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Performance of circular CFST column to steel beam frames under lateral cyclic loading

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ABSTRACT

This paper presents the study on the behavior of composite frames with circular concrete filled steel tubular (CFST) columns to steel beam. Six composite frames were tested under a constant axial load on the CFST columns and a lateral cyclic load on the frame. Each frame specimen consisted of two CFST columns and a steel beam to represent an interior frame in a building. A finite element analysis (FEA) model was developed to investigate the behavior of the composite frame. The results obtained from the FEA model were verified against those experimental results. Detailed analysis was carried out on longitudinal stress in steel beams, axial stress distribution in concrete, concrete stress along the column height and at the connection panel. Parametric studies were conducted to investigate the influence of axial load level, beam to column linear stiffness ratio on the structural behavior of composite frames. A simplified hysteretic lateral load (P) versus lateral displacement (Δ) model was proposed for such composite frames.

1. Introduction

Concrete filled steel tubular (CFST) members are well recognized for their excellent performance owing to the combination of the merits of steel and concrete materials. Therefore, concrete filled steel tubes are being increasingly used in high-rise buildings. Fig. 1 shows a composite frame structure with circular CFST columns and steel I-beams connected by external diaphragms in China.

Up until now, there have been a large number of research results on the performance of CFST members, which were reviewed by several state-of-the-art reports or papers, such as Shams et al. [1], Shanmugam et al. [2], Gourley et al. [3] and Nishiyama et al. [4]. Little research, however, has been done to investigate the behavior of composite frames consisting of CFST columns [3]. Monotonic or pseudo-dynamic tests were performed by Matsui [5], Kawaguchi et al. [6] and Tsai et al. [7] in the past in this regard. Using the nonlinear dynamic time history analysis method, Muhummud [8] and Herrera [9] presented the seismic behavior of multi-story CFST composite frames. More recently, Tort and Hajjar [10] proposed a mixed finite element modeling of rectangular CFST column to steel beam frames under static and dynamic loads.

Apart from the above research, a research program has recently been carried out by the authors to investigate the performance of steel beam to CFST column frames under cyclic loading, and part of the research results has already been published. Han et al. [11] presented the behavior of composite frames with concrete filled square hollow section (SHS) columns to steel beam under a constant axial load on columns and a lateral cyclic load on the frame, and developed a finite element model (FEM) to simulate the behavior of composite frames. Wang et al. [12] reported the mechanism of composite frames with square CFST columns based on the experimental research presented by Han et al. [11]. Parametric studies were conducted to investigate the influence of axial load level, beam to column linear stiffness ratio on the structural behavior of composite frames, and a simplified hysteretic lateral load (P) versus lateral displacement (Δ) model was proposed for such composite frames.

It is well known that, in general, circular CFST columns have more excellent mechanical behavior than square CFST columns, because the confinement effect of circular section members is more effective than that in square sections. But the beam to column connections are more convenient for square CFST columns than for circular columns, and the stiffness of square CFST columns is higher than that of circular columns with a same sectional size as a whole. So it is expected that the behavior of composite frames with circular CFST columns is different from that of frames with square CFST columns, and each type of frames should be investigated accordingly.

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Nomenclature

A_c	Concrete cross-sectional area
A_s	Steel cross-sectional area
b_f	Overall width of steel I-beam
CFST	Concrete filled steel tube
D	Sectional diameter of circular CFST
E_a	Dissipated energy ability
E_c	Concrete modulus of elasticity
E_{cu}	Concrete modulus of elasticity under unloading and re-loading stages
E_s	Steel modulus of elasticity
f_c'	Concrete cylinder compressive strength
f_{cu}	Concrete cube compressive strength
f_t	Concrete tensile strength
f_y	Yield strength of steel
h	Overall height of steel I-beam
h_e	Equivalent damping coefficient
i_b	Linear stiffness ratio of beam
i_c	Linear stiffness ratio of column
H	Height of column of composite frame
k	Beam to column linear stiffness ratio ($k = i_b/i_c$)
K_1	Lateral rigidity of composite frame when Δ is equal to Δ_y
K_j	Lateral rigidity of composite frame
L	Length of beam of composite frame
M_{ub}	Ultimate flexural strength of steel beam
M_{uc}	Ultimate flexural strength of CFST column
n	Axial load level ($n = N_o/N_u$)
N_o	Axial load of CFST column
N_u	Ultimate compressive resistance of CFST column
P	Lateral load of connection
P_{ua}	Estimated ultimate lateral load capacity of frame by ABAQUS
P_{ue}	Ultimate lateral load capacity of frame by experiment
P_y	Yield lateral load capacity of frame
$P_{85\%}$	85% of ultimate lateral load capacity (P_{ue}) of composite frame
t_f	Flange thickness of I-beam
t_s	Wall thickness of steel tube
t_w	Web thickness of I-beam
α	Steel ratio ($\alpha = A_s/A_c$)
Δ	Lateral displacement of frame
Δ_y	Yield displacement of frame
Δ_u	Lateral displacement when lateral load of frame falls to 85% of P_{ue}
μ	Displacement ductility coefficient.

This paper thus investigates the mechanical behavior of composite frames with circular CFST columns to steel beam. Both theoretical and experimental studies have been carried out, where new test data pertaining to the behavior of CFST circular columns to steel beam frames is presented. Each specimen consisted of two circular CFST columns and a steel I-beam to represent a typical interior frame element in a building frame, and was tested under a constant axial load and a cyclically increasing lateral load. Another objective of this study is to compare the behavior of composite frames with circular and square CFST columns.

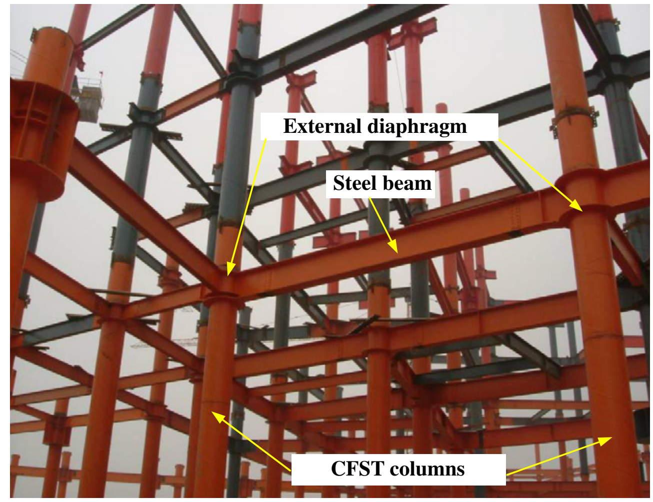

Fig. 1. A CFST composite frame under construction.

2. Experimental study

2.1. Specimen preparation and loading apparatus

Six circular CFST columns to steel beam composite frame specimens were tested. The tested composite frame represents a basic element from the real structures, as shown in Fig. 2(a). Fig. 2(b) shows the sketch of loading and boundary conditions of the tested frame element.

Fig. 2 also shows the connection and beam configurations of the test frames in detail, where the column height and the steel beam span were 1450 mm and 2500 mm, respectively. b and t_1 in Fig. 2(b) were the width and thickness of the stiffened ring, respectively. The frame specimens were designed in accordance with the concept of strong-column/weak-beam, so beam failure mode was expected to occur in the tests. The ultimate flexural strengths of columns and beams are shown in Table 1, respectively, where the ultimate flexural strength (M_{uc}) of circular CFST columns was determined according to the specification of Eurocode 4 [13], and the ultimate flexural strength (M_{ub}) of beams was determined according to the Chinese code for the design of steel structures GB50017-2003 [14].

The test frames with circular CFST columns were designed to investigate the effects of the following parameters on the behavior: the level of axial load n (=0.07 or 0.06, 0.3 and 0.6) in the column, the steel ratio α (=0.06 and 0.103) of the composite column, and the beam to column linear stiffness ratio k (=0.36–0.58). The level of axial load is defined as $n = N_o/N_u$, where N_o is the axial load applied in the column and N_u is the axial compressive capacity of the circular column determined by specification Eurocode 4 [13]. The steel ratio (α) is defined as $\alpha = A_s/A_c$, where A_s and A_c are the cross-sectional area of steel tube and core concrete, respectively. The beam to column linear stiffness ratio is defined as $k = i_b/i_c$, where i_b and i_c are the linear stiffness of steel beam and CFST column, respectively. i_b is defined as E_sI_b/L, where I_b is the moment of inertia for steel beam, E_s is the modulus of elasticity of steel and L is the length of beam, respectively. i_c is defined as $(EI)/H$, where H is the height of column. The stiffness of circular CFST column (EI) is $E_sI_s + 0.8E_cI_c$ according to the code DBJ13-51-2003 [15], where E_s and E_c are modulus of elasticity of steel and concrete, respectively, and I_s and I_c are moments of inertia for hollow steel cross section and core concrete cross section, respectively.

Table 1 gives the details of each frame specimen, where h, b_f, t_w, and t_f are the overall height, overall width, web thickness and flange thickness of the I-beam, respectively; D and t_s are the