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Experimental and Computational Parametric Analysis of CFST and CFFT Columns

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Abstract: ***'Concrete Filled Steel Tubes (CFST)'/ 'Concrete Filled FRP Tubes (CFFT)' comprises of a steel/ 'Fiber Reinforced Polymer (FRP)' hollow pipe of circular or rectangular shape filled with plain or reinforced concrete. Need of such composite columns in the field of building construction is due to advancements in technology, need of bigger space in smaller land area, ease in construction workability, and a lot of other modern time requirements. This paper defines an experimental and computational project carried out by testing a total of 49 CFST columns and 60 CFFT columns. Three Finite Element models were also made using the software pack ABAQUS. Variables for the study were aspect ratio of columns, Shape of columns (i.e. square, circular or rectangular) and material (i.e. steel or FRP). Basic aim of the project was to find structural parameters like load-deflection behaviour, deflection pattern, maximum load carrying capacity etc. The Steel reinforced concrete-filled fiber reinforced polymer (FRP)tubular column is proposed as a new form of composite column to obtain higher mechanical performance. A comparative analysis was also carried out using three main resulting indices like Ductility Index (DI), Strength Index (SI) and Concrete Contribution Ratio (CCR). Comparative observations between CFST/CFFT columns of different shapes and sizes is carried out, also experimental results were compared with analytical results obtained from ABAQUS software.***

Keywords: Ductility Index (DI), Strength Index (SI), Concrete Contribution Ratio (CCR), Finite Element Method.

I. INTRODUCTION

The past few decades have seen outstanding advances in the use of composite materials in structural applications. There can be little doubt that, within engineering circles, composites have revolutionized traditional design concepts and made possible an unparalleled range of new and exciting possibilities as viable materials for construction. In structural engineering, composite construction exists when two different materials are bound together so strongly that they act together as a single unit from structural point of view. The most important and most frequently encountered combination of construction materials is that of steel and concrete, with applications in multi-storey commercial buildings and factories, as well as in bridges.

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These materials can be used in mixed structural systems, for example concrete cores encircled by steel tubes, as well as in composite structures where members consisting of steel and concrete act together compositely. These essentially different materials are completely compatible and complementary to each other; they have almost the same thermal expansion; they have an ideal combination of strengths with the concrete efficient in compression and the steel in tension. A CFST column consists of a hollow steel `tube of circular, square or rectangular cross-sectional shape, filled with plain or reinforced concrete. There are a number of research works carried out to understand the behaviour of CFST columns and they are being used in many countries for columns in high-rise buildings. In this project, CFST columns have been experimentally investigated as well as analytical modelling of the same has also been done. There are a number of applications of such composite columns and they are widely being used around the globe. A great number of studies have been devoted to evaluate the behaviour of concrete filled-FRP tubes (CFFT). One of the most important issues in civil engineering applications is the safety implications of using FRP materials. In order to avoid catastrophic failure of an entire structure, it is desired to dissipate energy by post-elastic deformations [1]. However, FRP materials are generally known for their linear elastic response to failure. Over the past decade, fibre reinforced polymer (FRP) composites have become increasingly more popular as a confining material for concrete columns, both in the retrofitting of existing reinforced concrete columns with an FRP jacket and in the use of concrete-filled FRP tubes as structural members in new construction. In these composite columns, the external FRP jackets or tubes can provide a permanent formwork and confinement for the concrete to enhance the compressive strength of the concrete. And the columns are also highly durable because the outer FRP tubes have high corrosion resistance in harsh conditions. Hollow steel/FRP pipe provides a confining effect to the concrete core resulting in increased compressive strength of column. Same way the concrete placed inside of the hollow pipe provides a restraining force resulting in delayed buckling of the column. In order to investigate the behaviour of axially loaded CFST and CFFT columns using normal strength concrete, tests on one hundred and nine specimens were conducted on three different shaped (circular, square and rectangular) columns. Total 49 CFST columns were tested while 60 CFFT columns were tested.

The objectives of this investigation are as follows:

- The first aim of this study is to compare the difference of the axial load capacity due to the different slenderness ratio (3, 5, 7 etc.) for the circular, square and rectangular CFST and CFFT columns.
- Some important parameters like the Ductility Index (DI), the Strength Enhancement Index (SI) and the Concrete Contribution Ratio (CCR) are compared and evaluated for the circular, square and rectangular CFST and CFFT columns.
- To compare the experimental results with the result predicted by available current international design codal provisions.
- To verify the experimental results with the ABAQUS software.
- To observe fracture parameters like failure pattern and crack growth in both experimental testing and ABAQUS modelling.

Comparisons between results obtained from concrete filled steel tubes and concrete filled FRP tubes were obtained.

II. EXPERIMENTAL METHODOLOGY

For resisting compression, steel/FRP tubular sections or Hollow steel/FRP tubular sections are more advantageous than any other sections. The section with the high yield strength gives them a high strength to weight ratio and make them a natural choice for high-rise building structures. In addition, hollow sections can achieve a constant external dimension for all weights of a given size, which enables them to achieve standardization of architectural and structural details throughout the full height of the building. A composite section is produced, by filling hollow sections with concrete as shown in figure below, which is popularly known as Concrete Filled Steel/FRP Tubular (CFST/CFFT) section. The load carrying capacity of the CFST/CFFT column is more [5]. Alternatively, for the same original load capacity, it permits smaller composite sections to be used. In case of fire, the presence of the concrete filling acts as a heat sink.

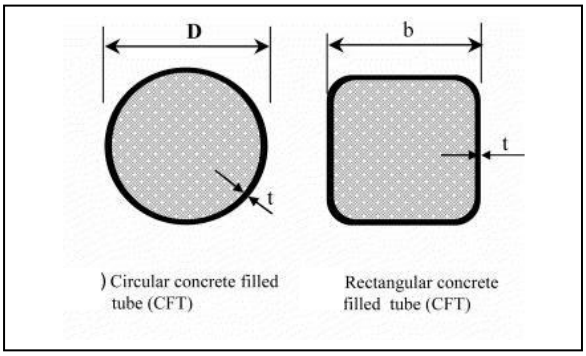

Fig. 1. Schematic of CFST/CFFT column cross-section

The steel tubes were purchased as per the size given in IS 1161-2014. Studies were made to observe the effects of shape & size when the axial load was applied in the columns for the following specimens. The circular, square and rectangular hollow steel tubes were filled with same grade of concrete.

The average values of yield strength and ultimate tensile strength for the steel tube as per manufactured data was 310 and 450 N/mm2 respectively. The modulus of elasticity (E) of Mild Steel (MS) tube is 2.0 x 105 N/mm^2 [2-3]. In the present experimental work, the parameters of the test specimens are the shape of specimen, size of specimen & slenderness ratio of column.

Three shapes of columns such as circular, square and rectangular steel tubes were used. Three different sizes of columns in each shape were used. Also, steel tubes of same thickness of 4.8 mm were used as shown in Table 1. For circular and square column specimens, three different H/d ratios (3, 5 and 7) were used and for rectangular specimen, four different H/d ratios (3, 5, 7 and 9) were used and experimental works were carried out in this study

Table-I: Details of steel tubes

Column Dimensions	H/D Ratio	Height of Column (mm)	No. Of Specimens
1) Circular section Dia = 88.9 mm (3.5 inch) thickness = 4.8 mm.	3	266.7	4
	5	444.5	5
	7	622.3	4
2) Square section 72 x 72 mm thickness = 4.8 mm.	3	216	5
	5	360	5
	7	504	6
3) Rectangular section 98 x 48 mm thickness = 4.8 mm.	3	144	5
	5	240	5
	7	336	5
	9	432	5

Three shapes of columns such as circular FRP tube, square FRP tube and rectangular FRP tubes were used. Three different sizes of columns in each shape were used. Also, FRP tubes of same thickness of 4.5 mm were used. The FRP tubes were purchased as comparatively similar possible as that of steel for comparative reasons. Studies were made to observe the effects of shape & size when the axial load was applied in the columns for the following specimens. The circular, square and rectangular hollow FRP tubes were filled with same grade of concrete. The average values of yield strength and ultimate tensile strength for the FRP tube as per manufactured data was 63 and 75 N/mm^2 respectively.

TableII: Details of FRP tubes

Column dimensions	H/D Ratio	Height of column*(mm)*	no. of specimen
1) Circular section 76 mm diameter thickness = 4 mm.	3	228	6
	5	380	6
	7	532	6
2) Square section 63.5mm x 63.5mm thickness = 4 mm.	3	190.5	6
	5	317.5	6
	7	444.5	6
3) Rectangular section 80mm x 60mm thickness = 5 mm.	3	180	6
	5	300	6
	7	420	6
	9	540	6

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III. MATERIAL

Hollow sections were filled with the concrete and there was no requirement of additional equipment. The enhancement in the overall efficiency obtained by filling a steel/FRP structural hollow section with concrete allows the designer a wider choice of sections. Filled hollow section columns combine the advantages of economy in the use of materials with the construction advantages of the use of steel work as well as that of FRP. Concrete filling of the hollow section columns can take place on or off site. The hollow section columns were filled from the top with same grades of M20 concrete [6].

The materials used in this investigation were: Ordinary Portland Cement (Ultratech), coarse aggregate of crushed rock with a maximum size of 10 mm, fine aggregate of clean river sand and potable water.

Cement: Ordinary Portland cement of 53 grade (Ultratech), conforming to IS 12269-1987 was used. The cements were stored in air tight atmosphere, free from moisture and purchased from single hand.

Fine Aggregate: Natural river sand was used as fine aggregate. Uniformly graded sand available near Sankheda was procured and used. It was clean, free from organic matter, silt and clay. The results obtained from sieve analysis indicate that the sand conforms to Zone-I of IS: 383-1970. The properties of sand were determined by conducting tests as per IS: 2386 (Part I) - 1963.

Coarse Aggregates: Crushed stones obtained from local quarries were used as coarse aggregate. Coarse aggregates are inert materials used for increasing the volume and strength of concrete. Graded, crushed stones of 10 mm of maximum size and conforming to IS 383-1963, available in and around Sankheda, was used. They are free from adherent coatings, coal residues and clay lumps. They do not contain organic or other impurities. The properties of coarse aggregate were determined by conducting tests as per IS: 2386 (Part III) - 1968.

Water: Potable water, free from salt and available in the campus was used for concreting and curing of specimens as per IS: 456-2000 recommendations. The water used for both mixing and curing was free from injurious amount of oils, acids, alkalis, salts organic materials or other substances.

After 28 days of curing, 6 concrete cubes were tested and the average of 27 N/mm^2 of strength was obtained.

IV. TESTING PROCEDURE

The columns were tested for static axial load with the following arrangements using Hydraulic Universal Testing Machine (200T capacity). The schematic diagram and complete test set up used for all the specimens are shown in figure for square, circular and rectangular CFST and CFFT columns. The end condition for all column sections was chosen to simulate actual conditions on the field. Bottom end of each specimen during the experiment were kept fixed in order to prevent the loaded ends of the specimens from moving laterally, while offering little resistance to out of plane rotation of the plate elements.

The testing procedures for all the columns were the same. A column was placed on the base of the platform and properly centred for loading axially. Before conducting the test, the dial gauges were checked and the initial measurements were set at zero reading. In each test, initially the column was loaded with small load (5 kN approximately) and then released to check the effectiveness of the instrument set-up and loading. The axial load was applied by means of a hydraulically operated oil pump and axial shortening values were measured for each increment of 50kN with the help of the dial gauges up to the ultimate load stage. I.e. CFST/CFFT specimens were subjected to a process of monotonic axial loading up to the ultimate load.

Fig. 2 Column testing setup

The linear deformations at all points had more or less uniformly increased up to the initiation of local buckling. As the load was further increased, it leads to global buckling. The specimens were loaded at constant rate and test was carried out till the ultimate stage was reached, and the specimen'sbehaviour was observed during throughout the whole experiment. The loading on the column continued till the final failure of the specimen for getting failure patterns of circular, square and rectangular CFST/CFFT specimen with M20 grade of concrete. After that, the load increments were controlled depending upon the visible deflection capacity of the column. Longitudinal deflections of the columns were measured using digital dial-gauge with least count of 0.01 mm. Axial shortening were measured at the top and bottom of the column using dial gauges for all columns. The dial-gauge was attached with connecting rods and placed above the base plate

V. PERFORMANCE INDICES

Some important parameters are defined to compare the ductility and the strength enhancement of the CFST columns. Those parameters are the ductility index (DI), the strength enhancement index (SI), and the concrete contribution ratio (CCR).

- **Ductility Index**

It is defined as the ratio of the elastic limit deformation and the total deformation at maximum load.

$$DI = \frac{\delta_u}{\delta_{85\%}} \qquad (1)$$

- **Strength Index**

It is defined as the ratio of maximum compressive load carrying capacity of the CFT column to the sum of the strength of the individual constituents. (Concrete core & Steel/FRP hollow section)

$$SI = \frac{Pu,filled}{Asfy+Acfck} \quad (2)$$

- **Concrete Contribution Ratio**

The factor defined as the ratio of the contribution of ultimate load of composite column to the ultimate load of hollow column.

$$CCR = \frac{Pu,filled}{Pu,hollow} \quad (3)$$

Where, Pu_{filled} is the ultimate load reached in the tests; pu_{hollow} is the ultimate load of the un-filled steel tubes; δu is the axial shortening at the ultimate load; δ85% is the axial shortening when the load falls to 85% of the ultimate load; As and Ac are the cross-sectional area of the steel tube and the concrete, respectively; f_y and f_{ck} is the yielding stress of the steel tube and the characteristic compressive strength of the concrete, respectively.

VI. FINITE ELEMENT MODELLING

Finite Element Method (FEM) is an analytical method used for a number of applications including structural analysis, fluid dynamics, machine designing etc. ABAQUS is finite element method-based software used for structural analysis. In this project, ABAQUS has been used to model and solve composite concrete filled steel tubular (CFST) columns. A total sum of three CFST models were generated and solved using software package ABAQUS. To model CFFT columns, thorough knowledge of surface interactions between FRP pipes and concrete is required and hence has not been included in this project. With some literature references, interaction surface between steel and concrete was modelled and CFST columns were analysed. A circular CFST column with outer diameter of 88.9 mm was modelled in ABAQUS. Height of the column was kept at 623 mm making the H/d ratio = 7. A square CFST column with outer dimensions of 72 mm x 72 mm was modelled in ABAQUS. Height of the column was kept at 504 mm making the H/d ratio = 7. A rectangular CFST column with outer dimensions of 98 mm x 48 mm was modelled in ABAQUS. Height of the column was kept at 336 mm making the H/d ratio = 7. Figure below is a schematic of the circular CFST column that was generated in ABAQUS.

In this project, stresses, displacements and maximum values of loads and displacements have been taken into consideration. Load v/s displacement curves have been plotted for all three models of circular, square and rectangular CFST columns. These curves are then compared with the experimentally generated load v/s displacement curves and percentage of error has been calculated. Same comparison has been carried out for maximum load and maximum displacement values.

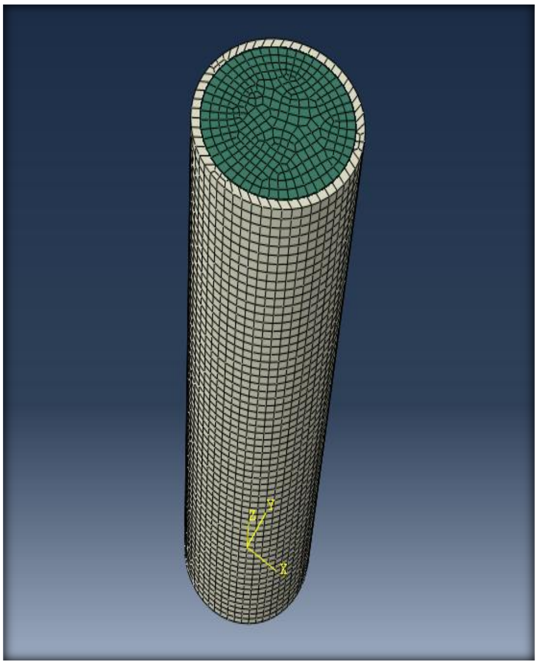

Figure 3: - FEM model of circular CFST column

VII. RESULTS AND DISCUSSIONS

The results of compression strength conducted on CFST and CFFT specimens are presented. Further, the axial shortening curves (i.e. axial compression load v/s vertical deflection) are prepared for three different shapes i.e. circular, square and rectangular CFST as well as CFFT columns filled with M20 grade concrete. And some important parameters, the Ductility Index (DI), the Strength Enhancement Index (SI) and the Concrete Contribution Ratio (CCR) are evaluated and compared for the circular, square and rectangular CFST and CFFT columns of different slenderness.

Note that due to a restriction in height of displacement gauge, it was not possible to obtain any values of displacements for some specimens of small sizes. Due to this, it was not possible to plot their load v/s displacement graphs, it was not possible to derive their ductility index and it was tough to determine maximum displacement for some FRP pipes and CFFT columns. Obtained results have been compromised because of this reason.The ductility of the specimens is assessed in terms of the ductility index (DI). The strength enhancement index (SI) can be described as the ratio the axial load capacity of the composite section to the sum of the strengths of the steel tube and the concrete core. The level of strength enhancement arising from the concrete filling is represented by the CCR that is defined as the ratio the maximum load of composite column to the hollow column. Following is a table showing average values for DI, SI and CCR for all samples.

TableIII :Indices Results For CFST Columns

MATERIAL	SECTION	H/D	DIA	CCR	SI
CFST	Circular	3	3.75	1.7	1.34
		5	1.87	1.55	1.21
		7	3.1	1.76	1.29
	Square	3	3.32	1.17	1.9
		5	2.99	1.17	1.9
		7	2.62	1.18	1.85
	Rectangular	3	#	1.14	1.44
		5	2.59	1.24	1.45
		7	2.72	1.26	1.45
		9	2.27	1.19	1.38

TableIV :Indices results for CFFT columns

MATERIAL	SECTION	H/D	DI	CCR	SI
CFFT	Circular	3	#	1.51	2.3
		5	1.5	1.53	2.17
		7	1.48	1.56	2.17
	Square	3	1.69	1.03	1.82
		5	1.46	1.08	2.15
		7	1.75	1.04	2.08
	Rectangular	3	#	1.12	2.39
		5	1.61	1.11	2.16
		7	1.36	1.19	2.28
		9	1.26	1.04	2.26

Due to a restriction in height of displacement gauge, it was not possible to obtain any values of displacements for some specimens of small sizes

TableV: Comparison of experimental and FEM results

Sample	Maximum load obtained by experimental testing (kN)	Maximum load obtained by ABAQUS modelling (kN)	% error
Circular CFST with H/d = 7	63.46	73.06	13.13%
Square CFST with H/d = 7	86.6	93.27	7.15%
Rectangular CFST with H/d = 7	65.26	71.15	8.27%

Note that the results shown in the graphs are average values of three specimens for each sample. In both CFST and CFFT, a number of samples were tested and these results were obtained. It was observed that CFST columns were dominantly failing in local or global buckling of steel pipes whereas the CFFT columns were predominantly failing due to crushing of external FRP pipes. The nature of FRP is brittle and hence the CFFT columns were failing with a brittle kind of failure as opposed to a more ductile failure in CFST columns[10].

VIII. CONCLUSION

A total of 49 CFST column specimens and 60 CFFT column specimens were experimentally tested under direct compression loading. Different H/d ratios of columns and cross-sectional shapes were the changing comparative parameters for the project. Total three different sectional shapes of specimens i.e. circular, square and rectangular were prepared for both CFST and CFFT columns. Total three different H/d ratios of columns i.e. 3, 5, and 7 were prepared for circular and square columns while rectangular columns were prepared with H/d ratio of 3, 5, 7 and 9. A finite element method-based analysis models were prepared using a finite element pack ABAQUS. Out of these 3, 1 circular CFST with H/d ratio of 7, 1 square CFST with H/d ratio of 7 and 1 rectangular CFST with H/d ratio of 7 were designed. All these three models were analysed in ABAQUS and obtained results were compared with experimental results. Plain concrete of M20 grade was filled inside both CFST and CFFT columns. From a thorough analysis, following conclusions can be drawn.

1) Square CFST columns have the highest load bearing capacity compared to circular and rectangular columns for all H/d ratios of 3, 5 and 7. Rectangular CFST columns have the lowest value.
2) In case of CFFT columns, rectangular CFFT columns have the highest load bearing capacity compared to circular and square columns for all H/d ratios of 3, 5 and 7. Circular CFFT columns have the lowest values.
3) The load bearing capacity of a CFST/CFFT column decreases with increase in H/d ratio from 3 to 5 to 7. At the same time, the maximum deformation of columns increases with increment in H/d ratio for both CFST and CFFT columns.
4) CFST columns have a higher value of load bearing capacity then CFFT columns. Better mechanical properties of steel over FRP plays a valuable role as the values of confinement effect is better in steel resulting in increased maximum load carrying capacity in CFST then in CFFT.
5) Average approximated percentage decrease of load bearing capacity of circular CFFT column over circular CFST column for H/d ratio of 3, 5 and 7 are 45%, 47% and 46% respectively. Average approximated percentage decrease of load bearing capacity of square CFFT column over square CFST column for H/d ratio of 3, 5 and 7 are 25%, 30% and 29% respectively. Average approximated percentage decrease of load bearing capacity of rectangular CFFT column over rectangular CFST column for H/d ratio of 3, 5, 7 and 9 are 57%, 51%, 54% and 56% respectively.
6) Values obtained from the FEM modelling in ABAQUS software are in good agreement with values obtained from the experimental testing. Approximately 10% to 15% of error is observed between the two results. This error can be because of errors in eccentricity, rate of loading, equipment calibration, or human errors during experimental work and ABAQUS can be further used for successfully modelling CFST composite columns.

From these conclusions, new applications of CFFT columns can be defined as well as a better idea of behaviour of CFST columns can also be obtained. Effects of different structural parameters like slenderness of columns and cross-sectional shape can also be understood from these analyses and it can be used in terms of betterment of structural systems having composite columns.

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