BEHAVIOUR OF CFRP CONFINED CIRCULAR CFST COLUMN FILLED WITH LIGHTWEIGHT CONCRETE UNDER AXIAL LOADING

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Highlights

- Compressive behavior of CFRP-confined CFST column with lightweight concrete as infill.
- Numerical prediction of compressive strength based on Prabhu et al. (2015).
- Finite Element Modelling of Lightweight CFST column and its validation.

Keywords: *Concrete-filled steel tube, Lightweight concrete, Carbon Fiber Reinforced Polymer, Compressive strength, Failure modes.*

Nomenclature

A_c	Cross-sectional area of filled concrete
A_s	Cross-sectional area of a stainless-steel tube
D	Diameter (External) of circular cross-section
f'_{ccon}	Compressive strength of CFRP confined CFST circular column
f_{ck}	Cylinder compressive strength of concrete
f_{frp}	Tensile strength of FRP
f_{lcon}	Lateral confinement pressure
f_{uncon}	Unconfined compressive strength of CFST column
f_y	Yield stress of steel tube
k	Effective confinement coefficient
n	Number of CFRP layers
$N_{pl,Rd}$	Axial load carrying capacity
t_{frp}	Thickness of the FRP confinement

ABSTRACT

Recently, the use of Concrete Filled Steel Tubular (CFST) columns is popular because of the load resistance of both the steel and the concrete. The use of lightweight concrete as an infill in CFST columns can reduce its self-weight without much more reduction in its capacity and hence more convenient in the case of multi-storied buildings compared to normal reinforced concrete columns. By confining with Carbon Fiber Reinforced Polymer (CFRP) the strength of Light-Weight CFST (LWCFST) columns can be further improved. This paper consists of an experimental program, Finite Element Analysis, and numerical prediction for the determination of the behavior of CFRP-confined circular LWCFST columns. The strength of the LWCFST column increased considerably with the use of the CFRP confinement and it also depends on the thickness of the confinement.

1. INTRODUCTION

Over time, the construction industry has witnessed various composite structures for high-performance columns designed far better regarding strength and serviceability. CFST columns are such a structure that outstands conventional columns in various structural properties such as better bearing capacity, good ductility, fire resistance, etc. A steel tube filled with concrete as its core is termed as CFST column. It uses the benefits of both concrete and steel, which brings down the requirement of concrete by a significant amount and thus economizes the structure [1][2] [3]

Experimental studies show that with the increase in load, CFST usually buckles outward, and leads to damage to the structure by the reduction of confinement effect [4]. This is more common in CFST columns with high-strength steel because of its smaller cross-section and the larger width-to-thickness ratio [5][6][7]. To counteract this, the effective method is to strengthen it against buckling [8].

The main advantage of the CFST column is the bonding interaction between the concrete and steel tube, i.e., the restriction created by concrete delays the local buckling of the steel tube, and the confinement created by the steel tube enhances the strength of concrete, thus the compressive strength and ductility of the concrete and axial capacity of columns are enhanced. Since no formwork is required and no longitudinal or lateral concrete reinforcement is used, the speed of construction has increased a lot [9]. It rapidly increases the popularity of CFST columns.

Even though the interaction between concrete and steel increases the ductility of concrete and prevents the inward buckling of steel tubes, there still exist the failure mechanisms of a column by the outward buckling of steel tubes. Another problem encountered during the service period is the corrosion of steel tube in severe climatic conditions since it is directly exposed to the atmosphere. These problems give rise to the idea of providing CFRP confinement on the surface of the CFST column[10].

Due to the lightweight, high tensile strength, corrosion resistance, etc. the use of CFRP increased [11][12][13][14][15]. The buckling of the steel tube in the CFST column can be restrained considerably by CFRP confinement over it [16]. The CFRP consists of carbon fibers with high elastic strength embedded in the epoxy resin matrix. It provides sufficient confining effect to columns, thus preventing outward bulging of the steel tube and also protecting it from severe exposures to the environment [17].

Previous studies also show that confinement by Fiber Reinforced Polymer (FRP) can improve the capacity of the column. The improvement in load capacity is usually more observed in rectangular sections. Confined columns exhibit better ductility; hence failure is associated with shear [18]. Since the thickness of the tube influences the capacity of the column; the thickness and number of

FRP layers can also play an important effect on its performance [19]. The failure of the column is generally by wrap rupture of FRP, which occurred at corners in square columns whereas at mid-height in circular columns [20].

CFST columns are divided into three based on slenderness ratio – stub column, moderate slender column, and slender column. Commonly, the failure of the stub column is strength failure and for the slender column, it is due to overall buckling. Moderate column fails in between strength failure and instability failure. Research shows that the performance of CFRP-confined CFST columns under axial loading is mainly concentrated in stub columns [21] [22][23].

Lightweight concrete (LWC) was another revolutionary invention in the civil engineering field. It brings down the self-weight of the structure by a marginal amount but, it provides less strength as compared with generally used concrete. Lightweight concrete consists of lightweight aggregate such as pumice, scoria, etc. [24]. Multistory buildings constructed with LWCFST columns are way much better and serviceable as compared with normal steel or RCC column. The lightweight concrete also has importance in column behavior; since it can reduce about 25-30% of self-weight with not much reduction in its strength [25].

Partial CFRP wrapping with CFRP strip spacing over CFST columns are effective in strength increment and the economical strip spacing is 20 mm [26]. Strain hardening effect became more better for stainless steel with the increase in CFRP confinement layer on CFST column [27] . Effect of CFRP on CFST column improved with increase in CFRP layers, but decreased with increase in concrete strength [28]. Numerical prediction is done and verified with the experimental data [26][27][28]. Finite Element Model (FEM) of CFST column was developed and validated with experimental results [27].

There are only a limited number of studies related to the compressive behavior of LWCFST columns confined with CFRP. So, this paper includes the compression behavior of CFRP-confined circular LWCFST columns under axial loading. The experimental parameters included concrete strength and CFRP confinement. The failure mode was analyzed and the axial load-displacement curves were presented.

2. EXPERIMENTAL STUDY

2.1 Material Properties

The main components of CFRP-confined LWCFST columns are steel, lightweight concrete, and CFRP composite.

2.1.1 Steel

The size and properties of steel tubes used consisted of a tube thickness of 2 mm, an outer diameter of 76.2 mm, a length of 600mm, young's modulus of 1.9×10^5 MPa, and Poisson's ratio of 0.3.

2.1.2 Concrete

Lightweight concrete M30 (1:1.45:1.4 with w/c ratio of 0.38) was adopted. It was prepared using the materials such as; 53-grade OPC cement confirming to IS 12269:1987. LWC was prepared by using M-sand confirming to IS-383:1970 belonging to zone II, light-weight Pumice stone aggregate, the admixture of superplasticizer, and water. Three cubes of 150 mm x 150 mm x150 mm were tested to get the compressive strength. The prepared mix shows a satisfactory density of 1702.42 kg/m³ and exhibits an average 28-day strength of 32.3 MPa.

2.1.3 CFRP and Epoxy Glue

The confinement on the column was provided using CFRP composite sheet. The composite consisted of carbon fibers winded in a biaxial direction embedded in an epoxy resin matrix. The fibers exhibit an ultimate strength of 690 MPa axially with a tangent modulus of 230 GPa.

2.2 Preparation of Specimens

For the study of compressive behavior, a total of 9 LWCFST columns were prepared, of which, three columns are without FRP confinement, three columns are with 1 layer of FRP wrapping, and three columns are with 2 layers of FRP wrapping. The carbon fabric was wrapped by cutting it at the required size and applying a sufficient quantity of epoxy resin. 24 hours were provided for the curing of the resin. Fig. 1 shows the prepared specimens.

(a) (b)

Fig. 1. Preparation of Specimens: (a) casting of column specimen and (b) specimen wrapped with CFRP

2.3 Instrumentation and Test Setup

All the columns were tested under compression axial loads with a high degree of accuracy universal testing machine with a capacity of 100 Tonnes and the test setup is shown in Fig. 2. The column specimen was centered within the UTM to make sure that the axial compressive load is acting through the centroid of the specimen with no eccentricity as shown in Fig. 3. The ends of the specimen are ground for smoothened and leveled surfaces to get rid of any kind of surface irregularities and for uniform loading on the specimen surface.

The vertical displacement of the lower movable head of the testing machine was measured about the upper head of the testing machine using an LVDT of accuracy up to 0.01 mm. Readings of applied load from UTM and displacement from LVDT were recorded at regular intervals during the tests. The axial load was applied at a rate of 10 Tonnes/min. This implementation of the load continued up to the failure of the column. While testing, LVDT was connected to all specimens to the bottom face of the specimen by a steel plate to measure the displacement of the column under compression.

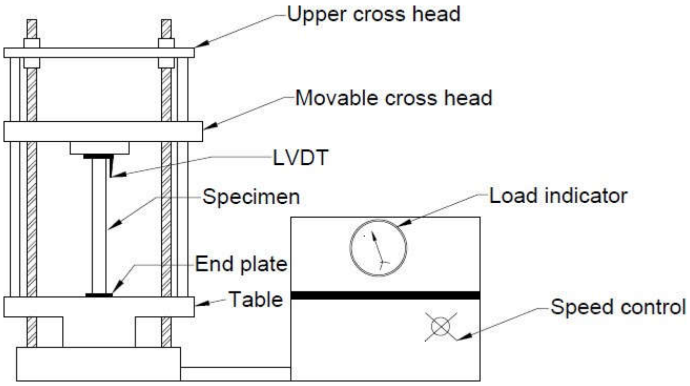


Fig. 2. Experimental Setup

(a) (b)

Fig. 3. Axial Compression Test on the Column: (a) unconfined LWCFST column and (b) CFRP-confined LWCFST column

3. RESULTS AND DISCUSSION

3.1. Experimental Results

3.1.1 Failure Modes

The failure modes of the tested LWCFST columns are shown in Fig. 4. In the initial stage, the columns were compressed axially under the action of load. For the steel tube, failure starts with the inward buckling of the tube. But the in-filled concrete prevents this inward buckling and increased the ductility of the column.

For the columns unconfined by FRP, the failure starts with local ring-shaped outward buckling of steel tube and was first formed near the ends and then near one-third height of the column from the base. The final failure was due to the global buckling about mid-height of the column.

In the case of CFRP-confined LWCFST columns, the FRP prevents the outward buckling of the steel tube by applying confining pressure on the steel surface. This delays the failure of the specimen and thus increases the ductility of the column. The specimen mainly fails by global buckling about mid-height of the column and local buckling at the ends of the column.

(a) (b) (c)

Fig. 4. Failure modes of LWCFST columns: (a) unconfined column, (b) confined with 1 layer of CFRP, and (c) confined with 2 layers of CFRP

3.1.2 Ultimate Load

Table 1 shows the average load-carrying capacity of the tested columns. The load-carrying capacity of the LWCFST column increased with the increase in thickness of the CFRP layer and is shown in Fig. 5.

Table 1. Load-carrying capacity of columns

Sl. No.	Number of CFRP layers	Load-carrying capacity (kN)	Percentage of increase (%)
1	0	176.60	-
2	1	220.70	25.00
3	2	274.70	55.50

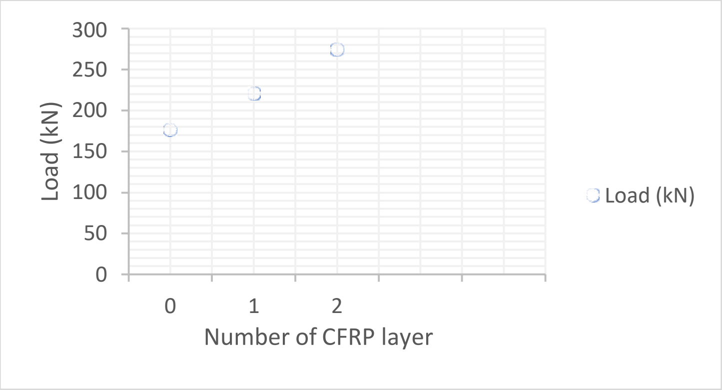


Fig. 5. Load-carrying capacity of columns

3.1.3 Load-Displacement Curves

Load-displacement curves of confined and unconfined LWCFST column is shown in Fig. 6. The graph shows that the ductility of the column increases with the effect of confinement.

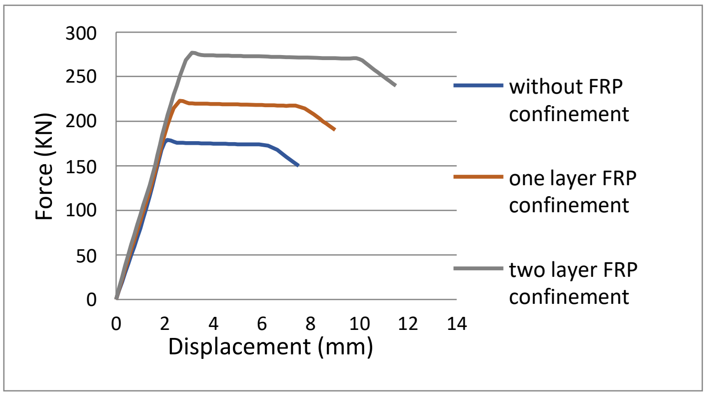


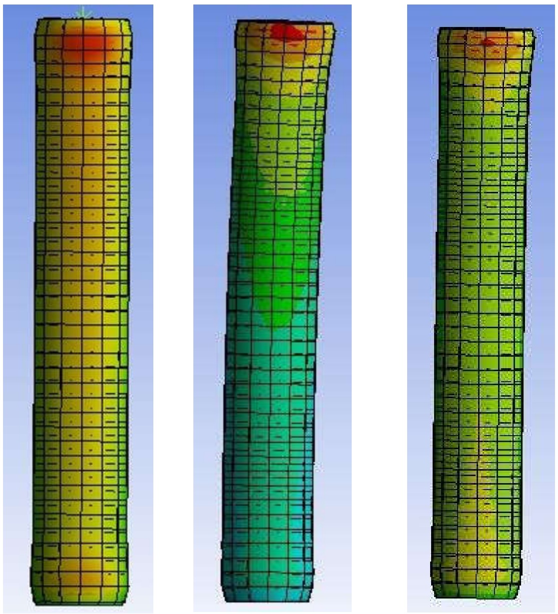
Fig. 6. Force-displacement curves of column specimens

3.2. Finite Element Model (FEM)

By using ANSYS 2021 R2, the finite element model of both unconfined and confined LWCFST columns was modeled and validated with the experimental results. The finite element type used for concrete was solid 186 and steel and CFRP was shell 181. At the top, all degrees of freedom (DOF) except longitudinal displacement were arrested. All DOF was arrested at the bottom. The model was analyzed under axial compression conditions.

3.2.1 Failure Modes

The results are shown in Fig. 7. The failure modes from Finite Element Analysis are well matched with the failure modes from experimental results.



(a) (b) (c)

Fig. 7. FEM Results of LWCFST columns: (a) unconfined, (b) confined with 1 layer of CFRP, and (c) confined with 2 layers of CFRP

3.2.2 Ultimate Load

Table 2 shows the load-carrying capacity of the modelled LWCFST column. The FEM results shows the same behavior of experimental results and is shown in Fig. 8.

Table 2. Load-carrying capacity of columns from FEM

Sl. No.	Number of CFRP layers	Load-carrying capacity from FEM results (kN)
1	0	172.50
2	1	234.40
3	2	286.45

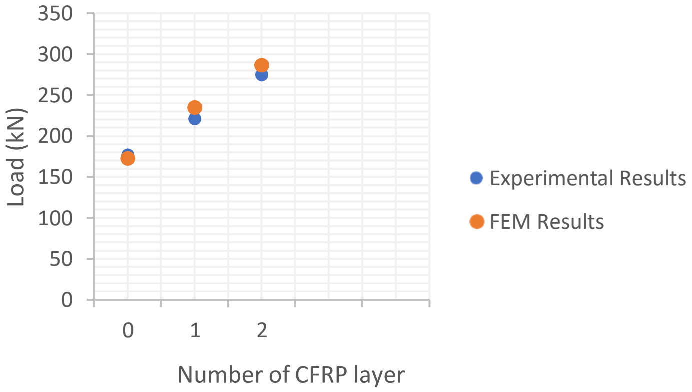


Fig. 8. Load-carrying capacity of columns from FEM

3.2.3 Load-displacement Curve

Load-displacement curves of confined and unconfined LWCFST column is shown in Fig. 9. Also, the curve match with the experimental results.

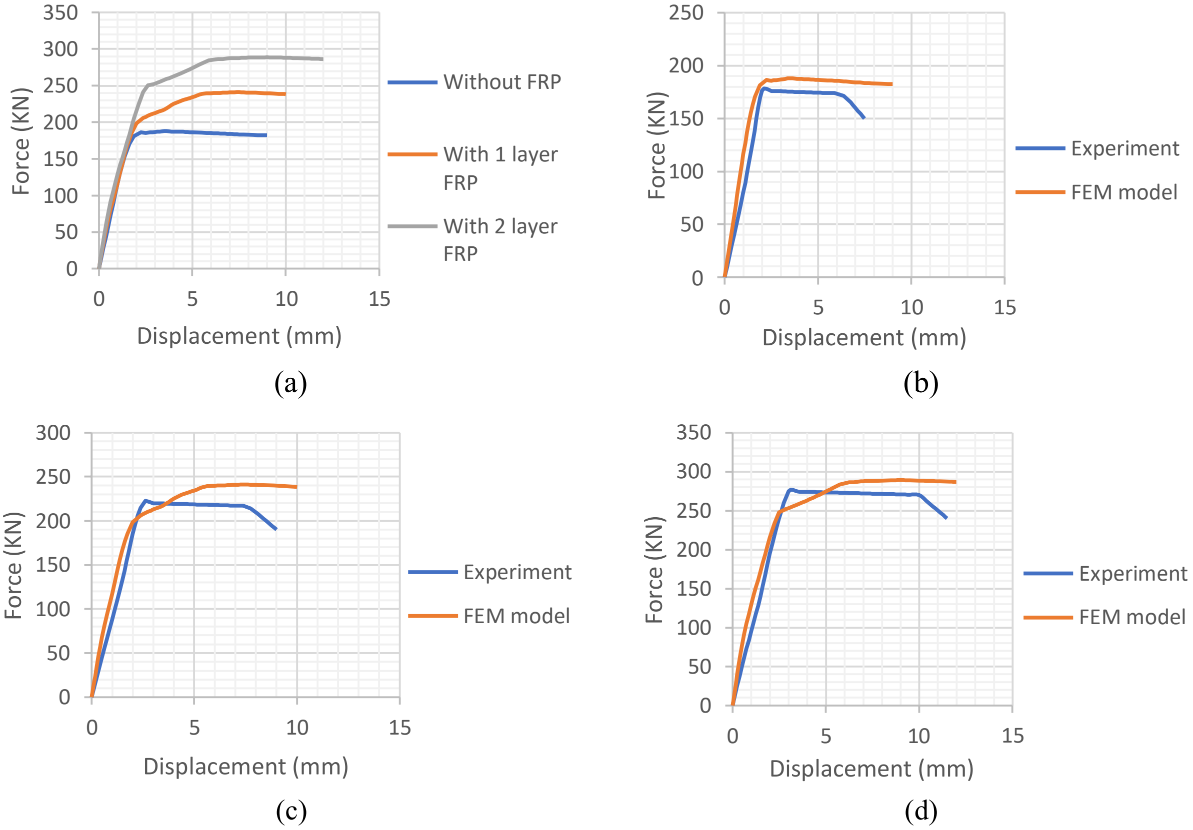


Fig. 9. Load-displacement curve of LWCFST columns: (a) from FEM modelling, (b) validation of unconfined columns, (c) validation of confined column with one layer of CFRP, and (d) validation of confined column with two layers of CFRP

3.3. **Numerical** ***Prediction of Load Capacity***

As per Eurocode 4, the axial load carrying capacity ($N_{pl,Rd}$) of the unconfined CFST column can be calculated from,

$$N_{pl,Rd} = A_s f_y + A_c f_{ck} \tag{1}$$

Prabhu et al. (2015) proposed a new model to determine the compressive strength of CFRP confined CFST circular column (f'_{ccon}) based on their study and research and is given by;

$$f'_{ccon} = [1 + k\frac{f_{lcon}}{f_{uncon}}]\, f_{uncon} \tag{2}$$

where f_{lcon} and f_{uncon} are the lateral confinement pressure exerted by CFRP and compressive strength of the unconfined CFST column respectively. Here, k is an effective confinement coefficient.

$$f_{lcon} = \frac{1.5\, f_{frp} n t_{frp}}{D}[1+(0.3(n-1)] \tag{3}$$

$$f_{uncon} = A_s f_y + A_c f_{ck} \tag{4}$$

The same numerical model is adopted for the current experimental study and the results are listed in Table 3.

Table 3. Predicted results of LWCFST columns

Sl. No.	Number of CFRP layers	Predicted results (kN)
1	0	183.85
2	1	224.60
3	2	279.20

6. COMPARISONS

Both the FEM results and predicted results well match the experimental results and are listed in Table 4. Also, the percentage variation of FEM and numerically predicted results are listed in Table 5.

Table 4. Comparison of results

Sl. No.	Number of CFRP layers	Experimental results (kN)	FEM results (kN)	Predicted results (kN)
1	0	176.60	172.50	183.85
2	1	220.70	234.40	224.60
3	2	274.70	286.45	279.20

Table 5. Validation of results

Sl. No.	Number of CFRP layers	Experimental results (kN)	Percentage variation of FEM results with experimental results (%)	Percentage variation of numerically predicted results with experimental results (%)
1	0	176.60	2.32	4.11
2	1	220.70	6.21	1.77
3	2	274.70	4.28	1.64

7. CONCLUSION

The following conclusions were obtained from the experimental study;

- CFRP confinement improves the compressive behavior and ductility of the LWCFST column. The confinement delays the buckling of steel tubes and prevents the initial failure modes.
- The number of confining layers is found to be proportional to the compressive strength and ductility of the column.
- The ductility of the column is enhanced to a greater extent by the FRP confinement by restraining the local buckling. It increases with the number of confining layers by the application of more restraining force. The specimens exhibit large deflections without failure by the confining effects. Failure of columns without confinement starts with local buckling which was absent in confined columns; hence increasing the strength and ductility.
- The compressive strength of the unconfined CFST column is increased up to 55.5% by using two layers of CFRP confinement. Even, a single layer of CFRP confinement can increase the strength of the LWCFST column up to 25%. Hence, it is clear that the CFRP confinement can effectively improve the compressive strength of LWCFST columns.
- Finite element analysis and a numerical prediction of the experimental study were done and the results from both studies are validated with the experimental results.

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