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Behavior of FRP wrapped concrete filled steel tubular columns

Gajalakshmi Pandulu*, **Revathy Jayaseelan, Jemimah Thong**

Department of Civil Engineering, B.S Abdur Rahman Crescent Institute of Science and Technology, Chennai, India

ABSTRACT

During earthquake loading, concrete filled steel tubular (CFT) columns subjected to buckling at plastic regions. To control these type of buckling, a new technique is imposed in this research work. Therefore, an additional transverse confinement using carbon fiber reinforcement polymer (CFRP) laminates are wrapped around the CFT columns. An experimental study was conducted on FRP wrapped concrete filled CFT (CCFT) columns. The test variables are thickness of steel tube, different grades of concrete, and number of layers of FRP laminates. Experimental results of CFT columns were compared with computed load carrying capacity of the existing design codes. Of all the codes compared, DL/T 1999 showed the least variations and is found to be more viable to predict ultimate load carrying capacity of CFT columns. Load strain plots obtained from experimental study reiterate the fact that CCFT columns wrapped with two layers of CFRP showed enhanced strength and ductility compared to other CCFT columns. The failure modes of CCFT columns were observed during experimental study.

Keywords: Fiber reinforced polymer laminate, Concrete filled steel tube, Yielding, Local buckling.

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Corresponding Author:
Gajalakshmi Pandulu
gajalakshmi@crescent.education

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1. INTRODUCTION

Research studies which have conducted in the past showed that CFT columns have become more widely accepted and used in tall buildings as well as arch bridges particularly, in the far-east region, like China and Japan. The main concept of CFT column system is that steel tube and in-filled concrete of CFT column system can cover up most advantages of each material. CFT columns are one of the successfully used composite systems, and many researches have asserted the high-strength, stiffness, ductility and better seismic resistance of the CFT column system (Gajalakshmi and Helena, 2012; Li et al., 2018). Theoretical models are also developed for evaluating uni-axial capacity of concrete filled steel tubular (CFST) columns with external ring confinement and verified (Guo and Zhang, 2018; Lai and Ho, 2014). Studies on CFT columns subjected to cyclic loading reveals that formation of local plastic buckling may occur at the ends of the steel tube followed by the crushing of internal concrete (Tabacu, 2016). Such failure mode also results in unstable hysteretic loading capacity, particularly for columns with higher axial load. Therefore, new technique is required to overcome the disadvantages of CFT columns, an additional transverse confinement is provided to achieve seismic resistance and also control and delay the buckling of steel tube and confine the concrete in the critical regions. Studies also conducted on behavior of FRP confined CFT columns under combined bending and tension (Wang, 2015) and cyclic loading (Yu et al., 2014; Pessiki et al., 2001; Muhammad et al., 2005). Mukherjee et al. (2004) concluded that circular cross section is a more effective shape for FRP confinement concrete column due to the most effective confinement effect. Hence in this research work, to resolve the problem of local buckling of CFT columns subjected to various loading conditions, carbon fiber reinforced polymer (CFRP) is introduced at the critical regions of CFT columns. This additional transverse confinement is expected to prevent or delay the local buckling of the steel tube and effectively confine the concrete in the plastic hinge regions of a CFT column, thus improving its seismic performance with the stable load carrying capacity. The main objectives of this research work are: To identify the failure modes of CFT and CCFT columns; to observe the behavior of hollow tubes, CFT and CCFT columns; to find out ultimate load carrying capacity of the CFT columns with and without confinement infilled with M20 and M30 grade of concrete using various thickness such as 2 mm and 3 mm.

2. EXPERIMENTAL PROCEDURE

A total of 28 specimens were tested under axial compression using 100t capacity universal testing machine. Specimen consists of four hollow tubes, eight conventional CFT columns and sixteen CCFT columns confined with 1 and 2 layers of CFRP confinement. All the specimens are of length 600 mm and diameter 112 mm. Details of the specimen is shown in Table 1.

2.1 Carbon Fiber Reinforced Polymer (CFRP) Jackets

For the CCFT specimens, the CFRP jacket system was installed along the epoxy saturated steel tube surface, and its fiber direction was configured according to the circumferential direction of the cylinder. To attach each layer of FRP sheet, first, a layer of epoxy was applied to the surfaces of both steel tube and FRP sheet by paint brushes. Secondly, the fully saturated FRP sheet was set up on the surface of steel tube, and another ply of epoxy was applied onto the surface. The final installation of FRP sheets on steel tube by machine. Installation of 1 layer and 2 layer CFRP sheets as shown in Fig. 1(a), 1(b), 2(a) and 2(b). Tensile tests were carried out for the tension coupon samples as per ASTM – A370 (1989). The yield stress found to be 290 N/mm^2 and the concrete mix was designed for M20 and M30 grade of concrete and the properties of materials satisfied as per specifications based on American Concrete Institute (ACI) committee 211.1.1991 recommendations (1991).

Table 1. Details of the specimen

Specimen type	Length (mm)	Diameter (mm)	Thickness (mm)	Grade of concrete (MPa)
HT2	600	112	2	-
HT3	600	112	3	-
CFT2,20	600	112	2	M20
CFT3,20	600	112	3	M20
CFT2,30	600	112	2	M30
CFT3,30	600	112	3	M30
CCFT2,20-1L	600	112	2	M20
CCFT3,20-1L	600	112	3	M20
CCFT2,30-1L	600	112	2	M30
CCFT3,30-1L	600	112	3	M30
CCFT2,20-2L	600	112	2	M20
CCFT3,20-2L	600	112	3	M20
CCFT2,30-2L	600	112	2	M30
CCFT3,30-2L	600	112	3	M30

Note: Specimen name example: HT2 refers to hollow steel tube with 2 mm thickness. CFT2-20 refers to CFT columns with 2 mm thickness filled with M20 concrete. CCFT2-20 -1 L refers to single layer FRP wrapped CFT columns with 2 mm thickness filled with M20 concrete.

(a) Wrapping of CFRP 1 layer **(b)** CFRP wrapped specimens

Fig. 1. Installation of 1 layer of CFRP sheet

(a) Wrapping of CFRP 2 layers
(b) CFRP wrapped specimens

Fig. 2. Installation of 2 layers of CFRP sheets

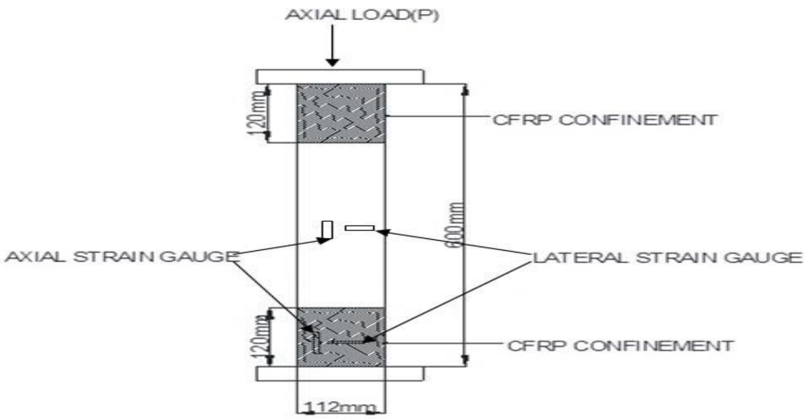

Fig. 3. Arrangement of test specimen

2.2 Test Setup and Instrumentation

The specimens were tested as per ASTM standards (1989) under axial compression using 100 ton capacity universal testing machine (UTM). In order to obtain the axial and lateral strain values a total four strain gauges of 120 Ohms with 5 mm gauge length were attached at each specimens, two at the bottom ends as well as at the mid span from the base axially and laterally. At each load increment strain readings were taken till specimens were loaded to failure. Test setup of the specimen is shown in Fig. 3.

3. RESULTS AND DISCUSSION

3.1 Behavior of CFT and HT Column

Fig. 4(a) and 4(b) show load – strain plots of CFT and HT columns subjected to pure axial compression. From the plots it is observed that all specimens exhibited linear relationship upto 70-80% of the ultimate load. CFT columns showed enhanced strength and ductility than that of the HT columns as mentioned in reference (Gajalakshmi and Helena, 2012) and not capable of taking more stress after reaching its ultimate load. The load carrying capacity of CFT2,30 was 1.17 times higher than that of CFT2,20 and 2.75 times higher than hollow tube HT2. The load carrying capacity of CFT3,30 was 1.16 times higher than that of CFT3,20 and 2.18 times higher than HT3. This is attributed to the reason that the outer steel tube increased the confinement of in-filled concrete. But these plots reiterate the fact that, CFT2,20 show better ductile performance than that of CFT2,30 due to fact that increased strength of in-filled concrete.

3.2 Comparison of Experimental Results vs Theoretical Results of CFT Columns

The theoretical loads calculated from the various design codes such as AIJ (1997), BS5400 (1979), EC4 (2004) and LRFD-AISC (1999) and DL/T (1999) for CFT columns. Comparisons of the experimental results of load carrying capacity with the predictions based on the current code provisions and the ratio between the ultimate load measured and computed by design codes are given in Table 2. The scatter between the test results and axial load computed by DL/T (1999) was small. Among the codes, DL/T (1999) predict the loads closer to the experimental results with an average mean of 0.917 and conservatively within a margin of 1%. DL/T can be taken as the best predictor and thus

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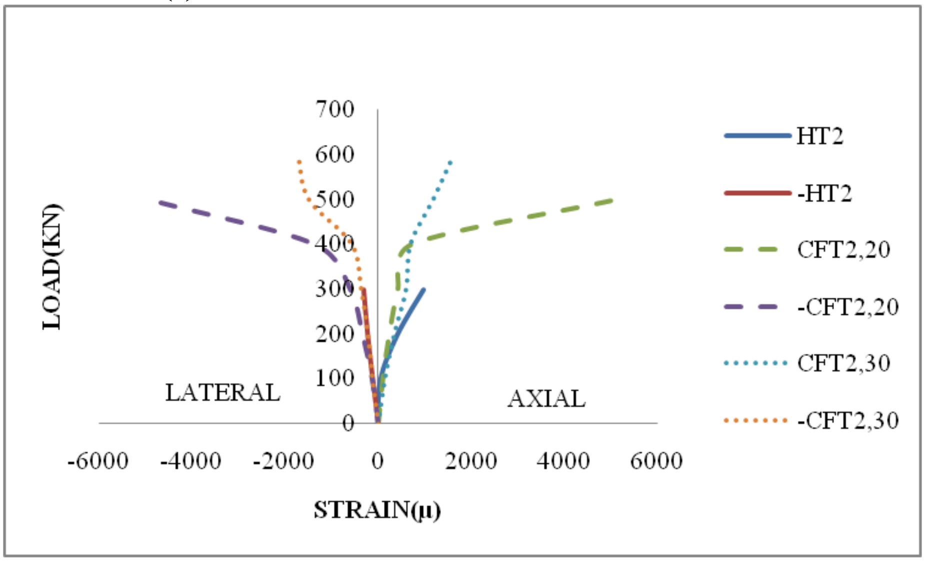
(a) load vs. strain behavior of 2 mm thickness steel tube



(b) load vs. strain behavior of 3 mm thickness steel tube

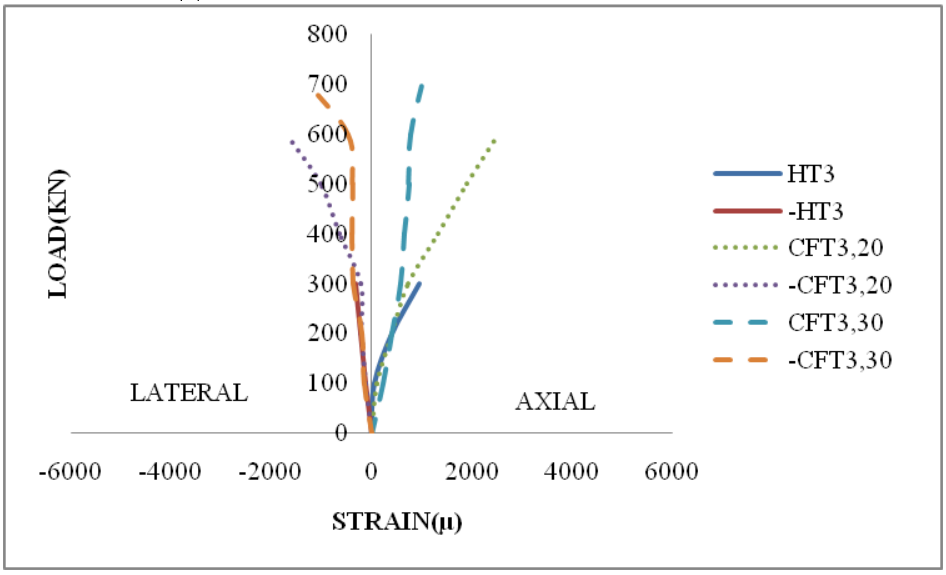


Fig. 4. Load vs. strain behavior of CFT and HT columns

Table 2. Comparison of experimental and theoretical results of CFT columns

Specimen	Experimental load (P_{exp}) (kN)	Ultimate load (kN) (P_{th})					P_{th}/ P_{exp}				
		EC 4	BS 5400	LRFD	AIJ	DL/T	EC 4	BS 5400	LRFD	AIJ	DL/T
CFT2,20	507	329	350	346	288	420	0.64	0.69	0.56	0.76	0.82
CFT3,20	610	398	472	399	377	590	0.64	0.77	0.61	0.81	0.96
CFT2,30	596	335	391	491	337	537	0.56	0.65	0.56	0.76	0.90
CFT3,30	711	449	511	381	424	697	0.63	0.78	0.60	0.79	0.98

acceptable for the calculation of axial strength of CFT columns. Results indicate that DL/T (1999) approach can be extended to design of CCFT columns with proper confinement ratio.

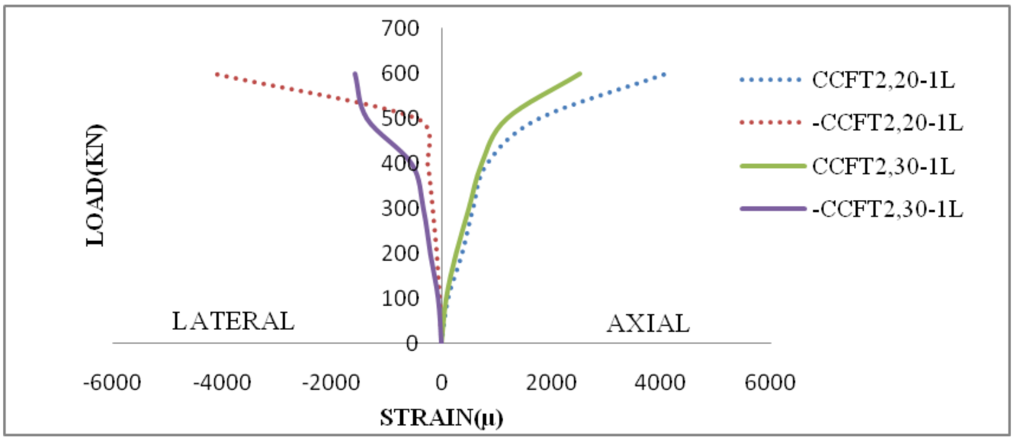


Fig. 5. Load vs. strain behavior of CCFT-1L for 2 mm thickness of steel tube

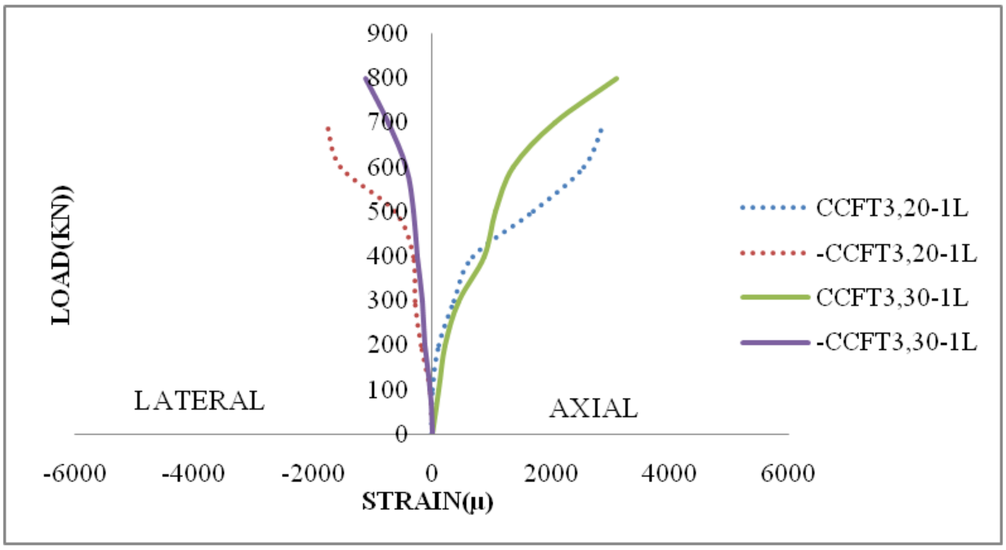


Fig. 6. Load vs. strain behavior of CCFT-1L for 3 mm thickness of steel tube

3.3 Behavior of Confined Concrete Filled Tubular Column Wrapped with 1 Layer of CFRP

The load-axial and lateral strain plots for confined concrete filled tubular column wrapped with 1 Layer of CFRP specimens are shown in Fig. 5 to Fig. 8, in which the strain values are taken at the middle and end section of the specimen as shown in Fig. 1. The ultimate load of the specimen was taken when the rupture of the CFRP wrap occurred at the critical regions of the specimens. The initial portion of the plots exhibited an almost linear behavior eventually of all specimens essentially followed the same curve till the attainment of characteristic strain and increased up to about 75% of its ultimate load. These plots reiterate behavior of all specimens wrapped with one layer of CFRP until the rupture of the CFRP layer.

3.3.1 Effect of Strength of Concrete

The mechanical behavior of the CFT columns was significantly improved by the CFRP confinement. The load carrying capacity of the CCFT2,30-1L was 1.57 times higher than that of the CCFT2,20-1L columns. From the Fig. 5, CCFT columns of 2 mm thickness wrapped with one layer of CFRP with M30 grade concrete performed better than other specimens due to increased in concrete strength. The load carrying capacity of the column CCFT3,30-1L infilled with M30 grade of concrete was 1.20 times higher than that of the CCFT3,20 -1L column with M20 grade of concrete. From the Fig. 5 and Fig. 6, CCFT columns of 3 mm thickness wrapped with one layer of CFRP with M30 grade concrete performed better than other specimens due to increased in concrete strength and steel tube thickness. From the plots it is observed that irrespective of the steel tube thickness, CCFT column infilled with M20 concrete exhibits better ductile behavior than that of CCFT column infilled with M30 concrete due to the fact of earlier lateral expansion of high strength in-filled concrete.

3.3.2 Effect of Steel Tube Thickness

The load carrying capacity of the CCFT3,20-1L 3 mm thickness was 1.20 times higher than that of the CCFT2,

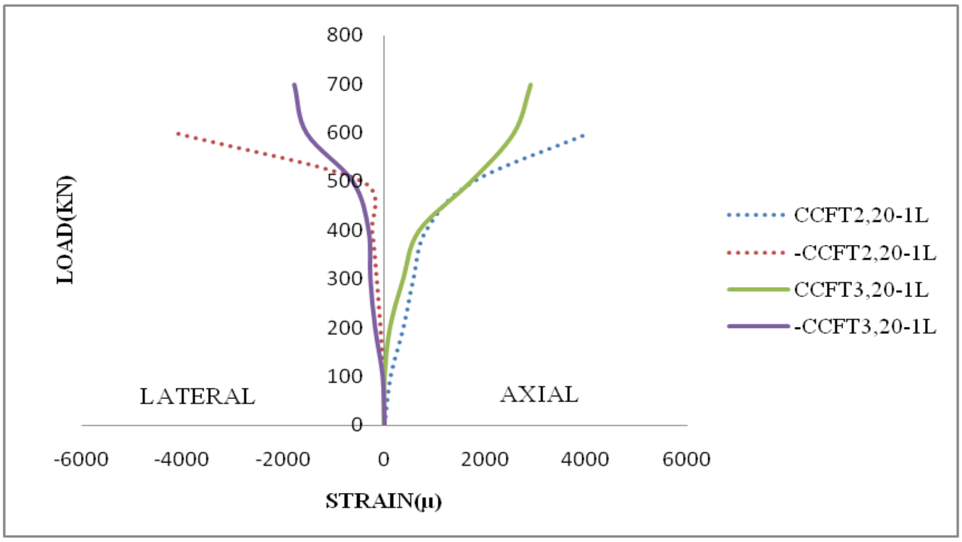


Fig. 7. Load vs. strain behavior of CCFT-1L for M20 grade of concrete

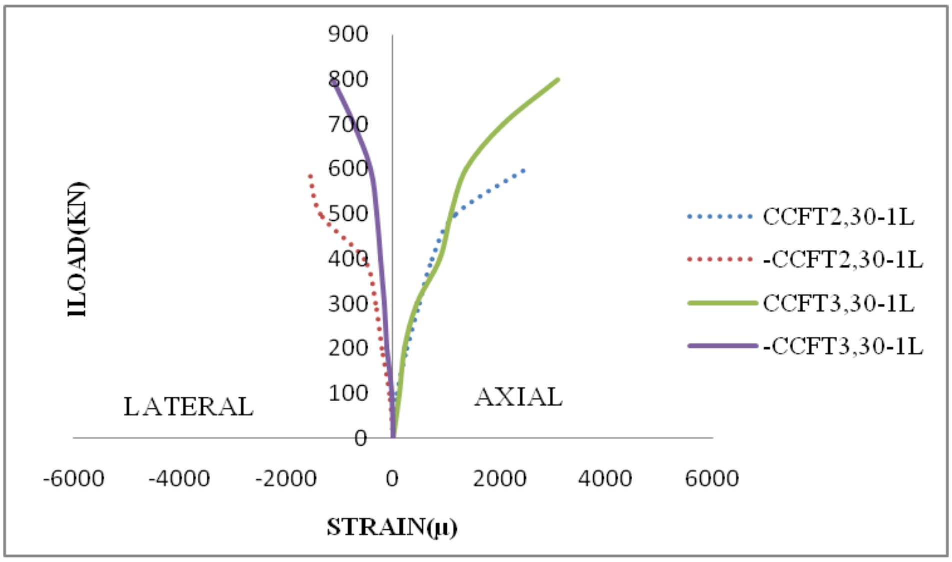


Fig. 8. Load vs. strain behavior of CCFT-1L for M30 grade of concrete

20-1L columns with 2 mm thickness. From the Fig. 7, CCFT columns of 3 mm thickness wrapped with one layer of CFRP with M20 grade concrete performed better than other specimens due to increased in steel tube thickness. From the Fig. 8, the load carrying capacity of the CCFT3,30-1L columns with 3 mm thickness was 1.08 times higher than that of the CCFT2,30-1L columns with 2 mm thickness. CCFT3-1L exhibits a good confining pressure when compared CCFT2-1L.

3.4 Behavior of Confined Concrete Filled Tubular CCFT-2 Layer CFRP

The strain values are taken at the middle and end section of the confined concrete filled tubular column wrapped with 2 layers of CFRP specimens as shown in Fig. 2 and the load-axial and lateral strain plots for those specimens are shown in Fig. 9 to Fig. 12. The specimens tested until the rupture of the CFRP wrap occurred at the critical regions. It is observed that all specimens exhibited almost linear behavior until the steel tube yielded. These plots exhibit better ductile behavior due to the excellence confinement provided by 2 layers of CFRP wrapped around the CFT columns.

3.4.1 Effect of Strength of Infilled Concrete

The mechanical behavior of the CFT columns was significantly improved by the CFRP confinement-2 layers. From the Fig. 9, load carrying capacity of the column CCFT2,30-2L was 1.17 times higher than that of the CCFT2,20-2L. From the Fig. 10, load carrying capacity of the CCFT3,30-2L column was 1.24 times higher than that of the CCFT3,20-2L columns. Irrespective of the steel tube thickness, CCFT2,20-2L and CCFT3,20-2L show enhanced

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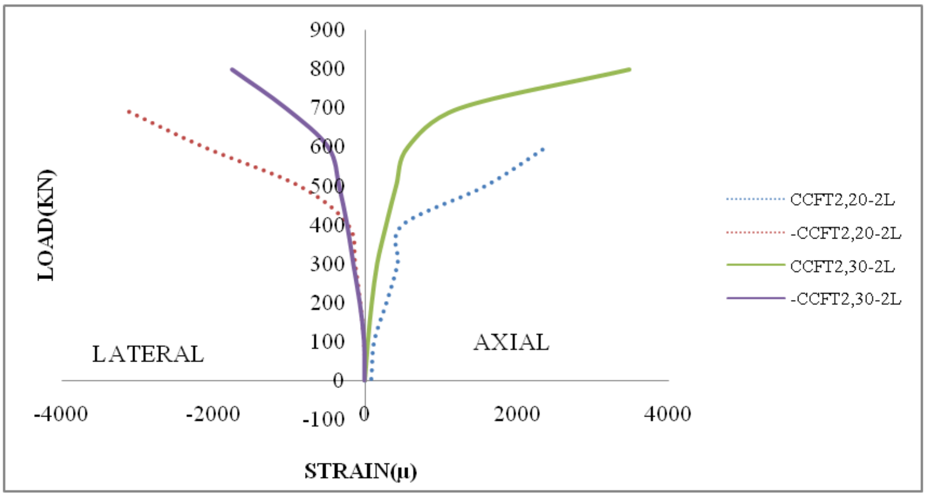

Fig. 9. Load vs. strain behavior of CCFT-2L for 2 mm thickness of steel tube

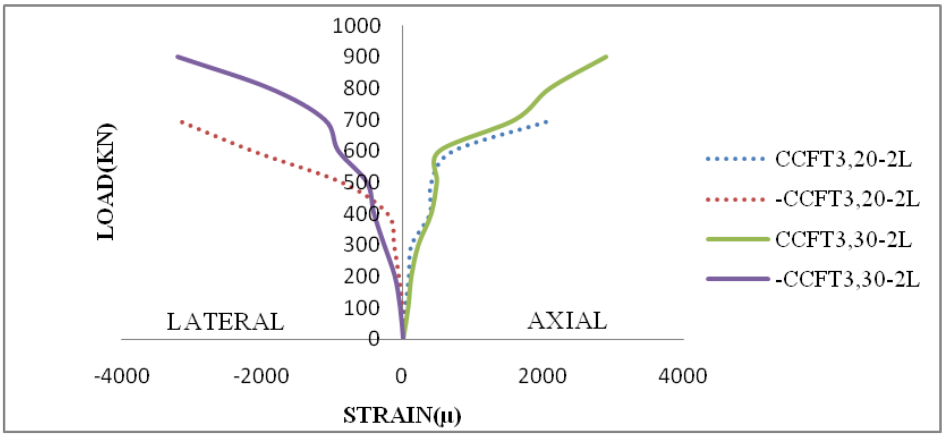

Fig. 10. Load vs. strain behavior of CCFT-2L for 3 mm thickness of steel tube

ductile performance than that of CCFT2,30-2L and CCFT3,30-2L. Irrespective of the strength of the concrete, CFT columns wrapped with 2 layers of CFRP exhibit higher load carrying capacity.

3.4.2 Effect of Steel Tube Thickness

Load carrying capacity of the CCFT3,20-2L columns with 3 mm thickness was 1.14 times higher than that of the CCFT2,20-2L columns with 2 mm thickness which is depicted by Fig. 11. CCFT3,20-2L exhibits a good confining pressure when compared to CCFT2,20-2L. From the Fig. 12, load carrying capacity of the column CCFT3,30-2L with 3 mm thickness was 1.21 times higher than that of the CCFT2,30-2L columns with 2 mm thickness. CCFT3,30-2L exhibits a good confining pressure when compared to CCFT2,30-2L. Irrespective of the steel tube thickness, CFT columns wrapped with 2 layers of CFRP infilled with M20 grade concrete show better ductile performance compared to all other specimens.

3.4.3 Effect of Carbon Fiber-Reinforced Polymer (CFRP) Confinement

Fig. 13 shows comparison of load carrying capacity HT, CFT and CCFT specimens wrapped with one and two layers of CFRP. From all these plots, it is observed that all specimens behaved similarly till the steel tube yielded. When the steel tube yielded, the axial load of the specimens increased in an approximately linear way. This is because of the fact that the CFRP wrap provided confinement to the steel tube and the concrete when the steel tube yielded and delayed the decrease of the rigidity of the CFT columns.

From Fig. 13, it is observed that, irrespective of steel tube thickness, the ultimate load of CCFT specimen wrapped with one layer of CFRP and infilled with M20 grade concrete is 2 times greater than the HT and 1.2 times greater than the CFT specimens. Irrespective of strength of the concrete and steel tube thickness, the ultimate load of CCFT specimen wrapped with two layers of CFRP is 1.25 times greater than that of CCFT specimen wrapped with one layer of CFRP. CCFT specimen wrapped with two layers of CFRP exhibited higher load carrying capacity than that of all specimens.

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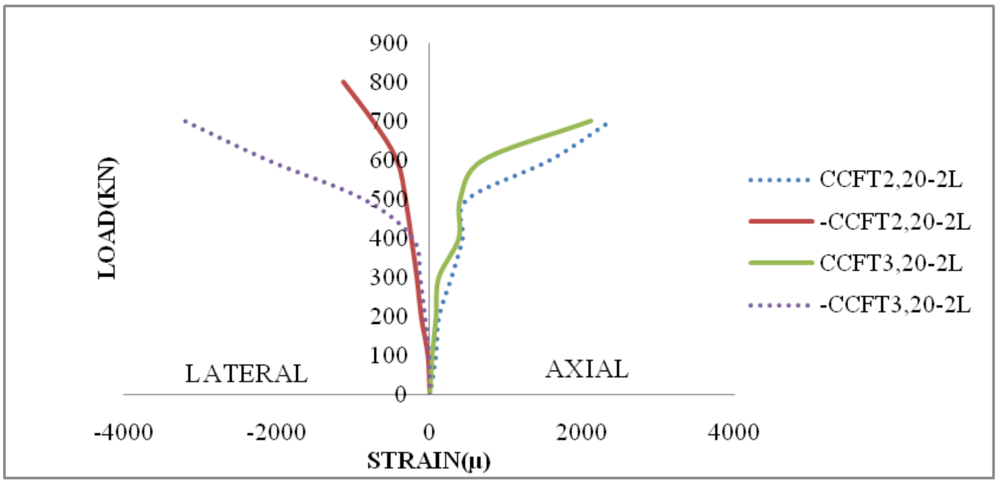

Fig. 11. Load vs. strain behavior of CCFT-2L for M20 grade of concrete

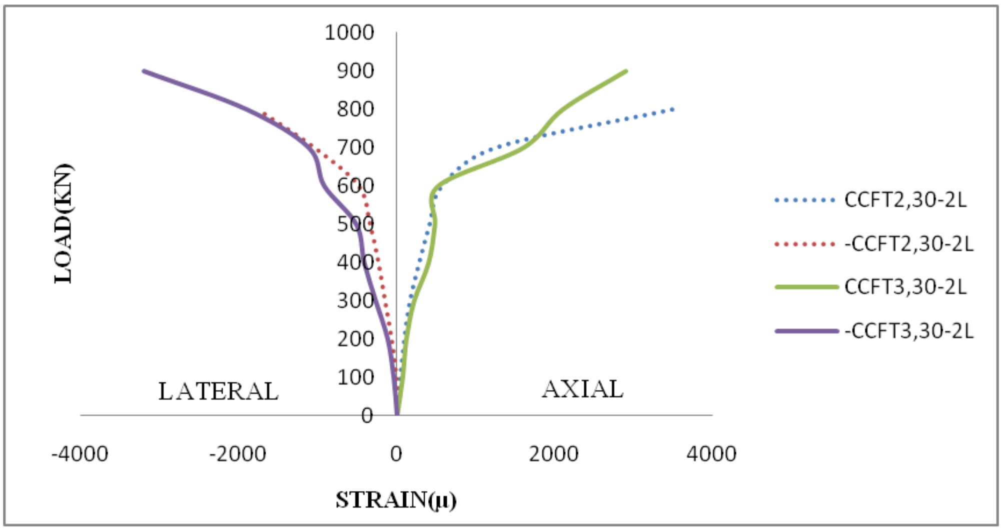

Fig. 12. Load vs. strain behavior of CCFT-2L for M30 grade of concrete

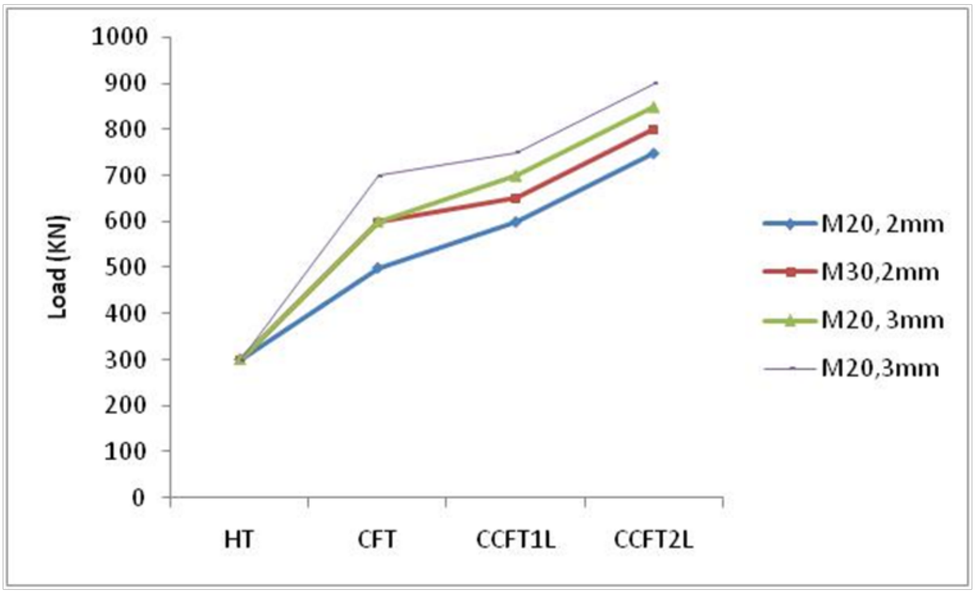

Fig. 13. Comparison of load carrying capacity of HT, CFT, CCFT1L and CCFT2L

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(a) local buckling at the ends **(b)** Failed HT specimens

Fig. 14. Failure modes of hollow tubular column

(a) Tested CFT specimen **(b)** Failed CFT specimen

Fig. 15. Failure modes of CFT columns

3.5 Failure Modes

3.5.1 Failure Modes of Hollow Tubular Column

Hollow tubes failed due to local buckling forming near the bottom and top supports. Premature local buckling due to yielding of steel tube occurred on thin walled column. These type of failure similar to the elephant foot shape buckling. The failure mode of the HT specimens are shown in Fig. 14.

3.5.2 Failure Modes of Concrete In-Filled Tubular Column

Concrete filled tubular column failed due to crushing of the infilled concrete and yielding of the steel tube causing outward bulging of the steel tubes at each ends. Local buckling occurred at the critical regions and followed by the crushing of concrete inside the steel tube.

Once the steel tube started yielding, there will be the lateral expansion of the in-filled concrete which leads to the failure of the CFT specimens. The failure mode of the CFT specimens is shown in Fig. 15.

3.5.3 Failure Modes of Confined Concrete Filled Tubular Column of 1 Layer CFRP

Confined concrete filled steel tubular column (CCFT) with 1layer of FRP failed due to local buckling of the steel tube just above the confined region and rupture of FRP occurred at excessive axial compression due to the increased internal hoop tension. The local buckling at the column ends equal to the diameter were effectively restrained by the additional CFRP confinement. The failure mode of the confined concrete filled tubular column specimens are shown in Fig. 16.

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(a) Tested CFT specimen **(b)** Failed CCFT specimens

Fig. 16. Failure modes of CCFT columns with 1 layer CFRP

(a) Tested CFT specimen **(b)** Failed CCFT specimens

Fig. 17. Failure modes of CCFT columns with 2 layers CFRP

3.5.4 Failure Modes of Confined Concrete Filled Tubular Columns of 2 Layers of CFRP

Confined concrete filled steel tubular column (CCFT) with 2 layers of FRP failed due to local buckling of the steel tube just above the confined region. No rupture of CFRP occurred. The deformation and local buckling at the column ends equal to the diameter were effectively restrained by the additional CFRP confinement. The failure mode of the confined concrete filled tubular column specimens are shown in Fig. 17.

4. CONCLUSIONS

This paper presents an experimental study on hollow tubular column, conventional concrete filled tubular column and confined concrete filled tubular column with one and two layers of CFRP under axial compression. The CFRP layers are provided to confine the concrete core and to constrain outward local buckling of steel tube. The examined parameters were the CFRP layer number, the thickness of the steel tube and the concrete strength. Theoretical study was also done based on various design codes. Based on that the following conclusions were made:

1. Hollow tubes failed due to local buckling because of the yielding of steel tube.
2. CFT columns showed the significant increase in ultimate strength and ductility compared to hollow tubes but it couldn't take up stress after its yielding. CFT columns failed due to crushing of the infilled concrete.
3. With the confinement of CFRP, the critical regions of the CFT columns were effectively restrained by controlling and delaying the local buckling at the ends and also increase in its ultimate load carrying capacity. It was also observed that the confinement action increases with the increase in thickness of the steel tube and increase in the layer of CFRP.

4. Irrespective of the strength of the concrete, CFT columns wrapped with 2 layers of CFRP exhibit higher load carrying capacity.
5. Irrespective of the steel tube thickness, CFT columns wrapped with 2 layers of CFRP infilled with M20 grade concrete show better ductile performance compared to all other specimens.
6. Failure of the specimens induced by rupture of the CFRP due to the lateral expansion of the concrete.
7. DL/T(1999) predicted closer to the experimental results with an average mean of 0.917, hence can be considered as best predictor for design of CCFT columns with confining factor. Prediction of confining factor for different layers of CFRP wrapped on the CFT columns will be scope for the future work of this study.

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