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Push-out tests of concrete-filled stainless steel SHS tubes

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ABSTRACT

A total of 32 push-out tests were conducted in this paper on concrete-filled stainless steel square hollow section (SHS) tubes with different values of height-to-width ratio, width-to-thickness ratio and concrete strength. The bond-slip behaviour of all specimens and the strain distribution on the exterior of stainless steel tubes along the longitudinal height direction were carefully investigated. Shear failure loads of bonding slip and the interface friction resistance generally decreased with more loading cycles of the repeated push-out test employed in the same direction. It can be concluded that 70% of the bonding strength at the interface was taken by the friction force of the interface elements, while the remaining 30% of the bonding strength at the interface was sustained by the chemical adhesive force and the mechanical interlock force. Furthermore, the strains at the locations close to the free end and loading end of the specimens increased with the increase of the axial load, in which the increase of the strains at the location close to the free end is much greater. On the other hand, it is demonstrated that the height-to-width ratio and the width-to-thickness ratio of the stainless steel SHS tube have insignificant influence on the shear resistance of the bonding strength of the interface elements, which generally decreased with the increase of the concrete strength. In addition, the current design rules of concrete-filled carbon steel SHS tubes were found to be inapplicable to the shear resistance of the bonding strength of concrete-filled stainless steel SHS tubes.

1. Introduction

Concrete-filled stainless steel tubes nowadays are increasingly used in high-rise buildings and arch structures. The characteristics of aesthetic appearance, excellent corrosion resistance and durability, good aseismic behaviour, and ease of construction as well as maintenance provide the concrete-filled stainless steel tubular members with the potential applications in onshore buildings, offshore platforms, bridges and many structures with high requirement for durability. Extensive researches [1–14] including experimental investigations and theoretical studies were conducted in the past decades on the behaviour of concrete-filled steel tubular (CFST) members subjected to various loadings. Early research on the bonding strengths of CFST was conducted by Virdi and Dowling [4] on the stocky circular hollow sections (CHS) filled with concrete of various grades. The push-out tests were performed to investigate the effects of various parametric variations including the age, strength, compacting and curing conditions of concrete, the interface length, the tube size and various surface treatments on the bonding strength. It was concluded that the mechanical behaviour between steel and concrete of CFST is the most significant factor contributing to the bonding strengths. Concrete-filled circular, square and octagonal hollow sections (CHS, SHS and OHS) were tested by Morishita et al. [5] to investigate the effects of cross-section shape and concrete grade on the bonding strength. The CFST with checkered internal walls was also tested by Tomii et al. [6] to study the influence of tube interface on the bonding strength. The bonding strengths of lubricated and non-lubricated concrete-filled CHS and rectangular hollow section (RHS) specimens were compared by Shakir-Khalil [7]. Furthermore, various interface conditions were also examined by Kilpatrick and Rangan [8]. Some other researches were carried out on the influence of cyclic shear force [9], cyclic push-out force [10], concrete compaction [11] and utilization of expansive cement [12] on the bonding strength. While the effect of elevated temperatures on the bonding strength was also evaluated [13]. In addition, the study was performed by Chen et al. [14] on the mechanisms contributing to the ultimate interface bonding strength.

Previous literatures were all performed on the bonding strengths of concrete-filled carbon steel tubular members. It should be noted that the interface behaviour between carbon steel and concrete compared to the interface between stainless steel and concrete are different due to different surface roughness. Therefore, the design rules for bonding

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behaviour of concrete-filled carbon steel tubular members may not be applicable to the bonding behaviour of concrete-filled stainless steel tubes. A systematic experimental study was carried out in this paper to investigate the shear bond behaviour of concrete-filled stainless steel square hollow sections (SHS) with different values of height-to-width ratio (H/B), width-to-thickness ratio (B/t), concrete strength (C) and the cyclic loading. It was concrete compressive strength in the paper when the value of concrete strength was used. The bond-slip relationship at the interface between the inner surface of stainless steel tube and core concrete was studied to obtain the bonding strength, which is the key factor to ensure that the outer stainless steel tube and core concrete to sustain the external loading simultaneously. Furthermore, the shear bond failure was also analyzed based on the strain development on the outer surface of stainless steel tubes.

2. Experimental study

2.1. Test specimens

A total of 32 concrete-filled stainless steel square hollow section (SHS) specimens with the identical outer width (B) of 50 mm were designed and tested in this study, which included different values of height-to-width ratio (H/B) ranged from 6.0 to 15.0, width-to-thickness ratio (B/t) ranged from 45.4 to 83.3 and concrete strength (C) ranged from 32.3 MPa to 51.7 MPa. The details of all specimens are summarized in Table 1, in which the label 'H300-t0.6-C20' defines a concrete-filled stainless steel SHS tube with height 'H' of 300 mm, thickness 't' of 0.6 mm and nominal concrete cube strength 'C' of 20 MPa. While, B, H, t and f_c represent the width, height and thickness of stainless steel SHS tube as well as the compressive strength of concrete. It is worth noting that a gap of 50 mm was deliberately produced at one end of each specimen between the outer stainless steel tube and core concrete in the fabrication of test specimens for the repeated push-out test.

The mechanical properties of stainless steel SHS tubes were obtained from uni-axial tensile coupon tests based on the recommendations of the Chinese Code of Metallic Materials (GB/T 228.1-2010) [15], which include the elastic modulus (E_s) of 206 GPa, 0.2% tensile proof stress (f_y) of 420 MPa and ultimate tensile stress (f_u) of 630 MPa. Furthermore, two grades of concrete were used in the specimens and the mechanical properties of concrete were determined from compressive concrete cube tests. Three concrete cubes with nominal side length of 150 mm were cast for each grade of concrete using commercially available materials with normal mixing and curing techniques [16,17]. The measured material properties of the concrete are summarized in Table 2, which include the measured concrete cube strengths and the mean values for three batches of concrete cubes for nominal concrete cube strengths of 20 MPa and 50 MPa, respectively.

2.2. Test procedure

All specimens were installed vertically and tested in the same loading machine with the self-balanced reaction frame, as shown in Fig. 1. A hydraulic jack was used to apply the axial compression to the test specimens and monitored by the load cell, which was positioned concentrically between the hydraulic jack and the reaction frame. The push-out tests were conducted on concrete-filled stainless steel SHS tubes with a gap of 50 mm between the outer stainless steel tube and core concrete at the bottom end of the specimens to enable the downward movement of core concrete under axial compression. In order to ensure that the axial compression force was uniformly applied to the core concrete only, a steel circular solid block with the cross-section area slightly smaller than that of the core concrete was used at the top end of the specimens, which was positioned concentrically to the core concrete of the test specimens. Therefore, the compression force was applied to the core concrete only by means of steel circular solid block at the top end of the specimens, which was resisted by the outer stainless steel tube only at the bottom end of the specimens. The bond-slip failure between the inner surface of stainless steel tube and core concrete was then occurred.

All specimens were initially subjected to the incremental monotonic static loading, which was first equally divided into comparatively large load levels (around 1/30 of the estimated peak load) within the elastic range, and then reduced to the comparatively small load levels after the occurrence of the nonlinear bond-slip failure between the inner surface of stainless steel tube and core concrete. The specimens were subsequently unloaded to zero until the core concrete at the bottom end of the specimens being fully contacted with the end plate placed at the bottom to support the specimens. The maximum bond slippage is approximately 40–50 mm since an initial gap of 50 mm was deliberately produced at the bottom end of each specimen between the outer stainless steel tube and core concrete. The first half-cycle of loading application was then completed. After that, the specimens were inverted and subjected to a reverse axial compression in the same loading way. This testing procedure was repeated four times in total for each specimen for a complete repeated push-out test.

Table 1
Details of test specimens.

Specimen	B (mm)	t (mm)	H (mm)	B/t	H/B	f_c (MPa)
H300-t0.6-C20	50	0.6	300	83.3	6	32.3
H300-t0.7-C20		0.7	300	71.4	6	
H300-t0.9-C20		0.9	300	55.5	6	
H300-t1.1-C20		1.1	300	45.4	6	
H450-t0.6-C20		0.6	450	83.3	9	
H450-t0.7-C20		0.7	450	71.4	9	
H450-t0.9-C20		0.9	450	55.5	9	
H450-t1.1-C20		1.1	450	45.4	9	
H600-t0.6-C20		0.6	600	83.3	12	
H600-t0.7-C20		0.7	600	71.4	12	
H600-t0.9-C20		0.9	600	55.5	12	
H600-t1.1-C20		1.1	600	45.4	12	
H750-t0.6-C20		0.6	750	83.3	15	
H750-t0.7-C20		0.7	750	71.4	15	
H750-t0.9-C20		0.9	750	55.5	15	
H750-t1.1-C20		1.1	750	45.4	15	
H300-t0.6-C50		0.6	300	83.3	6	51.7
H300-t0.7-C50		0.7	300	71.4	6	
H300-t0.9-C50		0.9	300	55.5	6	
H300-t1.1-C50		1.1	300	45.4	6	
H450-t0.6-C50		0.6	450	83.3	9	
H450-t0.7-C50		0.7	450	71.4	9	
H450-t0.9-C50		0.9	450	55.5	9	
H450-t1.1-C50		1.1	450	45.4	9	
H600-t0.6-C50		0.6	600	83.3	12	
H600-t0.7-C50		0.7	600	71.4	12	
H600-t0.9-C50		0.9	600	55.5	12	
H600-t1.1-C50		1.1	600	45.4	12	
H750-t0.6-C50		0.6	750	83.3	15	
H750-t0.7-C50		0.7	750	71.4	15	
H750-t0.9-C50		0.9	750	55.5	15	
H750-t1.1-C50		1.1	750	45.4	15	

Table 2
Measured concrete cube strengths.

Nominal concrete strength (MPa)	Batch	Measured concrete cube strength (MPa)	Mean value (MPa)
20	1	31.4	32.3
	2	31.1	
	3	34.4	
50	4	48.7	51.7
	5	50.8	
	6	55.5	