Seismic behavior of steel plate - concrete composite shear walls

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SUMMARY:
For the use of high-strength concrete in the super high-rise buildings, two new developed composite walls were proposed. Twelve specimens of the new developed HSC filled double-steel-plate composite wall and three specimens of the new developed steel-plate reinforced HSC composite wall were tested under high axial compressive forces and reversed cyclic lateral loading. No obvious local buckling phenomena were observed for the specimens with proper width-thickness ratios of steel plates, and the surface steel plates and infill concrete could work together until failure. The test results showed that this two type composite walls had high bearing and deformation capacities under high axial compressive force, and are favourable choices for the tube walls in the super high-rise buildings.

Keywords: concrete filled double-steel-plate composite walls; steel-plate reinforced concrete composite walls; high-strength concrete; cyclic loading test; seismic behaviour.

1. INTRODUCTION

Steel plate-concrete composite walls are lately developed forms of structural walls. Compared to the traditional reinforced concrete (RC) wall, the composite wall has higher bearing and deformation capacities. So the wall thickness can be reduced and more usable floor areas can be obtained when using the composite walls in the super high-rise buildings. The steel plate-concrete composite walls have been used in several super high-rise buildings and constructions in China [Ding et al. (2011), Liu et al. (2009), Sun et al. (2011)]. The developed steel plate-concrete composite walls can be divided into two types depending on the relative position of the steel plates and concrete: steel-plate reinforced concrete (SPRC) composite walls and concrete filled double-steel-plate (CFSP) composite walls. The general details for these composite walls are shown in Figure 1.1..

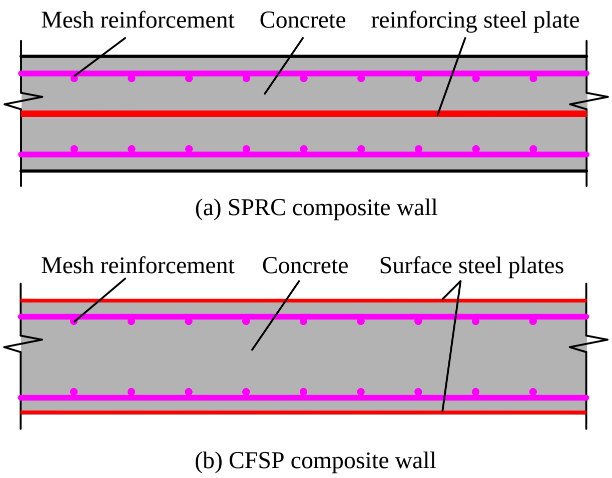
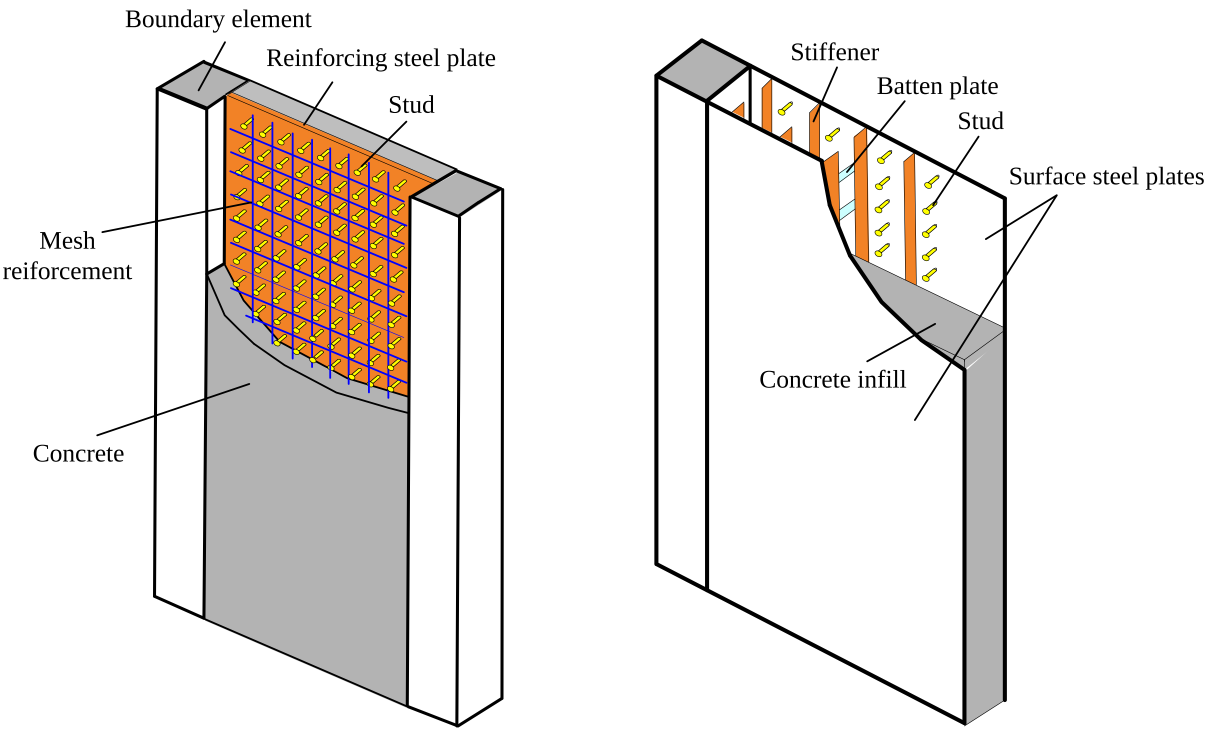


Figure 1.1. General details for SPRC and CFSP composite walls

Several experimental tests have been conducted on the seismic behaviour of SPRC walls [Lv et al. (2009), Chen et al. (2011)]. And the hysteretic behaviour, stiffness, strength and ductility were investigated. Studies on CFSP walls began quite earlier. Wright et al. (1995) first proposed a composite wall formed from two skins of profiled steel sheeting filled with concrete, and tested it under different loading conditions. In the mid-1990s, concrete filled double-steel-plate composite walls for nuclear power plants were proposed in Japan in order to reduce the gradually increased labor costs. Several experimental and theoretical studies were carried out by the Japanese researchers during that time [Takeda et al. (1995), Usami et al. (1995), Ozaki et al. (2001)]. In the 21st century, the static and cyclic behaviours of double skin composite beams and walls with steel plates connected by tie bars were studied by Clubley et al. (2003) and Eom et al. (2009).

For the use of high-strength concrete in the super high-rise buildings, two new developed composite walls were proposed as shown in Figure 1.2.. The new detailed SPRC wall contains concrete filled steel tube (CFST) columns or flanged CFSP walls at the boundaries of the wall. A reinforcing steel plate is inserted in the concrete of the wall body. Shear studs are welded on the reinforcing steel plate to make the steel plate and surface concrete to work together. Mesh reinforcement are also placed in the concrete of the wall body. The new detailed CFSP wall also contains concrete filled steel tube (CFST) columns or flanged CFSP walls at the boundaries of the wall. The wall body is divided into several rooms by vertical stiffeners transversely connected by batten plates, and the concrete in each room is confined by surrounding steel plates. This configuration is steel saving than the usage of vertical diaphragms.

Twelve specimens of the new developed HSC filled double-steel-plate composite walls and three specimens of the new developed steel-plate reinforced HSC composite walls were tested under high axial compressive forces and reversed cyclic lateral loading. Failure mechanism, hysteric behavior, bearing and deformation capacities, etc are studied.



(a) a new detailed SPRC wall

(b) a new detailed CFSP wall

Figure 1.2. Two new developed composite walls

2. **EXPERIMENTAL PROGRAM**

2.1 Test Specimens

Twelve specimens of the new developed HSC filled double-steel-plate composite walls and three specimens of the new developed steel-plate reinforced HSC composite walls were designed and tested. The primary parameters for the CFSP walls were the steel content ratio, concrete strength, steel plate thickness of the boundary columns and wall body, mesh reinforcement and shear span ratio. The primary parameters for the SPRC walls were the steel content ratio and concrete strength. The parameters of all the specimens are given in Table 2.1..

Table 2.1. Properties of the specimens

Specimen	Cross section (mm×mm)	Shear span ratio	Cubic (150mm×150mmm) compressive strength of concrete (N/mm^2)	Mesh reinforcement	Steel plate thickness of boundary columns (mm)	Steel plate thickness of wall body (mm)	Steel content ratio
CFSCW-1	1284×214	2.0	87.5	0	5	5	7.1%
CFSCW-2	1284×214	2.0	86.1	0	5	5	7.1%
CFSCW-3	1284×214	2.0	86.1	0	5	5	7.1%
CFSCW-4	1284×214	2.0	89.8	0	4	4	5.8%
CFSCW-5	1284×214	2.0	88.1	0	3	3	4.6%
CFSCW-6	1284×214	2.0	65.0	0	5	5	7.1%
CFSCW-7	1284×214	2.0	102.6	0	5	5	7.1%
CFSCW-8	1284×214	2.0	88.4	0	6	4	7.1%
CFSCW-9	1284×214	2.0	83.3	ϕ8@130mm	5	5	7.1%
CFSCW-10	750×125	2.0	83.7	0	3	3	7.1%
CFSCW-11	750×125	1.5	80.7	0	3	3	7.1%
CFSCW-12	750×125	1.0	88.0	0	3	3	7.1%
SRCW-1	1284×214	2.0	67.3	ϕ8@130mm	5	10	7.1%
SRCW-2	1284×214	2.0	87.8	ϕ8@130mm	5	10	7.1%
SRCW-3	1284×214	2.0	83.3	ϕ8@130mm	3	6	4.6%

Details of CFSCW-1~9 are given in Figure 2.1.. The specimens had square CFST boundary columns and the wall body was divided into 4 rooms by the vertical stiffeners transversely connected by batten plates. The layout of the batten plates is shown in Figure 2.1.(c). CFSCW-10~12 had similar configurations as CFSCW-1~9, with smaller section size.

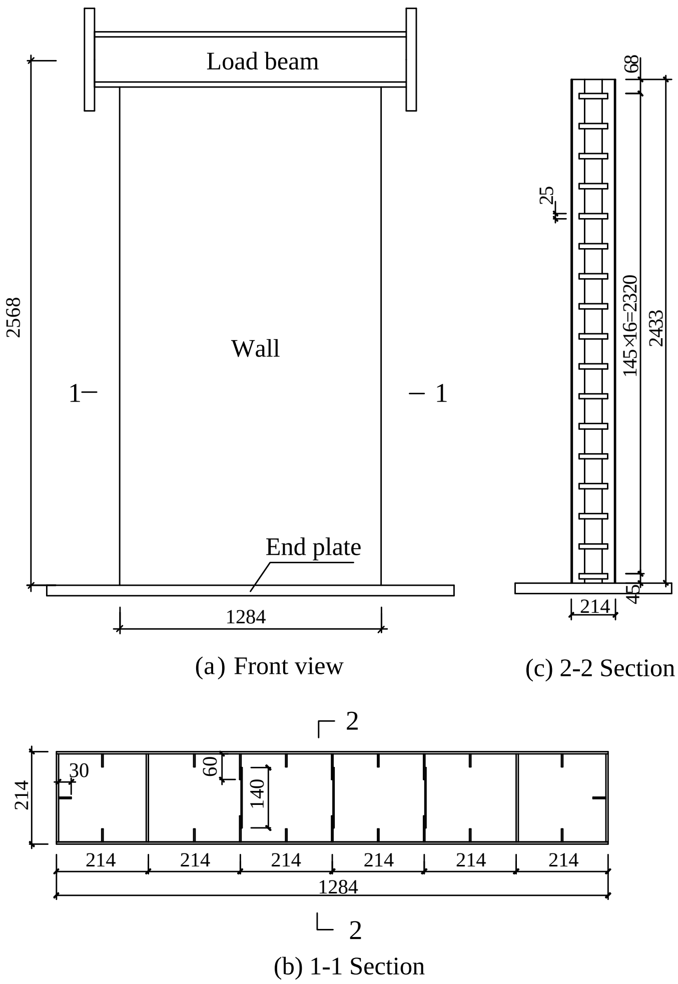
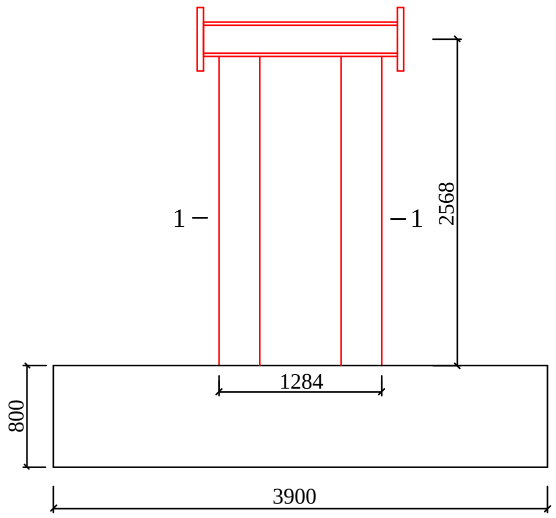
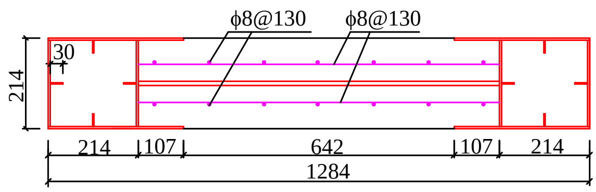


Figure 2.1. Details of CFSCW-1~9

Details of SRCW-1~3 are given in Figure 2.2.. The specimens also had square CFST boundary columns and a steel plate was inserted in the concrete of the wall body. The test SPRC walls were anchored in Steel reinforced concrete beams.



(a) Front view



(b) 1-1 profile

Figure 2.2. Details of SRCW-1~3

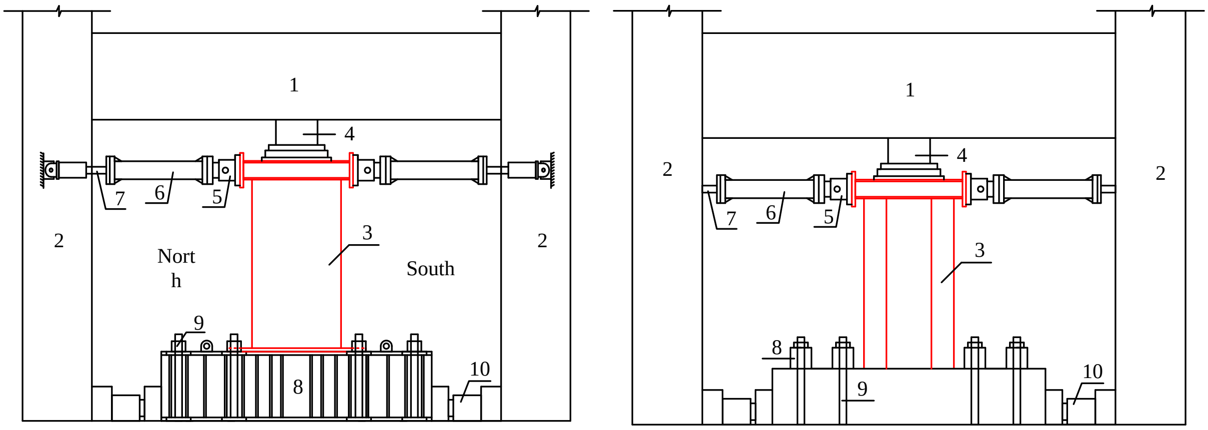
The cubic compressive strengths of the concrete for each specimen are given in Table 2.1.. The measured properties of the steel plates and reinforcing bar are given in Table 2.2..

Table 2.2. Measured properties of the steel plates and reinforcing bar

Type	component	Elastic modulus (N/mm^2)	Yield stress (N/mm^2)	Ultimate stress (N/mm^2)
Steel plate	3mm	190047	442.8	552.8
	4mm	186452	351.4	517.4
	5mm	205438	305.6	444.8
	6mm	212921	363.0	512.3
	10mm	210333	431.7	588.0
Reinforcing bar	HPB235(ϕ8)	195838	327.4	484.1

2.2 Test Setup and Loading Procedure

The specimens were tested by the 20000kN multi-functional loading device in Tsinghua University. The vertical loading capacity of the device was 20000kN, and the horizontal was 3500kN. The test setup is illustrated in Figure 2.3..



1—Girder of load frame 2—Column of load frame 3—Specimen 4—Hydraulic jack 5—Load head 6—Extending tube 7—Actuator 8—Steel pedestal 9—Lead screw 10—Handle jack

(a) For CFSCW-1~12

1—Girder of load frame 2—Column of load frame 3—Specimen 4—Hydraulic jack 5—Load head 6—Extending tube 7—Actuator 8—Steel beam 9—Lead screw 10—Handle jack

(b) For SRCW-1~3

Figure 2.3. Test setup

The axial compressive force was first applied by the vertical hydraulic jack. The axial compressive force N was calculated from Eqn. 2.1 when n_d was selected as 0.5.

$$n_d = \frac{1.25N}{f_c' A_c / 1.4 + f_y A_s / 1.11} \tag{2.1}$$

where n_d is the designed axial compression ratio for the specimens; f_c' is the compressive strength of the concrete; f_y is the yield strength of the steel plate; A_c and A_s are the cross-sectional areas of the concrete and steel plates, respectively.

The lateral force was first controlled by load and then by top displacement. The loading procedure for CFSCW-1~9 and SRCW-1~3 is given in Figure 2.4., and the loading procedures for CFSCW-10~12 were similar.

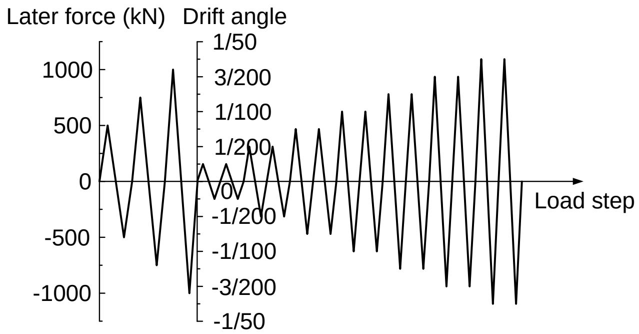


Figure 2.4. Loading procedure

3. EXPERIMENTAL RESULTS

3.1 Failure modes

The main failure modes of CFSCW-1~12 were local buckling of the surface steel plates, fracture of the vertical weld at the boundary columns and horizontal fracture of the steel plates, as shown in Figure 3.1.. No obvious local buckling phenomena were observed for the larger-size specimens except CFSCW-5, for thinner steel plate was used. Local buckling was observed very obvious for CFSCW-10 and CFSCW-11, and occurred along the whole length of the wall base at the end of the testing, as shown in Figure 3.1.(f).

The failure modes of SRCW-1~3 are shown in Figure 3.2.. local buckling of the surface steel plates fracture of the vertical weld at the boundary columns were observed. The concrete in the wall body didn’t crack seriously, and the concrete of SRCW-2 crushed at the end of the testing.

(a) Local buckling

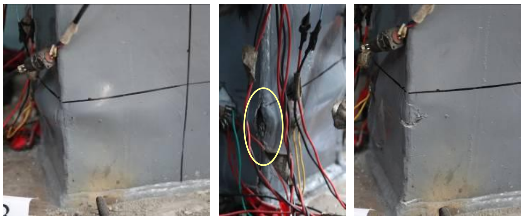
(b) Horizontal frature

(c) Vertical frature

(d) Failure mode of CFSCW-5

(e) Failure mode of CFSCW-8

(f) Failure mode of CFSCW-11



(g) Failure mode of CFSCW-12

Figure 3.1. Failure modes of CFSCW-1~12

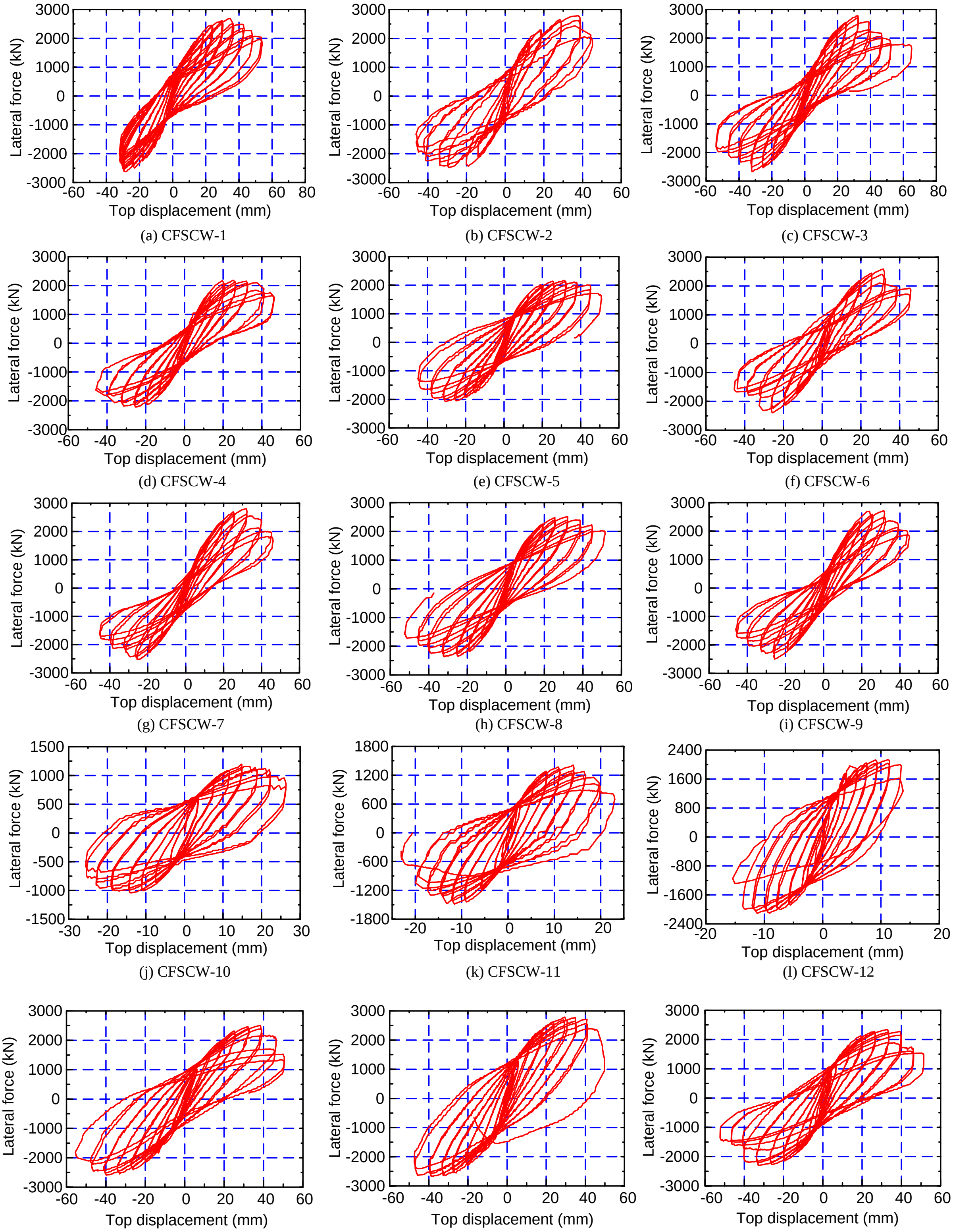
Figure 3.2. Failure modes of SRCW-1~3

3.2 hysteretic Behaviour, Strength and Deformation

Lateral force – top displacement curves for all the specimens are shown in Figure 3.3.. The shapes of hysteresis loops of CFSCW-1~9 and SRCW-1~3 are similar. The hysteresis loops of CFSCW-10~12 are much plumper than those of CFSCW-1~9. The measured strengths and displacements of all the specimens are listed in Table 3.1.. The ultimate drift ratios are between 1/76 and 1/54, with an average value of 1/64, which testifies the high deformation capacity of the test walls under high axial compressive force.

Table 3.1. Measured strengths and displacements

Specimen	Loading direction	P_m (kN)	$\delta_{top,m}$ (mm)	$\delta_{top,m} / h_w$	$\delta_{top,u}$ (mm)	$\delta_{top,u} / h_w$
CFSCW-1	(+)	2691	34.7	1/74	44.7	1/57
	(-)	2602	29.5	1/87	-	-
CFSCW-2	(+)	2655	28.3	1/91	40.6	1/63
	(-)	2422	31.6	1/81	41.6	1/62
CFSCW-3	(+)	2726	32.4	1/79	39.3	1/65
	(-)	2667	32.1	1/80	39.3	1/65
CFSCW-4	(+)	2181	25.1	1/102	42.0	1/61
	(-)	2215	25.2	1/101	39.9	1/64
CFSCW-5	(+)	2165	31.4	1/82	46.6	1/55
	(-)	2074	30.5	1/84	39.2	1/66
CFSCW-6	(+)	2472	32.2	1/80	38.6	1/67
	(-)	2242	26.4	1/98	35.4	1/73
CFSCW-7	(+)	2808	32.0	1/80	38.5	1/67
	(-)	2524	25.3	1/101	37.9	1/68
CFSCW-8	(+)	2511	32.1	1/80	46.9	1/55
	(-)	2365	32.1	1/80	43.1	1/60
CFSCW-9	(+)	2717	31.6	1/81	37.0	1/69
	(-)	2497	25.6	1/101	34.5	1/74
CFSCW-10	(+)	1194	14.9	1/101	23.3	1/64
	(-)	1040	13.9	1/108	23.1	1/64
CFSCW-11	(+)	1330	14.3	1/79	16.5	1/68
	(-)	1400	12.0	1/94	14.8	1/76
CFSCW-12	(+)	2064	11.5	1/65	13.9	1/54
	(-)	1971	11.9	1/63	13.7	1/55
SRCW-1	(+)	2512	38.4	1/67	43.1	1/60
	(-)	2591	39.8	1/64	47.3	1/54
SRCW-2	(+)	2789	29.5	1/87	44.9	1/57
	(-)	2669	37.7	1/68	45.7	1/56
SRCW-3	(+)	2337	33.0	1/78	42.4	1/61
	(-)	2297	32.9	1/78	40.7	1/63



(a) CFSCW-1 (b) CFSCW-2 (c) CFSCW-3
(d) CFSCW-4 (e) CFSCW-5 (f) CFSCW-6
(g) CFSCW-7 (h) CFSCW-8 (i) CFSCW-9
(j) CFSCW-10 (k) CFSCW-11 (l) CFSCW-12
(m) SRCW-1 (n) SRCW-2 (o) SRCW-3

Figure 3.3. Lateral force – top displacement curves

4. **CONCLUSIONS**

Twelve specimens of a new developed HSC filled double-steel-plate composite wall and three specimens of a new developed steel-plate reinforced HSC composite wall were tested under high axial compressive forces and reversed cyclic lateral loading. No obvious local buckling phenomena were observed for the specimens with proper width-thickness ratios of steel plates, and the surface steel plates and infill concrete could work together until failure. The test results showed that this two type composite walls had high bearing and deformation capacities under high axial compressive force, and are favourable choices for the tube walls in the super high-rise buildings.

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