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Tests on fiber reinforced concrete filled steel tubular columns

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Abstract. This paper deals with the strength and deformation of both short and slender concrete filled steel tubular columns under the combined actions of axial compression and bending moment. Sixteen specimens were tested to investigate the effect of fiber reinforced concrete on the ultimate strength and behavior of the composite column. The primary test parameters were load eccentricity and column slenderness. Companion tests were also undertaken on eight numbers of similar empty steel tubes to highlight the synergistic effects of composite column. The test results demonstrate the influence of fiber reinforced concrete on the strength and behavior of concrete filled steel tubular columns.

Key words: composite column; hollow steel tube; fiber reinforced concrete; slenderness ratio; eccentricity; ultimate load; ductility.

1. Introduction

Concrete filled steel tubular columns have become more popular in recent years throughout the world as they offer a number of advantages attaining economy in the construction and have been used in variety of applications, see Bode (1976), Kilpatrick & Vijayarangan (1999). Further economy is achieved using high strength concrete with thin walled steel tube of high yield strength. The obvious advantages in using infilled tubular columns have attracted the researchers all over the world to study this structural member. A number of experimental studies on circular concrete filled steel tubular columns have been reported in the past. (Furlong 1967, Gardner & Jacobson 1967, Neogi *et al*. 1969, Knowles & Park 1969, Ramamurthy & Srinivasan 1978). The results of tests (Vijayarangan & Mathew 1992, Kilpatrick & Vijayarangan 1999) performed on eccentrically loaded slender circular steel tubular columns filled with high strength concrete provides data on the behavior of full scale columns.

Based on the experimental study on concrete filled steel tubular columns, Kilpatrick & Vijayarangan (1999) have concluded that the beneficial effects of confinement of the infill concrete by steel casing diminished as load eccentricity and column slenderness increased due to more strain gradient

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associated with increasing flexure. Furthermore, the recent test results have also shown that, because of the slenderness effects the concrete filled steel tubular columns did not exhibit the beneficial effects of composite behavior in terms of increased concrete strength due to the confinement, see Johansson & Gylltoft (2001). The above researches demonstrated that slender columns did not exhibit the beneficial effects of composite behavior because of pronounced flexure. This necessitates the use of fiber reinforced concrete as infill material, as it has greater flexural strength, ductility & tensile strength than plain concrete. To utilize fully the advantages of fiber reinforced concrete in concrete filled steel tubular columns, it is necessary to understand the behavior of such columns by conducting tests covering an adequate range of parameters.

2. Experiments

2.1. Test program

Sixteen circular CFST columns were tested to study the influence of Fiber reinforced concrete upon their strength and load-deformation behavior. Both the load eccentricity and column slenderness of the

Table 1 Test program

Specimen type	Specimen no.	Column section *D*×*t*, mm	Column length *L*, mm	Eccentricity *e*, mm	Age at test, days
Plain concrete filled steel tubular columns (Type A)	A1	76.0×2.0	645	15	28
	A2		875	15	
	A3		1105	15	
	A4		1330	15	
	A5		1555	15	
	A6		1785	15	
	A7		1555	0	
	A8		1555	25	
Fiber reinforced concrete filled steel tubular columns (Type B)	B1		645	15	
	B2		875	15	
	B3		1105	15	
	B4		1330	15	
	B5		1555	15	
	B6		1785	15	
	B7		1555	0	
	B8		1555	25	
Steel tube without infill (Type C)	C1		645	15	29
	C2		875	15	
	C3		1105	15	
	C4		1330	15	
	C5		1555	15	
	C6		1785	15	
	C7		1555	0	
	C8		1555	25	

specimen were varied. A summary of the test program is given in Table 1. Of these sixteen specimens, eight were plain concrete filled steel tubular columns (Type A specimens), eight were fiber reinforced concrete filled steel tubular columns (Type B specimens). Tests were also carried out on eight companion empty steel tubes (Type C specimens). In this table, the reported length L is the length of the column itself excluding arrangement for load application. The buckling length l is taken as total length of the column between loading surfaces excluding the end capping and shown in Fig. 3.

2.2. Materials

2.2.1. Steel tube

All specimens were constructed from commercially available 76.0×2.0 mm ($D\times t$) circular hollow steel tube, which was supplied in stock length of 6 m. The steel tube was manufactured by cold forming and high frequency electric resistance welding to produce a strong pipe and conformed with the requirements of relevant Indian standards. Tests on tension coupons were carried out on specimens taken from the steel tube. Typical stress strain relationship for the tensile coupon is shown in Fig. 1. Compression tests were also carried out on short steel tubes to obtain the squash load of short steel sections and also to compare the compressive design strength with that obtained from the tension coupons. The results of these tests are summarized in Table 2. The material values given are the average values of three tensile tests.

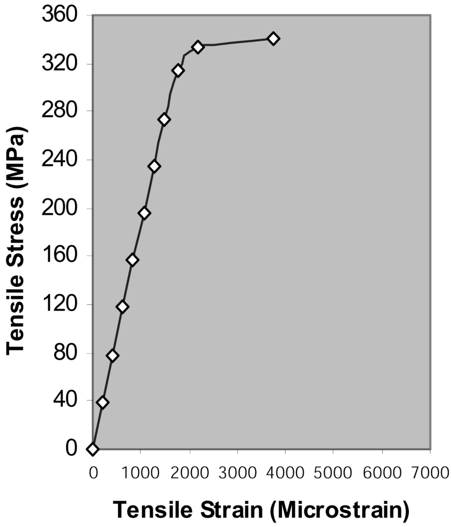


Fig. 1 Stress-strain curve

Table 2 Material properties of the steel

f_{sy} (N/mm^2)	f_{sy}* (N/mm^2)	f_u (N/mm^2)	E_s (kN/mm^2)
275	280	340	205

Table 3 Details of concrete mix

Cement	450 Kg/m^3
10 mm aggregate	810 Kg/m^3
Sand	810 Kg/m^3
Water	225 l/m^3
Super plasticizer	2.25 l/m^3
Type of fiber	Steel corrugated fiber
Aspect ratio	60
Diameter of fiber	0.45 mm
Volume of fiber	1%
Density of fiber	7650 KN/m^3

Table 4 Material properties of the concrete

Type of concrete	f_{cc} (N/mm^2)$^{(1)}$	f_{ck} (N/mm^2)$^{(2)}$	f_{ct} (N/mm^2)$^{(3)}$	E_c (kN/mm^2)	
				Test$^{(4)}$	IS 456*
Plain concrete	52.0	4.5	1.9	35	36.1
Fiber reinforced concrete	52.0	5.2	2.3	37	36.1

(1): Average of five cubes
(2): Average of three prisms
(3) & (4): Average of three cylinders
*: $E_c = 5000(f_{cc})^{1/2}$

2.2.2. Concrete

In the experimental work reported here, a concrete mix of 1:1.8:1.8/0.5 was used, with maximum size aggregate of 10 mm. All specimens were cast from the same batch of Portland Pozzolona cement of 53 grade and river sand of maximum size 2.36 mm. Concrete mix proportion was calculated based on the guidelines given in ACI Committee 211 (1969). A sulphonated naphthalene formaldehyde based super plasticizer at 0.5% by weight of cement was added to improve the workability of fiber reinforced concrete. Details of the concrete ingredients are given in the Table 3. For each type of concrete, five 150 mm cubes, six 150×300 mm cylinders and three 150×150×600 mm prisms were prepared in order to obtain the cube strength, split tensile strength and flexural strength. These specimens were tested as per relevant Indian standards on the same day of the column testing and the mean values of the concrete material properties are summarized in Table 4.

The average unconfined compressive strength was found to be same for both plain and fiber reinforced concrete cubes. The average values of split tensile strength and flexural strength were found to be high for fiber reinforced concrete than plain concrete. Another three 150×300 mm cylinders were tested to find the elastic modulus of concrete. The resulting experimental values of the elastic modulus of concrete as obtained from the slope of stress strain curve are given in Table 4, together with the values calculated in accordance with IS 456 (2000).

2.3. Test specimens

A total of twenty-four test specimens were constructed and tested under eccentric compression producing single curvature bending. In preparation for the column tests, all empty tubes were accurately machined to required length and faced at both the ends in a lathe. The tubes were degreased inside and outside using detergent powder and thoroughly washed with water. Measurements were taken for the tube diameter and thickness at various points and an average is worked out. One end of each tube was tack welded at three points by a steel plate and sealed against leakage of concrete slurry. Concrete mix was placed into the steel tubes in layers and each layer was compacted by a steel rod. Light tamping of steel tube using wooden hammer helped to achieve uniform and void free concrete. The measured slump at the time of placement inside the steel tube was 60 mm and the mix remained cohesive. The top end of the tube was covered with a cap plate. To attain the maximum strength at the top, water was periodically added through the air space beneath the top plate. After one week, the tack welds securing the bottom end plate were removed. To make up the top surface uniform, it was filled with high strength concrete grout enabling uniform loading on both steel and concrete.

2.4. Test equipment and procedure

The specimens were instrumented to measure both longitudinal strains and deflection at the middle portion of the columns. 10 mm Electrical resistance strain gauges were fixed on the diagonally opposite faces of steel tubes to measure the longitudinal strains of columns. Dial gauge was fixed at the mid height of the columns to measure lateral deflection. Tests were conducted in a 2MN AVERY universal testing machine. The columns were partly fixed at both the ends and loaded with axial compressive load with an initial end eccentricity. The eccentricity was equal at both the ends and the columns were subjected to single curvature bending. To apply eccentric loading on the specimens, end capping was fabricated for each eccentricity since the standard machine accessories were suitable only for concentric loading. A detailed drawing of the end capping is given in Fig. 2. The ends of the column

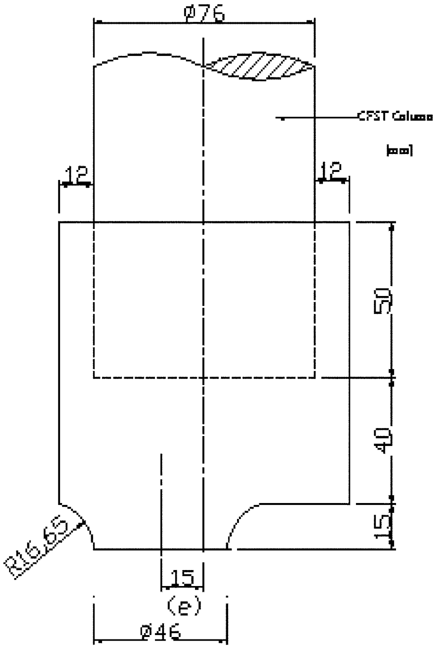


Fig. 2 End capping

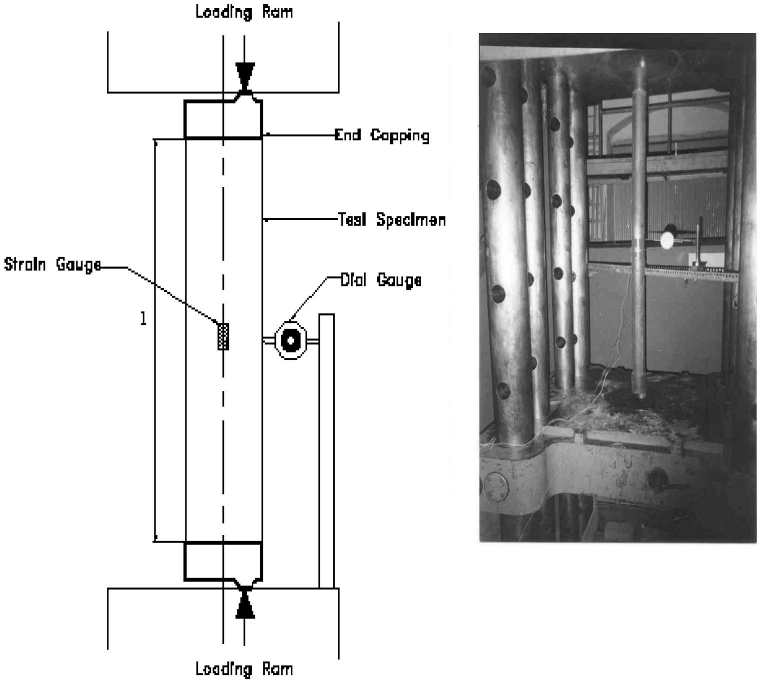


Fig. 3 Test setup

were not allowed to rotate by the sidewall of the end capping. Throughout the testing the capping proved to be robust and reliable. End capping were secured over the top and bottom end of the column and placed in the testing machine. Special attention was given to verify the correct position of the column before any loading. A small pre-load of about 5 kN was applied to hold the specimen upright. The load arrangement and instrumentation of the column is shown in Fig. 3. The working of strain gauges was tested by applying small load and after necessary adjustments initial readings were taken. The initial reading on dial gauge was also noted. The load was applied in small increment of 20 kN and the observations such as longitudinal strains on opposite faces and lateral deflection at mid height of the column specimen were recorded. The ultimate load was observed and recorded for all the specimens. Fig. 4 shows column A6 under test at its failure load. All specimens were loaded to failure. The mode of failure in all columns followed an almost parallel course. Failure was by an overall buckling mode with no sign of local buckling of the steel section. The failure pattern of column specimens is shown in Fig. 5. In hollow steel tubular columns local buckling appeared first near mid-height of the column and then followed by overall buckling at failure.

3. Test results and discussions

In addition to the slenderness ratio (L/D) and eccentricity ratio (e/D), Table 5 gives also the ultimate load P_u and mid-height deflection δ at failure of the column specimens. As shown by this table, slenderness ratio in this study ranged from 8.5 to 23.5 and the eccentricity ratio ranged from 0 to 0.33.

Fig. 4 Column A6 under test

Fig. 5 Failure pattern

Table 5 Summary of test results

Sp. no.	L/D	e/D	P_u (kN)	δ (mm)	P_u / P_{ref}(1)
A1	8.5	0.20	290	4	2.32
A2	11.5	0.20	267	6	2.26
A3	14.5	0.20	245	10	2.23
A4	17.5	0.20	226	12	2.15
A5	20.5	0.20	206	15	2.10
A6	23.5	0.20	185	18	2.06
A7	20.5	0	355	6	2.09
A8	20.5	0.33	130	18	2.17
B1	8.5	0.20	275	3.5	2.20
B2	11.5	0.20	255	4.5	2.16
B3	14.5	0.20	235	7.5	2.14
B4	17.5	0.20	218	8	2.08
B5	20.5	0.20	206	8.5	2.10
B6	23.5	0.20	195	9	2.17
B7	20.5	0	330	5	2.00
B8	20.5	0.33	140	9	2.30
C1	8.5	0.20	125	3	--
C2	11.5	0.20	118	5	--
C3	14.5	0.20	110	6	--
C4	17.5	0.20	105	8	--
C5	20.5	0.20	98	10	--
C6	23.5	0.20	90	12	--
C7	20.5	0	165	3	--
C8	20.5	0.33	60	12	--

(1)P_{ref}: The load resistance of the unfilled reference column (Type C specimen)

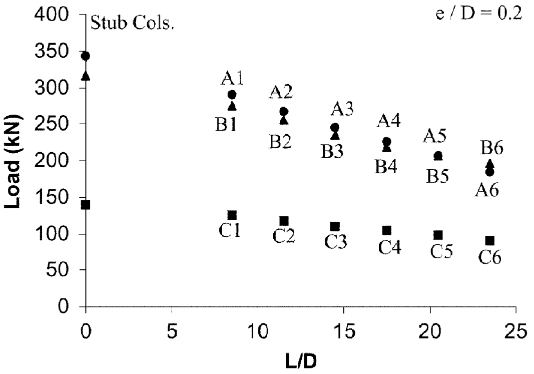


Fig. 6 Effect of slenderness on ultimate load

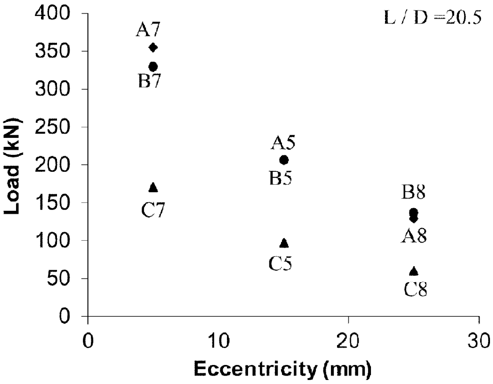


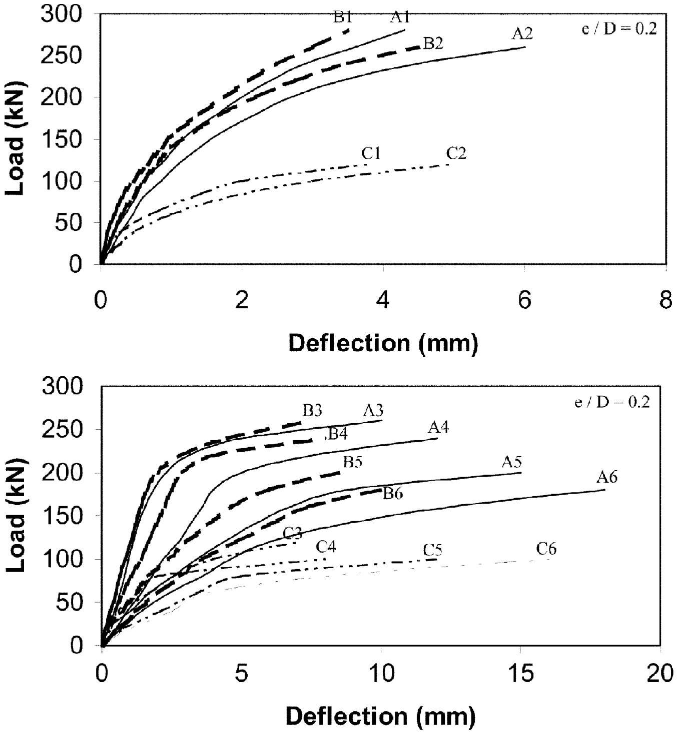
Fig. 7 Effect of eccentricity on ultimate load

3.1. Ultimate load

The ultimate load of each column is plotted against its slenderness ratio having constant eccentricity ratio (*e/D* = 0.2) and shown in Fig. 6. Included on this diagram are points showing the ultimate load of the concentrically loaded stub columns (*L/D* = 3.5), which were also tested. The trend shows that slenderness ratio has marked detrimental effect upon ultimate load. It is seen that, ultimate load tends to decrease as slenderness ratio increases for all type of column specimens (Type A, Type B & Type C specimens). From Fig. 6 it is seen that, prior to slenderness ratio of 20.5, Type A specimens attains higher ultimate load than Type B specimens. Beyond 20.5, Type B specimen (B6) gains the increase in its ultimate load than Type A specimen (A6). Fig. 7 shows a plot of load versus eccentricity for columns A5, A7, A8, B5, B7, B8, C5, C7 & C8 for which slenderness ratio was kept constant at 20.5. The reduction in ultimate load with increasing load eccentricity for all type of specimens is again similar to the results that are found previously in the effect of slenderness upon ultimate load. Also it can be seen from Fig. 7 that at large eccentricity of 25 mm, the ultimate load is greater for Type B specimen (B8) than Type A specimen (A8). Table 5 indicates that, slender columns exhibit greater mid-height deflection than columns of low slenderness ratio. Also it is observed from the Table 5 that, Type B specimens have lesser mid-height deflections than Type A specimens. In comparison with the hollow steel tubes (Type C specimens) the test results shows that, the infill concrete increased the load resistance of Type A and Type B specimens by a factor varied between 2 to 2.32.

3.2. Load-deflection relationships

The load-deflection curves at mid-height were plotted for all column specimens, and Figs. 8 & 9 shows this relationship for columns A1-A6, B1-B6 & C1-C6 for which eccentricity ratio was kept constant to *e/D* = 0.2. The load-displacement relationships are seen to be non linear and are characterized by an ascending branch up-to failure. The load-deflection curve shows that Type B specimens have relatively less deflection at any given load, than Type A specimens indicating high stiffness. Load versus deflection for columns A5, A7, A8, B5, B7, B8, C5, C7 & C8 are shown in Fig. 10. It is seen that columns subjected to small eccentricity of load exhibit a stiff response up-to failure than corresponding columns subjected to large eccentricity .It is also seen that when column



Figs. 8 & 9 Slenderness effect on Load-deflection response of short and slender columns

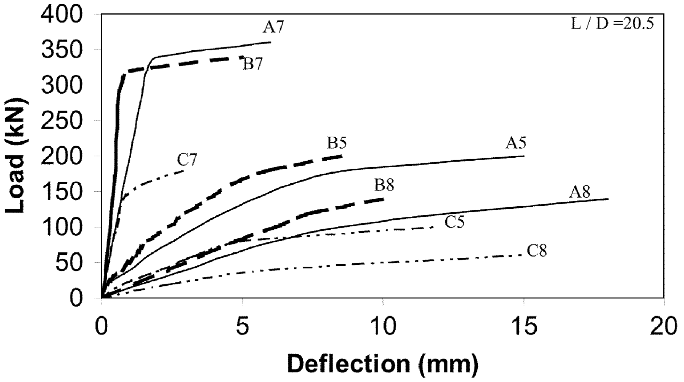
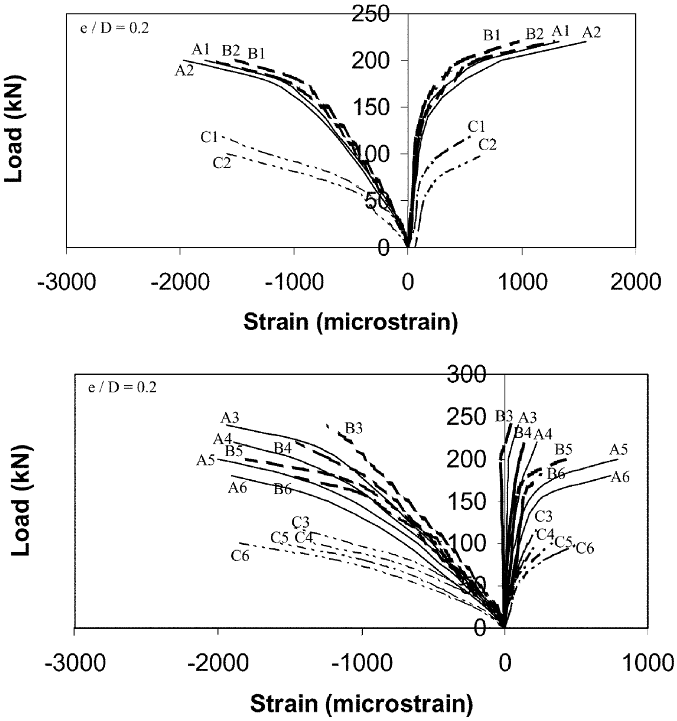


Fig. 10 Eccentricity effect on Load-deflection response of slender columns

ubjected to large eccentricity, a more flexible response is apparent in the ascending portion with a substantial reduction in column strength of both Type A and Type B specimens. There is no significant difference between the responses of hollow steel tubes, except that the ultimate load and stiffness was very much less than that of filled specimens.



Figs. 11 & 12 Slenderness effect on strain variations of short & slender columns

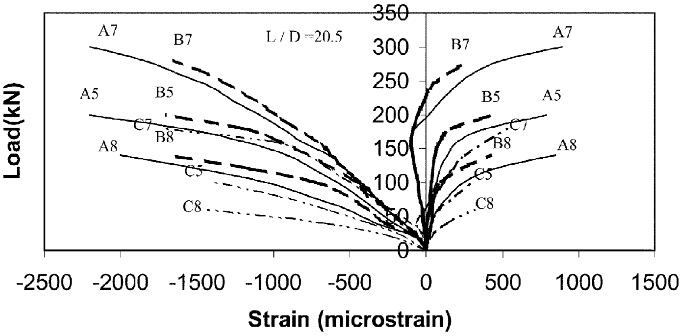


Fig. 13 Eccentricity effect on strain variations of slender columns

3.3. Load-strain relationships

Strains measured during the tests were plotted against the loads for all columns and Figs. 11-13 gives a summary of the recorded mid-height longitudinal strains for columns A1-A8, B1-B8 & C1-C8. The non-linearity exhibited by strains is of the same nature as that exhibited by deflections. In all the column tests as seen from the above figures, the strains in the steel section reached the yield strain values at loads which are close to the failure loads. The graph shows that Type B specimens have relatively less strain gradient than Type A specimens until failure occurred. The strain at any given load corresponding to Type B specimens is low when compared with Type A specimens. Type A and Type B specimens have shown large strain variation than Type C specimens. Generally the responses of the hollow steel tubes are similar over the entire load-strain range.

3.4. Ductility

Ability of a structure to undergo large deformation is an important aspect of structural performance. Ductility is defined as the ability to possess nonlinear deformations under loading. It may be expressed as the ratio of deflections/curvatures/or rotations. Ductility factor of the specimen is defined herein as the ratio of lateral deflection at ultimate load to lateral deflection at yield load. Further it is observed from the load-deflection curves and load-strain curves that Type B specimens have slightly better ductile behavior than Type A specimens.

4. Conclusions

From these test results the following conclusions are drawn:

1. The use of fiber reinforced concrete has resulted moderate improvement upon the behavior of concrete filled steel tubular columns subjected to eccentric loading.
2. At large slenderness ratio and eccentricity ratio fiber reinforced concrete filled specimens showed 5 to 8 percent increase in ultimate load than plain concrete filled specimens.
3. The load deflection curves showed that fiber reinforced concrete filled steel tubular columns have relatively more stiffness than plain concrete filled steel tubular columns as it undergoes less deflection.
4. The ductile behavior of fiber reinforced concrete filled specimens is found to be slightly better than plain concrete filled specimens.
5. Concrete filled steel tubular columns showed large enhancement of load carrying capacity as compared to hollow steel tubular columns and can sustain large strains and deformations.

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Notation

D : steel tube outside diameter
t : steel tube wall thickness
Pu : ultimate load of column
e : load eccentricity
δ : mid-height deflection
L : length of column
f_{cc} : characteristic 28 day cube strength of concrete
f_{ck} : flexural strength of concrete
f_{ct} : split tensile strength of concrete
E_c : elastic modulus of concrete
f_{sy} : yield strength obtained from tension coupons
f_{sy}^* : yield strength obtained by compression on 100 mm long steel tubes
f_u : ultimate strength obtained from tension coupons
E_s : modulus of elasticity of steel

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