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Mechanical behavior of a steel tube-confined high-strength concrete shear wall under combined tensile and shear loading

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ABSTRACT

The steel tube-reinforced concrete (STRC) shear wall is a type of composite shear wall that consists of a reinforced concrete shear wall embedded into high-strength concrete-filled steel tube (CFST) columns in the boundary element and/or the center of a shear wall. The use of STRC walls has gained popularity in the construction of high-rise buildings because their performance is superior to conventional reinforced concrete (RC) walls. To study the influence of various parameters (i.e., the number of CFSTs embedded in the shear wall, the shear span ratio, the ratio of the vertical reinforcement, the strength of the concrete outside the embedded steel tube, and the initial tensile stress) on the mechanical properties of an STRC composite shear wall under combined tension and shear forces, tensile shear tests were conducted on 9 specimens whose shear span ratios were less than or equal to 1.0. The experimental results demonstrated that the STRC shear wall retained its high shear capacity and its good ductility under a high axial tensile force. Using statistical analyses, a formula to calculate the bearing capacity of an STRC shear wall was proposed. The calculated values are in good agreement with the experimental results.

1. Introduction

The bottom of a high-rise structure often requires the use of thicker shear walls, and the confining boundary elements of the shear walls need dense stirrups to meet the appropriate code provisions for the axial pressure and stirrups. A variety of steel–concrete composite walls have been developed, and they have been increasingly used in seismic zones as the primary lateral resistance system for high-rise building structures [1–4]. Recently, to reduce the thickness of the shear wall at the bottom of a high-rise structure, reduce the density of the stirrups, improve the compressive capacity of the shear wall, and improve the bending and seismic performance, a new type of steel **t**ube-**r**einforced **c**oncrete (STRC) composite shear wall [5,6] has been proposed and studied in China. In this new technology, circular high-strength **c**oncrete-filled **s**teel **t**ube (CFST) columns are embedded into the confining boundary elements or into the middle of the wall structure. Great effort has been devoted to studying the seismic behavior of STRC shear walls [5–11]. Qian et al. [5,6] first studied the seismic behavior of 6 STRC walls with circular high-strength CFST columns embedded in the wall boundary element to investigate the limit value of the axial compressive load ratio and the stirrup requirements in the confined boundary elements. Bai et al. [7] tested 2 STRC walls with circular CFST columns embedded in the wall boundary element. Ji et al. [8] designed 2 STRC walls with circular or square high-strength CFST columns embedded in the wall boundary element and then investigated the seismic behavior of the walls. Zhao et al. [9,10] designed 7 STRC walls with circular high-strength CFST columns embedded in the wall boundary element and/or the center of a composite wall to investigate the seismic behavior. The STRC composite shear wall was first proposed, researched and applied in mainland China. Few studies about STRC composite walls in other countries can be found. Some relevant studies on ductile concrete walls with square CFST columns embedded in the wall boundary elements to alleviate congestion of reinforcement in these regions based on reversed cyclic-loading tests have been performed [4,11]. These experimental tests [5–11] have demonstrated that these walls have the excellent cyclic behavior of increased strength and deformation capacity. In order to appreciate the differences from other researchers' studies [4–8,10], the parameters of the specimens for the experimental tests are shown in Table 1. The STRC composite shear walls have excellent seismic performance and collapse prevention capacity. To study the mechanical properties of an STRC shear wall, the authors' research team conducted a series of tests, including an axial compression test of

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Table 1
Design parameters of the specimens for the experimental tests in other similar studies (ϕ-HPB300, Φ-HRB400).

References	Number and steel shape	Location of steel tubes	Concrete (inside/outside) f_{cu} (N/mm^2)	Reinforcement details		Shear span ratio λ	Axial forces ratio for tests	Wall height *h* (mm)
				Horizontal web reinforcement	Vertical web reinforcement			
Dan D. et al [4]	2 × □	Boundary	54.7/54.7	ϕ8@150	ϕ10@100	2.6	0.02	2600
Qian J. et al [5,6]	2 × ○	Boundary	44.3/57.5	ϕ8@80	ϕ8@195	2.0	0.26	2600
	2 × ○	Boundary	40.5/57.5	ϕ8@53	ϕ8@195	2.0	0.31	2600
	2 × ○	Boundary	40.1/57.5	ϕ8@53	ϕ8@195	2.0	0.38	2600
	2 × ○	Boundary	46.7/57.5	ϕ8@80	ϕ8@195	2.0	0.32	2600
	2 × 2○	Boundary	49.8/57.5	ϕ8@80	ϕ8@195	2.0	0.31	2600
	2 × ○	Boundary	47.3/57.5	ϕ8@53	ϕ8@175	2.2	0.34	2600
Bai L. et al [7]	2 × 2○	Boundary	71.9/70.0	Φ8@80	ϕ6.5@175	2.1	0.16	2320
	2 × 2○	Boundary	75.4/70.0	Φ8@80	ϕ6.5@175	2.1	0.19	2320
Ji X. et al [8]	2 × □	Boundary	41.3/41.3	ϕ8@80	ϕ8@120	2.3	0.34	2550
	2 × ○	Boundary	37.1/37.1	ϕ8@80	ϕ8@120	2.3	0.32	2550
Zhao Z. et al [10]	2 × 2○	Boundary	73.8/58.7	Φ8@50	Φ8@110	2.1	0.19	2550
	2 × 2○	Boundary	65.0/58.7	Φ8@50	Φ8@110	2.1	0.28	2550
	2 × 3○	Boundary	60.6/58.7	Φ8@50	Φ8@110	2.1	0.25	2550
	2 × 3○	Boundary	59.4/58.7	Φ8@50	Φ8@110	2.1	0.32	2550
	2○ + 2○ + 2○	Boundary and middle	71.7/58.7	Φ8@50	Φ8@145	2.1	0.22	2550
	2○ + 2○ + 2○	Boundary and middle	66.9/58.7	Φ8@50	Φ8@145	2.1	0.27	2550
	6○, Uniform distribution	Boundary and middle	62.0/58.7	Φ8@50	Φ8@110	2.1	0.24	2550

20 specimens [12], an axial tensile test of 7 specimens [13], a bending performance test of 8 specimens [14], a shear performance test of 22 specimens under axial pressure [15], and a seismic performance test of 10 specimens [16]. The test results indicated that the STRC shear wall had a high bearing capacity, high ductility and good energy dissipation capacity. Currently, there are few studies about the mechanical properties of STRC shear walls under combined tension and shear forces. In practical engineering, under the action of a horizontal wind load or an earthquake, the lower levels of high-rise and super-high-rise structures sustain large tension forces and shear forces on the bending side of building. The tension and shear forces are simultaneously and locally applied on the shear wall. If catastrophic shear failure occurs, the vertical bearing capacity of the structure will be compromised, resulting in the sudden collapse of the entire structure. Therefore, it is important to study the failure mechanism and the bearing capacity of STRC shear walls under combined tensile shear stress. This research improves the design theory for this problem. In this study, 9 STRC shear wall specimens were designed, and their tensile shear properties were tested. The effects of the number of concrete-filled steel tubes embedded in the wall, the height-width ratio (shear span ratio), the ratio of vertical reinforcement, the strength of the concrete outside the steel tube, and the initial tensile stress on the mechanical properties of STRC shear walls under combined tension and shear loading were investigated.

2. Experimental

2.1. Design of the specimens

In the experiment, 9 STRC composite shear wall specimens with cross-sections of 150 × 800 mm were fabricated. The specimens were labeled using notation such as SW1-3-8-I to distinguish the different parameters considered in the experimental program. The first number denotes the specimen number, the second number denotes the number of steel tubes embedded in the concrete wall, the third number denotes the diameter of the vertical web bar, and the letter (I) denotes the type of shear span ratio. Three equally spaced shear rings 6 mm in diameter were welded on the surfaces of the steel tubes embedded in the walls. The two ends of the steel tube were anchored with two 8 mm-thick steel plates. The plates were welded to the steel tubes. The length of the foundation beam was 1.6 m. The length of the loading beam was 1.0 m. Four shear ring bars 8 mm in diameter were welded to both the loading beam and the steel tube surface inside the foundation beam. Fig. 1 shows the overall geometry and reinforcement details of specimen SW6-3-8-II as an example, and the design parameters and cross-section of each specimen are shown in Table 2 and Fig. 2. The shear span ratio (λ) has a greater influence on the mechanical properties of shear walls. A concrete shear wall with a low shear span ratio is prone to shear failure under a combined shear and axial tensile force [17,18]. This paper mainly studies the shear failure of a composite wall under tension-shear loading; therefore, specimens with adverse shear span ratios ($\lambda \le 1$) were designed.

The series number Q235B steel tube was used. The reinforcement embedded in the wall was grade HPB300 (ϕ) steel bar. Grade HRB400 (Φ) steel bar was used in the foundation and in the loading beam. The mechanical properties of the steel tube and the bars are listed in Table 3. The grades of concrete used in the test were C80 and C60. All concrete used was self-compacting. Each batch of concrete cast was sampled, and two sets of standard cubic specimens with dimensions of 150 × 150 × 150 mm were fabricated. The strength of the concrete was determined using the principle of simultaneous casting and curing under the same conditions. In accordance with the standard for testing the mechanical properties of ordinary concrete [19], a splitting tensile test using a concrete block and a compressive test with a cubic specimen were conducted. According to the code for the design of concrete structures [20] and the method of high performance concrete [21], the mechanical properties of the concrete were calculated; the values are listed in Table 4.

2.2. Device and measurements

The specimen was placed between the reaction walls and fixed by the limit jack and the reaction beam anchored with slot bolts. Tensile loading was applied on the wall using four 500-kN hydraulic jacks. The lifting force on the top was balanced using multiple top diverter valves. To apply the load, two hydraulic jacks were placed on the southern and