ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 20, No. 4. 2014

Experimental Study of Concrete-filled Carbon Fiber Reinforced Polymer Tube with Internal Reinforcement under Axially Loading

Wenbin SUN *, **Qiangqiang ZHU**, **Weizhong HE**

Faculty of Architecture and Civil Engineering, Huaiyin Institute of Technology, 89 Beijing North Road, Huaian, Jiangsu 223001, China

crossref http://dx.doi.org/10.5755/j01.ms.20.4.6035

Received 13 February 2014; accepted 17 November 2014

Comparing with the circular concrete columns confined with fiber reinforced polymer (FRP) wrap or tube, the rectilinear confined columns were reported much less. Due to the non-uniform distribution of confining pressure in the rectilinear confined columns, the FRP confinement effectiveness was significant reduced. This paper presents findings of an experimental program where nine prefabricated rectangular cross-section CFRP tubes with CFRP integrated crossties filled concrete to form concrete-filled FRP tube (CFFT) short columns and three plain concrete control specimens were tested. All specimens were axially loaded until failure. The rest results showed that the stress-strain curves of CFFTs consisted of two distinct branches, an ascending branch before the concrete peak stress was reaches and a second branch that terminated when the tube ruptured, and that the CFFTs with integrated crossties experienced most uniform confinement pressure distribution. Test research also found that the stress-strain curves of CFFTs indicated an increase in ductility. These demonstrate that this confinement system can produce higher lateral confinement stiffness.

Keywords: concrete-filled FRP tube, internal reinforcement, axial strain, transverse strain, confinement stiffness.

1. INTRODUCTION

*The desire to increase the axial capacity of reinforced concrete (RC) columns is not a new view in academic circle of civil engineering. In 1903, Considere performed triaxial test on motor cylinder, he found that a constant confining lateral pressure can substantially increase its compressive strength. Richart et al. [1, 2] were the earliest explorers who studied the nominal strength concrete under lateral confinement. This pioneering work was then continued by other researchers. In columns, this confining pressure can be provided by using steel stirrups of various forms [2 – 4], steel tube [5].

Since the end of the Cold War, many advanced military technologies and products have been transferred to the civil engineering industry. Carbon fiber reinforced polymer (CFRP) composite material applied to structure strengthening and retrofitting is one of the most successfully transferred technologies. The merits of CFRP composite material include high ratio of the strength to weight, anti-corrosion, easy cutting and construction, as well as high elastic modulus. For these reasons, CFRP composite material has been widely used in the retrofitting and strengthening of RC structures, especially in regions under high seismic risk or regions subject to high chloride corrosion. Fardis and Khalili [6] conducted uniaxial compression tests on concrete cylinders wrapped with CFRP fabrics and reported enhanced strength and ductility due to confinement. They [7] later proposed an analytical hyperbolic model for the compressive strength of confined concrete. Katsumata et al. [8] presented results of an experimental investigation on the seismic behavior of columns retrofitted with CFRP with Ten 1/4 scale column models tested. The results showed that the ultimate displacement as well as energy dissipation capacity increased linearly with the amount of CFRP wrapping.

In 1995, Mirmiran and Shahawy [9] proposed a concrete-filled FRP tube (CFFT), in which the tube acts as a form-work for the encased concrete, hoop and longitudinal reinforcement, and corrosion-resistant casing for the concrete. The CFFT was proposed for bridge columns as well as for pile splicing. Echary [10] evaluated the effects of the ratios of length to diameter (L/D) and diameter to thickness (D/t) on the behavior of the CFFT. The test results indicated that up to a ratio L/D of 5 : 1, slenderness effects are negligible. Pico [11] tested a total of nine square concrete-filled FRP tubes under axial compression to study the effect of the cross section. No bond was provided between the concrete core and the FRP tube. A marginal increase in strength was observed independent of the jacket thickness. The over-riding parameter in controlling the confinement was shown to be the product of the corner radius and the confining pressure.

Circular columns confined with FRP wrap or tube and subjected to axial compression exhibit a uniformly distributed lateral pressure over the cross-section, therefore provide an efficient utilization of FRP composite materials. Most of the existing studies have been concerned on circular confined concrete columns [6 – 10, 12 – 16]. However, rectilinear confined columns were reported much less than circular columns. It is mainly due to the non-uniform distribution of confining pressure, provided by the FRP confinement that varies over the rectilinear concrete cross-section and resulting significant reduction in confinement effectiveness. In general, corner rounding of rectilinear sections can reduce the detrimental effect on FRP rupture strain at a sharp corner and to improve the confinement effectiveness. Researches [17 – 18] have shown that the confinement effectiveness is dependent not only on the sectional shape of columns, but also the stiffness of FRP confinement.

*Corresponding author. Tel:+86-517-83591179, Fax:+86-517-83591148. E-mail: *sunwb1969@163.com, sunwb1969@hyit.edu.cn* (W. Sun)

This paper presents findings of an experimental program where nine prefabricated rectangular cross-section CFRP tubes with CFRP integrated crossties filled concrete to form CFFT short columns and three plain concrete control specimens were tested. All specimens were axially loaded until failure. There was a particular research objective to quantify the influence of integrated crossties on confinement effectiveness. No research on such new confinement systems has been reported in the open literatures.

2. DESCRIPTIONS OF SPECIMENS

Prefabricated CFRP tubes with CFRP integrated crossties were filled concrete to form CFFTs. CFRP tube functions as a stay-in-place formwork, free of steel reinforcement, and forms a corrosion resistant structural system. In addition, another asset of CFRP stay-in-place formwork was its confining ability of the concrete core, Fig. 1.

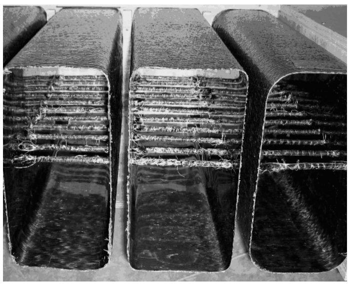

Fig. 1. CFRP tube

In this study, the test specimens had a 150 mm × 300 mm rectangular cross-section and a length of 600 mm. A total of 12 specimens including 9 CFFTs and 3 unconfined plain concrete short columns as control specimens were presented in the Table 1, where S, R, D_e and L represented spacing of CFRP integrated crossties, corner radius, equivalent diameter of the rectangular cross section, and CFRP layers respectively, for example Letter C meant integrated crossties, R10 meant 10 mm corner radius, L3 meant 3 layers CFRP filament.

Table 1. Details of the specimens

Specimens	Number	S, mm	R, mm	D_e, mm	R/D
PC	3	–	–	–	–
R10-L3-C	3	50	10	240	1 : 24
R20-L3-C	3	50	20	240	1 : 12
R40-L3-C	3	50	40	240	1 : 6

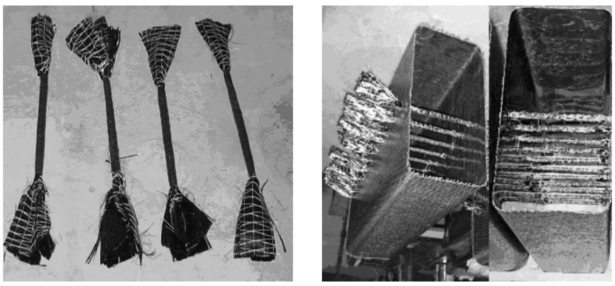

Fig. 2. Crossties, a tube with insertion of crossties and after covering the third CFRP sheet

Manually wet-lay-wet technique was employed to manufacture the CFRP tubes in the Structures Test Centre of Huaiyin Institute of Technology. The tubes were manufactured to have 3 layers of CFRP with 10 mm, 20 mm or 40 mm corner radius. The CFRP crosstie was designed to have a same amount of CFRP materials and be placed internally at the mid span of longer face of rectangular section, and had 50 mm longitudinal spacing. In proportion to the CFRP crossties diameter, small holes were drilled on the tubes followed by the insertion of crossties, Fig. 2. The anchors at the ends of CFRP crossties were bent and glued to the existing tube; a final layer of CFRP sheet was applied to cover the entire tube after the insertion of CFRP crossties, Fig. 2.

3. MATERIALS PROPERTIES

All specimens were cast from a single batch of concrete from local supplier with specified target compressive strength at 28-day of 25 MPa. An initial concrete slump was about 180 mm. All specimens were cast vertically and vibrated thoroughly. After a 24 hour curing, the wooden formworks were removed and all specimens were checked for irregularities and imperfections, they were then covered with wet cloths and watered for a 14-day cure followed by dry-air laboratory condition for another 14 days.

The CFRP tubes were manufactured from the carbon fiber sheets with epoxy resin. The unidirectional carbon fiber sheets with non-structural weave in secondary direction that holding the unidirectional fibers together was used for all specimens.

Table 2. Properties of carbon fibers and epoxy resin

Carbon fiber	Test values	Epoxy resin	Test values
Tensile strength	3243 MPa	Tensile strength	42 MPa
Modulus	226 GPa	Modulus	2610 MPa
Ultimate tensile elongation	2.04 %	Ultimate tensile elongation	1.63 %
Thickness of layer	0.111 mm	Bonding strength	4.1 MPa
Sheet width	600 mm	Compressive strength	84 MPa

The carbon fiber sheets (TRAC, Type 2-200), epoxy resin (Tiger, TGE-2) were supplied from Shanghai Dongwei Chemical & Building Materials Co. Ltd., China. The material properties were summarized in Table 2. To determine the material properties of carbon fiber sheets and epoxy resin, some CFRP tensile tests in accordance with GB/T3354 [19] and GB50367 [20] were conducted.

4. TEST PROCEDURES

The average axial strain was measured using four LVDTs attached on the either side over 200 mm gauge length in the middle portion of the specimens, in Fig. 3. The average longitudinal strain was also measured using another four LVDTs at the either corner between the actuator head and base of the specimens; they were also used to detect possible eccentricity. The mid-height LVTDs were removed prior to catastrophic failure in order to protect the LVDTs from damage. The transverse strain gauges were used to measure the distribution of the hoop strain on the FRP tubes. The strain gauges had 10 mm, 20 mm, the 10 mm strain gauge at up-left corner was labeled number 1, and the others were successively labeled from 2 to 8 along the clockwise direction, in Fig. 4. All strain gauges and LVDTs were connected to a data acquisition system and a microcomputer for data recording.

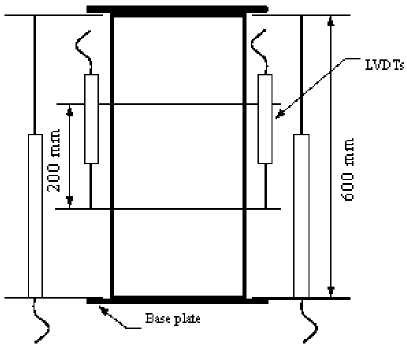

Fig. 3. LVDTs for the specimens

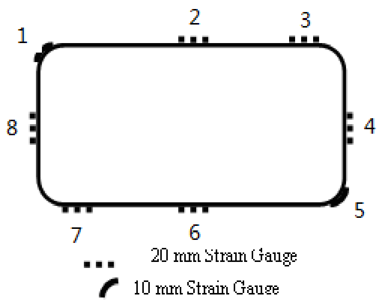

Fig. 4. Transverse strain gauges configuration

Compression tests took place after 28 days of concrete cure. All specimens were tested using a general hydraulic pressure testing machine which had the axial compression capacity of 5000 kN. The force was measured by using a pressure transducer load cell of 2500 kN capacity, and the data were monitored using an automatic acquisition system. All specimens were tested until failure under monotonically increasing uniaxial compression, under loading at rate about 2.0 kN/s accordance to the GB/T50081 [21].

5. TEST RESULTS

The test results of plain concrete specimens are summarized in Table 3. This table gives the values of peak axial load (P_{co}), concrete peak stress (f'_{co}) and its average strength, axial displacements (Δ), axial strain (ε_{co}) corresponding to peak stress, and transverse strain (ε_t). The stress-strain curve according to the average value of three control specimens was illustrated in Fig. 5.

Table 3. Test results of plain concrete specimens

Specimens	P_{co}, kN	f'_{co}, MPa	Δ, mm	ε_{co}, %	ε_t, %
PC-1	1087.6	24.17	1.35	0.225	0.085
PC-2	1076.9	23.93	1.45	0.242	0.097
PC-3	1105.7	24.57	1.32	0.220	0.094

For all plain concrete specimens, the measured average axial strain at peak concrete stress is about 0.0023. It should also be noted that the axial deformation of the unconfined concrete specimens was averaged based on the assumption of the loading was perfectly concentric, in spite of a small amount of eccentricity was observed.

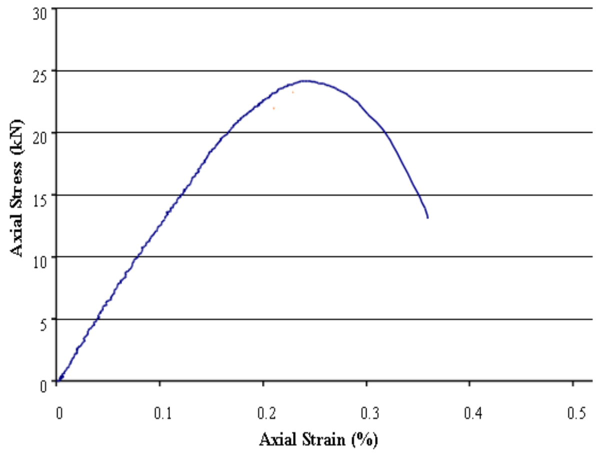

Fig. 5. Stress-strain curve of plain concrete

All CFFTs experienced typical failure modes, where the tube ruptured at or near the corner. Once the tube confinement fail, the concrete core was no longer able to withstand the axial loading. The rupture of FRP tube hence triggered the failure mechanism, which resulted in the catastrophic failure of the specimens. Although, the stress-strain curves of CFFTs indicated an increase in ductility, Fig. 6, the failures of these specimens occurs without much apparent warning and catastrophically. Nevertheless, popping noises can be heard during the various stages of axial loading.

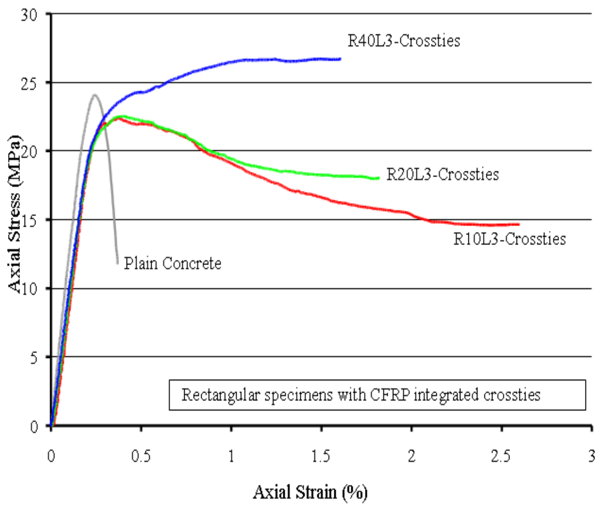

Fig. 6. Stress-strain curve of CFFTs

All CFFTs were also axially loaded until failure. The test results are presented in Table 4, which gives the values of peak axial load (P'_{co}) and concrete peak stress at the end of first branch, also gives the ultimate axial strain (ε_{cc}), the ratio of ultimate axial strain (ε_{cc}) to axial strain (ε_{co}) corresponding to peak stress in Table 3, and transverse strain (ε_t). It is noted that each value in the Table 4 is the average of three specimens in each series. The stress-strain curves according to the average values of three specimens in each series are illustrated in Fig. 6. Fig. 6 shows the axial stress-strain curves of CFFTs. The axial stress vs axial strain plots shows that the stress-strain relationship of CFFTs consisted of two distinct branches; an ascending branch before the concrete peak stress is reached, and a second branch that terminated when the tube ruptured. Extensive experimental results have shown a typical axial stress-strain response of FRP-confined concrete that features a bilinear shape [22 – 24].

Table 4. Test results of CFFTs

Specimens	P_{co}', kN	f_{co}', MPa	ε_{cc} , %	$\varepsilon_{cc}/\varepsilon_{co}$	ε_t , %
R10-L3-C	1008.2	22.40	2.598	11.55	0.146
R20-L3-C	1006.9	22.37	1.823	7.53	0.107
R40-L3-C	1060.7	23.57	1.820	8.27	0.374

Based on the axial stress-strain plots in Fig. 6, the first ascending branch of stress-strain curves are increased until the peak compressive strength of plain concrete was reached. During the initial stage of axial loading, the lateral expansion or dilation of concrete core was not enough to cause significant strain of CFRP tube in the circumferential direction. After reaching the peak stress of plain concrete, the concrete core started to dilate excessively as the internal micro cracks were developed in the concrete core. Fig. 6 also demonstrates the axial stress-strain behavior of CFFTs with integrated crossties used as internal reinforcement. The test results show that the integrated crossties increase the lateral stiffness of the tube thus reduced outward bulging and buckling of the tube. Furthermore, increase in corner radius improved the uniformity of confining pressure and hence increases the confinement effectiveness. It was found that the ultimate load-carrying-capacity of R40-L3-C with 40 mm corners was about 129 % of that of control specimens.

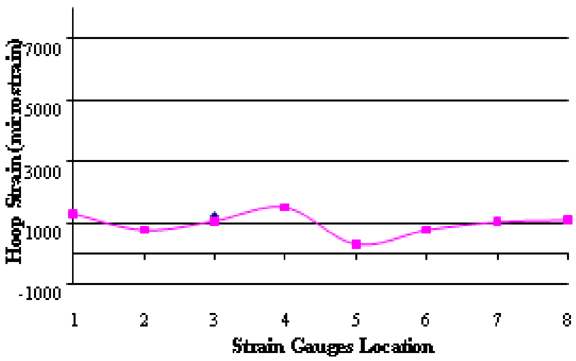

Fig. 7. R40-L3-C transverse strain profiles under the axial strain 0.00114

In former study [25], the experimental results of the transverse strain profile of CFFTs with square cross-section showed that the strain values are non-uniform around the circumference at different loading stages. In this research, a new confinement system has been developed, which involved the use of internal FRP reinforcement in the form of integrated crossties. This innovative system significant improves in confinement effectiveness. Fig. 7 shows that CFFTs with integrated crossties experienced most uniform confinement pressure distribution. This is due to the fact that this confinement system produces higher lateral stiffness.

6. CONCLUSIONS

Due to the confinement form the CFRP tubes and the internal crossties, the stress-strain curves of CFFTs indicated an increase in ductility, but, the failures of CFFTs also occurred without much apparent warning and catastrophically.

The stress-strain curves of CFFTs consisted of two distinct branches; an ascending branch before the concrete peak stress was reached, and a second branch that terminated when the tube ruptured.

The CFFTs with integrated crossties experienced most uniform confinement pressure distribution. This demonstrated that this confinement system can produce higher lateral stiffness.

Acknowledgments

This work has been financially supported by the Jiangsu Undergraduate Innovation Planning under No. 201311049011Z granted by the Jiangsu Provincial Department of Education, China. The authors would also like to thank the Huaian Testing Center for Construction Engineering Co., Ltd (Jiangsu, China) for providing CFRP composite materials and technical support to fabricate CFRP tubes.

REFERENCES

1. **Richart, F. E., Brandtzaeg, A., Brown, R. L.** A Study of the Failure of Concrete under Combined Compressive Stresses. Engineering Experimental Station, University of Illinois, Bulletin no. 185, 1928.
2. **Richart, F. E., Brandtzaeg, A., Brown, R. L.** The Failure of Plain and Spirally Reinforced Concrete in Compression. Engineering Experimental Station, University of Illinois, Bulletin no. 190, 1929.
3. **Iyengar, K. T. S. R., Desayi, R., Reddy, K. N.** Stress-strain Characteristics of Concrete Confined in Steel Binders *Magazine of Concrete Researches* 22 (72) 1970: pp. 173 – 184.
4. **Ahmad, S. H., Shah, S. P.** Stress-strain Curves of Concrete Confined by Spiral Reinforcement *Australia Journals* 79 (6) 1982: pp. 484 – 490.
5. **Gardner, N. J., Jacobson, E. R.** Structural Behavior of Concrete Filled Steel Tubes *ACI Materials Journal* 64 (7) 1967: pp. 404 – 413.
6. **Fardis, M. N., Khalili, H. H.** Concrete Encased in Fiber Glass-reinforced Plastic *ACI Materials Journal* 78 (6) 1981: pp. 440 – 446.
7. **Fardis, M. N., Khalili, H. H.** FRP-encased Concrete as a Structural Material *Magazine of Concrete Researches* 34 1982: pp. 191 – 201.
8. **Katsumata, H., et al.** A Study with Carbon Fiber for Earthquake-Resistant Capacity of Existing Reinforced Concrete Column *Proceedings of the Ninth Conference on Earthquake Engineering* Tokyo, Japan 7 1998: pp. 517 – 522.
9. **Mirmiran, A., Shahawy, M.** A New Concrete-filled Hollow FRP Composite Column *Composites Part* 27 (3 – 4) 1995: pp. 263 – 268.

10. **Echary, H.** Length Effect on Concrete Filled FRP Tubes Using Acoustic Emission. University of Central Florida, Orlando, Florida, 1997.
11. **Pico, O.** Confinement Effectiveness of Square FRP Tubes in Hybrid Columns. University of Central Florida, Orlando, Florida, 1997.
12. **Saadatmanesh, H., Ehsani, M. R., Li, M. W.** Strength and Ductility of Concrete Columns Externally Reinforced with Fiber Composite Straps *ACI Material Journal* 91 (4) 1994: pp. 434 – 447.
13. **Karbhari, V. M., Gao, Y.** Composite Jacketed Concrete under Uniaxial Compression Verification of Simple Design Equations *Journal of Materials in Civil Engineering* 9 (4) 1997: pp. 185 – 193.
14. **Samaan, M., Mirmiran, A., Sahawy, M.** Model of Concrete Confined by Fiber Composites *Journal of Structure Engineering* 124 (9) 1998: pp. 1025 – 1031.
15. **Toutanji, H.** Stress-Strain Characteristics of Concrete Columns Externally Confined with Advanced Fiber Composite Sheets *ACI Material Journal* 96 (3) 1999: pp. 397 – 404.
16. **Li, G.** Experimental Study of FRP Confined Concrete Cylinders *Engineering Structures* 28 2006: pp. 1001 – 1008. http://dx.doi.org/10.1016/j.engstruct.2005.11.006
17. **Mirmiran, A, Shahawy, M, Samaan, M, et al.** Effect of Column Parameters on FRP-confined Concrete *Journal of Composite Structures* 2 (4) 1998: pp. 175 – 185.
18. **Rochette, P., Labossiere, P.** Axial Testing of Rectangular Column Models Confined with Composites *Journal of Composite Structures* 4 (3) 2000: pp. 129 – 136.
19. GB/T3354-1999. Test Method for Tensile Properties of Oriented Reinforced Fiber Plastics. Chinese Standard Press, Beijing, 1999 (in Chinese).
20. GB50367-2006. Design Code for Strengthening Concrete. Chinese Architecture & Building Press, Beijing, 2006 (in Chinese).
21. GB/T50081-2002. Standard for Test Method of Mechanical Properties on Ordinary Concrete. Chinese Architecture & Building Press, Beijing, 2002 (in Chinese).
22. **Xiao, Y., Wu, H.** Compressive Behavior of Concrete Confined by Carbon Fiber Composite Jackets *Journal of Materials in Civil Engineering* 12 (2) 2000: pp. 139 – 146.
23. **Fam, A. Z., Rizkalla, S. H.** Flexural Behavior of Concrete-filled FRP Circular Tubes *Journal of Composite Structures* 6 (2) 2002: pp. 123 – 132.
24. **Teng, J. G., Lam, L.** Behavior and Modeling of Fiber Reinforced Polymer-Confined Concrete *Journal of Structure Engineering* 130 (11) 2004: pp. 1713 – 1723. http://dx.doi.org/10.1061/(ASCE)0733-9445(2004)130:11(1713)
25. **Sun, W. B.** Experimental Study on the Compressive Behavior of CFRP/ECCs *Journal of Southwest Jiaotong University* 18 (4) 2010: pp. 295 – 302.