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Cyclic loading tests on concrete-filled double-skin (SHS outer and CHS inner) stainless steel tubular beam-columns

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ABSTRACT

This paper reports a series of cyclic loading tests on concrete-filled double-skin stainless steel tubular (CFDSST) beam-columns with square hollow section (SHS) outer and circular hollow section (CHS) inner. A total of 24 specimens were tested under constant axial compressive load and cyclically increasing flexural loading to investigate the structural performance of the composite beam-columns. The test parameters included the axial compressive load level (n), the thickness of the outer stainless steel tube (t_o), the hollow ratio (χ) and the concrete strength (f_{cu}).

The failure modes and hysteresis curves of the concrete-filled double-skin stainless steel tubular (CFDSST) beam-columns have been reported. Based on the test results, the effects of the test parameters on the lateral load (P) versus lateral displacement (Δ) envelope curves, ductility coefficient, dissipated energy and stiffness degradation have been investigated. The results shows that, generally, the axial compressive load level and thickness of outer tubes have a primary influence on the behavior of the test specimens while the hollow ratio and the concrete strength have a little effect when the axial compressive load level is low. Finally, comparisons of initial section flexural stiffness and ultimate bending moments of the beam-columns which were obtained from the tests are made with the predicted ones using the existing design codes and design method.

1. Introduction

The use of concrete-filled steel tubes (CFST) has become widespread in the past few decades for the advantages of high bearing capacity and ductility, easy construction and cost saving [1–4]. However, the core area of the concrete infill makes little contribution to the flexural stiffness and, on the contrary, increases the punching load to the base of the column. Therefore, a new type of composite member section, concrete-filled double-skin steel tube (CFDST), with lots of advantages over CFST including light weight, generally good damping characteristics and better cyclic performance [5,6], were proposed by some researchers and then studied for their mechanical properties as structural members in recent years.

On the other hand, stainless steel is being increasingly used in architectural and structural applications since it combines high strength, durability, weldability, improved fire resistance, ease of maintenance and an aesthetically clean surface with high corrosion resistance [7–9]. Although the initial high cost associated with stainless steel has significantly limited its structural use in the past decades, the lower full life-cycle cost makes stainless steel gain more attention nowadays. Concrete-filled double-skin stainless steel tubular (CFDSST) columns, combining the advantages of CFDST and the stainless steel, are expected to be used in ocean platforms, high piers of bridges in valleys or other high rise buildings in which the durability is a major consideration. It is well known that circular hollow section (CHS) provides much better confining effects to concrete infill while square hollow section (SHS) is easier to be connected to the other structural members. Hence, the concrete-filled double-skin stainless steel tubes with square hollow section (SHS) outer and circular hollow section (CHS) inner have been considered in this study.

In the literature, a series of research has been carried out on concrete-filled double-skin carbon steel tubular (CFDCST) members subjected to both static loading and dynamic loading [5,6,10–16]. All the previous research results showed that the CFDCST members perform well in strength, ductility and energy dissipating capacity. The mechanical models and design rules of the CFDCST members under static loading were proposed by Han

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et al. [17], which were also used to predict the structural performance of the CFDCST members under cyclic loading.

So far, research on concrete-filled double-skin stainless steel tubes (CFDSST) is very limited. Only concrete-filled double-skin steel tubes with external stainless steel tubes and internal carbon steel tubes were studied by Han et al. [18] and by Hassanein et al. [19,20]. Compared to structural carbon steel, stainless steel has low proportional limit and extended strain-hardening capability. The mechanical properties of stainless steel are quite different from those of carbon steel. Hence, it is necessary to investigate the structural performance of concrete-filled double-skin stainless steel tubular members.

The purpose of this paper is to experimentally investigate the structural behavior of concrete-filled double-skin (SHS outer and CHS inner) stainless steel tubular beam-columns under cyclic loading. A total of twenty-four concrete-filled double-skin stainless steel tubular beam-columns, with different parameters including the axial compressive load level (n), the thickness of the outer stainless steel tube (t_o), the hollow ratio (χ) and the concrete strength (f_{cu}), were tested under constant axial compressive loading and cyclically increasing flexural loading. The failure modes and hysteresis curves of the concrete-filled double-skin stainless steel tubular beam-columns have been reported. Based on the test results, the effects of the test parameters on the lateral load (P) versus lateral displacement (Δ) envelope curves, ductility coefficient, dissipated energy and stiffness degradation have been investigated. The initial flexural stiffness obtained from the tests were compared with the predicted ones calculated using the general design codes, such as AISC-LRFD [21], AIJ [22], EC4 [23] and BS5400 [24]. The design rules proposed by Han et al. [17] were also tentatively used to predict the ultimate bending capacities.

2. Experimental investigation

2.1. Test specimens

A total of twenty-four concrete-filled double-skin stainless steel tubular beam-column specimens with square hollow section (SHS) outer and circular hollow section (CHS) inner were tested under constant axial compressive load and cyclically increasing flexural loading. Two different section size SHS tubes (S1 and S2), as shown in Table 1, were chosen in this study for the outer skin with measured overall width-to-thickness (B/t_o) ratios ranging from 32.6 to 42.3, where B and t_o were the overall width and the thickness of the outer skin, respectively, as shown in Fig. 1. Two different section size CHS tubes (C1 and C2), as shown in Table 2, were chosen for the inner skin with measured diameter-to-thickness (d/t_i) ratios ranging from 9.3 to 18.9, where d and t_i were the diameter and the thickness of the inner skin, respectively, as shown in Fig. 1. The stainless steel SHS and CHS tubes were fabricated from austenitic stainless steel type 304. The specimen lengths (L) were chosen to prevent overall buckling of the composite beam-columns. The nominal length was 700 mm for all specimens.

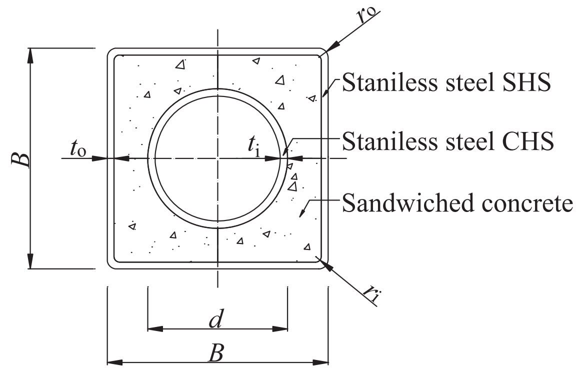

Fig. 1. Definition of symbols for concrete-filled double-skin stainless steel tubular section.

The design parameters of the tests included the axial compressive load level (n), the thickness of the outer stainless steel tube (t_o), the hollow ratio (χ) and the concrete strength (f_{cu}). The axial compressive load level (n) in this paper is defined as $n = N_0/N_u$, where N_0 is the axial compressive load applied on the composite specimens and N_u is the axially compressive capacity of the composite columns, which could be determined by using the simplified formulas described in [17]. Three different nominal axial compressive load levels (n) ranging from 0.2 to 0.6 were considered in the tests. The hollow ratios (χ) ranging from 0.333 to 0.675 were considered in this study, which was defined as $\chi = d/(B - 2t_o)$ [6]. The composite beam-column specimens were tested using nominal concrete cubic strengths of 50 and 75 MPa. The details of the concrete-filled double-skin (SHS as outer and CHS as inner) stainless steel tubular beam-column specimens are listed in Table 3.

In Table 3, the test specimens are labelled such that the outer skin, inner skin, nominal concrete cubic strength and axial compressive load level could be identified from the label. For example, the label "S1C1-C50-0.2" defines the following specimen:

- The first two letters indicate that the outer skin was constructed using the SHS tube of S1.
- The second two letters indicate that the inner skin was constructed using CHS tube of C1.
- The following notation "C50" indicates the nominal concrete cubic strength in MPa, where "C50" indicates 50 MPa.
- The last notation "0.2" indicates the axial compressive load level of 0.2.

2.2. Material properties of stainless steel tubes

The material properties of the stainless steel tubes were determined by tensile coupon tests. For the square hollow section (SHS) tubes S1 and S2, the coupons were taken from the center of the web of the SHS tubes in the longitudinal direction. The coupon specimens were prepared in accordance with the Chinese Standard GB/T 228.1-2010 [25] using 15 mm wide coupons with a gauge length of 50 mm. The coupons were tested in a displacement controlled testing machine using friction grips. Two strain gauges and a calibrated extensometer of 50 mm gauge length were used to measure the longitudinal strain. A data acquisition system was used to record the load and strain at regular intervals during the tests. The material properties obtained from the tensile coupon tests are summarized in Table 1, which includes the static 0.2% tensile proof stress ($\sigma_{0.2}$), static tensile strength (σ_u), initial Young's

Table 1
The dimensions and mechanical properties of the outer stainless steel SHS tube.

Outer SHS tube	B (mm)	t_o (mm)	B/t_o	r_o (mm)	$\sigma_{0.2}$ (MPa)	E_0 (GPa)	σ_u (MPa)	ε_f (%)
S1	120.11	2.84	42.3	6.5	308.5	165.7	724.0	71.3
S2	119.93	3.68	32.6	8.5	379.1	175.3	763.4	65.2