EXPERIMENTAL STUDY ON BEHAVIOUR OF RETROFITTED SQUARE HOLLOW SECTION SLENDER COLUMNS UNDER AXIAL COMPRESSION

Haiying Wan, Jia Zhu and Ran Feng*
School of Civil Engineering, Hefei University of Technology, 193 Tunxi Road, Hefei, Anhui, China (230009).
*Email: r.feng@hfut.edu.cn

ABSTRACT

An experimental investigation was conducted in this study on axially loaded square hollow section (SHS) slender columns retrofitted by carbon fiber reinforced polymer (CFRP). A total of seven specimens with identical cross section dimensions and raw material properties were compressed between pinned ends to identify the influence of the CFRP, in which six specimens were retrofitted by the CFRP. The effects of many influential factors including different layers of the CFRP, retrofitting directions of the CFRP and retrofitting sequences of the CFRP on the behaviour of the CFRP strengthened SHS slender columns were carefully evaluated. The column strengths obtained from the experimental investigation are compared with the design strengths calculated using the design equations given in the British Standard (CIRIA) and the equations modified based on the section conversion method proposed by Canadian Standard (CAN/CSA-S16-01). It is shown from the comparison that the ultimate strengths of the SHS slender columns were enhanced by retrofitting with the CFRP. The retrofitting directions of the CFRP in the longitudinal directions were found to have a great influence on the ultimate strengths of the CFRP strengthened SHS slender columns. Furthermore, a correction factor (β_c) is proposed in this paper for the stability of the CFRP retrofitted SHS slender columns under axial compression.

KEYWORDS

Carbon fiber reinforced polymer (CFRP), square hollow section (SHS), retrofitted slender column, axial compression, section conversion method.

INTRODUCTION

Steel construction has been widely manufactured with the universalized conventional material. Steel can be applied to various fields of construction, such as civil engineering, petrochemical industry and many other relevant fields. However, the steel structures inevitably have some imperfections and damages to some extent. In order to ensure a good environment for steel structures and prevent them from failure, an alternate approach needs to be urgently proposed to upgrade and repair steel structures (Yue *et al*. 2009). The carbon fiber reinforced polymer (CFRP) was developed as a good choice. The CFRP is a composite material mixed by high-performance carbon fiber with a certain percentage resin and other materials using the processing technology. Compared with the traditional retrofitting methods, such as bolting or welding steel plates to the damaged components, the CFRP has many advantages including light weight, high strength-to-weight ratio and excellent resistances to fatigue and corrosion (Li 2011). The CFRP has a broad application in the retrofitting fields.

CFRP sheets have been successfully demonstrated on concrete structures (Ma 2011). However, there is quite limited research on retrofitting steel structures using CFRP sheets. Most of scholars in this field focused on slender and stub tubular columns strengthened by composite fibers (Shatt and Fam 2006; Bambach 2009; Gao 2013), and different shapes of cross section including square hollow section (SHS) and circular hollow section (CHS) (Haedir and Zhao 2011; Sundarraja *et al*. 2014). It was found that the longitudinal CFRP layers provided better confinement for slender specimens, whereas the transverse direction perpendicular to the longitudinal fibers was the optimum for stub tubular columns (Shatt and Fam 2006). For CHS tubular columns, it was found that the relationship between the number of layers and the ultimate capacity was proportional (Gao 2013).

Whilst there are some researches about elucidating the efficacy of applying CFRP sheets to compression columns, limited study on full-scale experiment on tubular specimens under axial loading has been examined. The efficient theoretical system has also been in an immature state. Therefore, the investigation on axially compressed full-scale columns strengthened by CFRP can satisfy the current design requirement.

In order to provide theoretical support for the upgrade of Chinese Code for Reinforcement Design of Steel Structures, an experimental program has been carried out to investigate the reinforcement effect of CFRP sheets of two different fiber orientations, with two or four CFRP layers. The influential factors include the number of

CFRP layers (two and four layers), the fiber orientation (transverse and longitudinal), and the arrangement of CFRP (transverse fiber only, longitudinal fiber only, and transverse fiber followed by longitudinal one). Accordingly, the maximum enhancement can be gained by comparing different types of strengthening. Based on the British Standard (CIRIA) (Cadei *et al*. 2004) and Canadian Standard (CAN/CSA-S16-01), this study is intended to integrate test values with equations in relevant design codes, and modify the theoretical equations used for ultimate loads of components retrofitted by CFRP under axial compression.

EXPERIMENTAL PROGRAM

Theoretical Foundation

The section conversion method in British Standard (CIRIA) and Canadian Standard (CAN/CSA-S16-01) is applied to calculate the cross-sectional area of specimens strengthened by CFRP under axial compression. The cross-sectional area and the moment of inertia for the steel section have been replaced by converted sectional area and moment of inertia, respectively. The equations of converted section are given as follows:

$$A_t = A_s + \sum_{i=1}^{N}\left(\frac{E_{f_i}}{E_s}A_{f_i}\right) \quad (1)$$

$$I_t = I_s + \sum_{i=1}^{N}\left(\frac{E_{f_i}}{E_s}I_{f_i}\right) \quad (2)$$

where A_t and I_t are the converted cross-sectional area and moment of inertia, respectively; A_s, I_s and E_s are the cross-sectional area, moment of inertia, and Young's modulus of the steel section, respectively; A_{fi} and I_{fi} are the cross-sectional area and moment of inertia of the *i*th CFRP layer, respectively; E_{fi} is the effective Young's modulus in the longitudinal direction of the column for the *i*th CFRP layer; N is the number of CFRP layers.

Then the slenderness ratio of composite specimens based on the modified cross section is given by Eq. 3:

$$\lambda_c = \frac{L_0}{i_t} = \frac{L_0}{\sqrt{I_t/A_t}} \quad (3)$$

where λ_c is the slenderness ratio of the composite specimens; L_0 is the effective length of retrofitted SHS columns; i_t is the radius of gyration of converted sections.

After that, the ultimate strengths of SHS columns can then be introduced. Although the reinforcement of components under axial compression has been mentioned in British Standard (CIRIA) and Canadian Standard (CAN/CSA-S16-01), the study on axially compressed specimens is very limited (Liu 2007). The design equation for the ultimate capacity of retrofitted axially compressed specimen is still unavailable. With reference to the theories above, a correction factor β_c reflecting the effect on reinforcement of axially compressed members is introduced. The modified equation is given as follows:

$$\frac{N}{\beta_c \varphi_c A_t} \leq f \quad (4)$$

where N is the ultimate stabilizing capacity of retrofitted specimens under axial compression; β_c is a correction factor considering the impact of orientations of CFRP fiber, whose value is estimated by experimental analysis; φ_c is the stabilizing factor of compressed members after reinforcement, which is obtained from the current Chinese Code (GB 50017-2003) according to the slenderness ratio λ_c of composite members after retrofitting; f is the design strength of steel, determined according to the current Chinese Code (GB 50017-2003).

Test Setup and Instrumentation

Seven slender SHS columns were tested in the experiment, one of which was unreinforced for comparison, while the other six specimens were retrofitted by CFRP sheets using different numbers of CFRP layers, orientations of CFRP fiber and fiber configurations of CFRP. The nominal length of all specimens is 3000 mm, with the identical SHS cross section of 150×150×10 mm. The details of specimens are shown in Table 1.

Table 1 Details of test specimens

Specimen	*B*/mm	L_0/mm	*t*/mm	Layers of CFRP	Arrangement of CFRP
A-0	150	3000	10	0	—
A-2L	150	3000	10	2	2L
A-2T	150	3000	10	2	2T
A-1T1L	150	3000	10	2	1T1L
A-4L	150	3000	10	4	4L
A-4T	150	3000	10	4	4T

A-2T2L	150	3000	10	4	2T2L

Note: 2L means two longitudinal CFRP layers; 2T means two transverse CFRP layers; 1T1L means one transverse CFRP layer followed by one longitudinal CFRP layer.

Test setup is shown in Figure 1. In order to record and analyze the strains of SHS columns, the strain gauges were pasted on the surface of steel columns and CFRP sheets, while the displacement transducers were positioned on the relevant places (Shi *et al*. 2013). The locations of strain gauges and displacement transducers on steel tube and CFRP sheets are shown in Figures 1-3.

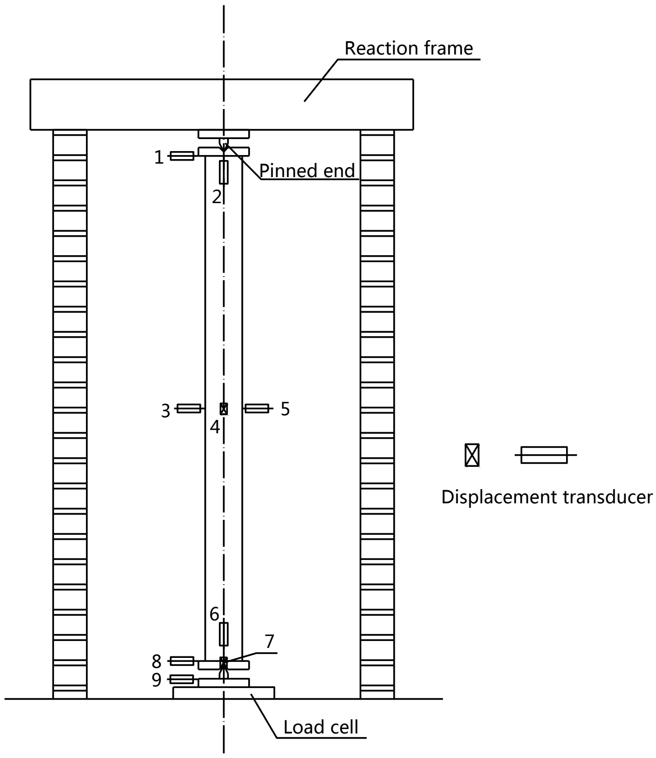
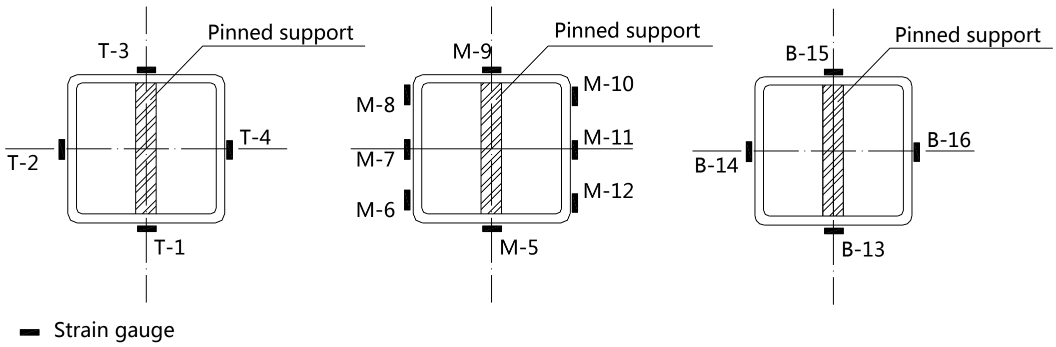
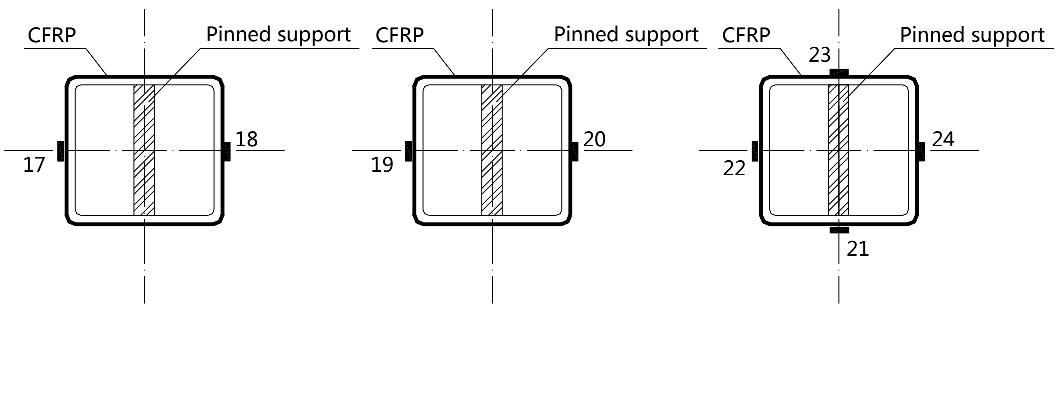


Figure 1 Test setup

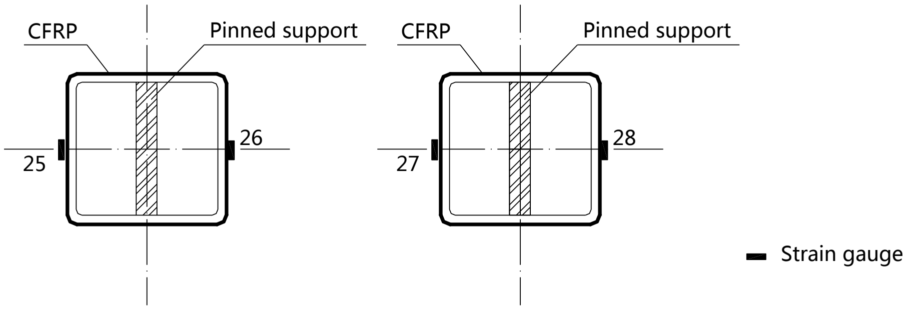


(a) Top end of column (b) Middle of column (c) Bottom end of column

Figure 2 Location of strain gauges on steel tube



(a) Top end of column (b) L_0/4 away from top end of column (c) Middle of column



(d) L_0/4 away from bottom end of column (e) Bottom end of column

Figure 3 Location of strain gauges on CFRP

First, each specimen was preloaded to 100 kN for several times to calculate the loading eccentricity (Wang *et al*. 2014). After that, the axial load was formally applied to the specimens. The data acquisition instrument was used to record the readings of strain gauges and displacement transducers until the failure of specimen.

RESULTS AND ANALYSIS

Failure mode

All specimens failed by the overall bucking of the column combined with the delamination of CFRP at the mid-length of the column, as shown in Figure 4.

(a) Overall bucking of column (b) Delamination of CFRP at the mid-length of column

Figure 4 Typical failure mode

Experimental Analysis

The initial eccentricities of seven specimens are shown in Table 2, where v_1, v_2 and v_3 are the initial geometrical eccentricities on the cross section of $L_0/4$, $L_0/2$ and $3L_0/4$ away from top end of column, respectively; v_0 is the maximum of v_1, v_2, v_3; e_{0t} and e_{0b} are the initial loading eccentricities on the top and bottom end of column, respectively; e is the assembly initial eccentricity, $e=v_0+(e_{ot}+e_{0b})/2$; e/L_0 is the ratio related to the assembly initial eccentricity.

Table 2 Initial eccentricities of test specimens

Specimen	v_1/mm	v_2/mm	v_3/mm	v_0/mm	e_{0t}/mm	e_{0b}/mm	e/mm	e/L_0
A-0	1.5	2.0	2.5	2.5	0.38	1.78	3.58	1.19‰
A-2L	1.0	1.5	2.0	2.0	-1.86	4.38	3.26	1.09‰
A-2T	2.5	2.5	1.5	2.5	10.15	-2.95	6.10	2.03‰
A-1T1L	4.5	4.0	3.0	4.5	3.28	2.43	7.31	2.44‰
A-4L	1.0	0.5	0.5	1.0	7.92	-2.53	3.70	1.23‰
A-4T	-1.5	-2.0	-2.5	-2.5	-3.75	-0.26	-4.51	1.50‰

A-2T2L	1.0	2.5	2.0	2.5	-6.35	-7.35	-4.35	1.45‰

Seven specimens were generally subjected to brittle failure. The experimental and analytical values are shown in Tables 3 and 4, respectively, where L_0 is the effective length of columns, e is the value of initial eccentricity, P_u is the experimental ultimate capacity, δ is the displacement in the middle of the column, A_t and I_t are the converted cross-sectional area and moment of inertia, respectively, λ_c is the slenderness ratio of composite specimens, ϕ_c is the resistance factor of composite specimens, and P is the analytical ultimate capacity. Comparing the effects of reinforcement in different ways, the most pronounced effect occurred on the specimens retrofitted by longitudinal layers of CFRP, in which the ultimate capacity of two layers in longitudinal direction was improved by 30.9%, followed by bonding transverse layers prior to longitudinal ones. And the minimal effect occurred on the specimen strengthened by transverse layers only. It is different from the previous study on stub columns that the transverse layers have the most pronounced effect. Further studies on the effect of CFRP are still required. The P-δ curves of test specimens strengthened by different layers of CFRP are shown in Figures 5 and 6.

Table 3 Experimental ultimate capacity of test specimens

Specimen	L_0/mm	e/mm	P_u/kN	Enhancement of ultimate strength	δ/mm	δ/L_0
A-0	3000	3.58	1437.6	—	14.97	5.0%
A-2L	3000	3.26	1881.3	30.9%	12.35	4.1%
A-2T	3000	6.10	1455.8	1.3%	10.70	3.6%
A-1T1L	3000	7.31	1487.1	3.4%	21.68	7.2%
A-4L	3000	3.70	1864.8	29.7%	15.86	5.3%
A-4T	3000	-4.51	1490.9	3.7%	23.10	7.7%
A-2T2L	3000	-4.35	1570.9	9.3%	12.86	4.3%

Table 4 Analytical ultimate capacity of test specimens

Specimen	A_t/mm^2	I_t/mm^4	λ_c	ϕ_c	P/kN	P_u/P
A-0	5428.32	1.839×10^7	51.547	0.7595	1459.3	0.985%
A-2L	5656.44	1.927×10^7	51.358	0.7695	1533.3	1.227%
A-2T	5656.44	1.927×10^7	51.427	0.7654	1532.5	0.950%
A-1T1L	5656.44	1.927×10^7	51.392	0.7656	1532.9	0.970%
A-4L	5884.56	2.015×10^7	51.301	0.7662	1595.9	1.169%
A-4T	5884.56	2.015×10^7	51.301	0.7662	1595.9	0.934%
A-2T2L	5884.56	2.015×10^7	51.266	0.7664	1596.3	0.984%

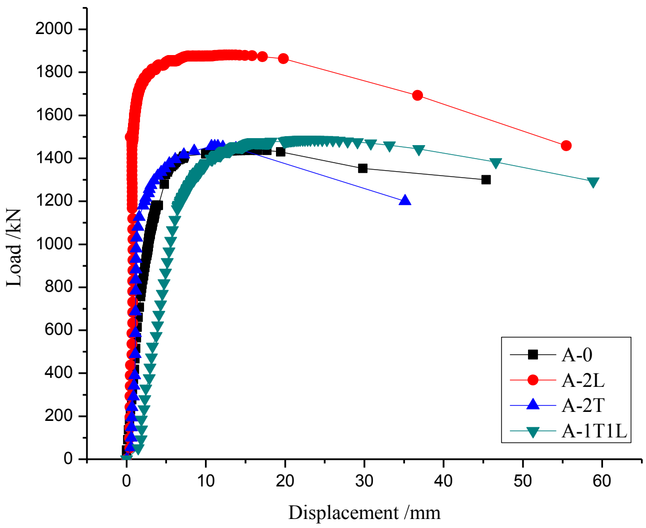


Figure 5 P-δ curves of test specimens strengthened by two layers of CFRP

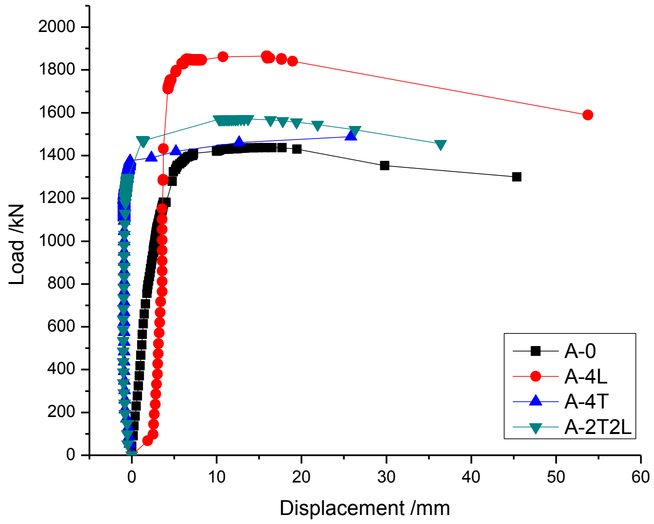


Figure 6 *P-δ* curves of test specimens strengthened by four layers of CFRP

Comparing Figures 5 and 6, the curves show that the best effect of reinforcement is on specimens A-2L and A-4L, whose ultimate capacity was increased by 30.9% and 29.7%, respectively. It indicates that the strengthening method of longitudinal layers is the most effective, whereas the other two methods can merely increase the ultimate capacity by less than 10% (transverse layers followed by longitudinal ones and transverse layers only). The reinforcement effect of transverse layers on SHS columns was found in this paper to be different from the conclusions given in the research (Gao *et al*. 2013) that the transverse layers have a better reinforcement effect on CHS columns.

Furthermore, with the same orientation of CFRP layers (Specimens A-2L and A-4L), the reinforcement effect on SHS columns cannot be improved with the increase of CFRP layers. The strength enhancement in specimens A-2L and A-4L are almost the same even though twice amount of CFRP was used for specimen A-4L. It may attribute to the delamination of outer CFRP layers that cannot cooperate well with SHS columns. Therefore, the tensile strength of CFRP cannot be fully utilized.

It can also be summarized that, according to curves in Figures 5 and 6, the ultimate capacity of specimen A-2T2L is much lower than that of specimen A-2L, although the same amount of longitudinal CFRP was used and two additional transverse layers were further applied for specimen A-2T2L. According to the experimental results, the buckling shape of SHS columns is one side bulked outwards, and the other side bulked inwards. It makes the CFRP boned on the inward bulking side cannot synergize well with SHS columns, thereby weakened the reinforcement effects.

Finally, the curves of specimens A-2L and A-1T1L in Figure 5 indicate that the strength enhancement of specimen strengthened by longitudinal CFRP layers is much higher than that of the specimen retrofitted by transverse CFRP layers prior to longitudinal ones, although the same number of CFRP layers were used. It may result from the transverse CFRP layers boned on the SHS columns, which weakened the reinforcement effects of the longitudinal CFRP layers.

From the analysis above, it was found that the longitudinal CFRP layers can remarkably enhance the ultimate capacity of SHS columns compared to the transverse CFRP layers.

Correction Factor β_c

Based on Tables 3 and 4, considering the deviations of experimental and analytical values, the optimal reinforcing method is to strengthen SHS columns with longitudinal CFRP layers only. Therefore, this retrofitting method is intensively recommended. Furthermore, two other ways of reinforcement – transverse CFRP layers only and transverse CFRP layers prior to longitudinal CFRP layers are inadvisable choices in the practical applications. A correction factor β_c of the stabilizing capacity in Eq. 4 can be preliminarily determined as β_c=1.05. Further researches on this aspect are still required.

CONCLUSIONS

This paper presents an experimental investigation on the ultimate capacity of CFRP retrofitted steel SHS columns under axial compression. Accordingly, it can be concluded that the effect of strengthening has an inseparable relationship with the orientation of CFRP, among which the most effective one is the reinforcing method of two longitudinal CFRP layers. It can also be concluded that there is no significant enhancement on the ultimate capacity by using different numbers of CFRP layers in the same fiber orientation. Furthermore, the transverse CFRP layers boned on the SHS columns have detrimental influence on the reinforcement effects of the longitudinal CFRP layers. Comparing the experimental values with the equations given in British Standard (CIRIA) and Canadian Standard (CAN/CSA-S16-01), a correction factor β_c of stabilizing capacity in different situations is proposed.

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