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FRP Strengthening of Slender CFST Members under Compression

Sindhuja.S[1] and M.C. Sundarraja[2]

[1]PG Student Thiagarajar College of Engineering
[2]Thiagarajar College of Engineering
E-mail: [1]sindhuselvaraj93@gmail.com, [2]mcsciv@tce.edu

Abstract—*Concrete filled tubular (CFST) members are widely used in the construction industry especially in the massive structures owing to its large load carrying capacity, better seismic resistance and even for aesthetical appearance. Even though these members have wide applications, they are highly explosive towards deterioration due to environmental conditions. This study mainly focused on enhancing the structural performance of CFST slender columns by externally strengthening with the CFRP and AFRP fabrics. In the present investigation, thirteen CFST columns of 42.4 mm diameter, 3.2 mm thickness and 1500 mm height were used. Carbon and Aramid fibres were used for external wrapping. Among those columns, one was kept as controlled specimen and other 12 columns were categorized as two sets of specimens in which one set of columns were wrapped with carbon fabric strips and other were wrapped with aramid fibre strips. The parameters includes failure modes, load carrying capacity and lateral deformation control with respect to the number of wrapping layers, strip width and spacing were discussed and compared. The results resemble that there exist an appreciable enhancement in the load carrying capacity and the control in lateral deformation.*

1. INTRODUCTION

Concrete filled steel tubular (CFST) members are widely used as compression member in massive structures and bridges owing to its high carrying capacity and seismic resistance. It can also be used with smaller cross section in the structures instead of reinforced concrete column with increased cross section. But due to environmental conditions these columns are mostly exposed to deterioration. Instead of demolishing the structure, it is necessary to strengthen the deteriorated structure in an economical way. Various techniques like plate bonding, near surface mounting, etc is in practice. Among those, a technique of strengthening using FRP composites is a promising alternative technique to strengthen the deteriorated components, which are externally wrapped with FRP composites having high strength to weight ratio. Usually, bare steel hollow column fails by inward buckling. If the hollow section is infilled with the designed proportion of concrete then there exists an enhanced stiffness and strength throughout the section in service condition, which makes the section to buckle outwards. By providing external wrapping of FRP composites on the surface of CFST columns, it results in enhancement in the load carrying capacity and control in lateral deformation. Zhong Tao and Han Lin-Hai [2] presented the results of axial compression and bending tests of fire-damaged CFST tubes rehabilitated using unidirectional CFRP composites. Both circular and square specimens were tested to investigate the strengthening effects of CFRP composites on them. The test results indicated that the load-carrying capacity of CFRP strengthened CFST stub columns increased while their ductility decreased with the increasing number of CFRP layers. In another study, Zhong Tao et al [2] rehabilitated the fire-exposed CFST beams and columns by unidirectional CFRP composites. The test results showed that the fibre jackets to some extent enhanced the load-bearing capacity, while the influence of CFRP repair on stiffness was not apparent. From the past research, it can be observed that there have been investigations done with the use of CFRP as a strengthening material for metallic members and also presence of CFRP significantly enhance the behavior of steel tubular members. However research related to strengthening of slender CFST members using fibre are not widespread and also more tests are required to derive an optimal combination of fibre orientation, number of layers and sequence in applying CFRP layers. The main focus of the study is to experimentally investigate the suitability of carbon fibre reinforced polymer and Aramid fibre reinforced polymer (AFRP) fabrics for strengthening of slender CFST column members and also compare the effectiveness of geometric shapes (i.e. wrapping schemes) of the upgrading material in strength gain. Finally, suitable wrapping scheme that can be used to repair CFST members was recommended.

2. MATERIAL PROPERTIES

2.1 Steel

The hollow steel tube of diameter 42.4 mm, thickness 3.2 mm and height 1500 mm of circular cross section is used. Its slenderness ratio is 141.5, confirming to IS 1161-1998 [3]. As per manufacturer's details, 250 Mpa is the yield strength of the steel tube.

2.2 CFRP and AFRP

The unidirectional carbon fibre called M-Brace 240 and the bidirectional Aramid fibre called Aramid-120 were used. As per manufacturer's specifications, the properties of CFRP and AFRP are given in the Table 1 below.

Table 1: Properties of CFRP & AFRP.

S. No	Properties	CFRP	AFRP
1	Modulus of elasticity	240 kN/mm2	120 kN/mm2
2	Weight of the fibre	400 g/m2	123 g/m2
3	Tensile strength	3800 N/mm2	2900 N/mm2

2.3 Adhesive

A most suitable adhesive called CERA Bond-EP is used which consists of two compounds such as resin and hardener with the mixing ratio 1:3 (B:H).

2.4 Concrete

The specimens were cast with the designed proportion of concrete of mixing ratio 1:1.47:2.5 and water cement ratio 0.55. The average compressive strength of the concrete cubes for 28 days curing is 24.6 N/mm^2.

3. EXPERIMENTAL INVESTIGATION

3.1 General

In the present investigation, mild steel tube of 6m length was cut into 1.5 m length. And CFRP & AFRP fabrics were used to enhance the structural performance of the CFST columns. These columns were wrapped with CFRP & AFRP strips in two patterns and tested under axial compression in order to investigate the contribution of fibres in the strength enhancement of the columns. The following designation of specimens are used for identification of columns: CS, CW-400-150-1, CW-400-150-2, CW-400-150-3, CW-700(250)-150-1, CW-700(250)-150-2, CW-700(250)-150-3, AW-400-150-1, AW-400-150-2, AW-400-150-3, AW-700(250)-150-1, AW-700(250)-150-2 and AW-700(250)-150-3. For example, AW-400-150-2 indicates that the specimen was wrapped with two layers of 400 mm width of AFRP strip with the spacing of 150 mm and CW-700(250)-150-1 specifies that the specimen was wrapped with one layer of carbon fibre having 700 mm strip width at the mid height of the column and 250 mm strip width at the edges with the spacing of 150 mm and CS as control specimen.

3.2 Specimen fabrication

3.2.1 Casting and curing of specimens

Mild steel tube of 42.4 mm diameter, 3.2 mm thickness and 6 m length was cut into 1.5 m as required and the edges of the tubes were levelled using a linear surface grinding machine. Using a wire brush, the specimens were cleaned in order to eliminate the rust. Then the specimens were cast with the designed mix proportion of concrete. While casting, the bottom edge of the steel tube was covered with a steel plate to avoid the slurry leakage. The concrete was thoroughly compacted to remove the air voids within the concrete. Then the specimens were cured for 28 days.

3.2.2 Specimen preparation

The specimens were sandblasted to make the surface of the specimens rough enough to provide proper bonding between the surface and the fibre. After sandblasting the surface, the specimens were cleaned using acetone solution to remove tiny rust particles. The sandblasted specimens are shown in Fig.1.

Fig. 1: Sand blasted specimens

3.2.3 Application of FRP composites

After cleaning the specimens, the specimens were coated with the resin in the specified proportion. One layer of glass fabric was applied to avoid galvanic corrosion. After that the CFRP and AFRP strips of mentioned width was tailored and externally bonded to the surface of the specimen. This procedure was followed upto the third layer bonding of fabric. While application, a ribbed roller is used to avoid the existence of entrapped air between the fabric and the surface of the specimen.

3.2.4 Experimental procedure

All the specimens were tested under axial compression using a column testing machine of capacity 2000 kN. Each specimen were centered, and placed for testing using sprit level and plumb bob. Three LVDT (linear variable displacement transducer) were used to measure the lateral deformation. These LVDT's were connected to a 16 channel data acquisition system to record the lateral deformation and load carrying capacity. The parameter includes failure modes, load carrying capacity and lateral deformation were recorded for each specimen until failure. The experimental set up of the specimen is given below.

4. RESULTS AND DISCUSSIONS

The following parameters were discussed for each specimen in order to investigate the optimized contribution of CFRP and AFRP in load carrying capacity enhancement and lateral deformation control in the aspect of number of wrapping layers, spacing of strips and strip width.

- Failure modes
- Load carrying capacity
- Axial load Vs Lateral deformation

Fig. 2: Experimental setup

4.1 Failure modes

All the FRP wrapped CFST specimens were tested until failure. The experimental set is shown in Fig. 2. In the case of control specimen, the maximum lateral deformation about 18.2 mm was observed at the mid height of the column and failed at the load of 82 kN. The specimen CW-400-150-1 started buckling at the load of 84.36 kN followed by the rupture of fibre at 92.21 kN and failed at 105.94 kN whereas the specimen CW-400-150-2 buckled at the mid height at 79.46 kN and failed at 120.66 kN which is higher than the single layer wrapped specimen. But in three layers wrapped specimen, the buckling was observed at 91.22 kN just above the mid height of the column and failed at 126.54 kN. The AFRP specimens such as AW-400-150-1 and AW-400-150-2 buckled at the mid height and rupture of fibre was taken place near the loading plates. The single and two layered specimens with 400 mm strip width failed at 103.72 kN and 118.75 kN respectively whereas the specimen AW-400-150-3 failed at the ultimate load of 123.60 kN and buckling happened at just above the mid height of the column. In case of specimen wrapped with 700 mm strip at the mid height and 250 mm strip width at the edges with 150 mm spacing possessed lesser deformation, which was observed at the mid height of the column. In the case of AFRP wrapped specimens such as AW-700(250)-150-1, AW-700(250)-150-2 and AW-700(250)-150-3, the failure was noted at the mid height of the column and failed at the load of 117.85 kN, 122.97 kN and 130.65 kN respectively whereas the CFRP wrapped specimens such as CW-700(250)-150-1 failed by lateral buckling followed by rupture of fibre at 96.14 kN but in the case of specimen CW-700(250)-150-2, the rupture of fibre was delayed and failed at 131.45 kN. The three layered specimen CW-700(250)-150-3 failed by buckling followed by rupture of fibre at 139.30 kN. In both the wrapping schemes, the critical buckling portion ie, mid height of the column were completely wrapped. But in the case of specimen wrapped with 700 mm strip width possess better structural performance in the aspect of load carrying capacity and lateral deformation. Here the wrapped portion of the specimen is considered to be the effective, which is greater for the specimen wrapped with 700 mm strip width than the specimen wrapped with 400 mm strip width. Even though both the set of specimens were wrapped with AFRP and CFRP fabric, but the specimen wrapped with 700 mm strip width gives better lateral deformation control owing to effective wrapped zone in the mid height of the column. In no such case, delamination of fibre was taken place, which shows that there exists excellent bonding between specimen and the fibre. The failure modes of some of the specimens are given in Fig 3.

Fig. 3: Failure modes

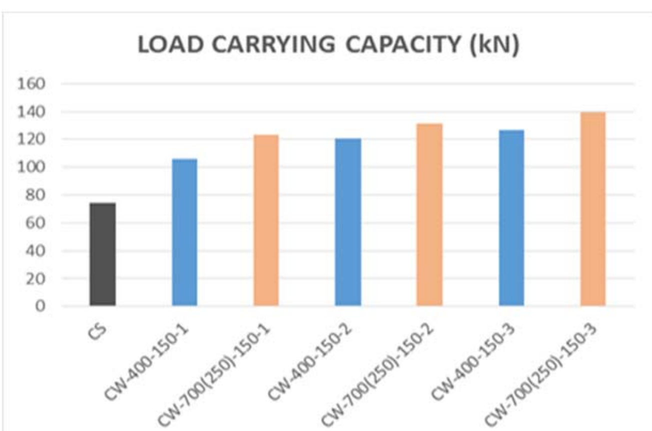
4.2 Load carrying capacity

This experimental investigation mainly focused in providing optimized and economical wrapping scheme of CFRP and AFRP fabric in order to attain enhanced load carrying capacity and appreciable lateral deformation control. The control specimen possessed the capacity of 82 kN and failed by lateral buckling. The experimental results revealed that there exists an increase in load carrying capacity of the wrapped specimens than the unwrapped specimen. When compared to the control specimen, CFRP wrapped specimens such as CW-400-150-1, CW-400-150-2 and CW-400-150-3 possessed

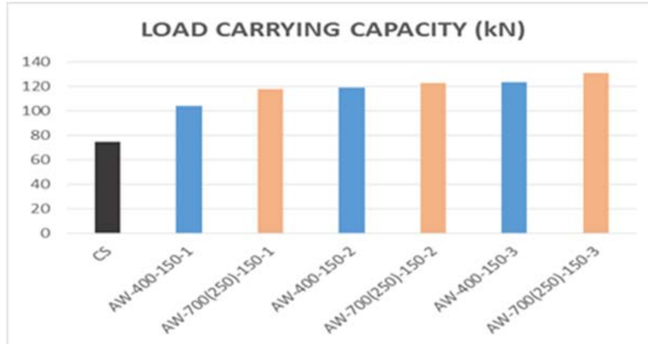
29.19%, 47.14% and 54.31% increase in load carrying capacity. The AFRP wrapped specimens AW-400-150-1, AW-400-150-2 and AW-400-150-3 showed 39.22%, 44.84% and 50.73% increase in strength than the control specimen but showed 10.03%, 7.17% and 3.58% lesser than the CFRP wrapped specimens, which were wrapped with 400 mm strip width with respect to control specimen. The specimens wrapped with carbon strip of 700 mm width have given 50.75%, 60.30% and 69.87% more effective strength when compared to control specimen whereas AFRP wrapped specimens AW-700(250)-150-1, AW-700(250)-150-2 and AW-700(250)-150-3 possessed about 43.72%, 49.97% and 59.33% than the control specimen and also it is about 7.03%, 10.33% and 10.54% than CFRP wrapped specimens with respect to control specimen. The tabulation of load carrying capacity of specimens and the percentage increase in it with respect to the control specimen are given in Table 2.

Table 2: Load carrying capacity.

`S. No	Specimen	Load carrying capacity (kN)	Increment in capacity compared to CS (%)
1	CS	82	-
2	CW-400-150-1	105.94	29.19
3	CW-400-150-2	120.66	47.14
4	CW-400-150-3	126.54	54.31
5	CW-700(250)-150-1	123.60	50.75
6	CW-700(250)-150-2	131.45	60.30
7	CW-700(250)-150-3	139.30	69.87
8	AW-400-150-1	103.72	39.22
9	AW-400-150-2	118.75	44.84
10	AW-400-150-3	123.60	50.73
11	AW-700(250)-150-1	117.85	43.72
12	AW-700(250)-150-2	122.97	49.97
13	AW-700(250)-150-3	130.65	59.33



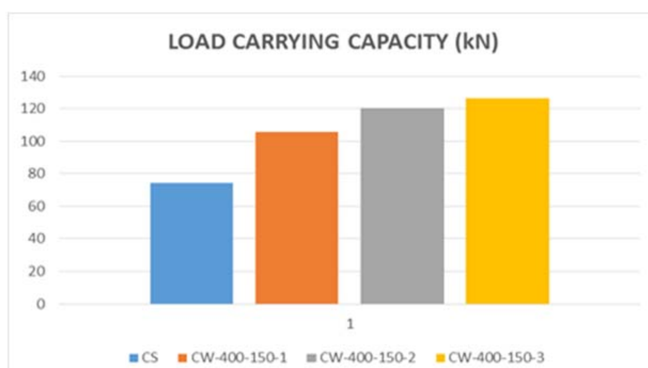
(a) CW-400-150 Vs CW-700(250)-150



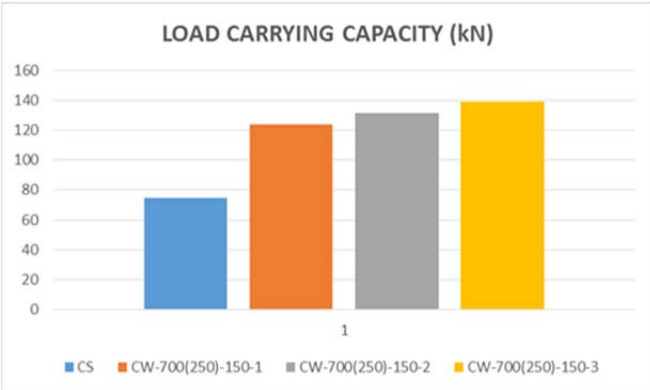
(b) AW-400-150 Vs AW-700(250)-150

Fig. 4: Graphical representation of Load carrying capacity with respect to type of fibre

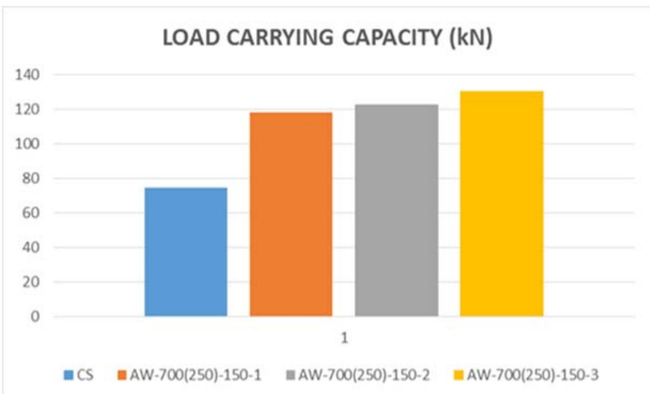
While comparing specimens wrapped with 700 mm strip width at the mid height and 250 mm strip width at the edges with the specimens having 400 mm strip width of spacing 150 mm have given better performance of about 11.98%, 3.43% and 5.39% with respect to the number of wrapping layers. The CFRP wrapped specimens such as CW-400-150-1, CW-400-150-2 and CW-400-150-3 possessed about 14.28%, 8.20% and 9.16% of difference in strength as compared to the specimens CW-700(250)-150-1, CW-700(250)-150-1 and CW-700(250)-3. The test results revealed that the load carrying capacity of wrapped specimen increases with increase in number of wrapping layer. The increase in capacity of CFRP strengthened specimens was higher than the AFRP wrapped specimens. Among the CFRP strengthened specimens, the specimens wrapped with 700 mm strip width possess higher enhancement in load carrying capacity. The capacity attained by the specimen wrapped with two layers carbon fibre strip of 400 mm width is somewhat similar to the capacity of three layered wrapped specimen of 700 mm strip width. While considering AFRP wrapped specimen, the specimen wrapped with 700 mm strip width possess higher capacity but it is lesser than the CFRP wrapped specimen. The graphical representation of load carrying capacity with respect to type of fibre used is given in Fig. 4 and with respect to number of layers shown in Fig. 5.



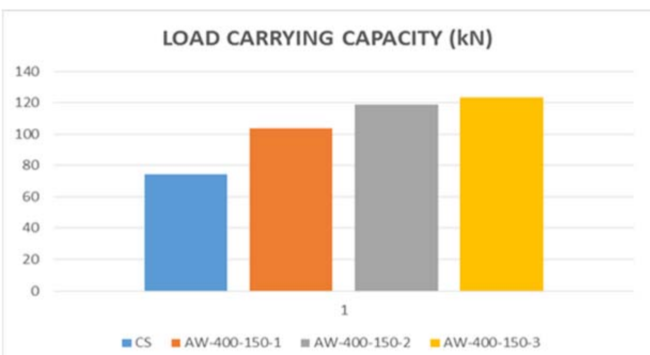
(a) CW-400-150



(b) CW-700(250)-150



(c) AW-400-150



(d) AW-700(250)-150

Fig. 5: Load carrying capacity with respect to number of layers

4.3 Axial load Vs Lateral deformation

The CFST specimens strengthened using FRP composites possess better performance in the aspect of lateral deformation control. By providing external wrapping of FRP composites, there exists confinement, which reduced lateral buckling. The investigation results implied that the control specimen failed by maximum lateral deformation of about 18.2 mm at the mid height of the column whereas the other wrapped specimen at the ultimate load of CS possess lesser lateral deflection. This proved that there is an increase in strength and stiffness of the column due to confinement provided by external wrapping. The specimens wrapped with carbon fibre fabric with 400 mm strip width such as CW-400-150-1, CW-400-150-2 and CW-400-150-3 have given lateral deformation of 12.72 mm, 11.63 mm and 10.47 mm and the percentage increase in deformation control is about 30.10%, 36.09% and 42.47% respectively as compared to the control specimen. But the other set of CFRP wrapped specimens CW-700(250)-150-1, CW-700(250)-150-2 and CW-700(250)-150-3 possessed about 34.61%, 44.06% and 53.68% as compared to CS which is higher than the CFRP specimens wrapped with 400 mm strip width. The lateral deformation of specimens CW-400-150-1, CW-400-150-2 and CW-400-150-3 showed drawdown of 6.89%, 14.24% and 24.19% and 4.51%, 6.38% 11.21% compared to the control specimen. The control in lateral deformation of CFRP wrapped specimens is higher than the AFRP wrapped specimens. AW-400-150-1, AW-400-150-2 and AW-400-150-3 has showed 11.98%, 3.43%, 5.39% and 18.35%, 32.30%, 37.26% higher while comparing with specimens wrapped with aramid fibre strip of 700 mm width and the control specimen respectively. Among the AFRP wrapped specimens, AW-700(250)-150-1 showed better control in deflection of about 9.83 mm which is 13.92% higher than the specimen wrapped with 400 mm strip width and also 8.68% higher than the control specimen. The lateral deformation control provided by two layered wrapped specimens CW-700(250)-150-2 is somewhat similar to CW-400-150-3. It was observed that there exists an appreciable control in lateral deformation as the number of layer of wrapping increased.

5. CONCLUSION

Two types of FRP composites were used in this experimental investigation to examine the axial behavior of CFRP and AFRP strengthened Slender CFST columns. The following conclusions were made based on the results and observation in the aspect of parameters including failure modes, load carrying capacity and lateral deformation control.

Table 2: Lateral Deformation

S. No`	Specimen	Lateral deformation (mm)	Increment in capacity compared to CS (%)
1	CS	18.2	-
2	CW-400-150-1	12.72	30.10
3	CW-400-150-2	11.63	36.09
4	CW-400-150-3	10.47	42.47
5	CW-700(250)-150-1	11.9	34.61
6	CW-700(250)-150-2	10.18	44.06
7	CW-700(250)-150-3	8.43	53.68
8	AW-400-150-1	14.86	18.35
9	AW-400-150-2	12.32	32.30
10	AW-400-150-3	11.42	37.26
11	AW-700(250)-150-1	13.37	26.53
12	AW-700(250)-150-2	10.78	40.74
13	AW-700(250)-150-3	9.83	45.94

- The load carrying capacity of the CFRP strengthened specimen is higher than the AFRP wrapped specimen.
- Since the column is slender, the CS failed by lateral buckling but the strengthened specimens showed appreciable percentage increase in lateral deformation control.
- Among strengthened specimens, the specimens wrapped with fibre strip of 700 mm width such as AW-700(250)-150-3 and CW-700(250)-150-3 possessed about 69.87%, 59.33% and 53.68%, 45.94% percentage increase in load carrying capacity and deformation control respectively as compared to the control specimen.
- From the experimental research work, it is concluded that by providing an optimized and economical wrapping scheme, an existing deteriorated structural elements can be strengthened by means of increased capacity and lateral deformation control.

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