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Behaviour of concrete-filled steel columns subjected to lateral cyclic loading

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ABSTRACT

This paper reports the findings of an experimental study that was undertaken to investigate the cumulative damage of in-filled steel columns subjected to quasi-static loading. The parameters studied are, the diameter-to-thickness ratio of the steel tube and two types of in-fills namely Plain cement concrete and Steel fiber reinforced concrete. This paper summarizes the results of phase I testing that consisted of benchmark tests to establish the hysteresis behaviour under variable amplitude cyclic loading and phase II testing that consisted of constant amplitude cyclic loading that focused on the effects of amplitude and number of cycles on damage accumulation of in-filled columns. Findings of these studies highlight the significant increase in ductility and energy absorption capacity and decrease in the damage index of Steel fiber reinforced concrete-filled steel columns compared to plain cement concrete-filled columns. A simplified equation for cumulative damage has been proposed to predict the damage index of in-filled columns. This index can be used as a measure for predicting the safety of new and existing in-filled columns against earthquake.

1. Introduction

Post earthquake reconnaissance and follow up research have indicated that most of the damage in structural members like columns is a result of insufficient column ductility and energy absorption capacity to sustain the large lateral displacement. In-filled steel columns are effective structural forms for such purposes because of their high compressive strength, energy absorption capability and ductility. Under the action of seismic forces, the damage induced in critical regions of in-filled steel tube columns is due to the cumulative damage of the steel tube caused by repeated cyclic loading in the post yield strain region. [1]

To investigate the seismic behaviour of concrete in-filled steel tube (CFT) columns, many quasi-static cyclic loading tests have been carried out in the past, such as Sakino and Tomii [2], Nakanishi et al. [3], Nakahara et al. [4], Elremaily and Aziznamini [5], Xiao et al. [6], Marson and Bruneau [7], Amir fam et al. [8], Kingsley et al. [9], Yaochun Zhang et al. [10]. All the aforementioned studies focused on standard loading protocols with ramping drift amplitude to obtain the cyclic behaviour. Studies on the effects of amplitude and number of cycles on damage accumulation are found lacking. Therefore issues related to correlation of observed hysteretic behaviour to damage of columns are found to be necessary to model and calibrate cumulative seismic damage of in-filled columns. The effort described in this paper is an initial step in this direction.

In this paper, a detailed experimental study on circular CFT columns has been undertaken under constant and variable amplitude loading combined with constant axial load. This study has been extended to steel fiber reinforced concrete in-filled steel tube (SCFT) columns and the results have been compared with CFT columns. The system variables and measured response were tailored to model and calibrate the cumulative seismic damage.

2. Experimental investigation

2.1. Details of experimental program

The experimental program consisted of tests on CFT and SCFT columns of diameter-to-thickness ratio (D/t) 38 and 57. The tests were conducted in two phases. Phase I testing consisted of benchmark tests on CFT and SCFT columns under variable amplitude loading combined with constant axial load. Phase II testing consisted of tests on CFT and SCFT columns under constant amplitude loading histories.

The hollow steel tubes used were 1 m long and were seam welded along the length. The range of steel tube diameter-to-thickness ratio chosen satisfies the limitations specified by various codes, namely, AISC LRFD $[D/t \le (8E/f_y)^{1/2}]$ [11], CAN/CSA-S16.1-4(1994) $[D/t \le (28000/f_y)]$ [12], and AIJ (Qie 1994) $[D/t \le (23520/f_y)]$ [13], where f_y is the yield strength of steel and E is the modulus of elasticity of steel. All specimens were welded and strengthened with four numbers of 6 mm thick gusset plates at the bottom to ensure a strong connection with the footing. The columns were fixed at the bottom. The details of specimens and loading pattern are elaborated in Table 1.

2.2. Material properties

Tensile tests were carried out as per ASTM-A370 [14], on coupon samples that were cut from the steel tubes used to fabricate the columns. The

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Table 1
Details of specimens.

Specimen	*D*(mm)	*t*(mm)	f_{ck}(MPa)	f_y(MPa)	P_o(kN)	Loading pattern
CFT57-V	114	2	32.44	293	105.9	Variable drift amplitude
CFT57-C2	114	2	32.44	293	105.9	Constant drift amplitude at 2%
CFT57-C4	114	2	32.44	292	105.9	Constant drift amplitude at 4%
CFT57-C6	114	2	32.44	292	105.9	Constant drift amplitude at 6%
SCFT57-V	114	2	57.78	293	155	Variable drift amplitude
SCFT57-C2	114	2	57.78	293	155	Constant drift amplitude at 2%
SCFT57-C4	114	2	57.78	294	155	Constant drift amplitude at 4%
SCFT57-C6	114	2	57.78	294	155	Constant drift amplitude at 6%
CFT38-V	114	3	32.44	293	182	Variable drift amplitude
CFT38-C2	114	3	32.44	293	182	Constant drift amplitude at 2%
CFT38-C4	114	3	32.44	293	182	Constant drift amplitude at 4%
CFT38-C6	114	3	32.44	293	182	Constant drift amplitude at 6%
SCFT38-V	114	3	57.78	295	205	Variable drift amplitude
SCFT38-C2	114	3	57.78	295	205	Constant drift amplitude at 2%
SCFT38-C4	114	3	57.78	295	205	Constant drift amplitude at 4%
SCFT38-C6	114	3	57.78	293	205	Constant drift amplitude at 6%

Note: Specimen name example: CFT57-V refers to CFT column with steel tube having diameter-to-thickness ratio (D/t) of 57 tested under variable drift amplitude; CFT57-C2, CFT57-C4 and CFT57-C6 designates the CFT model column with steel tube having diameter-to-thickness ratio of 57 tested under constant drift amplitude of 2%, 4% and 6% respectively; f_{ck} = cube compressive strength; f_y = yield strength of steel.

yield stress and ultimate stress were found to be 270 N/mm^2 and 410 N/mm^2 respectively and the percentage elongation was found to be 13% and modulus of elasticity was found to be 2.05×10^5 N/mm^2.

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 2.36 mm (max.) size fine aggregate was based on ACI committee 211.1.1991 recommendations [15]. From the concrete mix, concrete cubes and cylinders were prepared and tested to obtain the actual material properties. To prepare SCFT columns, initially three different volume fractions of steel fibers were chosen, namely, 0.75%, 1.00% and 1.25% to find the optimum volume fraction of fibers that has to be added to PCC. Crimped steel fibers having an aspect ratio of 70 (length of the fiber (l_f) = 30.80 mm and diameter of the fiber ((d_f) = 0.44 mm) were used. As it is very difficult to achieve a uniform mix if the aspect ratio of the fiber is greater than 100 [16], an aspect ratio of 70 was chosen in this study so that proper mixing, placing and finishing is possible. The material properties of PCC and SFRC are listed in Table 2 and the stress–strain curves are shown in Fig. 1. It was found that there is reduction in compressive strength when the volume fraction of fibers added is above 1.00%. After several trials, the optimum volume fraction of fibers to be added was found to be 1.00% and this has been used in the present study to carry out the cyclic load tests.

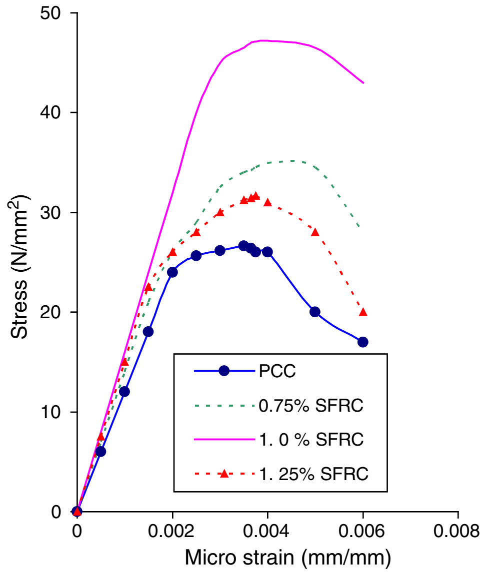

Fig. 1. Stress–strain behaviour of concrete.

2.3. Test set-up and instrumentation

The loading apparatus adopted for the tests as shown in Fig. 2 enables the application of cyclic lateral load and a constant axial compressive load. A 500 kN capacity hydraulic jack with spherical ball seat arrangement was used to apply a constant axial compressive load to the column. Lateral force was applied horizontally at a height of 850 mm from the base through a horizontal 100 kN capacity pseudo-controlled hydraulic actuator. All the specimens were subjected to a constant axial load of 0.3 P_0 (where P_0 is the pure compressive load obtained from column tests). 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. Electrical resistance strain gauges were used to measure the strain at mid-

Table 2
Material properties of PCC and SFRC.

Sl. no.	Type of in-fill	Cube strength N/mm^2	Flexural strength N/mm^2	Split tensile strength N/mm^2	Young's modulus (E_c) (by test) ($\times10^4$) N/mm^2
1	Plain cement concrete	32.44	4.24	4.10	2.968
2	0.75% steel fiber reinforced concrete	41.78	4.94	5.15	3.230
3	1.00% steel fiber reinforced concrete	57.78	5.86	6.55	3.800
4	1.25% steel fiber reinforced concrete	38.60	4.40	5.10	3.109