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Composite frame of circular CFST column to steel-concrete composite beam under lateral cyclic loading

Fa-xing Ding[a], Guo-an Yin[a,*], Li-zhong Jiang[a], Yu Bai[b]

[a] School of Civil Engineering, Central South University, Changsha, Hunan Province 410075, PR China
[b] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia

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ABSTRACT

In this paper we investigate the performance of composite frames composed of circular concrete-filled steel tubular (CFST) columns connected to steel-concrete composite beams subjected to a constant axial load and a cyclic lateral load. Seven single-story and single-bay in-plane frames were fabricated and tested. The effects of the slenderness ratio (λ), the axial compression ratio (n), and the beam-to-column linear stiffness ratio (k) on the seismic performance of the composite frame were studied. The experimental results, including damage development and stiffness degradation, load-deformation responses, energy dissipation capacity and ductility are discussed. It was found that these composite frames exhibited satisfactory seismic performance. Furthermore, a finite element (FE) model was developed and validated by comparisons with the experimental results, considering both material and geometrical nonlinearity for confined concrete and steel. The results obtained from the FE modeling were in good agreement with the experimental results in terms of failure modes, load-displacement hysteretic curves, and skeleton curves.

1. Introduction

Concrete-filled steel tubular (CFST) columns have been widely applied in bridges and high-rise buildings [1–4], not only due to their favorable structural properties such as higher strength and stiffness, higher ductility, and greater energy absorption capacity but also due to their capacity for rapid construction without the need of much formwork. CFST columns are often connected to steel beams in such structural applications [5,6], and reinforced concrete (RC) floor slabs are usually installed to the steel beams through shear connections.

The performance of structural applications using CFST columns and steel-concrete composite beams has been the subject of strong research interest in recent years. Wang et al. [7] performed fatigue tests of steel-concrete composite beams and proposed an accurate method for calculating the deflection of such beams. They concluded that the equation in AASHTO *LRFD bridge design specifications* (AASHTO 2010) [8] was the safest equation for predicting the fatigue life of studs in practical design. Liu et al. [9] and Ding et al. [10] investigated the flexural capacity and stiffness of simply supported steel-concrete composite beams under positive bending moment, and provided a superior method for estimating the flexural capacity and stiffness of such composite beams in comparison to other standards. Zhou et al. [11] studied the distortional buckling of steel-concrete composite box beams in negative moment areas. Nie et al. [12] conducted a loading capacity analysis for prestressed continuous steel-concrete composite beams. Much research has also focused on CFST columns in past decades, such as that of Chang et al. [13], Alam et al. [14], Ataei et al. [15], and Nie et al. [16].

Results of investigations into the seismic performance of composite frames consisting of CFST columns and steel-concrete composite beams are also limited, in terms of both experimental and modeling investigations. Kawaguchi et al. [17] examined four planar frame specimens consisting of concrete-filled square hollow-section steel tubular columns and an H-shaped steel beam under cyclic loading. The results showed excellent earthquake resistance for such CFST frames, evidenced by the low value of the reduction factor D_s in accordance with the building standard law of Japan [18]. Two quarter-scale, 2-bay and 3-story specimens consisting of steel-reinforced concrete (SRC) beams and steel-reinforced ultra-high-strength concrete (SRUHSC) columns were tested under low reversed cyclic loading by Zhang et al. [19]. The results indicated that the use of encasing structural steel and high-strength stirrups within the ultra-high-strength concrete was effective in alleviating brittle failure of the concrete and improving structural carrying capacity, taking advantage of the high compressive strength of the concrete and the associated improvement in structural ductility. Muhummud et al. [20] studied the seismic behavior of multi-story CFST composite frames using the nonlinear dynamic time-history analysis

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* Corresponding author.
E-mail address: 124812242@csu.edu.cn (G.-a. Yin).

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software DRAIN-2DX; numerical models were developed based on fiber beam-column elements.

The seismic behavior of composite frames consisting of circular CFST columns connected to steel-concrete composite beams has not yet been well studied (experimentally in particular), although this topic is highly important for applications in high-rise buildings located in seismic regions. In this work, seven single-story and single-bay frames at the scale of 1:2 were fabricated and prepared at Central South University in China to investigate the seismic performance of CFST columns to steel-concrete composite beam frames under a constant axial load and a lateral cyclic loading. Nonlinear finite element (FE) analysis of the composite frames was performed using ABAQUS. On the basis of the valuable experimental and numerical results, failure process, load-deformation responses, strength and stiffness degradation, energy dissipation capacity, and ductility were analyzed and discussed. The results of this work will provide solid support for applications of such composite frames in seismic zones.

2. Experimental program

2.1. Design of specimens

Seven single-story and single-bay in-plane frames at the scale of 1:2, designated SCF1 to SCF7, were designed according to the criteria of "strong column–weak beam" and "strong joint–weak member", for experiments resulting in beam failure as the expected failure mode. A summary of specimen information is given in Table 1. The tested parameters were:

(1) Axial compression ratio n (0.3, 0.5, 0.7) of CFST columns. The axial compression ratio was defined as $n = N_0/N_u$, where N_0 is the axial load applied in the CFST column. N_u (as $f_sA_s + f_cA_c$) is the axial compressive capacity of the CFST column. Steel and concrete mechanical properties were measured based on Chinese codes GB/T 228-2010 [21] and GB/T 50081-2016 [22] and were used in the calculation, where f_s is the yielding strength of steel and f_c is the uniaxial compressive strength of concrete. A_s and A_c are the cross-sectional areas of the steel tube and concrete core, respectively.

(2) Slenderness ratio λ (34.7, 45.7, and 52.0) of CFST columns. The slenderness ratio λ was defined as $4H/D$ according to the code DL/T 5085-1999 [23], where H is the height of the CFST column and D is the corresponding sectional diameter.

(3) Beam-to-column linear stiffness ratio k (1.8, 2.8 and 3.3). k was defined as i_b/i_c, where i_b and i_c are the linear stiffness ratios of the steel-concrete composite beam and CFST column, respectively. i_b was defined as E_sI_{eq}/l_b, where I_{eq} is the moment of inertia of the transformed section according to the code GB 50017-2003 [24] and l_b is the length of the composite beam. i_c was defined as E_hI_h/H. The stiffness of the circular CFST column (E_hI_h) was calculated using $E_sI_s + 0.8E_cI_c$ according to the code AISC-LRFD [25], where E_c and E_s are the modulus of elasticity of concrete and steel, I_s and I_c are the moments of inertia for the hollow steel cross section and core concrete cross section, respectively.

Table 1
Summary of specimen properties.

Specimen number	Member	$b_f \times h_b \times t_w \times t_f$ or d (mm)	L (mm)	k	n	λ
SCF1	beam	80 × 140 × 9.1 × 5.5	3750	2.8	0.3	34.7
	column	φ219 × 6	1900			
SCF2	beam	80 × 140 × 9.1 × 5.5	3750	1.8	0.3	34.7
	column	φ245 × 6	2125			
SCF3	beam	100 × 200 × 11.4 × 7	3750	3.3	0.3	34.7
	column	φ219 × 6	1900			
SCF4	beam	80 × 140 × 9.1 × 5.5	3750	2.8	0.5	34.7
	column	φ219 × 6	1900			
SCF5	beam	80 × 140 × 9.1 × 5.5	3750	2.8	0.7	34.7
	column	φ219 × 6	1900			
SCF6	beam	100 × 200 × 11.4 × 7	3750	2.8	0.3	45.7
	column	φ245 × 8	2800			
SCF7	beam	116 × 250 × 13×8	3750	2.8	0.3	52.0
	column	φ273 × 8	3549			

Table 2
Measured mechanical properties of steel and concrete.

Member	I14	I20	φ219	φ245	φ273	φ8	φ6	C30
f_s or f_{cu} (MPa)	290.50	296.45	335.52	301.27	322.62	556.83	444.51	31.34
f_u (MPa)	397.55	403.58	413.06	463.07	440.30	562.57	508.73	NA
E_s (GPa)	206	206	206	206	206	200	198	30.24
v_s or v_c	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.2

Q235 steel with nominal strength of 235 MPa was used for the steel tube. Hot-rolled plain bars (HPB) with the nominal yield strength of 235 MPa and diameter of 6 mm were used as stirrups spaced by 100 mm. Eight hot-rolled ribbed bars (HRB) with the nominal strength of 335 MPa and diameter of 8 mm were placed on the concrete slab for longitudinal reinforcement. Tensile coupling tests were carried out for the structural steel and reinforcing bars according to GB/T 228-2010 [21]. Concrete standard cube specimens were tested in compression for the cubic strength f_{cu} according to standard GB/T 50081-2016 [22]. The normal compressive strength of concrete for the frame specimens was 30 MPa and the average compressive strength and Young's modulus were measured as 31.34 MPa and 30.24 GPa respectively. Table 2 provides the material characteristics of the steel and concrete used in these frame specimens.

2.2. Experimental setup

Each frame specimen was subjected to a cyclic lateral load to simulate earthquake action and a constant axial load to simulate axial load transferred from the superstructure. Fig. 1 shows a schematic view of the specimens. A ground anchored groove and reaction wall was employed for loading purposes. The specimens were fastened to the strong floor through the steel base and high-strength post-tensioned steel rods. The constant axial load (N_0) was applied by a hydraulic jack with a maximum load capacity of 2000 kN. Meanwhile, a load-distribution beam was used to achieve more uniform stress distribution (see Fig. 1). Four high-strength rods were connected with the cross beams and the steel base, forming a force transfer system to transmit axial load to the steel base. Because of the flexibility of the high-strength rods, hydraulic jacks were allowed to move with the specimen so as to maintain the vertical direction of the axial loading. The lateral load was applied by imposing lateral displacement varying cyclically at the end of the connecting beam by a hydraulic actuator with a stroke of ± 100 mm and capacity of 500 kN.

A 20 mm steel cover plate was welded on the top of the column (after concrete curing) to provide full contact to the top surface of the steel tube and concrete core for better transfer of the vertical load to the column. Fig. 2 shows the configurations of the testing specimens. The same width and thickness of the RC slab (680 mm and 60 mm respectively, Fig. 2a) and the same profiles of stiffening ribs at the bottom of the CFST column (Fig. 2c) applied for all specimens. To shift the plastic zone away from the column face, an external circular diaphragm (see Fig. 2b) was welded to the beam by complete penetration butt welds. Furthermore, the loading end of the steel beam was further strengthened by welding a 150 mm length steel section extended and connected to the lateral hydraulic jack, as shown in Figs. 1 and 2b.

Strain gauges (see Fig. 3) were installed in the joint area, on the surfaces of the CFST column and the external diaphragm to study their