Axial Behaviour of FRP Strengthened Slender CFST Members

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Abstract- **Concrete filled steel tubular (CFST) members has its successive footprints in the construction industry, owing to its high load carrying capacity, improved ductile performance, large energy absorption capacity etc. But these members as columns, have some adverse effects under increased load and climatic conditions. Though lot of techniques is available in the past, plate-bonding technique using fibre reinforced polymer (FRP) plays the maximum role in the strengthening process, as it is flexible. In this research work, experiments are carried out on 13 circular CFST columns of 1500mm height with 42.4mm and 3.2mm diameter and thickness respectively. The study focused on types, width and spacing of FRP strips. Carbon and aramid fibres are bonded with the specimens in order to compare the behavior of externally strengthened slender CFST columns, under the effect of failure modes, axial load Vs lateral deformation and load carrying capacity. Among thirteen columns, each six columns are bonded using 200mm and 300mm width of carbon and aramid fibre strips with 60mm and 100mm spacing. The above research work revealed that there is an improvement in the performance of slender circular CFST columns under axial compression strengthened using FRP fibres.**

Keywords: CFST members, carbon fibre, aramid fibre, slender, compression.

INTRODUCTION

Among the composite structures, concrete filled steel tubular (CFST) structures are gaining more popular in high-rise buildings, bridge piers etc (1). The CFST member also has variety of applications such as columns supporting platforms in offshore structures, roofs of oil storage tanks, large industrial workshops and tall structures, bridges and open-air overhead traveling cranes and also used as piles in foundation. Their use in multistoried building has increased load carrying capacity for reduced cross section resulting in net floor space has been realized. In Japan, they have been used in earthquake resisting structures (2). In the CFST structures, CFST columns are widely used because of its structural and constructional advantages. Here the steel tube acts as a formwork and so, economical effects can also be expected (3). When a CFST column is subjected to an axial compression load, the infill concrete laterally expands due to Poisson's effect and the expansion is confined by circular steel tube (4). The steel tube stiffened by concrete core can prevent inward buckling of steel tube and so increases the strength and stability of column (5). Besides the compressive strength, the ductility capacity is also improved by means of infill concrete.

However, there is a major shortcoming of adopting CFST columns, which is the imperfect interface bonding between concrete and steel tube during initial elastic stage because steel dilates more than concrete. This imperfect bonding will reduce the confining pressure provided by the steel tube and thus reduce the initial stiffness and elastic strength of columns. During their service life, the columns can undergo deterioration caused by environmental effects or fatigue of its constituent materials thus leading to the reduction of the column's strength. Instead of demolishing and then rebuilding the columns, retrofitting or strengthening can be taken as an alternative way to maintain the columns.

In recent years, research has been carried out on FRP strengthening for structural members. FRP are suited as it has high strength-to-weight ratio, good fatigue properties, and excellent resistance to corrosion (6). Their application in civil engineering structures has been growing rapidly in recent years, and is becoming an effective and promising solution for strengthening deteriorated concrete members. Because, FRPs are applied quickly and easily, their use minimizes labor costs and can lead to significant savings in the overall costs of a project. Wrapping FRP transversely with respect to column's axial axis was mostly used in the previous study. These studies proved that circumferential FRP wraps provide considerable confinement pressure to the concrete core under compressive loads delaying the crushing of concrete and buckling of longitudinal steel reinforcement, as a result, increasing the compressive strength and deformation capacity of the column. However, research related to FRP applications to steel structures has started quite recently and there are still few applications in practice due to uncertainties concerning the long-term behaviour of these applications and the bonding between the composite materials and steel.

Y. Che, Q.L. Wang, and Y.B. Shao (7) investigated the behavior of circular CFST stub columns strengthened using carbon fibre reinforced polymer (CFRP) jackets, in terms of strength and stiffness using experimental and analytical expressions, under axial compression. A governing relationship was framed to determine the composite action between steel tube and

CFRP jackets and an ABAQUS model was created and analyzed. Finally, the experimental results matched well with the predicted values for load-deformation relationships. Xiao Yan and Shen Yali (8) reported the effect of CFRP in confining the CFT stub columns in transverse direction, under impact loading condition using drop hammer machine. Failure patterns, impact force time histories, deformation time histories and residual strains were investigated and discussed. Test outcomes showed that the thickness of steel tube and the number of CFRP layers enhanced the resistant behavior of CFT columns.

Zhong Tao and Han Lin-Hai (9) presented the test results of unidirectional CFRP composites in repairing the fire damaged CFST columns and beams under axial compression and bending. CFST columns and beams were tested for square and circular cross sections. Load carrying capacity and stiffness of the specimens were increased with the number of layers. Sherif Yehia, Ghanim Kashwani (10) discussed the research work contributed in the field of composite structures and construction materials, which were exposed high temperature effects. Several experimental investigations, numerical models and design requirements were included in the survey. In addition, behavior of composite structures was discussed. Temperature level, exposure time, protection, and methods used to control a fire have great impact on the performance of structures during and after fire. M.C. Sundarraja and G. Ganesh Prabhu (11) examined the adoptability of unidirectional CFRP strips in improving the axial response of stub CFST members. The CFST columns of square cross sections were strengthened with CFRP strips of width 50mm, with the spacing of 20mm and 30mm. The experimental observations interpreted that the load carrying capacity was increased and the axial deformation was reduced while using CFRP strips. These results differed by ±4%, from the predicted analytical results.

From the past work, the studies has shed some light on FRP, as a confining material in the field of structural engineering both in the aspects of repairing and rehabilitation. However limited research has been conducted in the area of strengthening of slender CFST members using FRP composites. This paper compliments the above uncovered area, by reviewing the following effects that has received recent development; the orientation of FRP fibers, width of the fiber, spacing of the fiber, number of layers, etc.,

MATERIALS PROPERTIES

Steel Tube

The steel tube confirming to IS 1161:1998 is used in this investigation. The properties of steel sections are given in Table 1.

Table 1 Properties of steel sections

Steel tube	Diameter (mm)	Thickness (mm)	Height (mm)	Yield strength MPa
	42.4	3.2	1500	250

CFRP and Aramid Fibre

The unidirectional carbon fibre called MBrace 240, fabricated by BASF India Inc and Aramid fibre 120 were used in this study. The mechanical properties of CFRP and Aramid fibre are given in Table 2.

Table 2 Properties of CFRP and Aramid fabrics

S.No.	Properties	CFRP	Aramid
1.	Modulus of elasticity	240 kN/mm^2	120 kN/mm^2
2.	Tensile Strength	3800 N/mm^2	2900 N/mm^2
3.	Weight of fibre	400 g/m^2	123 g/m^2

Adhesive

The most suitable adhesive material with FRP laminate is MBrace saturant supplied by BASF India Inc is used in this investigation. The main properties as supplied by the manufacturer are given in Table 3.

Table 3 Properties of Saturant

S.No.	Properties	Values
1.	Mixing ratio, by weight	100(Base):50(Hardener)
2.	Mixed Density (kg/litre)	1.13±0.03
3.	Mixed Viscosity (at 25°C)	4000±500
4.	Setting time	< 3 hrs at 25°C
5.	Full cure	7days

Concrete mix

The compressive strength of concrete made out of cubes of size 150x150x150mm, after 28 days was 27.5N/mm^2. The mix proportions of 1:1.6:3.1 with the water-cement ratio of 0.55 was designed using IS code, to achieve the strength of 20N/mm^2.

EXPERIMENTAL PROGRAM

Designation of Specimens

The mild steel tube of 1.5m height was cut from the initial 6m length steel tube. It is circular, with the size of 42.4mm diameter, 3.2mm thickness. The tubes were filled with normal strength concrete and were bonded with CFRP strips to enhance its behavior. One control column and sum of six columns with external wrapping of CFRP strips were tested and observed under axial compression. The following designation was used to identify the specimens: CS, CF-200-60-1, CF-200-60-2, CF-200-60-3, CF-300-100-1, CF-300-100-2, CF-300-100-3, AF-200-60-1, AF-200-60-2, AF-200-60-3, AF-300-100-1, AF-300-100-2, AF-300-100-3. For example, CF-200-60-1 specified that the specimen bonded with one layer of 200mm width carbon fibre strip having 60mm spacing and AF-200-60-1 indicated that the specimen wrapped with one layer of

200mm width aramid fibre strip having 60mm spacing. CS specifies control specimen.

Preparation of Specimens

Initially, a 6m steel tube of 42.4mm diameter, 3.2mm thickness was machined to a height of 1.5m. The tubes were cleaned by using steel wire brush to remove the rust and loose debris. They were then filled up by concrete and allowed for curing. In order to provide surface roughness and to make bond between steel and fibre fabrics, the CFST specimens were subjected to sand blasting process and then the surface was cleaned with acetone solution. One layer of GFRP fabrics was wrapped around the column specimens to prevent direct contact between carbon fibre and steel so as to avoid galvanic corrosion between them, which is shown in Fig. 1. Then longitudinal wrapping of CFRP strips followed it with the specimens as shown in Fig. 2. Then another set of specimens was wrapped with aramid fibre (AFRP) fabrics and is shown in Fig. 3. To remove the entrapped air between the fibre and steel tube, the ribbed roller was used in the direction of fibres. At the end, the specimens were allowed to cure for the period of 10 days.



Fig. 1 GFRP wrapped specimens Fig. 2 CFRP wrapped specimens Fig. 3 AFRP wrapped specimens

Experimental set up and Test Procedure

A hydraulic testing machine of 2000kN capacity was used to test all the specimens under compression. Initial adjustments of placing, centering and levelling were made using plumb bob and spirit level. Linear voltage displacement transducers (LVDT) were fixed at top of the jack and at the mid height of specimens, to measure the axial and lateral deformations. The retrieved data were stored in the 16-Channel Data Acquisition System. An initial load of 20kN was applied, to keep the column in a stable position and then the actual loads were applied at some intervals to study the failure modes, axial deformations, lateral deformations and enhancement in load carrying capacity. The experimental set up is shown in Fig. 3.

EXPERIMENTAL RESULTS AND DISCUSSIONS

This investigation studies included the CFRP and AFRP strips of different width, spacing and number of layers. The compressive behavior of CFRP and AFRP bonded CFST columns were observed and analyzed.

Failure Modes

The overall buckling of steel tube at the mid height was observed in control specimen, as the concrete thrust the steel tube away from its original position and is shown in Fig. 5. On the other hand, inward buckling was restricted by in filled concrete. In case of columns like CF-300-100-1, CF-300-100-2 and CF-300-100-3, the tearing of fibres with loud sound was visualized at the ultimate load of 95 kN, 108 kN and 119 kN respectively, at the mid height of the specimens followed by lateral buckling. The failure of above specimens is shown in Fig. 6. The tearing of fibres occurred along the height of the columns as the steel tube dilated outward created tension in the longitudinal direction of the fibres. Some of the columns like CF-200-60-1, CF-200-60-2 and CF-200-60-3 failed at 86 kN, 89 kN and 93 kN respectively, by crushing of resin followed by rupture of fibre fabrics and is shown in Fig. 7. Similar pattern of failure was recognized in the case of specimens bonded with aramid fibres of 200 mm width strips such as AF-200-60-1, AF-200-60-2 and AF-200-60-3 while reaching the peak load of 84 kN, 88 kN and 90 kN respectively which is shown on Fig. 8. Another set of columns like AF-300-100-1, AF-300-100-2 and AF-300-100-3 shown in Fig. 9 was failed after attaining the load of 91 kN, 94 kN and 98 kN respectively with the bursting of fibre. Beyond the breaking of fibres, no further increment in the strength was monitored. In none of the case, delamination of fibres was observed and this shows the existence of excellent bonding between steel tube and fibre strips.


Fig. 4 Experimental Set up Fig. 5 Failure mode of CS

Fig. 6. Failure of CF-200-60 Specimen

Fig. 7. Failure of CF-300-100 Specimens

Fig. 8. Failure of AF-200-60 Specimens

Fig. 9. Failure of AF-300-100 Specimens

Axial load Vs Lateral deformation

The strength and stiffness of CFST columns were highly influenced by FRP composites. Whilst, the contribution of FRP composites in sustaining the behaviour of CFST columns was reasonable, as the slenderness of CFST columns are under instability problem, which is shown in Figs. 10 and 11.

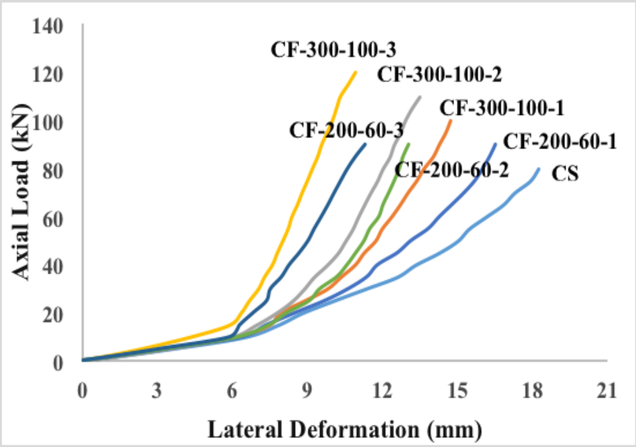

Fig. 10 Axial Load Vs Lateral deformation of CFRP – CFST columns

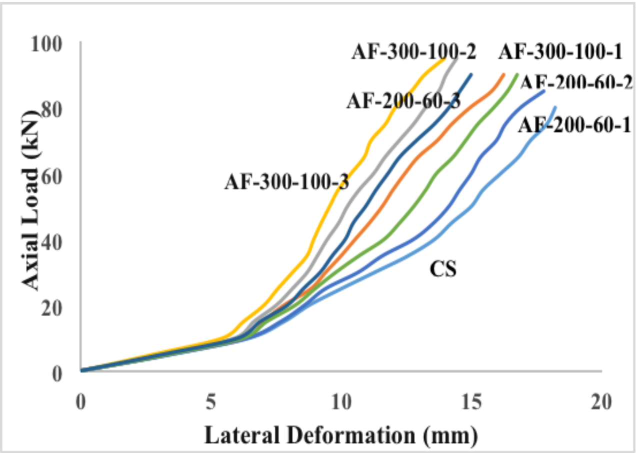

Fig. 11Axial Load Vs Lateral deformation of AFRP – CFST columns

The maximum lateral deformation of 9.51%, 26.98% and 38.13% was observed in the case of columns such as CF-200-60-1, CF-200-60-2 and CF-200-60-3 respectively and when compared with the unstrengthen CFST column, the percentage difference in deformation of above specimens at the failure load of control specimen is in the order of 12.31%, 30.61% and 41.98%. In case of columns bonded with 300mm width CFRP strips such as CF-300-100-1, CF-300-100-2 and CF-300-100-3, the maximum ultimate deformation was found to be 19.34%, 27.75% and 40.22% respectively when compared with control specimen, and, at the ultimate load of bare CFST column, the percentage reduction in control of deformation was found to be 25.16%, 34.18% and 49.67% respectively which is shown in Fig. 12.

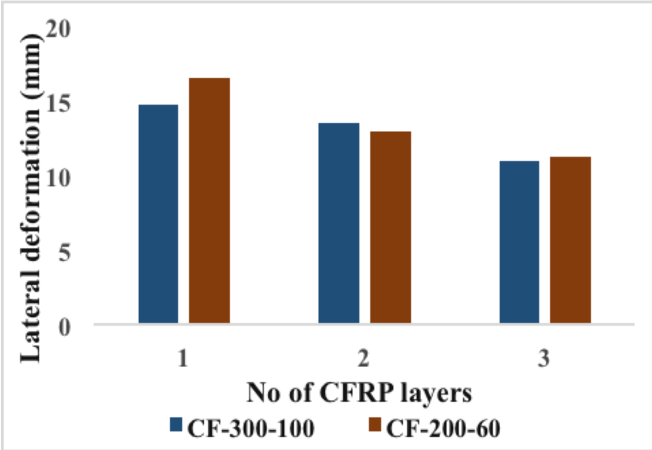

Fig. 12 Lateral deformation Vs Number of CFRP layers

In the similar manner, for the peak load of control column, AFRP wrapped CFST columns AF-200-60-1, AF-200-60-2 and AF-200-60-3, showed drawdown in the rate of lateral deformation of 7.31%, 12.97% and 22.42% respectively. In addition, the above columns showed the peak deformation of 2.42%, 8.02% and 17.75% respectively when compared to bare CFST column. In another set of aramid fibre strips wrapped columns such as AF-300-100-1, AF-300-2 and AF-300-100-3, the lateral deformation was governed in the order of 10.88%, 20.77% and 23.35% with the percentage drop in deformation of 17.97%, 27.36% and 33.74% respectively at the peak load of the unwrapped CFST column which is shown in Fig. 13. These results revealed that the FRP composites wrapped around the CFST columns act as a longitudinal reinforcement and in turn impede the buckling process and thereby complement the strength of CFST columns.

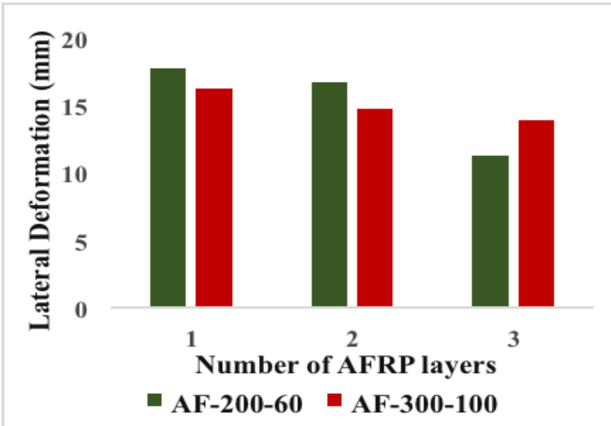

Fig. 13 Lateral deformation Vs Number of AFRP layers

While comparing the aramid fibre with carbon fibre, the percentage of effectiveness of CF-300-100-1, CF-300-100-2 and CF-300-100-3 over AF-300-100-1, AF-300-100-2 and AF-300-100-3 was 8.46%, 8.63% and 16.87% respectively. In case of CF-200-60-1, CF-200-60-2 and CF-200-60-3 columns, the lateral deformation was delayed by 7.09%, 18.96% and 20.38% than that of AF-200-60-1, AF-

200-60-2 and AF-200-60-3 respectively. The above variations in the results reported that the properties such as the modulus of elasticity and tensile strength in the case of carbon fibre are superior to that of aramid fibre. In the case of columns such as CF-300-100-1, CF-300-100-2 and CF-300-100-3, the lateral deformation was restrained to 14.68 mm, 13.45 mm and 10.88 mm respectively, whereas for CF-200-60-1, CF-200-60-2 and CF-200-60-3, the deformation lasted upto 17.76 mm, 16.47 mm and 14.97 mm respectively. This clearly defined that the spacing of FRP strips contributed more in inhibiting the deformation and supplementing the strength of CFST columns. In spite of spacing, the width of fibre enhanced the behaviour as it covered more regions.

The specimen externally bonded with three layers of carbon fibre strips such as CF-200-60-3 and CF-300-100-3 showed 28.62%, 11.15% and 15.77%, 6.38% restraining effect, when compared with the specimens strengthened by respective one and two layers of fibre strips. Similarly, the columns strengthened by three layers of aramid fibre AF-200-60-3 and AF-300-100-3 retained 15.33%, 9.73% and 12.47%, 4.23% lateral deformation than that of corresponding columns bonded with one and two layers. The above analysis interpreted that the performance of CFST columns was improved by increasing the number of layers of FRP composites. This was due to the effective confinement pressure provided by additional layers of FRP composites.

Load carrying capacity

The ultimate aim of this research work is to improve the axial load carrying capacity of slender CFST columns, as those are more prone to overall buckling under axial compression, which is shown in Table 4. Hopefully, it was reached, as the external bonding of longitudinal FRP strips over CFST columns enhanced the axial strength, by delaying the buckling phenomenon. The externally CFRP wrapped CFST columns such as CF-300-100-1, CF-300-100-2 and CF-300-100-3 showed an enhancement of 15.85%, 31.71% and 45.12% respectively and for columns like CF-200-60-1, CF-200-60-2 and CF-200-60-3 it was 4.65%, 8.53% and 13.41% respectively than that of control specimens which is shown in Fig. 14. Similarly, in the case of the CFST columns wrapped with aramid fibre, the enhancement in load carrying capacity of 10.98%, 14.63% and 19.51% respectively for AF-300-100-1, AF-300-100-2 and AF-300-100-3 was observed and it was 2.42%, 7.32% and 9.76% in case of AF-200-60-1, AF-200-60-2 and AF-200-60-3 and is shown in Fig. 15. These results acknowledged the proper association of steel tube with FRP strips under axial compression.

When compared the percentage of enhancement in load carrying capacity between CFST columns bonded with 300 mm width of carbon fibre and aramid fibre, it showed that the carbon fibre complemented the axial strength of 15.85%, 31.71% and 45.12% than that of aramid fibre and in similar manner it also showed 9.89%, 12.77% and 16.32% more in the case of columns wrapped with 200mm width of fibre fabrics. This variation is higher, since the modulus of elasticity and tensile strength of carbon fibre is more when compared with aramid fibre.

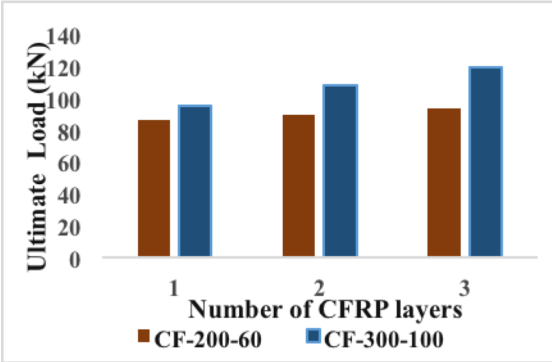

Fig. 14 Ultimate load Vs Number of CFRP layers

To be precise, it was the spacing and number of layers, which restricted the amount of FRP strips, in improving the behaviour of CFST columns. While comparing CF-300-100-1 with CF-200-60-1, the column CF-300-100-1 had (95 kN) more ultimate strength than CF-200-60-1 (86 kN). Moreover, AF-300-100-1 had (91 kN) enhanced load carrying capacity than AF-200-60-1 (84 kN). It seemed to be contrary, as the decreased spacing of FRP strips would restore the strength of CFST columns. But it occurred so, as the confinement width provided by 300 mm strip was greater than 200 mm strip, in spite of same area of wrapped zone.

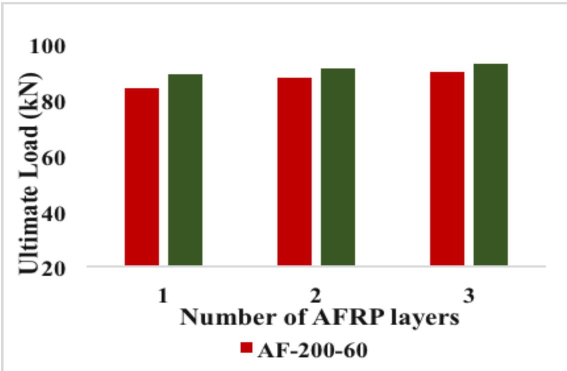

Fig. 15 Ultimate load Vs Number of AFRP layers

Increase in number of layers improves the performance of CFST columns by accelerating the load carrying potential. When comparing, CF-300-100-1 column had percentage difference in strength of 29.27% and 13.41% than CF-300-100-1 and CF-300-100-2 columns and in addition, CF-200-60-3 had 3.88% and 4.88% as the percentage difference in ultimate capacity, than CF-200-60-1 and CF-200-60-2. Correspondingly, AF-300-100-3 had difference of 2.88% and 3.56% for its respective one and two layers, and it was 2.07% and 4.43% for AF-200-60-3 column when compared with AF-200-60-1 and AF-200-60-2 columns. These results were admitted, as the intensity of confining pressure was improved for increasing the number of layers of FRP strips. Besides, it was comparatively less in case of one layer specimen, since the control deformation was smaller than two and three layers.

Table 4 Experimental results of CFRP wrapped CFST columns

Specimen details	Ultimate load (kN)	Maximum lateral deformation (mm)	Decrement in lateral deformation compared to CS (%)	Increment in load carrying capacity compared to CS (%)
CS	82	18.2	--	--
CF-200-60-1	86	16.47	9.51	4.65
CF-200-60-2	89	12.89	29.18	8.53
CF-200-60-3	93	11.26	38.13	13.41
CF-300-100-1	95	14.68	19.34	15.85
CF300-100-2	108	13.45	26.11	31.71
CF-300-100-3	119	10.98	39.67	45.12
AF-200-60-1	84	17.76	2.42	2.44
AF-200-60-2	88	16.74	8.02	7.32
AF-200-60-3	90	14.97	17.75	9.76
AF-300-100-1	91	16.22	10.88	10.98
AF300-100-2	94	14.72	19.12	14.63
AF-300-100-3	98	13.95	23.35	19.51

CONCLUSIONS

Two different types of fibres were used in this investigation to enhance the behavior of CFST columns under axial compression. Ultimate load, failure modes and axial load Vs lateral deformation were discussed and plotted. With respect to the response of CFRP and AFRP bonded CFST columns, the final conclusions can be made as:

- The CFST columns externally strengthened by FRP composites exhibited satisfactory performance than that of unstrengthen CFST column under axial compression.
- The overall buckling of the steel tube, rupture and tearing of fibres were the common failure modes observed in case of FRP wrapped CFST columns. Whist the overall buckling of steel tube was observed in CS, as it was having some structural instability problem of slenderness.
- When comparing the aramid fibre with carbon fibre, the percentage of effectiveness of CF-300-100-1, CF-300-100-2 and CF-300-100-3 over AF-300-100-1, AF-300-100-2 and AF-300-100-3 was 8.46%, 8.63% and 16.87% respectively
- Carbon fibre complemented the axial strength of bare CFST columns by 15.85%, 31.71% and 45.12% than aramid fibre with 9.89%, 12.77% and 16.32% for respective columns of 300 mm strip width and 100 mm spacing with increase in the number of layers.
- From the research work, it can be concluded that the performance of the CFST columns was improved both in terms of structural and functional aspects by using FRP composites. This aspect was more prominent in case of carbon fibre as its mechanical properties were predominant to aramid fibre. The need of FRP composites could be optimized by their width, spacing and number of layers, thereby paved way to an economy pack.

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