SEISMIC EXPERIMENTAL RESEARCH OF CONCRETE FILLED STEEL TUBE COLUMNS-CONCRETE COMPOSITE SHEAR WALL

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ABSTRACT：

Shear wall is the main component to resist lateral forces, which has been mostly used in high-rise buildings. So to develop shear walls which have better seismic behavior is one of the key techniques of seismic design. Concrete filled steel tube columns-concrete composite shear wall is a new kind of composite shear wall, which can combine the big lateral stiffness of concrete wall and good vertical load-carrying capacity and ductility of concrete filled steel tube column. The experimental study on the seismic behavior of fifteen specimens with different design parameters including material strength, axial-load ratio, shear-span ratio, shear connector has been done. Six specimens will be introduced in this paper. Based on the experiment, load-carrying capacity, ductility, stiffness and its degradation, hysteretic property, energy dissipation and failure phenomena of each shear wall are contrastively analyzed. The experimental results show that this kind of new shear wall can play the advantage of components and has good seismic performance.

KEYWORDS: concrete filled steel tube column, reinforced concrete, composite shear wall, seismic behavior

1 INTRODUCTION

Shear wall is the main component to resist lateral forces, which has been mostly used in high-rise buildings. So to develop shear walls which have better seismic behavior is one of the key techniques of seismic design. Research of composite shear wall increase recently (Goel *et al.* 2004, Zhao *et al.* 2004, Cao *et al.* 2007 and Zheng *et al.* 2006).Concrete filled steel tube columns-concrete composite shear wall is a new kind of composite shear wall, which combine concrete filled steel tube column and concrete wall. Shear connector can make reliable connection between concrete filled steel tube column and concrete wall.

This composite shear wall can combine the big lateral stiffness of concrete wall and good vertical load-carrying capacity and ductility of concrete filled steel tube column. This concrete filled steel tube columns-concrete composite shear wall has been applied in construction in China. For example, circular concrete filled steel tube columns and cast in site concrete composite shear wall has been used in Nan-an of Fujian province post office building. Vertical steel plate is welded on lateral surface of concrete filled steel tube column. Horizontal bar in shear wall connects with vertical steel plate by welding (Han *et al.* 2004). Saige plaza in Shenzhen which is finished in 1999 including 72 floors and Ruifeng international business building in Hangzhou which is finished in 2001 adopt composite reinforced concrete shear wall with circular concrete filled steel tube columns and quadrate concrete filled steel tube columns respectively (Liao *et al.* 2006). Xia-hanqiang *et al.* made finite element elastic analysis of composite shear wall with quadrate concrete filled steel tube columns by SAP2000(Xia *et al.* 2005). At present seismic researches of concrete filled steel tube are concentrated on beam, column and other basic members at home and aboard (Wang *et al.* 2005, Cai *et al.* 2003, Beutel *et al.* 2002 and

Azizinamini *et al.* 2004). Experimental researches on seismic behavior of concrete filled steel tube columns-concrete composite shear wall are still few and theory researches trail engineering practices. Therefore, in-depth researches on seismic behavior of this new shear wall are sufficiently necessary.

The experimental researches and relatively systematic analyses on the seismic behavior of concrete filled steel tube columns-concrete composite shear wall specimens with different design parameters have been done in the paper. Design parameters of shear wall specimens include concrete strength, axial-load ratio and shear-span ratio.

2 EXPERIMENTAL DETAILS

Six 1:4 scale shear wall specimens were designed, which was divided into three groups. The section of shear wall specimens was rectangular, and the depth of which was 175mm. All the specimens were designed symmetrically.
The two specimens of the first group were designed as the shear-span ratio of 2.0 and the axial compression ratio of 0.35, which were labeled as SW1 and SW2. The specimens were poured with concrete of strength grade designed as C60 which had an average measured cube concrete compressive strength of 60.1 MPa. SW1 was traditional reinforced concrete shear wall and was designed based on special first seismic grade. SW2 was concrete filled steel tube columns-concrete composite shear wall.

The two specimens of the second group were designed as the shear-span ratio of 2.0 and the axial compression ratio of 0.65, which were labeled as SW3 and SW4. The specimens were poured with concrete of strength grade designed as C30 which had an average measured cube concrete compressive strength of 35.2 MPa. SW3 was traditional reinforced concrete shear wall, the steel bar detail of which was the same with SW1. SW2 was concrete filled steel tube columns-concrete composite shear wall, the steel bar and steel detail of which was the same with SW2.

The two specimens of the third group were concrete filled steel tube columns-concrete composite shear walls, which were labeled as SW5 and SW6 and the shear-span ratios were 1.5.The specimens were poured with concrete of strength grade designed as C30 which had an average measured cube concrete compressive strength of 34.1 MPa. The axial compression ratio of SW5 and SW6 were 0.65 and 0.35 respectively. The steel bar and steel detail of SW5 and SW6 were the same with SW2, and the different was the height of specimens.

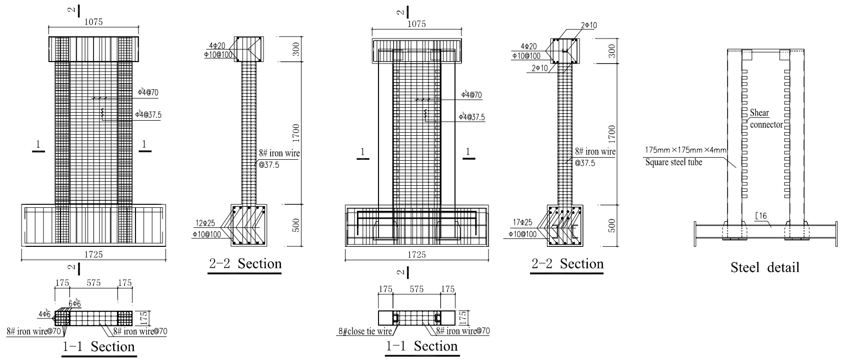
The mechanical properties of materials are tabulated in Table 1. Figure 1 shows the dimensions, reinforcement details and steel details of specimens.

Before horizontal load was applied, a vertical load was applied on the top of specimen and remain a constant during test, that is to say axial compression ratio is a constant. Then a low-frequency quasi-static cyclic loading was horizontally applied at the top beam of each specimen by a push and pull jack. Before the specimen was yielded, load value was used to control load applying; after that, displacement was used to control load applying.

All strains, displacements and loads were recorded and analyzed by an IMP data gathering system connected to the specimen. The cracking of the specimen was also visually monitored during the experiments. Horizontal lines were drawn at two sides of connecting surface of reinforced concrete shear wall and concrete filled steel tube column before loading to observe slippage between reinforced concrete shear wall and concrete filled steel tube column. A schematic view of the test arrangement is illustrated in Figure 2.

Table1 Mechanical properties of materials

Steel Plate and Steel Bar	Using Place	Yield Strength f_y/MPa	Ultimate Strength f_b/MPa	Elongation Rate /%	Elasticity Modulus /MPa
4 mm Steel Plate	Steel Tube of SW2, SW4 and SW5～SW6	320.85	472.65	21.00	1.96×10^5
2.5 mm Steel Plate	Shear Connector of SW2, SW4 and SW5～SW6	249.60	320.10	31.37	2.06×10^5
Φ^b4 Steel Bar	Distributing Steel Bar in SW1～SW6	—	793.53	10.00	1.80×10^5
Φ^b6 Steel Bar	Vertical Steel Bar in Frame Columns of SW1 and SW3	—	583.83	8.30	1.70×10^5



(a) SW1 (b) SW2

Figure1 Steel bar and steel details of models

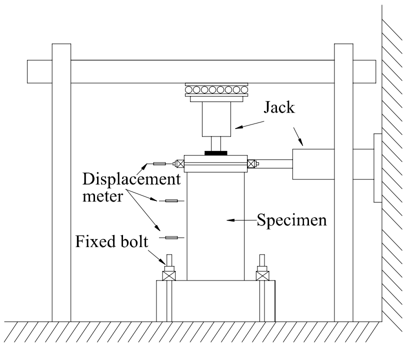


Figure2 Test set-up

3 EXPERIMENTAL RESULTS

3.1 Load-Carrying Capacity

The loads corresponding to measured points at concrete cracking, effective yielding of the section and ultimate load-carrying capacity of the specimens are tabulated in Table 2, where F_c is the concrete cracking load which is the load corresponding to the first occurrence of concrete cracking; F_y is the yield load; and F_u is the ultimate load which was the maximum horizontal load applied to the specimen. $\mu_{yu}=F_y/F_u$ represents the ratio of yield strength to ultimate strength.

It was observed form Table 2 that: （1）For the first and the second group, the cracking loads，yield loads and ultimate loads of the concrete filled steel tube columns-concrete composite shear walls were obviously bigger than that of the traditional reinforced concrete shear walls. The ratio of yield strength to ultimate strength of the composite shear walls were smaller than the traditional shear walls, which indicated that the progress from yielding to ultimate was long, that was to say the restrained yielding phase was long, and this was advantaged to “no collapse under serious earthquakes”. (2) For the third group, the cracking loads， yield loads and ultimate loads of SW5 with bigger axial compression ratio were increased respectively by 76%, 3.6% and 5.6% in comparison with SW6 with smaller axial compression ratio, which indicated that axial compression ratio made more obvious influence to cracking than yielding and ultimate.

Table 2 Measured cracking load, yield load and ultimate load

Specimen	F_c/kN	F_y/kN	F_u/kN	μ_{yu}
SW1	199.64	444.92	506.26	0.879
SW2	222.76	589.58	734.72	0.802
SW3	159.58	401.93	454.64	0.884
SW4	205.50	516.15	642.56	0.803
SW5	341.00	641.95	803.60	0.799
SW6	193.78	619.48	760.94	0.814

3.2 Stiffness

The measured stiffness and stiffness degradation coefficients of the test specimens are tabulated in Table 3, where K_0 is the initial tangent stiffness; K_c is the secant stiffness corresponding to the state of the wall at initial cracking; and K_y is the secant stiffness corresponding to the yield state of the wall; $\beta_{yo}= K_y/ K_0$ is the stiffness degradation coefficient from the initial elastic state to the yielding state.

For the first and the second group, the initial elastic stiffness of the concrete filled steel tube columns-concrete composite shear walls was bigger than that of the traditional reinforced concrete shear walls. The cracking stiffness and the yield stiffness of the composite shear walls showed an obviously increase over that of the traditional shear walls. The degradation coefficients β_{yo} of the composite shear walls were bigger than the traditional shear walls, which showed that the stiffness degradation speed of the composite shear walls became slower, so the stiffness and behavior of composite shear wall structure in the final stage was more stable than that of traditional shear wall structure and this was more favorable for seismic resistance.

Table 3 Measured stiffness and stiffness degradation coefficient

Specimen	K_o/kN.mm^{-1}	K_c/kN.mm^{-1}	K_y/kN.mm^{-1}	β_{yo}
SW1	195.00	79.54	44.45	0.228
SW2	225.01	92.05	57.41	0.255
SW3	165.00	74.57	41.06	0.249
SW4	196.00	88.98	55.86	0.285
SW5	425.92	164.73	82.83	0.194
SW6	410.27	164.22	72.71	0.177

3.3 Ductility

The measured displacement and ductility ratios of the test specimens are listed in Table 4, where all the displacements were measured at the top beams of the shear walls as indicated in Figure 2. The displacement at various stages shown in Table 4 are defined as: U_c is the displacement at the cracking state; U_y is the displacement at the yielding state; U_d is the elastic-plastic maximum displacement, which is defined as the point at which the load-carrying capacity dropped to 85% of the ultimate load; θ is the displacement drift corresponding to U_d and $\mu=u_d/u_y$ is defined as the ductility ratio of the shear wall.

Table 4 Measured displacements and ductility ratio

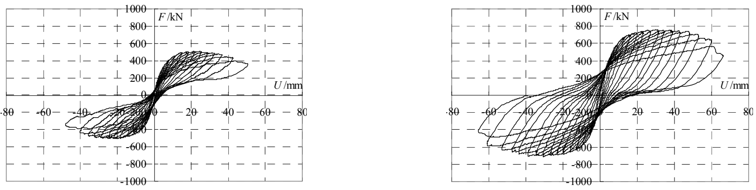
Specimen	U_c/mm	U_y/mm	U_d/mm	θ	μ
SW1	2.51	10.01	40.05	1/46	4.001
SW2	2.42	10.27	56.85	1/33	5.536
SW3	2.14	9.79	37.77	1/49	3.858
SW4	2.39	9.24	51.18	1/36	5.539
SW5	2.07	7.75	31.40	1/44	4.052
SW6	1.18	8.52	45.90	1/30	5.387

It was observed from Table 4 that: (1) For the first and the second group, the cracking displacements of the specimens showed closed. Compared with the traditional reinforced concrete shear walls, the ductility ratios of the composite shear walls were obviously increased. The ductility ratios of SW2 was increased by 38.4% in comparison with SW1 and that of SW4 was increased by 43.6% in comparison with SW2, which appeared the ductile behavior of the composite shear wall excel that of the traditional shear wall obviously. The elastic-plastic maximum displacements of the composite shear walls also were increased clearly compared with the traditional shear walls, which showed that the composite shear walls had better elastic-plastic deformation behavior than the traditional reinforced concrete shear wall.(2) For the third group, the displacement drift of SW5 with 0.65 axial compression ratio and SW6 with 0.35 axial compression ratio were respectively 1/44 and 1/30, which showed that both the two composite shear walls have good elastic-plastic deformation behavior. The elastic-plastic deformation behavior of the composite shear wall was obviously decreased when the axial compression increased. The elastic-plastic maximum displacement and the ductility ratio of SW5 were decreased respectively by 31.6% and 24.8% compared with SW6.

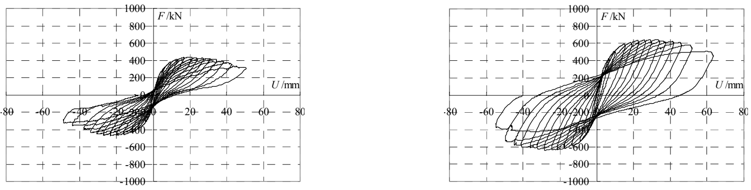
3.4 Hysteretic Behavior and Energy Dissipation Capacity

The measured load-displacement hysteretic loops of specimens are shown in Figure 3. It can be seen from the hysteretic loops of the first and the second group specimens that the hysteric loops of composite shear walls were clearly plumper and pinching of middle part were lighter than that of traditional reinforced concrete shear walls. Composite shear wall provided better load-carrying capacity and energy dissipation capacity. It can be seen from the hysteretic loops of the third group specimens that the hysteric loops of SW6 with 0.35 axial compression ratio was plumper than that of SW5 with 0.65 axial compression ratio and the general energy dissipation capacity of SW6 was stronger.

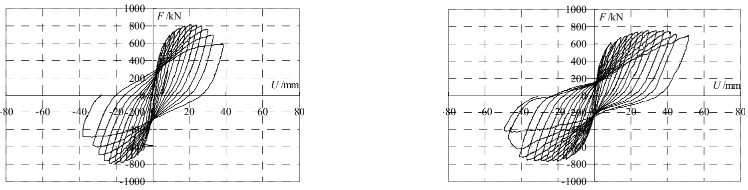
The elastic-plastic energy dissipation capacity of the specimens was evaluated using the inner area of the hysteretic loop. In the analysis described in this paper, the area of the hysteretic loop was computed and used as an index of energy dissipation capacity. The measured energy dissipation capacity of SW1 and SW2 were 29389 kN·mm and 81720 kN·mm respectively. Compared with the traditional shear wall SW1, the energy dissipation value of the composite shear wall SW2 was increased by 178.1%, which showed that the composite shear wall had significant seismic predominance than the traditional shear wall. The measured energy dissipation capacity of SW3 and SW4 were 31801 kN·mm and 73010 kN·mm respectively. The energy dissipation value of the composite shear wall SW4 was increased by 129.6% in comparison with the traditional shear wall SW3, which showed that under high axial compression the composite shear wall also had significant seismic predominance than the traditional shear wall. The measured energy dissipation capacity of SW5 and SW6 were 55972 kN·mm and 69108 kN·mm respectively. The energy dissipation of SW6 with 0.35 axial compression ratio was increased by 23.5% compared with SW5 with 0.65 axial compression ratio, which indicated that the energy dissipation capacity of the composite shear wall was obviously decreased when the axial compression increased.



(a) SW1 (b) SW2



(c) SW3 (d) SW4



(e) SW5 (f) SW6

Figure 3 Hysteretic curves of "load-displacement" of specimens

3.5 Failure Patterns

Photos of the specimens at failure are shown in Figure 4. The failure patterns have characteristic as follows:

(1) The concrete cracks in the traditional reinforced concrete shear wall SW1 and SW3 were relatively tiny, which distributed mainly over 1/2 under part of the wall. Diagonal cracks appeared early and grew quickly. Later, root concrete in two side of shear wall was crushed and shed. Main bars of hidden columns were bared and bended and specimen lost bearing capacity.

(2) Pattern at failure of the composite shear wall SW2 was different with that of the traditional shear wall SW1. The root of concrete filled steel tube column plumped during test and section of steel tube column at plumping place grew into roundness from squareness. At failure, there were many cracks distributed almost over the entire shear wall but there were no wide cracks. Small area corner concrete near steel tube columns was crushed and shed. Steel tube at plumping place was ripped and inner concrete power was leaked. Slipping stagger between concrete filled steel tube column and concrete shear wall was barely appeared before 1/50 displacement drift.

Failure process of the composite shear wall SW5 with bigger axial compression ratio was similar with that of SW2. The differences were that many dense crossed short diagonal cracks appeared in the concrete wall; new plumping appeared on the upside of the plumping place at root of concrete filled steel tube column; larger area corner concrete near steel tub e columns was crushed and shed.

(3) For composite wall SW5 with 0.65 axial compression ratio, the root of concrete filled steel tube column plumped and new plumping appeared on the upside of the plumping place; at failure, there were many cracks distributed almost over the entire shear wall but there were no wide or long cracks; large area concrete in 1/3 under part of the wall was crushed and shed. For composite wall SW6 with 0.35 axial compression ratio, small area corner concrete near steel tube columns was crushed and shed and steel tubes on the root of concrete filled steel tube column were ripped.

(a) SW1 (b) SW2 (c) SW3 (d) SW4 (e) SW5 (f) SW6

Figure 4 Photos of the specimens at failure

4 CONCLUSIONS

(1) The load-carrying capacity, ductility of concrete filled steel tube columns-concrete composite shear walls are obviously increased compared with traditional reinforced concrete shear walls, and the energy dissipation capacity is significantly increased also.

(2) The stiffness of concrete filled steel tube columns-concrete composite shear walls are obviously increased compared with traditional reinforced concrete shear walls. The stiffness degradation speeds of the composite shear walls are slower, so the behavior of structure is correspondingly stable and this is favorable for seismic resistance.

(3) The failure patterns of concrete filled steel tube columns-concrete composite shear walls are different with that of the traditional shear walls. The cracks obviously increase, which is important token of increasing of seismic energy dissipation capacity.

(4) The load values corresponding to each phase of composite shear walls are obviously increased with the rise of axial compression ratio, but the deformation capacities are obviously decrease.

(5) The research results can apply references for projects.

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