A Comparative Study on the Strength Behaviour of Circular Stiffened Concrete-Filled Steel Tube (CFST) and Concrete-Filled Aluminium Alloy Tube (CFAT) Columns

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Abstract - *Steel-concrete composite section is a new idea adopted which comprises of hollow-steel elements equipped with an infill of concrete that replaces either hot-rolled steel or reinforced concrete. Aluminium alloy is used as a building material in curtain walls, bridges and many other structural applications due to its high strength-to-weight ratio, excellent corrosion resistance, ease of extrusion into complex cross sections etc. The concrete filled in aluminium alloy hollow sections could effectively delay inward and outward local buckling failure of aluminium alloy members and greatly enhance load carrying capacity of structural components. However, little research has been carried out on concrete-filled aluminium alloy tube composite columns. Hence, there is a need to investigate the structural performance of concrete-filled steel tube (CFST) and concrete-filled aluminum alloy tube (CFAT) columns and the comparative study of CFST and CFAT. CFST and CFAT members sometimes fail due to detachment of steel and aluminium alloy tube from inside concrete surface. This bond breakage can be reduced by providing stiffeners which enhances bond strength, load-bearing capacity, ductility, buckling of steel and aluminium alloy tube reduced which indicate better bond performance and increase confining effect from steel and aluminium alloy tube to concrete. This paper focuses on experimentally comparing the axial load carrying capacity of circular stiffened CFST and CFAT columns by varying number and layers of stiffeners and determine the best arrangement of stiffeners for circular CFST and CFAT columns. This paper also focuses on experimentally comparing the energy absorption, ductility and failure patterns of circular CFST and CFAT columns with and without stiffeners and to compare the cost of circular CFST and CFAT columns.*

***Key Words*: Local buckling, Load carrying capacity, Concrete-filled steel tube, Concrete-filled aluminum alloy tube, Stiffeners, Ductility, Energy absorption, Failure patterns.**

1. INTRODUCTION

1.1 CFST Columns

Concrete filled steel tube columns have been popular for use as individual column elements. The confined concrete fill increases the axial load resistance but has little effect on the flexural resistance [2]. For that reason, it is unlikely that these columns would be a good choice for a moment resisting frame [9]. Filling the tube with concrete will increase the ultimate strength of the member without significant increase in cost [1]. The main effect of concrete is that it delays the local buckling of tube wall [1,2,3]. The concrete itself, in the restrained state, is able to sustain higher stresses and strains than when in the unrestrained state [12]. The CFST structural member has a number of distinct advantages over an equivalent steel, reinforced concrete, or steel-reinforced concrete member. Structures subjected to seismic loadings, composite column can provide a better ductility and load retention even after extensive concrete damage. CFST column is very useful for rehabilitation of structures such as bridge piers, high-rise buildings etc. [3]. The steel lies at the outer perimeter where it performs most effectively in tension and in resisting bending moment [10]. The concrete forms an ideal core to withstand the compressive loading in typical applications, and it delays and often prevents local buckling of the steel tube. The building which utilized concrete filled steel tubes was able to reduce the column dimension compared to ordinary column [1]. The design was able to generate large workspace thus unlocking the valuable space for commercial uses. The CFST columns has been used in residential buildings, high rise buildings, bridges, subway stations, power plant workshop, electricity pylon etc. [1,3,11].

The paper consists of an experimental investigation on the ultimate axial load carrying capacity, energy absorption, ductility and failure patterns of CFST and CFAT column specimens with and without stiffeners having difference in arrangement of stiffeners.

1.2 CFAT Columns

Aluminium alloy is used as building material in curtain walls, bridges and many other structural applications due to its high strength-to-weight ratio, excellent corrosion resistance, ease of extrusion into complex cross sections, ease of production etc. Furthermore, aluminum alloy tubes surrounding concrete eliminate permanent formwork, has high strength and high stiffness, and as such, construction time can be reduced [6,7,8]. Light-weight aluminum tubular members are used for structural applications, especially in space structures, claddings and curtain walls [6]. The concrete filled in aluminium alloy hollow sections could effectively delay inward and outward local buckling failure of aluminium alloy members and greatly enhance load carrying capacity of structural components [4,5]. The aluminum alloy tubular members are normally manufactured by heat-treated aluminum alloys, because heat-treated alloys have notably higher yield stress than non-heat-treated alloys. However, when heat-treated aluminum alloys are welded, the heat generated from the welding reduces the material strength significantly in a localized region, and this is known as the heat-affected zone (HAZ) softening [7].

1.3 Need of Stiffeners

CFST and CFAT members sometimes fail due to detachment of steel and aluminium alloy tube from inside concrete surface. This bond breakage can be reduced by providing stiffeners which enhances bond strength, load-bearing capacity, ductility in compression of CFST and CFAT members, buckling of steel and aluminium alloy tubes reduced which indicate better bond performance and increase confining effect from steel and aluminium alloy tubes to concrete [1,15]. The best arrangement of stiffeners for circular CFST and CFAT column is T-shaped stiffeners, ie., welding shear studs on internal tube surfaces, which enhances behavior of CFST columns in terms of strength and ductility [2]. Fig -1 shows T-shaped stiffener arrangement in CFST column.

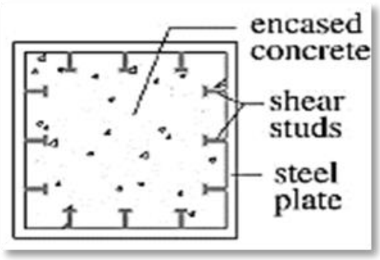


Fig -1: T-shaped stiffener arrangement in CFST column [2]

2. EXPERIMENTAL INVESTIGATION

2.1 Concrete Mix Design Details

A concrete mix of 25 MPa was used for this study. The concrete mix design was done as per IS 456:2000 and IS 10262:2009 inorder to achieve a 28th day compressive strength. The materials were tested for various properties needed for the mix design. Ordinary Portland Cement of grade 53 was used for the experiment. The coarse aggregates used were of size 10 mm and M-sand was used as fine aggregate. Admixture of type MASTER GLENIUM SKY 8433 produced by BASF Incorporation was added to increase the workability of concrete and to minimize the amount of water-cement ratio, for obtaining a desired slump range of 75 mm–125 mm for normal RCC work as per IS 456:2000, Cl.7.1. The final mix proportion adopted is as shown in the table -1.

Table -1: Concrete mix proportions

Grade	Mix Proportion			w/c ratio	Super-plasticizer	Compressive strength (N/mm^2)	
	Cement	Fine aggregate	Coarse aggregate			7^{th} day	28^{th} day
M25	1	2.43	2.13	0.42	0.20%	20.35	32.4

2.2 Details of CFST and CFAT specimens

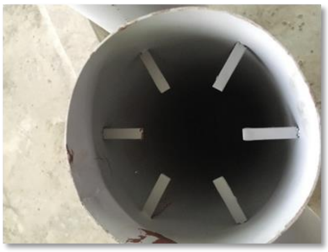
A total of ten column specimens were casted which includes five CFST column specimens and five CFAT column specimens. The required steel was mild steel (f_y= 270 N/mm^2) and aluminum alloy was 6061-T6 heat treated aluminium alloy (f_y= 270 N/mm^2) were purchased from the local market to fabricate the column. The mild steel sheet was fully welded throughout the seam and aluminium alloy sheet was riveted by overlapping the aluminium sheet and henceforth spot welded to obtain a tube shape. Each five CFST and CFAT column specimen includes one CFST and CFAT column without stiffener and four CFST and CFAT columns with different arrangement in number and layers of stiffeners. All the columns were 600 mm long with a diameter of 150 mm and a thickness of 1.5 mm. Stiffeners were provided at a 50 mm from top and bottom ends of the tubes having a total of 12 numbers in each tube with a length, breadth and thickness of 35 mm, 3 mm and 1.5 mm respectively. Stiffeners having equal area were provided throughout the height for all the columns. The bottom surface of CFST and CFAT was covered with a plate of 1.5 mm thick. All columns had the same geometrical dimensions and they are tested to failure. The columns are indicated by the label S1, S2, S3, S4, S5 for CFST specimens and A1, A2, A3, A4, A5 for CFAT specimens where 'S' represents steel, 'A' represents aluminium alloy and 1,2,3,4 and 5 represents different arrangement of stiffeners in terms of number and layers. The further details of specimens are as shown in table-2.

Table -2: Details of specimens

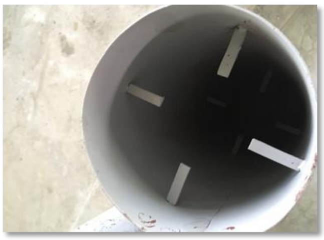
Label	Specimen Description
S2	CFST column specimen with 2 numbers of stiffeners in 6 layers
S3	CFST column specimen with 6 numbers of stiffeners in 2 layers
S4	CFST column specimen with 3 numbers of stiffeners in 4 layers
S5	CFST column specimen with 4 numbers of stiffeners in 3 layers
A1	CFAT column specimen without stiffeners
A2	CFAT column specimen with 2 numbers of stiffeners in 6 layers
A3	CFAT column specimen with 6 numbers of stiffeners in 2 layers
A4	CFAT column specimen with 3 numbers of stiffeners in 4 layers
A5	CFAT column specimen with 4 numbers of stiffeners in 3 layers

The different arrangement of stiffeners in Steel Tubes are shown in Fig -2.

(a) (b)



(c) (d)



(e)

Fig -2: Different arrangement of stiffeners in Steel Tubes: (a) S1 (b) S2 (c) S3 (d) S4 (e) S5

The different arrangement of stiffeners in Aluminium alloy Tubes are shown in Fig -3.

(a) (b)

(c) (d)

(e)

Fig -3: Different arrangement of stiffeners in Aluminium alloy Tubes: (a) A1 (b) A2 (c) A3 (d) A4 (e) A5

2.3 Casting of CFST and CFAT Column Specimens

For conducting experiment, the proportion of 1:2.43:2.13 was taken for cement, fine aggregate and coarse aggregate. Initially, the concrete floor of the laboratory was properly cleaned to avoid the undulations which was created by the small particles during the column casting. The machine mixed concrete was batched in the laboratory, poured into the steel and aluminium alloy moulds and compacted using tamping rod. After compacting, the surface of concrete was levelled and finished. From the next day, the columns were cured for 28 days in curing tank.

2.4 Experimental setup

The CFST and CFAT specimens were tested in Universal Testing Machine (UTM) having load carrying capacity of 1000kN. The columns were tested under axial loading. Deflection of the column specimens were measured using a dial gauge (deflectometer) of least count 0.01 mm. Load was applied axially on the top surface of the CFST and CFAT column specimens at a uniform rate till the ultimate failure occurred. For each load of 10 kN, the deflection were recorded. All specimens were subjected to load up till failure. Testing procedure for all the column specimens were same. Thus load carrying capacity of each column specimen would be calculated by applying load. The load was applied gradually up to an ultimate load and deflections were measured at various load stages. The experimental test setup of column specimens is shown in Fig -4.

Fig -4: Experimental test setup of column specimens

3. RESULTS AND DISCUSSIONS

3.1 Ultimate Load Carrying Capacity

A summary of test results for ultimate load carrying capacity and deflection of all CFST column specimens are shown in table -3.

Table -3: Observed test results of CFST and CFAT column specimens

Sl.No.	Specimen name	Ultimate load (kN)	Ultimate axial deflection (mm)
1.	S1	265	4.65
2.	S2	352	6.23
3.	S3	290	5.00
4.	S4	387	7.00
5.	S5	330	5.50
6.	A1	520	5.00
7.	A2	695	6.53
8.	A3	586	5.52
9.	A4	760	10.50
10.	A5	644	6.00

The load vs deflection curve for the column specimens without stiffeners (S1) and with stiffeners of different arrangement (S2,S3,S4,S5) were shown in chart -1.

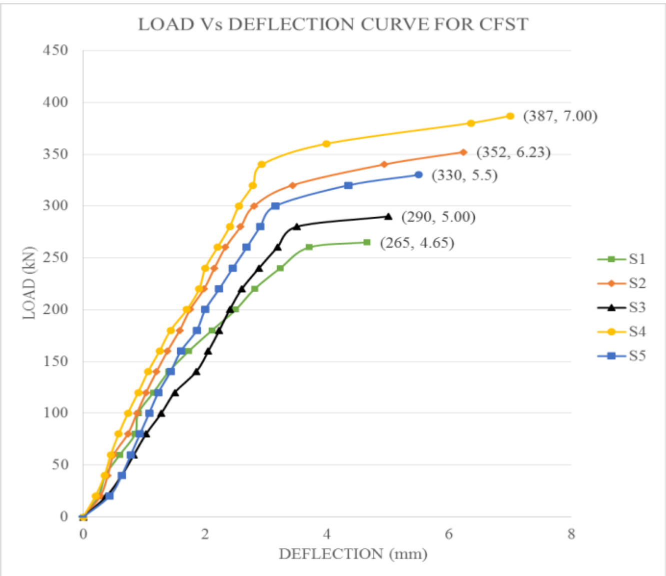


Chart -1: Load vs deflection curve for CFST column specimens with and without stiffeners

The load vs deflection curve for the column specimens without stiffeners (A1) and with stiffeners of different arrangement (A2,A3,A4,A5) were shown in chart -2.

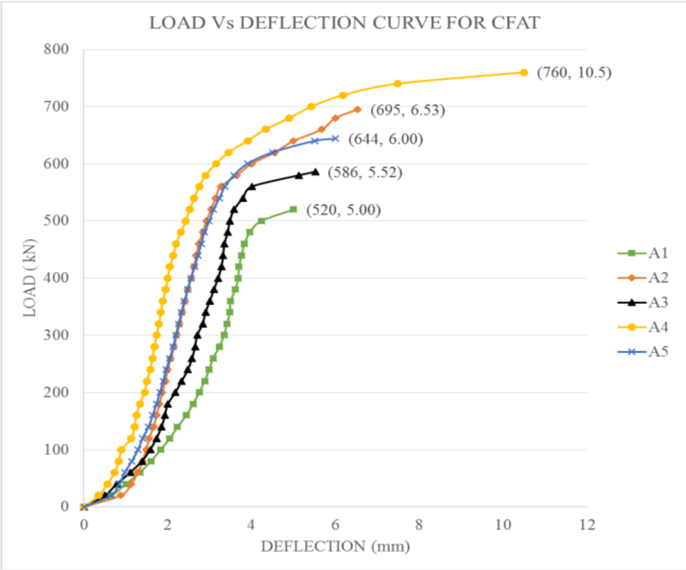


Chart -2: Load vs deflection curve for CFAT column specimens with and without stiffeners

The chart -3 shows Variation of Ultimate loads (kN) for CFST and CFAT column specimens.

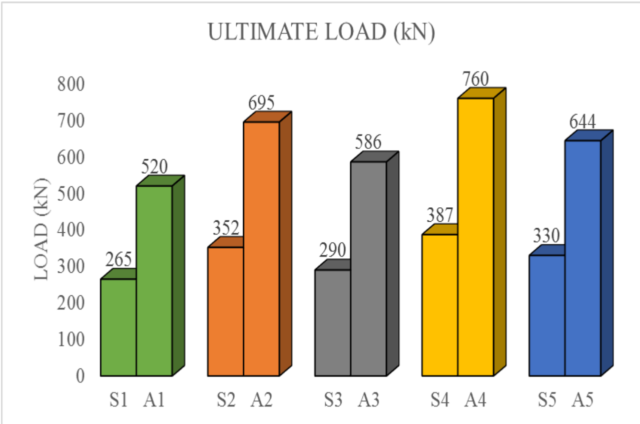


Chart -3: Variation of Ultimate loads (kN) for CFST and CFAT column specimens

The measured ultimate load carrying capacity of stiffened CFST and CFAT column specimens is larger when compared to CFST and CFAT column specimens without stiffeners. This increase is due to the increase in bond strength between steel or aluminium alloy tube and in-filled concrete in stiffened CFST or CFAT and due to larger effect of confining pressure provided by the stiffeners to the steel or aluminium alloy tube and the in-filled concrete. From the chart -3, we can conclude that the load carrying capacity for CFAT column specimens with and without stiffeners is almost double than that for CFST column specimens with and without stiffeners. This is because CFST can delay and prevent local buckling of the steel tube but in CFAT, the concrete filled in aluminium alloy hollow sections could effectively delay inward and outward local buckling failure of aluminium alloy members and thereby greatly enhance load carrying capacity of structural components.

The best arrangement of stiffeners in CFST is S4 (3 numbers of stiffeners in 4 layers) with an ultimate load of 387 kN and for CFAT is A4 (3 numbers of stiffeners in 4 layers) with an ultimate load of 760 kN. The ultimate load carrying capacity of stiffened CFST and CFAT increases as both the number of stiffeners in each layer and layer of stiffeners increases due to increase in bond strength between steel or aluminium alloy tube and concrete in-fill.

3.2 Deflection ductility index (DI)

As per IS 1893 (Part-1): 2002, the ductility of a structure or its members is the capacity to undergo large inelastic deformations without significant loss of strength or stiffness. The displacement ductility index, is defined as the ratio of deflection at ultimate load to the deflection at the yield load. The Table -4 represents the deflection ductility index and ratios of CFST column specimens.

Table -4: Deflection Ductility index and ratios of CFST and CFAT column specimens

Specimen name	Max deflection (mm)	Yield deflection (mm)	Deflection Ductility Index (DI)
S1	4.65	3.83	1.215
S2	6.23	3.00	2.077
S3	5	3.5	1.429
S4	7	2.93	2.389
S5	5.50	3.28	1.677
A1	5.00	4.23	1.182
A2	6.53	3.36	1.943
A3	5.52	4.13	1.337
A4	10.50	3.15	3.333
A5	6.00	4.05	1.481

The chart -4 shows Variation of deflection ductility index (DI) for CFST and CFAT column specimens.

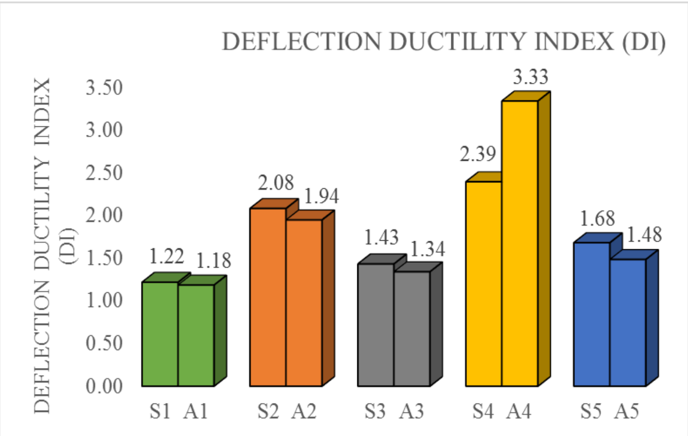


Chart -4: Variation of deflection ductility index (DI) for CFST and CFAT column specimens

The deflection ductility indices is greater for stiffened CFST and CFAT column specimens than CFST and CFAT column specimen without stiffeners due to increase in load carrying capacity, confining effect and bond strength in stiffened CFST and CFAT column specimens. From the chart-4, we can conclude that the deflection ductility index for CFST column specimens (S1, S2, S3 and S5) is slightly greater than that for CFAT column specimens (A1, A2, A3 and A5). This is because mild steel used in CFST has more ductility compared to aluminium alloy used in CFAT. As per chart -4, it is also observed that the deflection ductility index for A4 (CFAT) is greater than that of S4 (CFST). This is against the pattern of deflection ductility index variation observed for other specimen categories. This variation of increase in deflection ductility index can be presumed because of the maximum load and deflection resulted in the experiment.

3.3 Energy Absorption

The area under the load-deflection curve up to the ultimate load is taken as the energy absorbed by the CFST and CFAT column specimens with and without stiffeners. The chart -5 shows Variation of energy absorption (J) for CFST and CFAT column specimens.

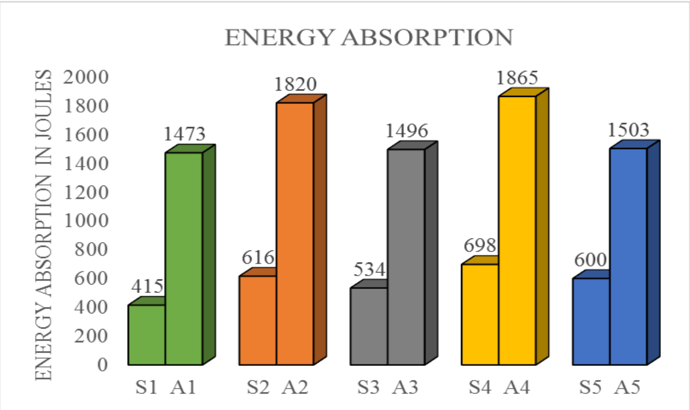
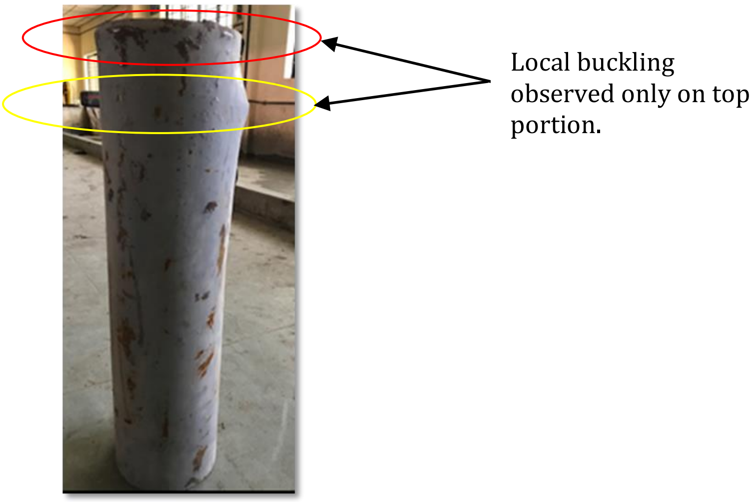


Chart -5: Variation of energy absorption (J) for CFST and CFAT column specimens

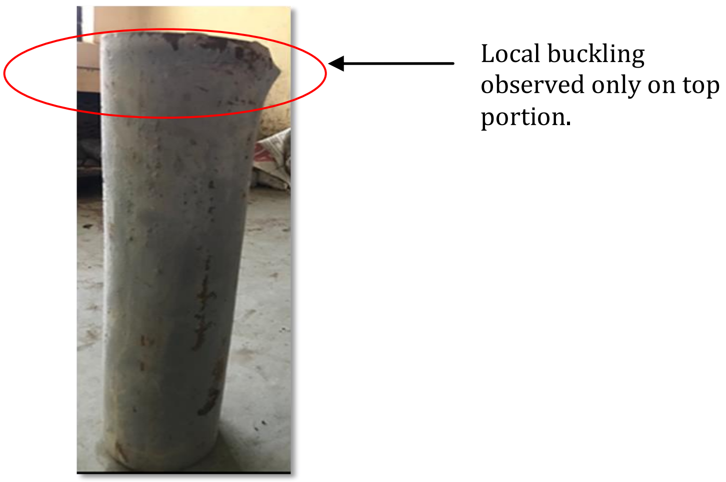
The CFST and CFAT columns with stiffeners has increased energy absorption compared to the CFST and CFAT columns without stiffeners. However, increasing both the number of stiffeners in each layer and layer of stiffeners in CFST and CFAT has improved the energy absorption due to the increased load carrying capacity of the same. From the chart -5, the energy absorption for CFAT column specimens with and without stiffeners is greater than that for CFST column specimens with and without stiffeners. This is because the load carrying capacity for CFAT column specimens is almost double than that for CFST column specimens.

3.4 Failure Pattern of CFST and CFAT Columns

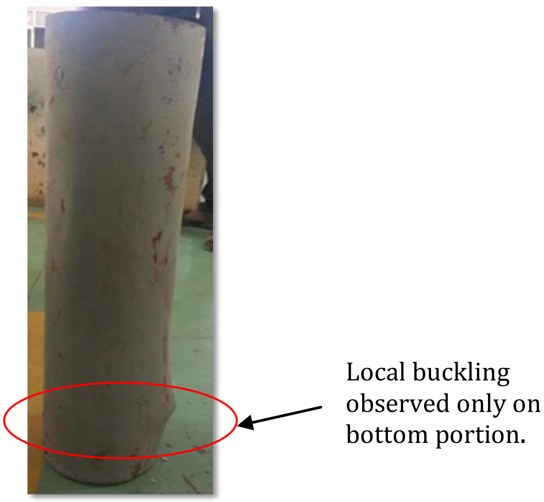
The local buckling of the steel and aluminium alloy tube was visible in all the specimens. In most of the CFST and CFAT specimens, local buckling was observed near the top portion (one fourth height of column) of the steel and aluminium alloy tube and a slight buckling was observed near the bottom portion in S3 and S4 of the CFST column specimens. The failure mode obtained for the stiffened and unstiffened CFST and CFAT columns are shown below.



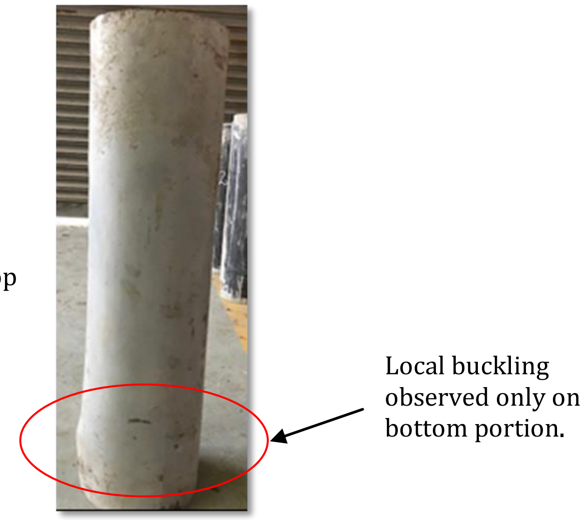
(a) S1



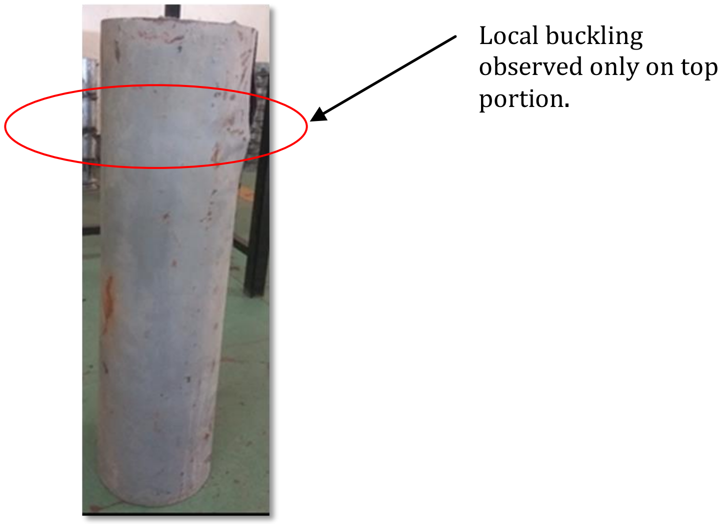
(b) S2



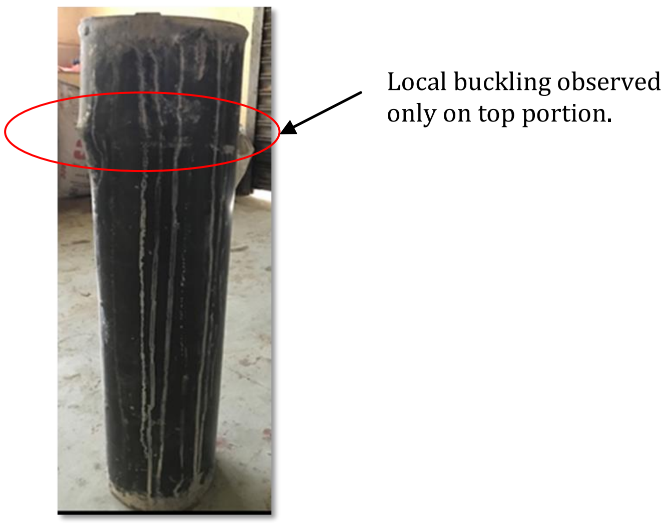
(c) S3



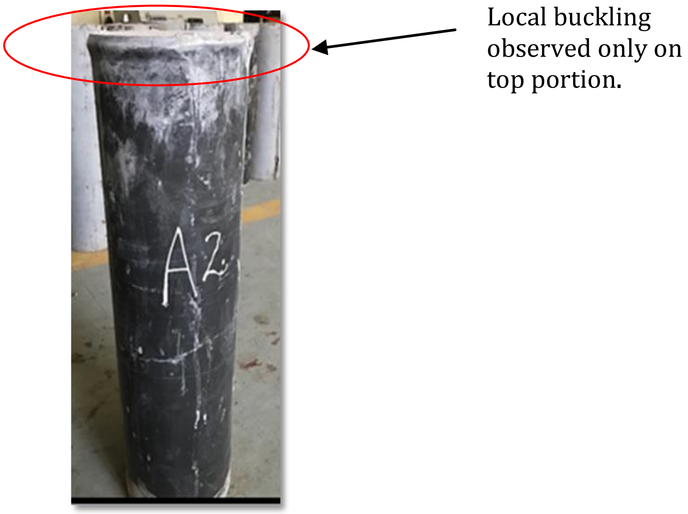
(d) S4



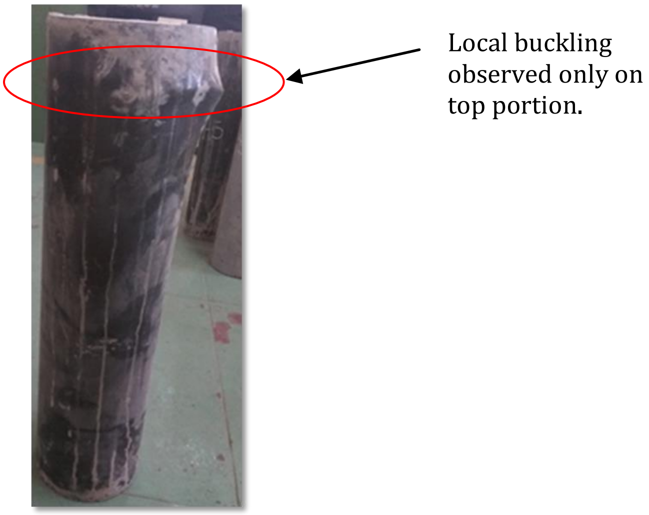
(e) S5



(f) A1

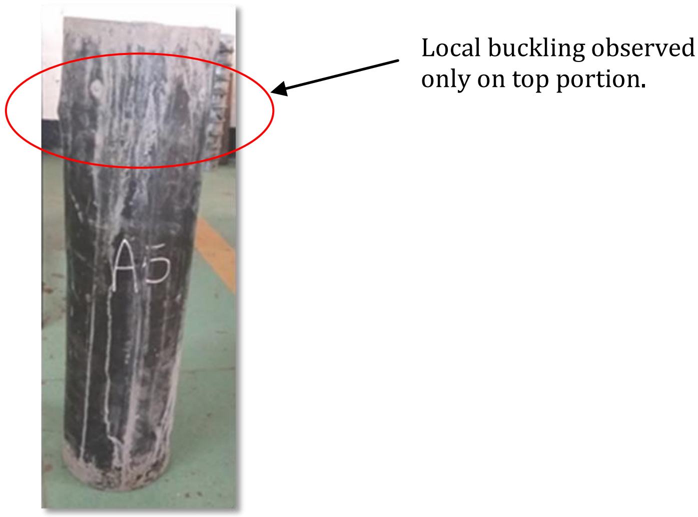


(g) A2



(h) A3

(i) A4



(j) A5

Fig -5: Failure patterns observed for CFST and CFAT column specimens

3.5 Cost Effectiveness of CFST and CFAT Column Specimens

- Cost of Mild Steel sheet= ₹270/kg
- Cost of Aluminium alloy sheet = ₹500/kg

The cost analysis considering ultimate load for each CFST and CFAT column specimen is shown in Table -5.

Table -5: Cost analysis for each CFST and CFAT column specimen

Specimen	Cost for each specimen (₹)	Ultimate load (kN)	Load increase in (%)	Cost increase in (%)
S1	300	265	-	-
S2	480	352	32.83	60
S3	480	290	9.43	60
S4	480	387	46.04	60
S5	480	330	24.53	60
A1	500	520	-	-
A2	860	695	33.65	72
A3	860	586	12.69	72
A4	860	760	46.15	72
A5	860	644	23.85	72

From the above results, it is clear that for CFST, the percentage increase in cost was found to be 60 and for CFAT, the percentage increase in cost was found to be 72. While comparing both CFST and CFAT in terms of cost, there is a percentage increase of 12% for CFAT compared to other. However, studies can be made with much economically viable aluminium alloy tubes for achieving cost effectiveness.

4. CONCLUSIONS

The major conclusions derived from the experimental investigations carried out on the stiffened and unstiffened CFST and CFAT column specimens are as follows:

- The measured ultimate load carrying capacity of stiffened CFST and CFAT column specimens is larger when compared to CFST and CFAT column specimens without stiffeners.
- The load carrying capacity for CFAT column specimens with and without stiffeners is almost double than that for CFST column specimens with and without stiffeners.
- The best arrangement of stiffeners in CFST is S4 (3 numbers of stiffeners in 4 layers) with an ultimate load of 387 kN and for CFAT is A4 (3 numbers of stiffeners in 4 layers) with an ultimate load of 760 kN.
- The deflection ductility indices is greater for stiffened CFST and CFAT column specimens than CFST and CFAT column specimen without stiffeners. The deflection ductility index for CFST column specimens is slightly greater than that for CFAT column specimens, however due to maximum load and corresponding higher value of deflection obtained for A4, deflection ductility index for A4 was greater than that for S4 CFST column specimen.
- The CFST and CFAT columns with stiffeners has increased energy absorption compared to the CFST and CFAT columns without stiffeners. The CFAT column specimens has more energy absorption capacity than CFST column specimens.
- In case of CFST, the percentage increase in cost was found to be 60 and for CFAT, the percentage increase in cost was found to be 72. While comparing both CFST and CFAT in terms of cost, there is a percentage increase of 12% for CFAT compared to other. However, studies can be made with much economically viable aluminium alloy tubes for achieving cost effectiveness.

Finally, it can be concluded that CFAT specimen is capable of taking more load compared to that of CFST specimen. It can be concluded that, from all aspects CFAT specimens is a better choice when compared with CFST specimens. Therefore we can conclude that CFAT specimen can be effectively used in structures like high rise buildings, bridges, curtain walls, subway stations, power plant workshop, electricity pylon etc.

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