EXPERIMENTAL INVESTIGATION ON THE BEHAVIOUR OF CONCRETE-FILLED STEEL COLUMNS

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ABSTRACT

Steel sections with concrete infill are being increasingly used as structural members, since filling the steel section with concrete increases both its strength and ductility without increasing the section size. However, the limitations imposed by certain drawbacks of cement concrete are not alleviated or moderated by the encasing steel tube, like its high shrinkage, creep, brittleness, reactivity and low tensile strength, may be a hindrance to the rapid and diversified application of concrete filled steel tubes in line with current emphasis on ductility-based seismic design. In this context, studies are presently being conducted on filled steel composite members, employing lighter, more ductile, high tensile strength and inert polymer-based fill materials for the steel tube. In the present paper, experimental results of concrete–filled steel columns and polymer modified concrete filled steel columns under axial load combined with lateral cyclic loading are reported. Findings of these studies relating to the hysteresis response of filled steel composite columns subjected to axial compression combined with lateral cyclic load highlight the significant increase in ductility and energy absorption capacity of polymer modified concrete-filled steel columns.

Keywords: Composite columns; polymer modified concrete; concrete-filled steel tubes; lateral load; cyclic load; energy absorption

1. INTRODUCTION

In designing a structure, ductility is one of the most important considerations. The potential economical advantages of concrete-filled steel columns (CFTs) in tall buildings could lead to significant savings of steel usage in comparison with pure steel buildings. Compared with reinforced concrete structural members, concrete filled steel columns have constructional merits, because the steel tubes can serve as stay-in-place formworks and shoring members for the infilled concrete. However, cement concrete has certain drawbacks which are not

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mitigated by the encasing steel tube, thus presenting a hindrance to the rapid evolvement and diverse application of CFTs. Noticeably, high shrinkage, creep and low tensile strength of cement concrete have lately been determined to significantly weaken the steel-concrete interface bond, thus hampering beneficial composite interaction, and resulting in the concrete shedding some of its stress to the steel [1-3]. Studies also indicate that the high strength concrete usually preferred for very tall CFTs leads to approximately a 50% reduction in ductility of the CFT when compared to CFT filled with normal concrete [1] . The severest doubt on the use of cement concrete in steel tubes has been cast by the extremely disastrous effects of the 1995 Hyogo-ken Nanbu Kobe earthquake in Japan on both steel and reinforced concrete structures, which prompted a change of seismic design perspective from the previous emphasis on structural strength to emphasis on structural ductility and energy absorption [4]. Accordingly, the fill material inside the steel tube is required to be of such quality as to increase the ductility, but not strength, of the composite member (particularly when the retrofitting or repair of damaged hollow steel structures is involved [5], and would be preferred to be of low weight to reduce the induced seismic loads. In this context, interest is now being directed towards evaluating the suitability of pure polymers like epoxy or polymer-based materials such as polymer concrete or latex modified cement mortar, for use as fill materials in filled steel composite members. This present study extends on the observations drawn from the aforementioned studies, and focuses on the hysteresis behaviour of polymer modified concrete (PMC) filled steel composite columns as compared to ordinary cement concrete (PCC) filled steel columns. Results obtained indicate the great potential of epoxies and fibre latex-cement mortar as alternative fill materials to cement concrete or which could be combined with ordinary concrete for enhanced ductility and energy absorption capacity of filled steel members.

1.1 Research significance

Generally, the philosophy of modern seismic codes is based on the energy dissipation capacity of structures. This is mainly achieved through the ductile behaviour, i.e. the ability of an element or a structural system to dissipate large amount of energy through inelastic cyclic deformations without substantial reduction of its resistance. The objective of this research work is to investigate the ductility and energy absorption capacity of circular polymer modified concrete- filled columns subjected to simulated earthquake loading. Experiments were carried out on concrete and polymer modified concrete steel columns subjected to combined axial load and lateral cyclic loading. This study advances the understanding of the seismic performance of polymer modified concrete filled columns.

2. EXPERIMENTAL INVESTIGATION

Circular CFT model columns with steel tube diameter-thickness ratio (D/t) of 57 were tested to failure. This ratio satisfies the limitations specified by various codes, including the AISC LRFD [D/t$\leq (8E/f_y)^{1/2}$], the CAN/CSA-S16.1- 4(1994) [D/t$\leq (28000/f_y)$], and AIJ (Qie1994) [D/t$\leq (23520/f_y)$], where f_y is the yield strength of steel and E is the young's modulus of steel. The details of specimen are given in Table 1.

Table 1: Details of test specimen

Specimen	Nomen clature	D/t (mm)	D (mm)	t (mm)	f_c (MPa)	f_y (MPa)
Hollow steel tubes	HC	57	114	2	---	270
Concrete filled steel tubes	CCFT	57	114	2	26.7	270
Polymer modified concrete filled steel tubes	PCFT	57	114	2	24	270

2.1 Material characteristics
2.1.1 Steel section

The hollow sections were fabricated from light gauge steel sheets, seam welded along its length. Tensile tests were carried out as per ASTM-A370 [6] on three coupon samples that were cut from the steel tubes used to fabricate the CFT columns. The yield stress and ultimate stress were found to be 270 N/mm^2 and 410 N/mm^2 respectively and the percentage elongation was 13% and modulus of elasticity was 2.05×10^5 N/mm^2.

2.1.2 In-filled concrete

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. The PCC (portland cement concrete) and PMC (polymer modified concrete) for the composite columns were mixed in two separate batches. To assess the compressive strength, cubes of size 150 x 150 x 150mm and cylinders of size 300 x 150mm were cast.

For applications where permeability resistance and high bond strength are required but colour fastness is not important, S-B latexes [7] are the polymers of choice, based on performance and cost. Hence for this study, SBR latex (styrene butadiene rubber) which is one of the most popular commercial cement modifier has been selected. It is specially designed for use as a bending aid and gauging liquid for cementitious systems. The results of the compressive strength tests on concrete carried out as per IS 516-1959 [8] are given in Table 2. Compressive strength was considered for arriving at the optimum percentage of polymer to be added to concrete. It was found that when the percentage of polymer added is above 2% there is gradual reduction in compressive strength. After number of trials, the optimum percentage of polymer to be added was found to be 2% and this is used in the present study to carry out the cyclic load tests. The stress vs micro strain curves for PCC and PMC were shown in Figure 1.

2.1.3 Load slip behaviour

To assess the bond between steel and concrete, load slip tests were conducted. The arrangement for conducting the test for load slip behaviour is shown in Figure 2. The steel interface provides frictional resistance due to the surface irregularities ("micro-locking") in the inner face of the steel shell. As the load reaches the ultimate value, mechanical interlocking of concrete fails and results in the movement of the concrete core vertically inside the steel tube.

Table 2: Material Properties of PCC and PMC

Sl. No.	Type of in-fill	Cube strength N/mm²	Cylinder strength N/mm²	Flexural strength N/mm²	Spilit tensile strength N/mm²	Young's modulus (E_c) ($\times 10^4$) N/mm²
1	Plain cement concrete	32.44	26.65	4.24	4.10	2.668
2	2.0% polymer modified concrete	31.54	23.64	4.40	5.10	2.600
3	2.5% Polymer modified concrete	26.58	22.38	4.00	4.58	2.500
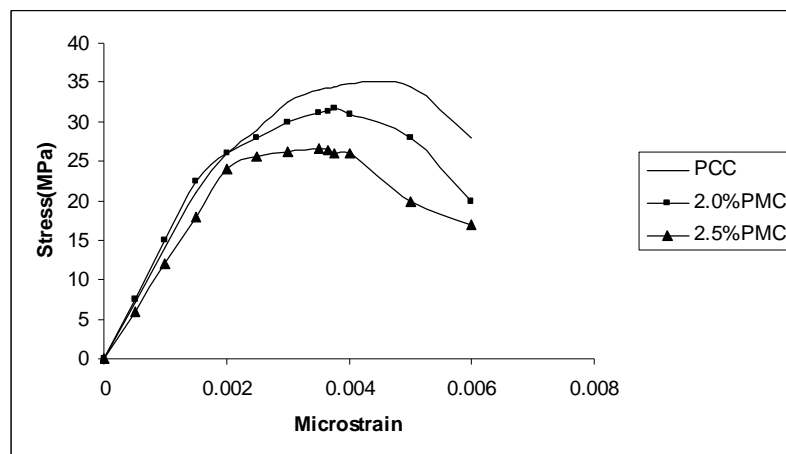
Figure 1. Stress vs microstrain curves for concrete and polymer modified concrete
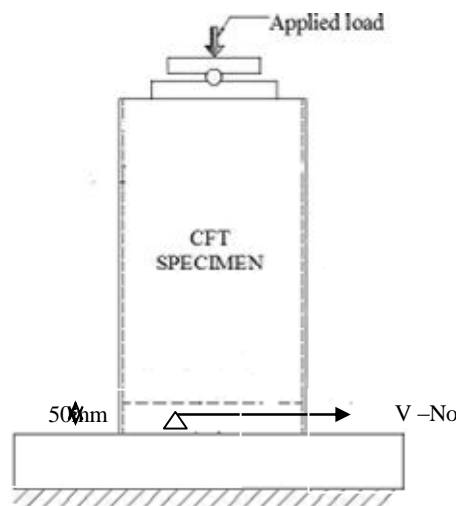

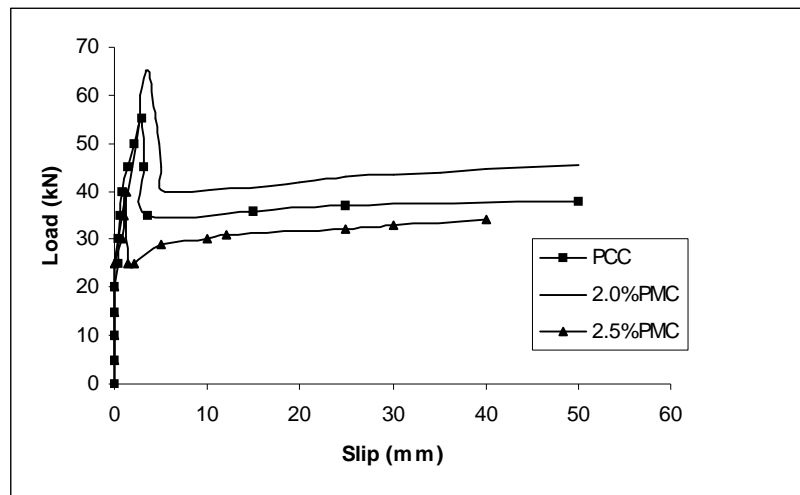Figure 2. Load slip test arrangement behavior of PCC and PMC specimens

Figure 3. Load slip

From the load versus slip behaviour shown in Figure 3, all the specimens were found to follow a similar pattern, and the average bond strength of the specimens filled with concrete was found to be 0.432 N/mm^2 and that of specimens filled with polymer modified concrete was found to be 0.597 N/mm^2 and it is clear that polymer modified concrete shows better bond performance compared to PCC.

2.2 Cyclic test on columns

All the CFT columns were tested using the test setup shown in Figure 4. The loading apparatus adopted for the tests is designed so as to enable the induction of a transverse load simulating seismic force and a compressive load due to the dead load of the superstructure on the specimens. Lateral force was applied at the top of the column through a 50 kN capacity pseudo controlled hydraulic actuator. For all tests, the specimens were subjected to constant axial load, $P = 0.3 \ P_0$ (where P_0 is the pure compression load obtained from stub column tests) through 500kN capacity hydraulic jacks and held constant during the testing. A pump and a pressure relief valve were used in conjunction with the above set up to minimize the variation of the axial load due to the shifting of the column axis during testing. The imposed lateral displacement was measured using the displacement transducer of the actuator. The built-in load cell of the actuator recorded the corresponding lateral force.

During testing, three single cycles of load were applied to the specimens corresponding to an increment of 0.25% peak drift ratio, and then three repetitive loading cycles were applied at peak drift ratios of 1%,1.5%,2%,3%,4% and 6%. The drift ratio is taken as the lateral displacement normalized by the height measured from the top of the bottom plate to the point of lateral load application. The loading procedure was continued until the failure of the specimen.
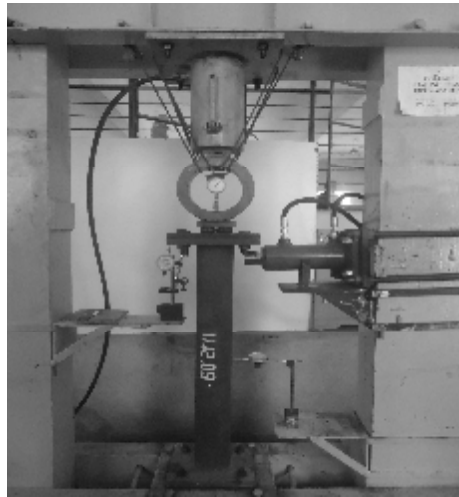
Figure 4. Test setup for lateral loading

3. RESULTS AND DISCUSSION

3.1 Failure modes of columns subjected to cyclic loading

The failure of the CFT columns was characterized by the rupture of the steel tube at the plastic hinge location leading to a visible crack in the tube and a drop in the peak lateral force by 20%. In all tests, it was observed that failure occurs through a combination of concrete crushing and local buckling of the steel tubes and in some cases eventual fracture in the steel tube in the regions of the plastic hinges.
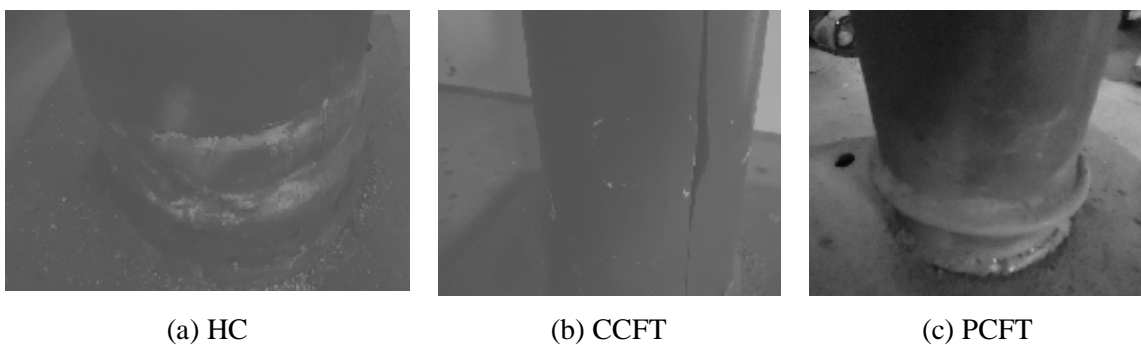

| (a) HC | (b) CCFT | (c) PCFT |

Figure 5. Failure pattern of the columns

Figure 5(a) shows the inward local buckling of HC specimens at a height of about 1/7 from the base during loading cycles at drift ratio 1% . On the reverse excursion also, similar local buckling was observed at nearly the same heights above the base. With additional cycles, steel tube rupture was visible at a height of 1/6 from the base at drift ratio 2%.

Figure 5(b) shows the outward local buckling followed by steel rupture of the CCFT specimens at a height of about 1/6 from the base, during the loading cycle at drift ratio 6%. As

expected the concrete prevented the inward local buckling and only outward local buckling occurred in such columns. Pulverized concrete fell out through the crack in the steel tube, indicating the crushing of the core concrete.

Figure 5(c) shows the elephant foot shaped buckling of PCFT specimens at height of about 1/5 from the base during the loading cycle at 8% drift ratio. With additional cycles, buckling progressed on both faces perpendicular to the loading direction followed by gradual strength and stiffness degradation.

From the visual inspection carried out on the tested specimens, it was observed that CCFT specimens had cracks in both the aggregate and the paste, which usually initiate from microcracks and voids in the matrix and finally form major vertical cracks as the transverse tensile strains reach their limiting values. Whereas, due to the adhesion between the styrene-butadiene modified mortar and aggregates, there was no visible crack in the paste in PCFT specimens.

3.2 Hysteretic curves

The horizontal load versus horizontal displacement hysteretic curves for the tested columns is shown in figures 6(a) to (c) respectively. It can be seen that there is a considerable increase in the strength of in-filled columns, due to increase in failure strain of concrete due to the confining effect of PCC and PMC by the steel shell compared to the hollow columns.

Figure 6 (a) shows the load versus displacement behavior of HC specimens. Pinching effects were explicitly observed during loading cycles at drift ratio 1% and with additional cycles, the strength degrades due to the initiation of inward local buckling followed by steel rupture.

Figure 6(b) shows the load versus displacement behavior of CCFT specimens. During loading excursion, the stiffness of CCFT specimens reduces gradually from its initial elastic value, due to both geometric and material non-linearity, as evidenced in each cycle of loading. The maximum strength achieved within each hysteretic cycle degrades as cycling proceeds, primarily due to local buckling of the steel tube and due to damage of the concrete. Pinching of the hysteretic curve was observed for CCFT specimens during the loading cycles at drift ratio 4%.

Figure 6 (c) shows the load versus displacement behavior of PCFT specimens. Quite distinctive from others, PCFT specimens showed a considerably high relative ductility, with a load-deflection curve depicting a linear elastic region followed by an extended near perfectly-plastic response. The stiffness gradually degraded and the column entered into the inelastic stage. With increasing lateral displacement, slight pinching effects were observed in the hysteresis loop for the PCFT specimens reflecting slippage between the steel tube and concrete core during loading cycles at 6%.

3.3 Ductility factor and energy absorption capacity

Ductility and energy-absorption capacity are important considerations in seismic design. The energy dissipation through hysteretic damping reduces the amplitude of seismic response thereby reducing the ductility demand of the structure. The ductility factor of a specimen can then be defined as the ratio of the ultimate drift displacement (δ_m) divided by the yield displacement (δ_y).
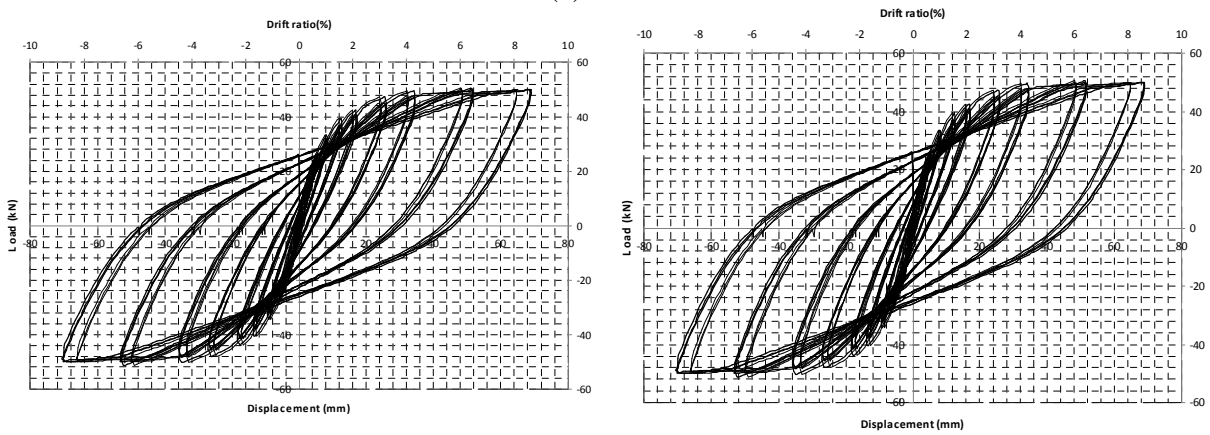
$$\text{Ductility factor,} \quad (\mu_m) = \delta_m / \delta_y \; [9] \tag{1}$$

(a) HC
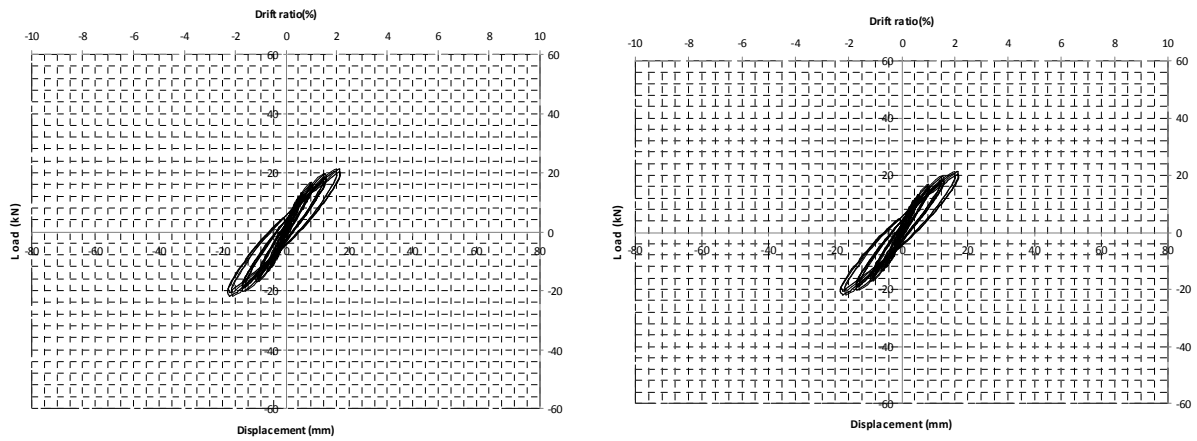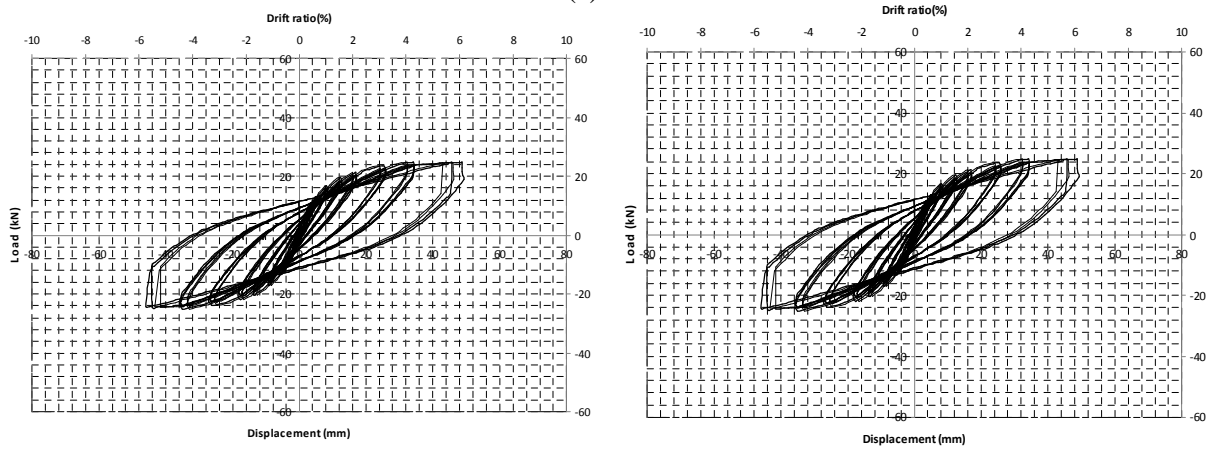
(b) CCFT

(c) PCFT

Figure 6. Hystersis loop for the columns

The ultimate drift displacement is taken as the displacement where the load carrying capacity degrades below 80% of the maximum capacity. Due to the better bond between the steel tube and PMC, PCFT specimens showed ductility of about 2.5 times higher than the CCFT specimens and 3.75 times higher than the HC specimens. From the above studies, it can be concluded that the filled-in polymer modified concrete is effective in improving the seismic behavior of steel columns.

Table 4: Ductility and energy absorption capacity

| Specimen | No. of cycles to failure | | | | | | μ_m | $\hat{E}$ |
| | Drift ratio | | | | | | | |
	1%	2%	3%	4%	6%	8%		
HC	3	3	3	3	3	--	1.0	59
CCFT	6	6	6	6	6	--	1.5	192
PCFT	6	6	6	6	6	3	3.75	250

The energy absorption capacity ($\hat{E}$), is

$$\hat{E} = \frac{1}{E_e} \sum_{i=0}^{n} E_i$$

$$E_e = \frac{1}{2} H_y d_y$$

(2)

Where, E_i = energy absorption at cycle i of the test , H_y is the lateral load at yield displacement and n is the number of cycles. In PCFT specimens, significant increase in both ductility and energy-absorption capacity were observed compared to hollow and concrete filled specimens. This is because addition of polymer modified concrete delayed the local buckling and increased the number of cycles to failure thereby enhancing the amount of energy dissipated.

4. CONCLUSIONS

This study mainly presents an experimental investigation on polymer modified concrete filled steel columns under axial load combined with lateral cyclic load. The parameter under investigation included effect of concrete inside the steel tube, aiming to determine how this factor influences the ductility and energy absorption capacity. The following conclusions can be drawn based on the limited research reported in this paper:
- Polymer modified concrete filled steel columns fail in a ductile manner and exhibit plump hysteretic loops with a slight pinching effect under the combination of axial load and lateral cyclic load.
- Polymer modified concrete columns exhibit ductility ratio as well as energy absorption

of about two times more than the concrete filled columns and three times more than hollow columns.

- Polymer modified concrete filled columns exhibit high ductility with moderate axial strength increase, an attribute that has become of great necessity in currently emphasized ductility oriented seismic design.

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