deformation. The main reason might be that the increase of the layer of CFRP could enhance the confinement effect. When reinforced columns entered into the plastic phase, the longitudinal deformation decreased obviously with the increase of the layer of CFRP. It is signified that CFRP could limit the buckling of steel jackets, resulting in the decrease of the longitudinal deformation. After the ultimate load, the load-longitudinal deformation curve of reinforced columns with two layers of CFRP descended more rapidly than that with less layer of CFRP. This result implied that the increase of the layer of CFRP would decrease the ductility of reinforced columns. The main reason might be that the confinement effect reduced when CFRP fractured.

5.3 Load-lateral displacement curves

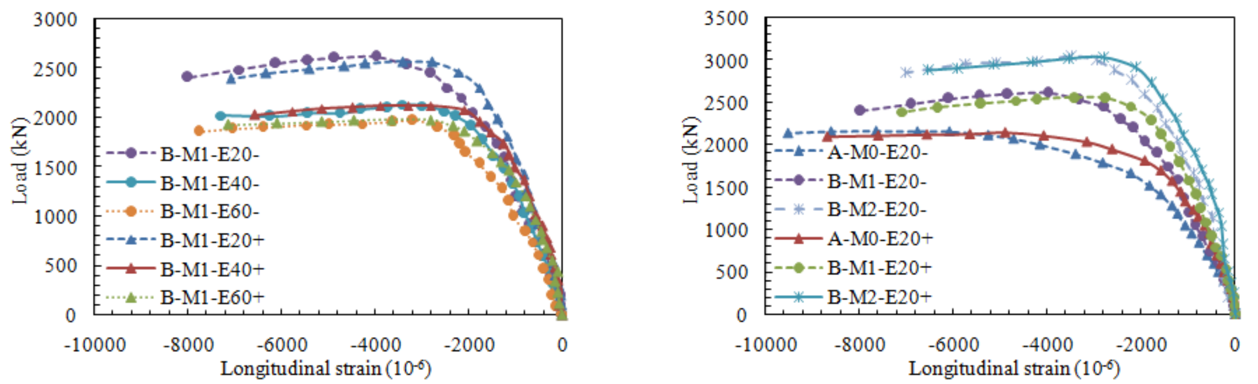
According to the lateral displacement measured by the LVDT D4, the load-lateral displacement curves at the middle of reinforced columns were obtained. The load-lateral displacement curves of all the reinforced columns were similar. Meanwhile, the influence of the eccentricity and the layer of CFRP on the load-lateral displacement curves was similar. Hence, the load-lateral displacement curves of partial reinforced columns with the different eccentricities of the compressive loading and different layers of CFRP are shown in Fig. 11. During the loading process, the characteristics of the load-lateral displacement curve were similar to that of the load-longitudinal deformation curve. However, the lateral displacement was much greater than the longitudinal deformation.

(1) For the influence of the eccentricity of the compressive loading, since the bending stiffness of reinforced columns was almost the same, their lateral displacement was mainly influenced by the



(a) Influence of the eccentricity of the compressive loading (b) Influence of the layer of CFRP

Fig. 12 Load-longitudinal strain curves of steel jackets



(a) Influence of the eccentricity of the compressive loading (b) Influence of the layer of CFRP

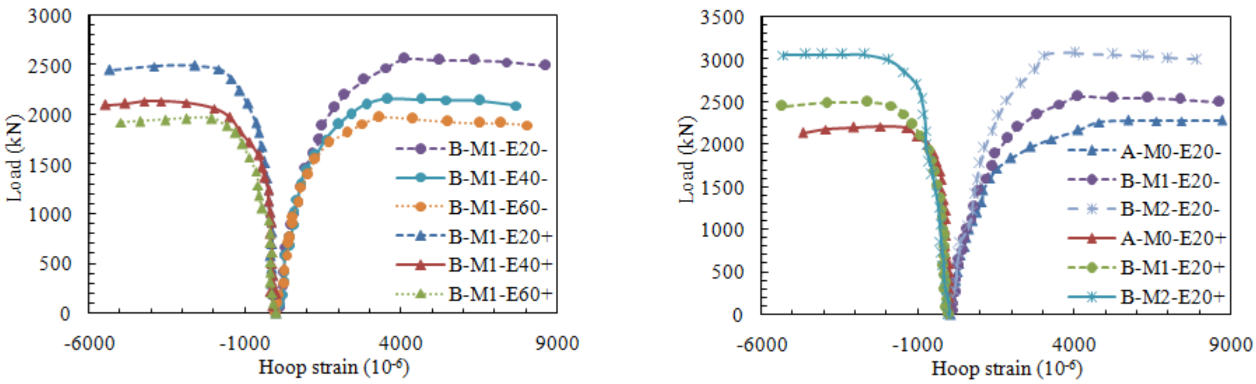
Fig. 13 Load-longitudinal strain curves of longitudinal bars

bending moment. Therefore, the lateral displacement of reinforced columns with 60 mm eccentricity of compressive loading deformed more rapidly than others.

(2) For the influence of the layer of CFRP, at the beginning of the loading process, their load-lateral displacement curves were very close. It is signified that the influence of the layer of CFRP on the initial bending stiffness of reinforced columns was slight. When reinforced columns entered into the plastic phase, CFRP improved the bending stiffness of reinforced columns obviously, resulting in that the lateral displacement decreased with the increase of the layer of CFRP. After the ultimate load, the load-lateral displacement curve of reinforced columns with two layers of CFRP descended more rapidly than that with less layer of CFRP.

5.4 Load-longitudinal strain curves

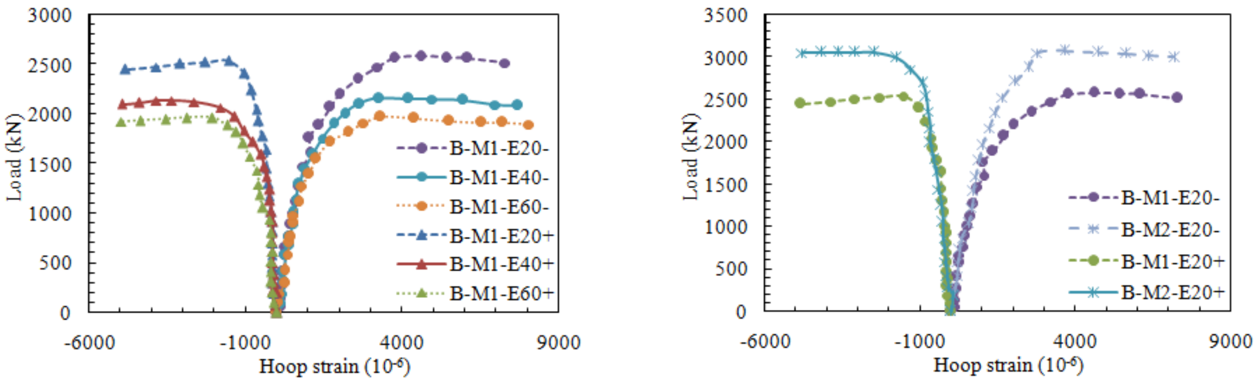
The influence of the eccentricity and the layer of CFRP on the load-longitudinal strain curves of steel jackets and longitudinal bars was similar. Thereby, the load-longitudinal strain curves of steel jackets and longitudinal bars of partial reinforced columns with the different eccentricities of the compressive loading and different layers of CFRP are shown in Figs. 12 and 13, respectively, where "-" represents the direction of the eccentricity of the compressive loading and "+" represents the opposite direction of the eccentricity of the compressive loading. During the test, steel jackets were subjected to longitudinal compressive stress on "-" side and longitudinal tensile stress on "+" side. Due to the eccentricity effect, the compressive strain was larger than the tensile strain (Fig. 12). The strain of all the longitudinal bars revealed a compressive response and the "-" strain was larger than the "+" strain, implying that all the longitudinal bars were subjected to compressive stress (Fig. 13). At the beginning of the loading process, the load-longitudinal strain curves exhibited an elastic behaviour. As the load increased, the strain performed a significant non-linear behaviour, meaning that steel jackets and longitudinal bars entered into plastic phase. Finally, the load-longitudinal strain curves became flatter and flatter, signifying the buckling of steel jackets and the yield of longitudinal bars. It could be concluded that (1) the longitudinal strain of steel jackets and longitudinal bars increased with the increase of the eccentricity of the compressive loading (Figs. 12(a) and 13(a)); (2) as the layer of CFRP increased, the longitudinal strain of steel jackets and longitudinal bars decreased (Figs. 12(b) and 13(b)). Hence, the confinement effect of CFRP jackets could improve the stiffness of reinforced columns and delay the buckling of steel jackets.



(a) Influence of the eccentricity of the compressive loading

(b) Influence of the layer of CFRP

Fig. 14 Load-hoop strain curves of steel jackets



(a) Influence of the eccentricity of the compressive loading

(b) Influence of the layer of CFRP

Fig. 15 Load-hoop strain curves of CFRP jackets

5.5 Load-hoop strain curves

The influence of the eccentricity and the layer of CFRP on the load-hoop strain curves of steel jackets and CFRP was similar. Hence, the load-hoop strain curves of steel jackets and CFRP jackets of partial reinforced columns with the different eccentricities of the compressive loading and different layers of CFRP are shown in Figs. 12 and 13, respectively. During the test, the hoop strain on the compressive side of steel jackets and CFRP jackets performed tensile behaviour, implying the confinement effect. Due to the longitudinal tensile deformation on the tensile side of steel jackets and CFRP jackets, their hoop strain exhibited compressive behaviour. At the beginning of the loading process, these load-hoop strain curves were very close. As the load increased, these curves began to separate. The hoop strain of steel jackets and CFRP jackets increased with the increase of the eccentricity of the compressive loading (Figs. 14(a) and 15(a)) or the decrease of the layer of CFRP (Figs. 14(b) and 15(b)). The hoop strain of steel jackets almost coincided with that of CFRP jackets, signifying a good collaborative work between steel jackets and CFRP jackets.

6. Formulae for the evaluation of the ultimate load of reinforced columns

6.1 Basic assumptions and constitutive relationships

Before theoretical derivations, four basic assumptions and corresponding constitutive relationships of components were made as follows:

(1) According to the experimental results, the bond behaviour between ordinary and self-compacting concretes was very good. Therefore, it could be assumed that the core concrete was loaded corporately and globally. Meanwhile, the bond slip and tensile stress of the core concrete were ignored. Gu *et al*. (2011) proposed the stress-strain model of the confined concrete under axial compressive loading. For the reinforced specimens under eccentrically compressive loading, due to the influence of the eccentricity e_0, the longitudinal and hoop stress presented a gradient distribution along the cross section. As a result, the confinement effect of the core concrete was weakened. Hence, a correction factor k_e was applied to the confinement effect factor ξ of the stress-strain model proposed by Gu *et al*. (2011). The correction confinement effect factor ξ' could be calculated by Eqs. (3) and (4), where, r_c is the radius of the core concrete.

$$\xi' = k_e \xi \tag{3}$$

$$k_e = \begin{cases} 1 - e_0 / r_c & (e_0 / r_c \le 1.0) \\ 0 & (e_0 / r_c > 1.0) \end{cases} \tag{4}$$

(2) Since the spacing of stirrups of existing RC columns was relatively large, the confinement effect of stirrups was ignored. In addition, longitudinal bars were in axial stress state. According to the Code for design of concrete structures (GB 50010-2015), the stress-strain relationship of longitudinal bars could be obtained. It went through four phases, including the elastic phase, the first perfect plastic phase, the strengthening phase and the second perfect plastic phase.

(3) The steel jacket was very thin. Hence, the hoop stress was uniform along its thin wall. Meanwhile, the radial stress could be ignored. As a result, the steel jacket could be simulated through the plane state with biaxial stress. The stress-strain relationship of steel jackets was similar to that of longitudinal bars. But the stress-strain relationship of steel jackets went through five phases, including the elastic phase, the elasto-plastic phase, the first perfect plastic phase, the strengthening phase and the second perfect plastic phase (Gu *et al*. 2011).

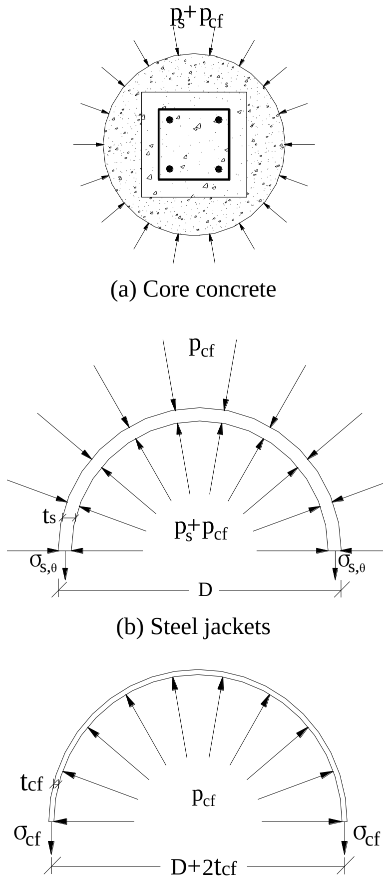
(4) The material property of CFRP was elastic. It only resisted the tensile stress along the fiber direction. When CFRP fractured, it lost the confinement effect immediately. Additionally, the bond slip between steel jackets and CFRP jackets was ignored.

6.1 Theoretical formulae based on the ultimate equilibrium theory

To simplify the formulae of the ultimate load of reinforced columns under eccentrically compressive loading, the theoretical formulae based on the ultimate equilibrium theory were proposed. The ultimate load of reinforced columns under axial compressive loading N_0 was developed firstly. Then, according to the experimental data, the reduction factor φ_e of the eccentricity of the compressive loading could be obtained through the statistical technology. Finally, the ultimate load of reinforced columns under eccentrically compressive loading N_{uT} was obtained.

The loading state of components is shown in Fig. 16, where p_s represents the tighten force of steel jackets, t_s the thickness of steel jackets, $\sigma_{s,\theta}$ the hoop stress of steel jackets, D the diameter of steel jackets, p_{cf} represents the tighten force of CFRP, t_{cf} represents the thickness of CFRP and σ_{cf} the hoop stress of CFRP. According to the static equilibrium condition, the tighten force of steel jackets and CFRP could be expressed by Eqs. (5) and (6).

$$p_s = \frac{2t_s}{D - 2t_s} \sigma_{s,\theta} \tag{5}$$



(a) Core concrete

(b) Steel jackets

(c) CFRP

Fig. 16 Loading state of components

$$p_{cf} = \frac{2t_{cf}}{D} \sigma_{cf} \tag{6}$$

It is assumed that the compressive strength of the confined concrete increased linearly with the increase of the tighten force. Hence, based on the Mohr-Coulomb failure criterion, the compressive strength f_{ck}' of the confined concrete could be calculated by Eq. (7), where f_{ck} is the compressive strength of the unconfined concrete and k represents the constant, which could be obtained through the experimental data.

$$f'_{\mathrm{ck}} = f_{\mathrm{ck}} + k(p_s + p_{cf}) \tag{7}$$

Steel jackets obeyed the Von-Mises failure criterion, as shown in Eq. (8), where $\sigma_{s,\mathrm{l}}$ represents the longitudinal stress of steel jackets and f_y is the yield strength of steel jackets.

$$[\sigma_{s,l}^2 + \sigma_{s,\theta}^2 - \sigma_{s,l}\sigma_{s,\theta}]^{1/2} = f_y \tag{8}$$

Combining Eq. (8) with Eq. (5), the value of the $\sigma_{s,\mathrm{l}}$ could be expressed in Eq. (9). In Eq. (9), the $\sigma_{s,\mathrm{l}}$ is the compressive stress.

When it reached to the ultimate load of reinforced columns under axial compressive loading N_0, longitudinal bars yielded. Therefore, the N_0 could be expressed in Eq. (10), where A_s, A_c and A_{s1} represent the cross section area of the steel jacket, core concrete and longitudinal bars, respectively and f_{y1} represents the yield strength of longitudinal bars.

$$\sigma_{s,l} = \sqrt{f_y^2 - 3(D-2t_s)^2 p_s^2 / 16t_s^2} - (D-2t_s)p_s / 4t_s \quad (9)$$

$$\begin{aligned} N_0 &= \sigma_{s,l} A_s + f_{ck}^{'} A_c + f_{y1} A_{s1} \\ &= A_s[\sqrt{f_y^2 - \frac{3(D-2t_s)^2 p_s^2}{16t_s^2}} - \frac{(D-2t_s)p_s}{4t_s}] \\ &\quad + A_c[f_{\text{ck}} + k(p_s + p_{cf})] + A_{s1} f_{y1} \end{aligned} \quad (10)$$

Because $D >> t_s$, the confinement effect factor of steel jackets ξ_s and the confinement effect factor of CFRP ξ_{cf} could be defined by Eqs. (11) and (12), where A_{cf} and f_{cf} represent the cross section area and tensile strength of CFRP, respectively. Meanwhile, Eq. (10) could be simplified in Eq. (13).

Combining Eq. (13) with Eqs. (11) and (12), the N_0 could be expressed in Eq. (14).

$$\xi_s = \frac{A_s f_y}{A_c f_{ck}} \approx \frac{\pi D t_s f_y}{\pi(D-2t_s)^2 f_{ck}/4} \approx \frac{4t_s f_y}{Df_{ck}} \quad (11)$$

$$\xi_{cf} = \frac{A_{cf} f_{cf}}{A_c f_{ck}} = \frac{\pi(D+2t_{cf})t_{cf} f_{cf}}{\pi(D-2t_s)^2 f_{ck}/4} \approx \frac{4t_{cf} f_{cf}}{Df_{ck}} \quad (12)$$

$$\xi_{cf} = \frac{A_{cf} f_{cf}}{A_c f_{ck}} = \frac{\pi(D+2t_{cf})t_{cf} f_{cf}}{\pi(D-2t_s)^2 f_{ck}/4} \approx \frac{4t_{cf} f_{cf}}{Df_{ck}} \quad (13)$$

$$\begin{aligned} N_0 &= A_s f_y (\sqrt{1 - \frac{3p_s^2}{\xi_s^2 f_{ck}^2}} - \frac{p_s}{\xi_s f_{ck}}) \\ &\quad + A_c f_{\text{ck}}(1 + k\frac{p_s}{f_{ck}} + k\frac{\xi_{cf}}{\xi_s}\frac{p_s}{f_{ck}}) + A_{s1} f_{y1} \\ &= A_c f_{\text{ck}} \left[1 + (k-1+k\frac{\xi_{cf}}{\xi_s})(\frac{p_s}{f_{ck}}) \right. \\ &\quad \left. + \sqrt{\xi_s^2 - 3(\frac{p_s}{f_{ck}})^2} \right] + A_{s1} f_{y1} \end{aligned} \quad (14)$$

It is observed that when $dN_0 / dp_s = 0$, the N_0 reached to the ultimate value. At that time, the p_s could be expressed in Eq. (15).

$$p_s = \frac{(k-1+k\frac{\xi_{cf}}{\xi_s})\xi_s f_{ck}}{\sqrt{36 + 3(k-1+k\frac{\xi_{cf}}{\xi_s})^2}} \quad (15)$$

Combining Eq. (14) with Eq. (15), the N_0 could be expressed in Eq. (16).

The reduction factor φ_e of the eccentricity of the compressive loading is presented in Eq. (17), where c represents the modified parameter. Finally, the ultimate load of reinforced columns under eccentrically compressive loading N_{uT} could be calculated by Eq. (18). Based on the experimental data, it is determined by the statistical regression technology that $k = 3.5$ and $c = 1.794$.

$$N_0 = A_c f_{ck} \left[1 + \frac{(k^2 - 2k + 7)\xi_s + (2k^2 - 2k + k^2 \frac{\xi_{cf}}{\xi_s})\xi_{cf}}{\sqrt{36 + 3(k-1+k\frac{\xi_{cf}}{\xi_s})^2}} \right] + A_{s1} f_{y1} \quad (16)$$

$$\varphi_e = \frac{1}{1 + c\frac{e_0}{r_c}} \quad (17)$$

$$N_{uT} = \varphi_e N_0 \quad (18)$$

The theoretical formulae were derived through the equilibrium condition when reinforced columns were in the ultimate state. Therefore, the theoretical formulae were simple and effective. They were more suitable for the application of the practical engineering program. The theoretical and experimental results on the ultimate load of reinforced columns are listed in Table 1. N_{uT} was the ultimate load obtained from the theoretical formulae based on the ultimate equilibrium theory. It is found that the ultimate loads N_{uT} were smaller than the experimental one N_u. The average ratio N_{uT}/N_u was 0.913 with the standard deviation of 0.039. These deviations were acceptable and safe in the practical engineering program. Therefore, the theoretical formulae based on the ultimate equilibrium theory provided an effective method for designers to calculate the ultimate load of reinforced columns under eccentrically compressive loading.

7. Conclusions

A new composite reinforced method, namely self-compacting concrete filled circular CFRP-steel jacketing, was proposed. The behaviour of RC square short columns reinforced with the new composite reinforced method under eccentrically compressive loading was investigated. The main conclusions were summarized as follows:

(1) The main failure modes of reinforced columns included the excessive bending deformation, serious buckling of steel jackets, crush of concrete and fracture of CFRP. For reinforced columns under axial compressive loading, the buckling occurred at the middle of steel jackets. For reinforced columns under eccentrically compressive loading, the bending deformation was similar to the half wave of the sine curve,

meanwhile the buckling of steel jackets and fracture of CFRP occurred in the compressive region. Reinforced columns had a post bearing and deformation capacity after the ultimate load, signifying that RC columns reinforced with the new composite reinforced method exhibited a ductile failure globally.

(2) The eccentricity of the compressive loading had a significant effect on the behaviour of reinforced columns. As the eccentricity of the compressive loading increased, the axial stiffness reduced, the deformation and hoop strain increased and the ductility decreased. Compared with reinforced columns under axial compressive loading, the ultimate load decreased by 25%, 37% and 42% averagely, when the eccentricity of the compressive loading was 20 mm, 40 mm and 60 mm.

(3) Since CFRP jackets could enhance the confinement effect, it could influence the behaviour of reinforced columns greatly. The axial stiffness and bending stiffness increased with the increase of the layer of CFRP, while the deformation, hoop strain and ductility decreased with the increase of the layer of CFRP. When the layer of CFRP increased from 0 to 1, the ultimate load improved by 16.2% averagely; when the layer of CFRP increased from 0 to 2, the ultimate load improved by 39.8% averagely. Thereby, the reinforcement effect of this new composite reinforced method was better than the reinforced method with CFS jackets.

(4) The theoretical formulae were calibrated with the experimental results. The theoretical formulae based on the ultimate equilibrium theory provided an effective, acceptable and safe method for designers to calculate the ultimate load of reinforced columns under eccentrically compressive loading.

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