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Experimental and numerical investigation of circular double-tube concrete-filled stainless steel tubular columns under cyclic loading

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ABSTRACT

This paper presents a cyclic loading investigation on double-tube concrete-filled stainless steel tubular (CFSST) columns with circular outer stainless steel tube and circular inner carbon steel tube. A total of eight specimens were tested under constant axial compressive load and lateral cyclic loading. The main variables explored in the test are: (a) axial load level (0.046–0.56); (b) diameter ratio of inner tube to outer tube (0.36, 0.57); and (c) presence of inner concrete or not. A finite element (FE) model was then developed and the prediction of lateral load (P)-lateral displacement (Δ) curves agree well with the test results. Furthermore, effects of various parameters on the P-Δ curves of the double-tube CFSST columns were analyzed in comparison to the double-tube concrete-filled steel tubular (CFST) columns.

1. Introduction

Concrete-filled stainless steel tubular (CFSST) columns have been developed based on the traditional concrete-filled steel tube (CFST) and have good static behavior [1–6], cyclic behavior [7] and fire performance [8,9]. Meanwhile, they have the advantages such as good appearance, durability, corrosion resistance and low maintenance cost due to the utility of the outer stainless steel tube. Hence, this type of columns has got increasing concern by engineers and researchers. However, the stainless steel is relatively more expensive than the traditional carbon steel. If a carbon steel tube is placed inside the CFSST, the amount of outer stainless steel will be reduced and better confinement to the core concrete will be achieved, which will result in the enhancements of load bearing capacity and ductility. The fire resistance will also be greater due to the protection of outer concrete to inner steel tube. Therefore, the innovative double-tube concrete-filled stainless steel tube (double-tube CFSST for short) has bright prospects in civil engineering. The double-tube CFSST columns can be used in high-rise buildings, industrial factory buildings, subway platforms, power transmission poles, offshore construction and long span bridge piers. They can also be applied in structural reinforcement.

Composite columns using double steel tubes have two suitable forms [10]: double-tube CFST (solid structure with inner concrete) and double-skin CFST (hollow structure without inner concrete). The typical circular cross-section forms of composite structures using the outer stainless steel are shown in Fig. 1, where D_o and D_i are the overall diameters of the outer stainless steel tube and the inner carbon steel tube, respectively; t_o and t_i are the wall thickness of the outer stainless steel tube and the inner carbon steel tube, respectively.

In the past, some research studies were carried out on the double-tube CFST columns. Wan and Zha [11], Liew and Xiong [12], Ekmekyapar and AL-Eliwi [13] conducted a series of tests to investigate the axial compression behavior of the double-tube CFST stub columns. Considering the high steel amount of double tubes, Wang et al. [14] studied the behavior of double-tube CFST stub columns with stiffened outer thin-walled steel tubes. Qian et al. [15] reported the experimental results on the hysteretic behavior of 8 double-tube CFST columns with square hollow section (SHS) outer and circular hollow section (CHS) inner. In terms of the double-skin CFST, a series of research was carried out to study the axial behavior, eccentric compressive behavior and hysteretic behavior of columns including circular, square and rectangular cross-sections [16–20]. In recent years, Romero et al. [21] tested 6 specimens of double-tube CFST and double-skin CFST columns at ambient and elevated temperatures. Xiong et al. [22] conducted the experimental and numerical studies on a total of 14 eccentrically loaded specimens including CFST, double-tube CFST and double-skin CFST infilled with ultra-high strength concrete. Those research results show that, compared with the CFST, the double-tube CFST columns have improved strength, ductility and stiffness. Actually, there are some differences on the material mechanical performance between the

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Nomenclature

A_{ci}	sectional area of inner concrete
A_{co}	sectional area of outer concrete
A_{si}	sectional area of inner carbon steel tube
A_{so}	sectional area of outer stainless steel tube
d	axial deformation
D_i	diameter of inner carbon steel tube
D_o	diameter of outer stainless steel tube
E	hysteretic energy
E_s	initial elastic modulus of steel
f_{ci}'	cylinder compressive strength of inner concrete
f_{co}'	cylinder compressive strength of outer concrete
f_{cu}	cubic compressive strength of concrete
f_u	ultimate strength of steel
f_y	yield strength of steel
f_{yi}	yield strength of inner carbon steel tube
f_{yo}	yield strength of outer stainless steel tube
K	secant stiffness
L	effective length
n	axial load level
N_0	axial compression applied on the columns
P	lateral load
$P_{u,dc}$	lateral ultimate strength of the double-tube CFST columns
$P_{u,ds}$	lateral ultimate strength of the double-tube CFSST columns
P_{uc}	calculated lateral ultimate strength
P_{ue}	measured lateral ultimate strength
t_i	wall thickness of inner carbon steel tube
t_o	wall thickness of outer stainless steel tube
Δ	lateral displacement
Δ_u	displacement when the lateral load falls to 85% of the ultimate strength
Δ_y	yielding displacement
ε	strain
ε_y	yield strain
λ	slenderness ratio
μ	displacement ductility coefficient
ν	Poisson's ratio
σ	stress

stainless steel and the carbon steel, which causes the differences on the behavior of the columns. Therefore, there is a need to study the behaviors of double-tube and double-skin CFSST with outer stainless steel tube.

With regard to the double-tube CFSST columns, existing studies have mainly focused on the axial compression behavior. Chang et al. [23] tested 4 circular double-tube CFSST and 2 CFSST stub columns under compression. The test parameters included nominal concrete strength (50 or 60 MPa), dimensions of inner carbon steel tube (diameter × thickness = 108 × 4 mm, 114 × 4 mm or 114 × 2 mm). A finite element (FE) model was then developed to analyze the behavior and parametric influence using software ABAQUS. FE models were also established by Hassanein et al. [24,25] to investigate the behavior of circular double-tube CFSST stub columns and slender columns, and the design formula on compressive strength were proposed finally based on the parametric analysis. As for the double-skin CFSST, 80 stub columns were tested by Han et al. [26] to study the axial compression behavior and the influences of sectional type, column type and hollow ratio. Numerical analysis was performed by Hassanein and Kharoob [27] to investigate the behavior of circular double-skin CFSST slender columns subjected to concentric compression. Cyclic testing results of 24 double-skin CFSST (SHS outer and CHS inner) columns were reported by Zhou and Xu [28]. It was found that axial load level and thickness of outer stainless steel tube are key factors affecting the cyclic behavior of the columns. However, no literature was found on the hysteretic behavior of the double-tube CFSST columns.

Therefore, in the present paper, tests on a total of eight composite columns were conducted to investigate the behavior of double-tube CFSST under constant axial compressive load and lateral cyclic loading.

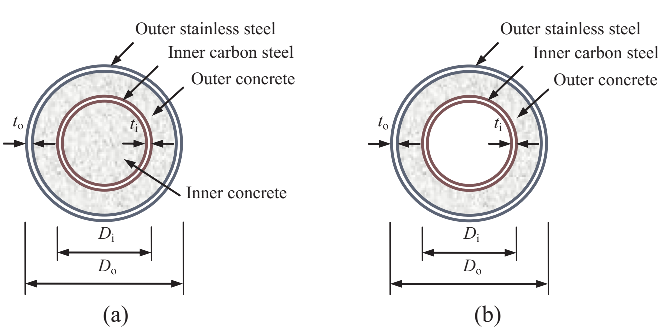

Fig. 1. Typical sections of double-tube CFSST and double-skin CFSST.

A finite element (FE) model was developed to simulate the behavior of the columns. Effects of various parameters on the lateral load-lateral displacement curves were analyzed.

2. Experimental program

2.1. Specimen preparation

Eight circular columns including six double-tube CFSST specimens and two double-skin CFSST specimens were designed and fabricated. The main parameters in the test include the axial load level (n), the diameter ratio of inner tube to outer tube (D_i/D_o) and the presence of inner concrete or not. Table 1 gives the detailed information of test specimens. The axial load level n is defined as $n = N_0/(f_{yo}A_{so} + f_{yi}A_{si} + f_{co}'A_{co} + f_{ci}'A_{ci})$, where N_0 is the axial compression applied on the columns; f_{yo} and f_{yi} are the yield strengths of the outer stainless steel tube and the inner carbon steel tube, respectively; f_{co}' and f_{ci}' are the cylinder compressive strengths of the outer concrete and the inner concrete, respectively; A_{so} and A_{si} are the sectional areas of the outer stainless steel tube and the inner carbon steel tube, respectively; A_{co} and A_{ci} are the sectional areas of the outer concrete and the inner concrete, respectively.

In the specimen labels of Table 1, the first letter C and the second letter C mean the circular cross sections of the outer and inner steel tubes, respectively; the third letter A or B stands for the diameter of the inner steel tube with 50 mm or 80 mm, respectively; the fourth letter S or K indicates the sectional type of the double-tube CFSST (with inner concrete) or double-skin CFSST (without inner concrete), respectively; the last number 0, 1 or 2 means the axial load levels of 0.046, 0.28 or 0.56, respectively. Due to the difference between the design strength and the practical strength of materials, there is a minor deviation for the axial load levels of the double-tube CFSST and the double-skin CFSST. It should be noted that, the axial load levels of 0.046, 0.28 and 0.56 exceed 0.05, 0.32 and 0.65 considering the slenderness ratio in accordance with the Eurocode 4 [29], respectively, while the load levels exceed 0.06, 0.36 and 0.73 in accordance with the code of DBJ/T13-51-2010 [30], respectively. The length of all the specimens is 1540 mm including the two steel endplates with 320 mm side length and 20 mm thickness.

2.2. Material properties

AISI 304 austenitic stainless steel was used for all the specimens.