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EXPERIMENTAL AND COMPUTATIONAL STUDY OF SFRC IN-FILLED STEEL CIRCULAR COLUMNS UNDER AXIAL COMPRESSION

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ABSTRACT

Experiments on circular steel tubes filled with steel fibre reinforced concrete (SFRC) and normal concrete have been performed to investigate the contribution of steel fibres to the load bearing capacity of short composite columns. The main variables considered in the test study are diameter to thickness ratio of the steel tube and the percentage of steel fibres added to the in-filled concrete. All the specimens were tested under axial compression until failure state realization. Extensive strain and deformation measurements were taken at compression and tension zones and the results show that 1.00% SFRC in-filled steel columns exhibit enhanced ultimate load carrying capacity, stiffness and ductility coefficient. Also a nonlinear finite element model was developed to study the load carrying mechanism of CFTs using the Finite Element software version ABAQUS. This model was validated using the experimental load–deformation curves and the corresponding modes of collapse. A comparison of the observed load carrying capacity and flexural stiffness with various codal recommendations has been carried out to check the applicability of the expressions recommended by the various codes of practice. Of all the codes compared, Eurocode 4 showed the least variation and is found to be more viable to predict the strength of normal as well as SFRC in-filled steel tubes under axial compression.

Keywords: Composite columns; concrete filled steel tubes; axial compression; finite element model; steel fibre reinforced concrete; ductility factor.

1. INTRODUCTION

Concrete-filled steel tube (CFT) columns have been extensively used in modern structures,

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mainly due to the combined advantages of the steel tube and concrete core. However, many researchers cast doubt on the use of plain concrete as in-fill material in steel tubes, due to the extremely disastrous effects of the 1995 Kobe earthquake in Japan on steel and concrete composite structures. This prompted a change of seismic design perspective from the previous emphasis on structural strength to emphasis on structural ductility and energy absorption [1]. Accordingly, the in-fill material inside steel tubes is required to be of the quality as to increase the ductility of composite columns. Many kinds of in-fill materials are used to improve ductility of composite columns. Among the various in-fill materials, steel fibre is gaining attention due to its high flexural strength, tensile strength, lower shrinkage, and better fire resistance. This paper presents the results of experiments and finite element analysis carried out on normal and steel fibre reinforced concrete-filled steel tube (SFRCFT) columns under axial compression.

Numerical investigation on elasto-plastic behaviour of CFT columns was carried out by Neogi et al. [3]. A series of tests were carried out by O'Shea and Bridge [4, 5] to study the behaviour of circular thin-walled steel tubes with diameter-to-thickness (D/t) ratio ranging between 55 and 200. The applicability of Eurocode 4 for design of CFTs which use high-strength concrete was examined by Kilpatrick et al. [7,8]. Brauns [9] stated that the effect of confinement exists at high stress level when structural steel acts in tension and concrete in compression and that the ultimate limit state of material strength is not attained for all parts simultaneously. Lu et al [10]studied the influence of SFRC filled steel tubes and found that the failure mode of these columns is similar to concrete filled steel tube columns.

Though design rules are available for specific situations regarding the local and post buckling behaviour of hollow and in-filled steel columns, the knowledge and design approaches for SFRC in-filled columns is low, their range of validity is unknown. Since PCC is brittle in nature, when used as an in-fill for steel hollow columns, its fundamental property will also change. Along with the steel skin the concrete will behave in a ductile manner to some extent. When steel fibres are added to the concrete, it again enhances the ductility property enabling its use in seismic prone zones. Until now, the effect of volume fractions of steel fibre on the behaviour of SFRCFT columns has not yet been studied. In this paper, the effects of volume fractions of steel fibre to concrete (0.75, 1.0 and 1.25%) on the behaviour of short SFRCFT columns under axial compression are presented.

2. EXPERIMENTAL PROCEDURE

In order to consider the behaviour of in-filled columns, specimens were tested with various concrete strength and wall thickness. 114 mm diameter hot finished circular hollow section (CHS) with 2 mm and 3 mm wall thickness were used for the tests. The column specimens were 1m long. All specimens were tested with fixed conditions at the bottom. All circular steel tubes to be tested were welded to a bottom end plate that was strengthened in the plastic region with four 6 mm thick gusset plates welded at the bottom. The ends of the columns and the end plates were machine ground to flatness so that the column end section and the end plates were in proper contact.

2.1 Plain Cement Concrete

The concrete mix was designed for a cube compressive strength of 20 MPa at 28 days. The design mix of 1:2.09:2.25 with a w/c ratio of 0.49, using 12.5 mm size (max.) coarse aggregate and 2.36mm (max.) size fine aggregate was used as per ACI committee 211.1.1991 recommendations [11].

2.2 Steel Fibre Reinforced Concrete (SFRC)

To prepare the SFRC in-filled steel composite columns, three different volume fractions of steel fibres were chosen viz., 0.75%, 1.00% and 1.25%. Crimped steel fibres having an aspect ratio of 70 (length of the fibre (l_f) = 30.80 mm and diameter of fibre (d_f) = 0.44mm) were used. An attempt has been made to arrive at the optimum volume fraction for the chosen type of fibre for in-filled columns. The stress strain behaviour of PCC and SFRC are given in Figure 1. The details of the specimens are given in Table 1.

2.3 Steel Properties

In order to determine the actual material properties, three steel coupons were cut from the steel tubular sections and tested to failure under tension as per ASTM-A370. The typical stress-strain behaviour of the tensile coupon test is shown in Figure 2.

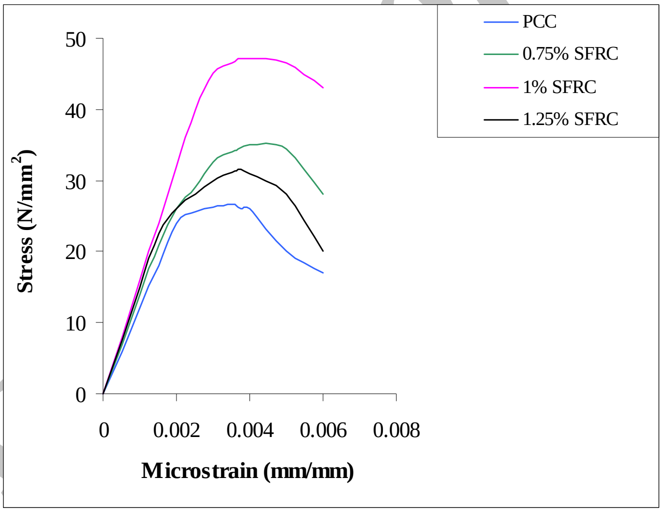
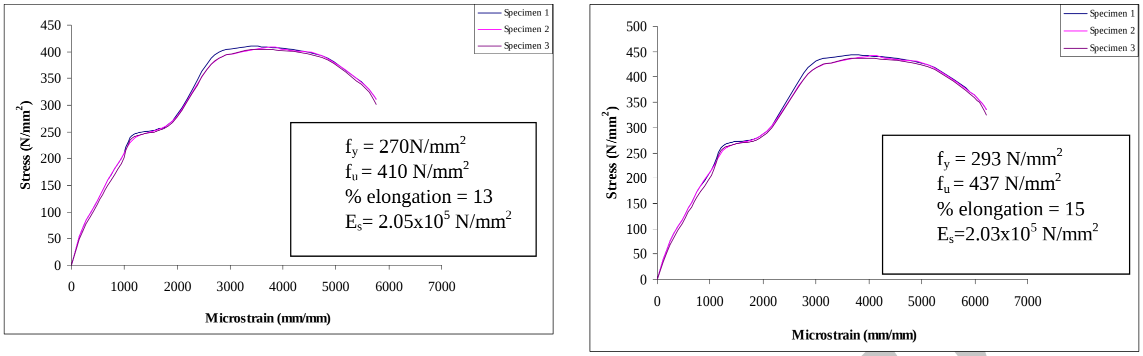


Figure 1: Stress - Strain Behaviour of PCC and SFRC



(a) 2mm thick plate (b) 3mm thick plate

Figure 2: Typical Stress - Strain Behaviour of Steel

2.4 Test Set-up and Instrumentation

In order to apply axial load, each column was mounted on a 1000 kN loading frame and the top end of the column was aligned with the machine so that the axis of the machine coincides with the axis of the column. Four 10mm electrical strain gauges with a gauge factor of 2 were used to measure the strains at a distance 'D' from the bottom. The specimens were loaded at 50 kN intervals at the beginning of the test (i.e. in the elastic region) and at a loading rate of 10 kN intervals after the column began to yield, in order to have sufficient data points to delineate the 'knee' of the stress– strain curve. The schematic drawing for the test set-up and instrumentation are shown in Figure 3.

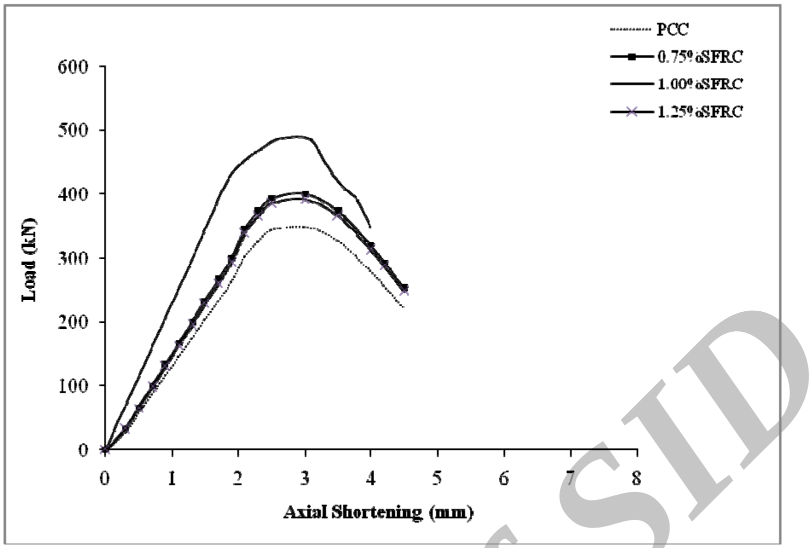
Table 1: Details of Specimens

Specimen	**Thickness of the Steel Tube (mm)**	**f_{ck} (N/mm^2)**	**f_y (N/mm^2)**	**Volume fraction of Steel fibres (V_f)**	**Slenderness value as per Eurocode 4**	**Initial Stiffness (kN/mm)**	**Ductility factor**
CFT	2	32.44	270	0	1.8	130	1.98
0.75% SFRCFT		41.78	270	0.75%	1.5	148	3.15
1.00% SFRCFT		57.78	270	1.00%	1.2	230	3.96
1.25% SFRCFT		38.60	270	1.25%	1.85	146	2.56
CFT	3	32.44	293	0	1.5	153	2.45
0.75% SFRCFT		41.78	293	0.75%	1.3	171	4.05
1.00% SFRCFT		57.78	293	1.00%	1.1	267	5.16
1.25% SFRCFT		38.60	293	1.25%	1.4	164	3.78

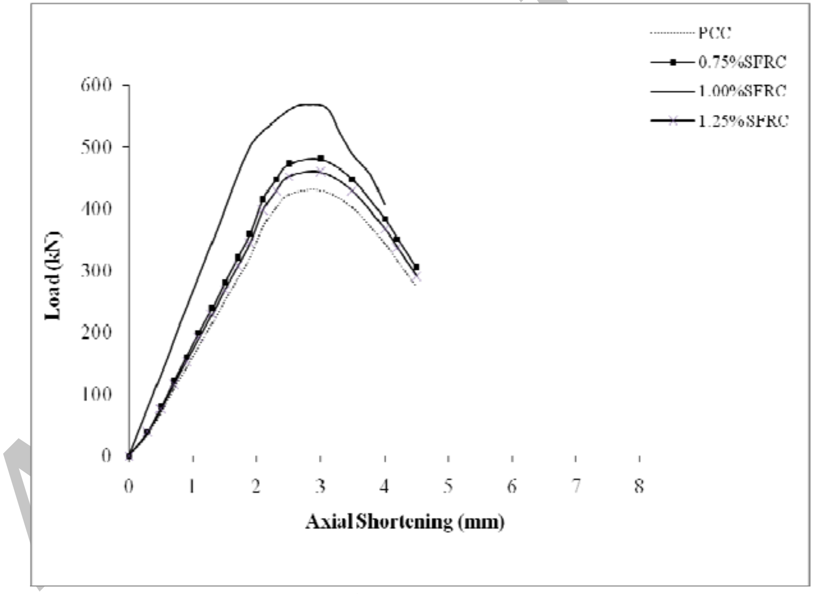
Figure 3: Test Set-up and Instrumentation

3. RESULTS AND DISCUSSION

The load versus axial shortening behaviour of all tested columns are shown in Figure 4 which provides useful information about initiation of yield, ultimate load capacity and ductility. The load - axial shortening responses of the specimens seem to exhibit a similar pattern, which consists of a linear relationship up to about 70-80% of the failure load. The degradation phase (the part beyond the ultimate load) was obtained by measuring the load for a set deflection. The axial shortening of SFRC in-filled columns are lesser due to increased characteristic compressive strength of the in-fill compared to plain concrete in-filled columns. Beyond the ultimate loads, the axial shortenings are significant and all the columns show considerable axial shortening before failure. It is observed that SFRC in-filled concrete has contributed substantially resulting in increased stiffness and strength when compared to PCC in-filled columns. The ductility factor of a specimen can be defined as the ratio of the ultimate drift displacement divided by the yield displacement which is given in Table 1. It is seen that increase in volume fraction from 0.75% to 1 % increases the load carrying capacity, initial stiffness and ductility of columns whereas, with further increase in volume fraction of 1.25%, the load carrying capacity, initial stiffness and ductility of columns drastically reduces. This is due to the clumping of fibres. The percentage increase in initial stiffness, ductility factor and ultimate load of SFRCFT columns compared to CFT columns is similar irrespective of the D/t ratio.



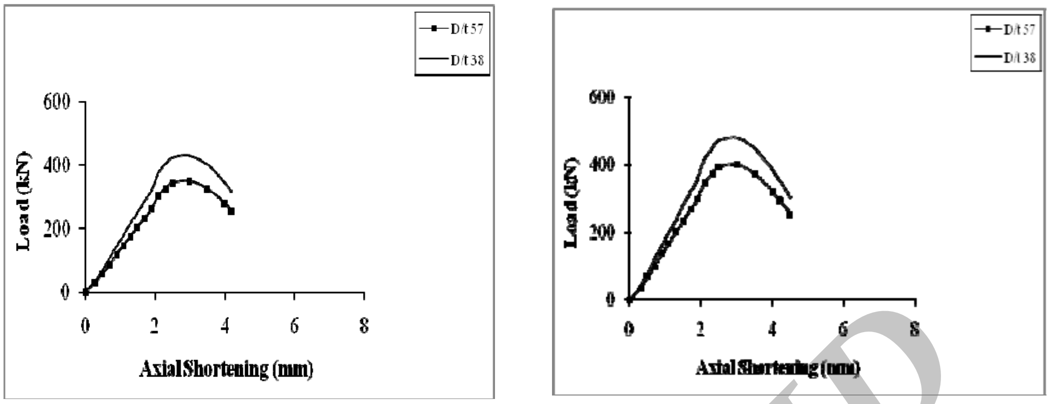
i) D/t ratio 57



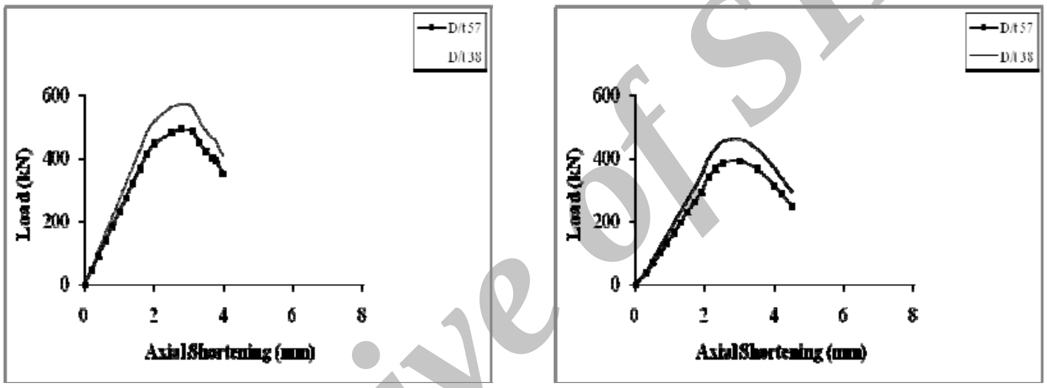
ii) D/t ratio 38

Figure 4: Load vs Axial Shortening behaviour of in-filled columns

Load versus Axial shortening plots of in-filled columns of D/t ratio 38 and 57 are shown in Figure 5. Thicker tubes exhibit enhanced load carrying capacity of the order of 1.2 times irrespective of the type of infill. The variation in initial stiffness is found to be marginal, whereas post elastic behavior is substantially influenced by the D/t ratio.



a) PCC b) 0.75% SFRC



c) 1.00 % SFRC d) 1.25 % SFRC

Figure 5: Load vs Axial Shortening Behaviour of In-filled Columns

3.2 Comparison with theoretical loads

Theoretical loads have been calculated based on the specifications in codal provisions like BS 5400-2005 and EC4-2004, AIJ-1997and AISC-LRFD-2010 and compared with the experimental results and are shown in Table 2. Comparing all the codes EC 4 is found to predict the ultimate loads within the margin of 10% with reference to the experimental values and hence can be taken as the best predictor and thus acceptable for the calculation of axial strength of SFRCFT and CFT short columns.

Table 2: Comparison between Theoretical Load and Experimental Load

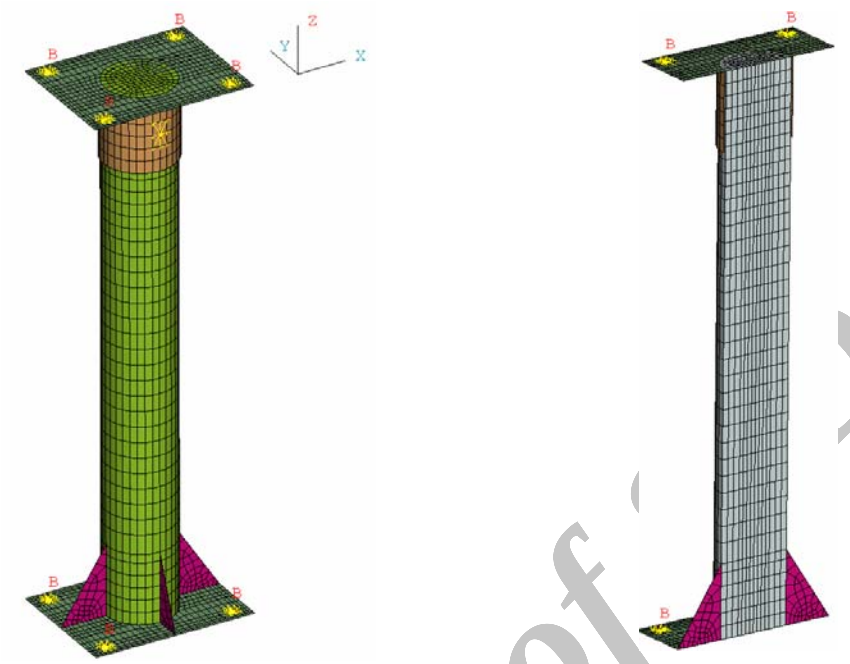
D/t ratio	**Specimen**	**Experimental Ultimate Load (kN) (P_{exp})**	**Ultimate Load (kN) (P_{th})**				**P_{th}/ P_{exp}**			
			EC 4	**BS 5400**	**AISC LRFD**	**AIJ**	**EC 4**	**BS 5400**	**AISC LRFD**	**AIJ**
57	CFT	350	346.55	322.04	346.3	311.47	0.99	0.92	0.989	0.89
	0.75% SFRCFT	400	397.12	384.14	399.53	351.4	0.993	0.96	0.999	0.878

	1.00% SFRCFT	490	483.75	490.52	490.72	419.79	0.987	1.001	1.001	0.857
	1.25% SFRCFT	382	379.9	363	381.41	337.8	0.995	0.95	0.998	0.884
38	CFT	430	423.39	366.02	418.19	390.57	0.985	0.851	0.973	0.908
	0.75% SFRCFT	480	472.14	425.88	469.5	429.06	0.984	0.887	0.978	0.894
	1.00% SFRCFT	560	555.64	528.43	557.4	494.98	0.992	0.944	0.995	0.884
	1.25% SFRCFT	460	455.54	405.5	452.03	415.95	0.99	0.882	0.983	0.904
						Standard Deviation	0.004	0.049	0.011	0.016
						Variance	2E-05	0.002	1E-04	0.0003

4. NUMERICAL STUDY

Two dimensional axisymmetric nonlinear finite element models were developed to study and to compare the experimental results of the axial load behaviour of concrete filled tubes. The general purpose finite element package ABAQUS (Version 6.5, 2005) was adopted for the numerical simulation. The solid element C3D8R, the conventional shell element S4R and the continuum shell element SC8R are used to model core concrete, square steel tube and circular steel tube respectively. The special feature of these elements has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. Multi linear elastic material and geometric nonlinear behaviour were used for the computational model. Nonlinear buckling analysis is more accurate than eigen value analysis because it employs non-linear large-deflection static analysis to predict buckling loads. Its mode of operation involves gradual increase in the applied load until a load level is found at which the structure becomes unstable (i.e. suddenly a very small increase in the load will cause very large deflections).

The true non-linear nature of this analysis thus permits the modeling of geometric imperfections, load perturbations, material nonlinearities and gaps. The Young’s modulus, yield stress and Poisson’s ratio of the mild steel tubes were approximately taken from the actual tests and selected to be 200 GPa, 360 MPa and 0.3, respectively. The frictional coefficient was taken equal to 0.2, whereas Young’s modulus and Poisson’s ratio for concrete were also chosen from the experimental values and were about 27.386 GPa and 0.15, respectively. Using the contact pair option, the top and bottom lines of the tube were picked as target surface and composite tube as contact surface, in which the target was made rigid and the contact body flexible. The top line of the tube was made rigid target and constrained in all degrees of freedom and the bottom line was constrained in all degrees of freedom except in the y-direction, whereas the axis of symmetry was constrained from the x-direction only. Typical finite element model of concrete filled steel tube is shown in figure 6.



(i) Overall View (ii) Sectional View

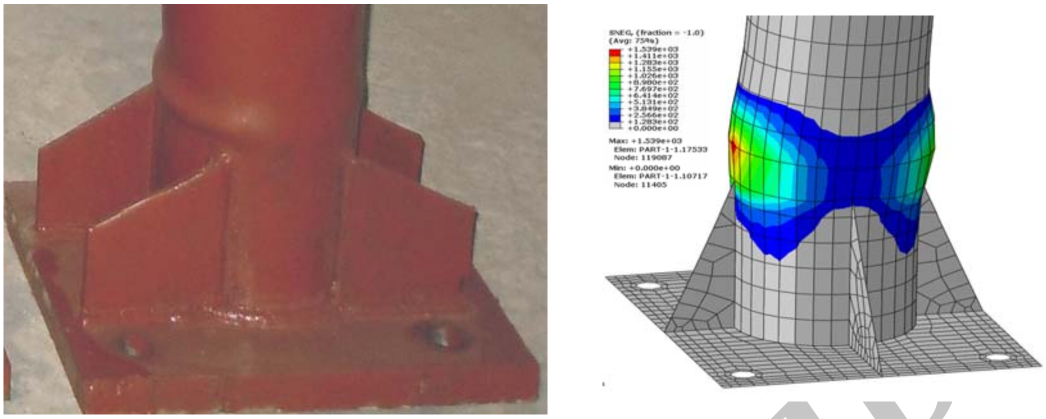
Figure 6: Typical finite element model of concrete filled steel tubes

4.1 Numerical results

In order to verify the accuracy of the numerical analysis, the experimental specimens are modelled and then the numerical analysis values of compressive capacity are compared to the experimental results.

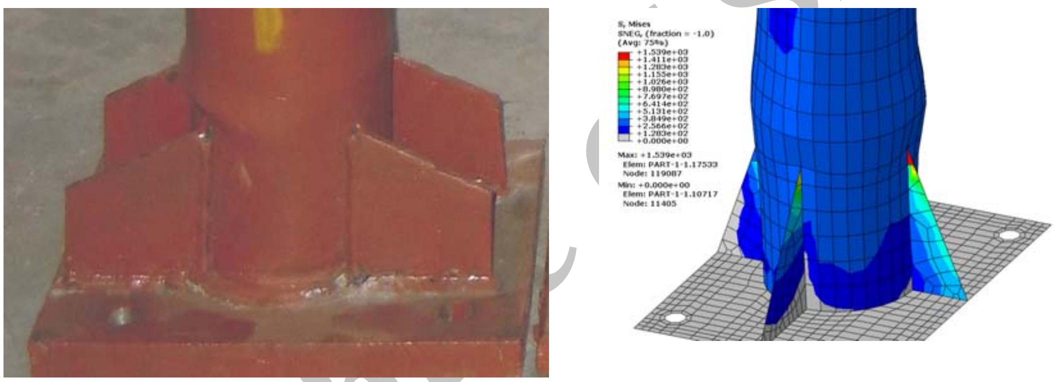
4.2 Failure Modes

The deformed shapes of the tubes match reasonably well with the corresponding experimental deformed shapes as shown in figures 7 and 8. The failure of the CFT is due to local buckling. Buckling progressed more aggressively on opposite faces of the columns of D/t ratio 57 compared to the columns with D/t ratio 38. The failure mode of SFRCFT is similar to that of CFT columns. However, the presence of steel fibres in concrete delays the buckling deflection of composite columns. This is due to increased confinement because of the addition of steel fibres. When the concrete cracks, with its concomitant volumetric expansion, confinement of concrete by the steel fibre relieves the stress on the encasing steel tube, until they fail almost simultaneously.



(i) Experimental (ii) Finite element analysis

Figure 7: Failure Mode of CFT specimens



Experimental Finite element analysis

Figure 8: Failure Mode of SFRCFT specimens

4.3 Comparison of numerical and experimental results

The computational values, which are simulated using ABAQUS, are compared with the experimental results and presented in figures 9 and 10. The peak load values from the experimental results are in fairly good agreement with the computational ones. The initial slope of the load–deformation curve is found to be closer in the case of the computational graph as compared to the experimental graph. The displacement at the yield point is found to be 2–3 mm (about 20%–30%) less in the case of the computational graphs when compared with the experimental one for all types of specimens.

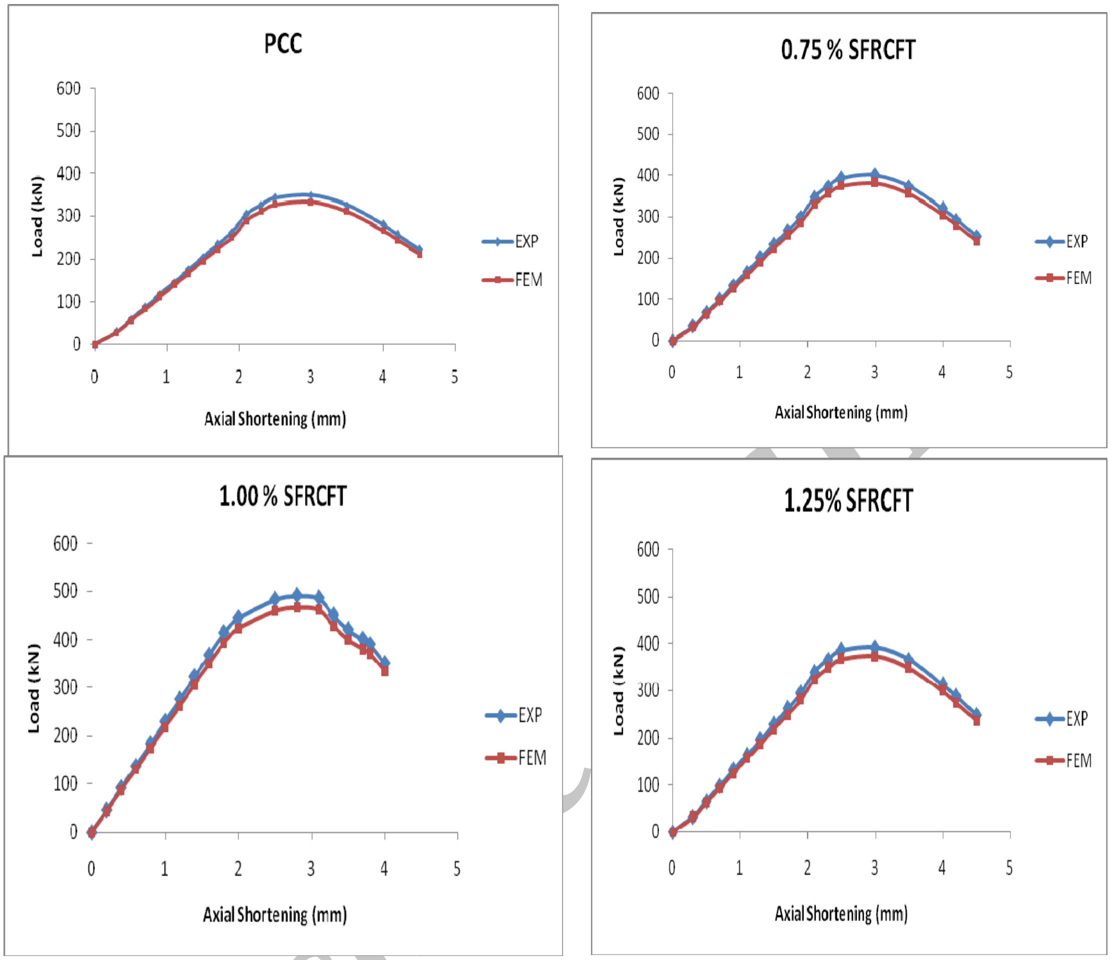
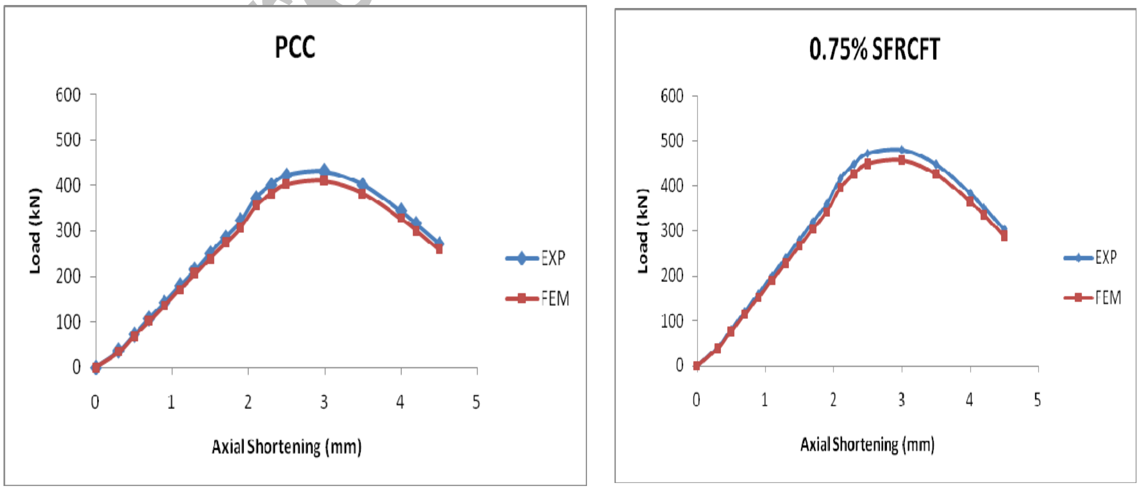


Figure 9: Load vs Axial Shortening plots for specimens with D/t ratio 57



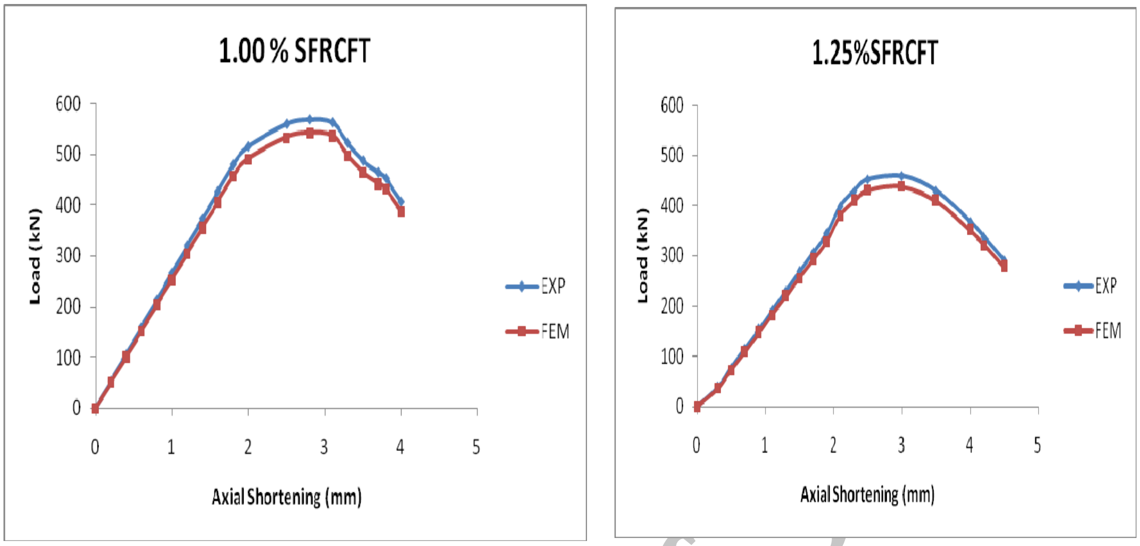


Figure 10: Load vs Axial Shortening plots for specimens with D/t ratio 38

5. CONCLUSION

In order to understand the behaviour of CFT and SFRCFT columns under pure compression, axial load tests were carried out. From these tests the following conclusions were drawn.

- There is a uniform increase in ultimate load, ductility factor and initial stiffness with increase in percentage of steel fibres upto 1.00%. However, when the percentage of steel fibres is increased to 1.25%, there is a drastic reduction in ultimate load, ductility factor and initial stiffness. This is due to the balling effect of steel fibres.
- Due to effective confinement and high compressive strength, initial stiffness increases by 1.6 times irrespective of the D/t ratio with increase in volume fraction of in-fill from 0.75% to 1.00%.
- Compared to all other columns, 1.00% SFRCFT columns exhibit significantly improved performance with large ductility, initial stiffness and load carrying capacity.
- Commencement of yielding is much prolonged in SFRCFT columns compared to CFT columns.
- D/t ratio governs the failure mode with local buckling progressing aggressively in thinner tubes compared to thicker tubes.
- EC4(2004) is capable of predicting the theoretical loads conservatively within a margin of 2%.
- The numerical model developed using ABAQUS software is found to closely simulate the behaviour and failure modes of both CFT and SFRCFT columns.
- The lateral load – deformation behaviour predicted using the finite element model agree well with the experimental loads with a margin of 1.50%.

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