STUDY ON SEISMIC PERFORMANCE OF SHEAR WALLS WITH CONCEALED STEEL TRUSS

CAO Wanlin, ZHANG Yaqi, ZHANG Jianwei, WANG Min, CHANG Weihua

College of Architecture and Civil Engineering ,Beijing University of Technoloy, Beijing, China
Email: wlcao@bjut.edu.cn

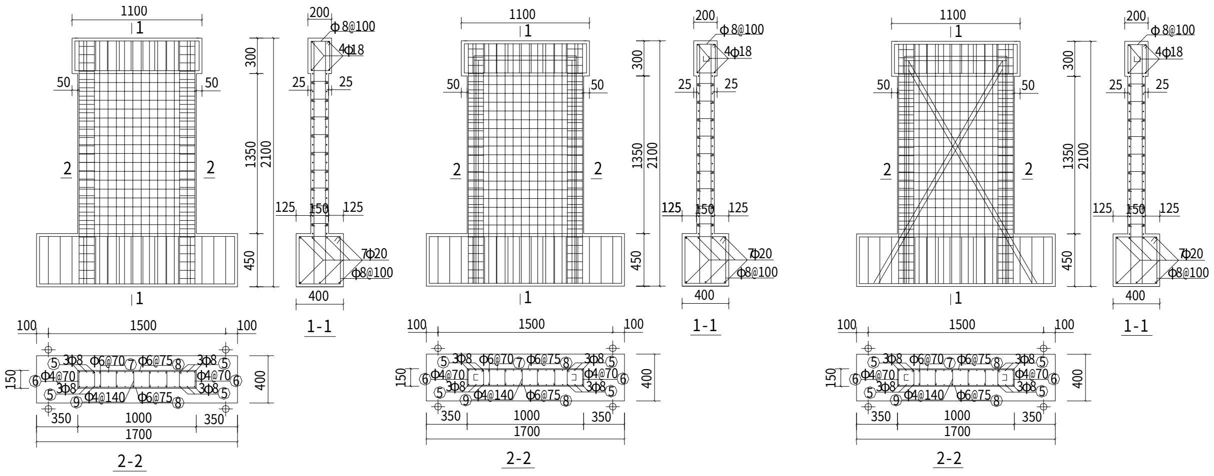
ABSTRACT：
In order to improve seismic performance of RC shear wall, the RC shear wall with concealed steel truss was proposed. This new shear wall included two kinds of composition. One was composition of truss and shear wall. The other was composition of steel and concrete. In other a word, it was a double composite shear wall. In this paper, the seismic performance of shear walls with concealed steel truss was investigated. An experimental study of twelve 1:3 scale shear wall specimens with height-to-length ratios equal to 1.5 or 2.2 were carried out, four of which were normal shear walls, four of which were shear walls with concealed steel frame and four of which were shear walls with concealed steel truss. The shear wall specimens were given an axial compression ratio of 0.2 or 0.5. Based upon the experimental study, the effects of concealed truss and axial compression ratio on the load-carrying capacity, stiffness, ductility, hysteretic behavior, energy dissipation and failure mechanism of shear wall were discussed. The formulas of calculating load-carrying capacity and stiffness were established. The results obtained from the formulas and those from experiment were in good agreement. Some suggestions for seismic design of RC shear wall with concealed steel truss were put forward. The experimental results showed that, compared with normal RC shear wall, the seismic performance of the RC shear wall with concealed steel frame and concealed steel truss was greatly improved.
KEYWORDS： reinforced concrete, shear wall, profiled steel, concealed steel truss, seismic performance

0 INTRODUCTION

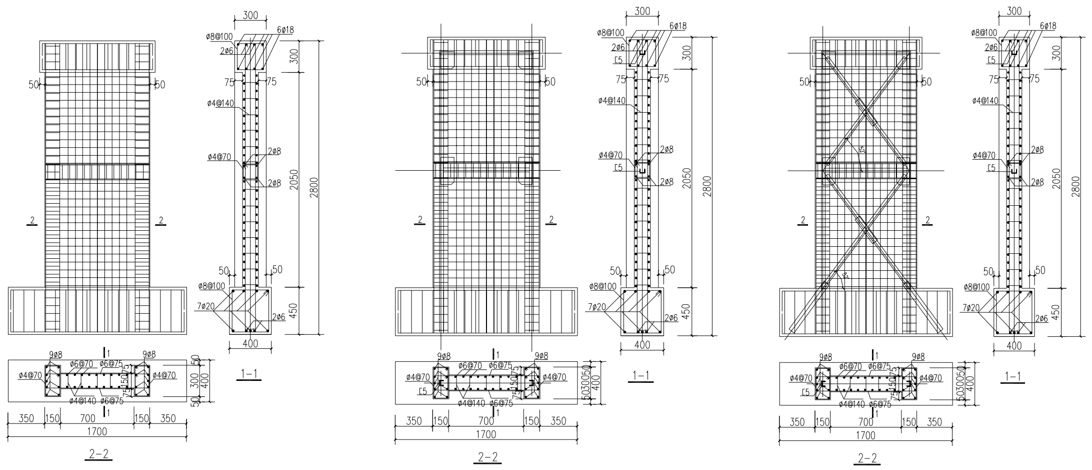
In the Code for Design of Concrete Structures (GB 50010—2002) and the Code for Seismic Design of Buildings(GB 50011—2001), Axial-load Ratio of the shear wall are limited under 0.6 commonly. At present seismic researches of Shear Walls are concentrated on the instances which the axial compression ratio are smaller at home, but the axial compression ratio of the shear wall are bigger in the bottom of high-rise buildings, which lead the ductility of structures reduced. In order to improve, the systematic researches on the seismic behavior of the shear wall with concealed bracing and concealed steel truss have been done by author (Cao *et al.* 2002, Cao *et al.* 2003, Cao *et al.* 2004, Cao *et al.* 2005, Cao *et al.* 2006, Cao *et al.* 2007, and Zheng *et al.* 2006) The research results showed that, compared with normal shear wall, the seismic performance of the shear wall with concealed bracing and concealed steel truss was greatly improved. For the sake of finding out the effects of different axial-load ratios on seismic performance of shear wall with concealed steel truss, the experimental researches and relatively analyses on the seismic behavior of two groups of shear wall specimens with different axial compression ratios have been done in the paper.

1 EXPERIMENTAL DETAILS

1.1 Design of the models



(a) SW1.5-1, SW1.5-2 (b) SW1.5-3, SW1.5-4 (c) SW1.5-5, SW1.5-6



(d) SW2.2-1, SW2.2-2 (e) SW2.2-3, SW2.2-4 (f) SW2.2-5, SW2.2-6

Figure 1 Steel bar and steel details of models

Twelve 1:3 scale shear wall specimens with shear-span ratios equal to 1.5 or 2.2 were designed, which was divided into four groups. The four specimens of the first group were labeled as SW1.5-1、SW1.5-3、and SW1.5-5, and the four specimens of the second group were labeled as SW1.5-2、SW1.5-4 and SW1.5-6, respectively, where the value of 1.5 refers to shear-span ratio. SW1.5-1 and SW1.5-2 were traditional reinforced concrete mid-rise shear walls. SW1.5-3 and SW1.5-4 were mid-rise shear walls with concealed steel frame. SW1.5-5 and SW1.5-6 were mid-rise shear walls with concealed steel truss. The four specimens of the third group were labeled as SW2.2-1、SW2.2-3、and SW2.2-5 , and the four specimens of the fourth group were labeled as SW2.2-2、SW2.2-4 and SW2.2-6, respectively, where the value of 2.2 refers to shear-span ratio. SW2.2-1 and SW2.2-2 were traditional reinforced concrete high-rise shear walls. SW2.2-3 and SW2.2-4 were high-rise shear walls with concealed steel frame. SW2.2-5 and SW2.2-6 were high-rise shear walls with concealed steel truss. The steel bar and steel detail of SW1.5-1 was the same with SW1.5-2, and the different was axial compression ratio. Analogically, SW1.5-3 was the same with SW1.5-4, and SW1.5-5 was the same with SW1.5-6 (Figure 1 a b c show). The steel bar and steel detail of SW2.2-1 was the same with SW2.2-2, and the different was axial compression ratio. Analogically, SW2.2-3 was the same with SW2.2-4, and SW2.2-5 was the same with SW2.2-6 (Figure 1 d e f show). The axial compression ratio of SW1.5-1 was 0.2. SW1.5-3, SW1.5-5, SW2.2-1, SW2.2-3 and SW2.2-5 was the same with SW1.5-1. The axial compression ratio of SW1.5-2 was 0.5. SW1.5-4, SW1.5-6, SW2.2-2, SW2.2-4 and SW2.2-6 was the same with SW1.5-2. The specimens were poured with concrete of strength grade designed as C35. The steel bar and steel detail were HPB235.

1.2 Test Contents and Procedure

This experiment is under low frequency reversed loading. Figure 2 is the test set-up. Before horizontal load was applied, a vertical load 500kN or 1250kN was applied on the top of specimen and remain a constant during test, that is to say axial compression ratio is 0.2 or 0.5. 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.

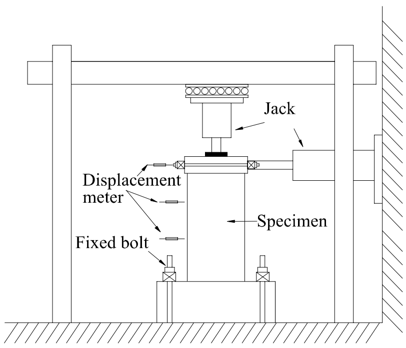


Figure 2 Test set-up

2 EXPERIMENTAL RESULTS

2.1 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 1, 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.

It was observed form Table 1 that:

(1)Whether the axial compression ratio lager or not, compared with the normal mid-rise and high-rise shear wall, the cracking load of the shear walls with concealed steel frame or truss is increased .

(2)Compared with the group of shear walls with smaller axial compression ratio, the yield load and ultimate load of the group of shear walls with bigger axial compression ratio were both significantly increased. For example, the measured ultimate load for SW1.5-2 was increased respectively by 69.7% in comparison with specimen SW1.5-1. The measured ultimate load for SW1.5-4 was increased respectively by 49.8% in comparison with specimen SW1.5-3.The measured ultimate loads for SW1.5-6 was increased respectively by 78.6% in comparison with specimen SW1.5-5. Similarly, the measured ultimate load for SW2.2-2 was increased respectively by 52.3% in comparison with specimen SW2.2-1. The measured ultimate load for SW2.2-4 was increased respectively by 43.7% in comparison with specimen SW2.2-3.The measured ultimate loads for SW2.2-6 was increased respectively by 37.9% in comparison with specimen SW2.2-5.

(3)When the axial compression ratio equal to 0.2, the measured ultimate loads for SW1.5-3 and SW1.5-5 were increased respectively by 37.1% and 73.9% in comparison with specimen SW1.5-1 and the measured ultimate load for SW2.2-3 and SW2.2-5 were increased respectively by 30.5% and 55.1% in comparison with specimen SW2.2-1, which indicated that the ultimate loads of the shear wall with concealed steel frame and concealed steel truss were greatly improved.

(4)When the axial compression ratio equal to 0.5, the measured ultimate loads for SW1.5-4 and SW1.5-6 were increased respectively by 21.1% and 42% in comparison with specimen SW1.5-2 and the measured ultimate load for SW2.2-4 and SW2.2-6 were increased respectively by 23.1% and 40.4% in comparison with specimen SW2.2-2, which indicated that the ultimate loads of the shear wall with concealed steel frame and concealed steel truss was greatly improved.

Table 1 Measured cracking load, yield load and ultimate load

Group	Specimen	F_c (kN)	F_y (kN)	F_u (kN)	F_u Relative Value of two groups	F_u Relative Value of the same group
first (λ_1=1.5) (n_1=0.2)	SW1.5-1	99.00	282.33	297.16	1.000	1.000
	SW1.5-3	119.49	376.21	407.46	1.000	1.371
	SW1.5-5	130.69	431.34	400.77	1.000	1.739
second (λ_2=1.5) (n_2=0.5)	SW1.5-2	110.49	424.20	504.18	1.697	1.000
	SW1.5-4	140.83	488.04	610.32	1.498	1.211
	SW1.5-6	161.75	564.24	715.70	1.786	1.420
third (λ_3=2.0) (n_3=0.2)	SW2.2-1	87.36	243.34	258.46	1.000	1.000
	SW2.2-3	101.05	275.90	337.25	1.000	1.305
	SW2.2-5	109.03	341.17	400.77	1.000	1.551
fourth (λ_4=2.0) (n_4=0.5)	SW2.2-2	98.92	293.14	393.55	1.523	1.000
	SW2.2-4	108.77	352.78	484.47	1.437	1.231
	SW2.2-6	112.35	396.07	552.54	1.379	1.404

2.2 Stiffness

The measured stiffness and stiffness degradation coefficients of the test specimens are tabulated in table 2, 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.

The following observations can be made from Table 2:

(1)Specimens, which have the same depth to width ratio of coupling wall-column section, have almost the same initial elastic stiffness K_0. The data indicate that in initial elastic stiffness is determined by concrete strength and specimen’s dimensions.

Table 2 Measured stiffness and stiffness degradation coefficients

Group	Specimen	K_o(kN/mm)	K_c(kN/mm)	K_y(kN/mm)	$\beta_{yo}=K_y/K_o$	β_{yo} Relative value of the two groups	β_{yo} Relative value of the same group
first	SW1.5-1	271.37	186.79	22.50	0.083	1.000	1.000
(λ_1=1.5)	SW1.5-3	259.25	202.53	36.14	0.139	1.000	1.681
(n_1=0.2)	SW1.5-5	266.26	210.79	44.06	0.165	1.000	1.996
second	SW1.5-2	269.57	109.40	41.47	0.154	1.855	1.000
(λ_2=1.5)	SW1.5-4	262.43	140.83	48.42	0.185	1.331	1.201
(n_2=0.5)	SW1.5-6	269.79	161.75	73.28	0.272	1.648	1.766
third	SW2.2-1	158.26	82.42	20.00	0.126	1.000	1.000
(λ_3=2.0)	SW2.2-3	165.24	85.64	22.50	0.136	1.000	1.080
(n_3=0.2)	SW2.2-5	173.30	102.86	28.15	0.162	1.000	1.286
fourth	SW2.2-2	137.14	82.433	35.149	0.256	2.032	1.000
(λ_4=2.0)	SW2.2-4	138.45	82.398	42.630	0.308	2.265	1.203
(n_4=0.5)	SW2.2-6	140.08	89.162	44.772	0.320	1.975	1.250

(2)The cracking stiffness K_c for the shear walls with concealed steel frame and concealed steel truss were bigger than that for the normal shear walls. When the axial compression ratio is bigger, the cracking stiffness declines obviously.

(3)The stiffness degradation coefficient β_{yo} for the groups which axial compression ratio equal to 0.5 shows a significant increase over that for the groups which axial compression ratio equal to 0.2. The stiffness degradation coefficient for SW1.5-2 was increased respectively by85.5% in comparison with specimen SW1.5-1. The stiffness degradation coefficient for SW1.5-4 was increased respectively by33.1% in comparison with specimen SW1.5-3. The stiffness degradation coefficient for SW1.5-6 was increased respectively by64.8% in comparison with specimen SW1.5-5. The stiffness degradation coefficient for SW2.2-2 was increased respectively by103.2% in comparison with specimen SW2.2-1. The stiffness degradation coefficient for SW2.2-4 was increased respectively by126.5% in comparison with specimen SW2.2-3. The stiffness degradation coefficient for SW2.2-6 was increased respectively by97.5% in comparison with specimen SW2.2-5.

(4)When the axial compression ratio equal to 0.2, the stiffness degradation coefficients for SW1.5-3 and SW1.5-5 were increased respectively by 68.1% and 99.6% in comparison with specimen SW1.5-1 and the stiffness degradation coefficients for SW2.2-3 and SW2.2-5 were increased respectively by 8.0% and 28.6% in comparison with specimen SW2.2-1 which indicated that the stiffness degradation coefficients of the shear wall with concealed steel frame and concealed steel truss were greatly improved.

(5)When the axial compression ratio equal to 0.5, the stiffness degradation coefficients for SW1.5-4 and SW1.5-6 were increased respectively by 20.1% and 76.6% in comparison with specimen SW1.5-2 and the stiffness degradation coefficients for SW2.2-4 and SW2.2-6 were increased respectively by 20.3% and 25.0% in comparison with specimen SW2.2-2 which indicated that the stiffness degradation coefficients of the shear wall with concealed steel frame and concealed steel truss were greatly improved.

(6)Whether the axial compression ratio lager or not, the concealed steel frame or truss restricted the expanding of concrete cracks and resulted in slower degrading of the stiffness. Therefore, the stiffness in the final stage is more stable for the shear wall with concealed steel frame or truss, which is more favorable for seismic resistance.

2.3 Ductility

The measured displacement and ductility ratios of the test specimens are listed in Table 3, where all the displacements were measured at the top beams of the shear walls. 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; and $\mu=U_d/U_y$ is defined as the ductility ratio of the shear wall.

Table 3 The measured displacements and ductility ratios

Group	Specimen	U_c(mm)	U_y(mm)	U_d(mm)	$\mu=U_d/U_y$	μ Relative value of the two groups	μ Relative value of the same group
first (λ_1=1.5) (n_1=0.2)	SW1.5-1	0.53	12.55	37.59	2.995	1.000	1.000
	SW1.5-3	0.59	10.41	41.83	4.018	1.000	1.342
	SW1.5-5	0.62	9.79	49.09	5.014	1.000	1.674
second (λ_2=1.5) (n_2=0.5)	SW1.5-2	1.01	10.23	22.81	2.230	0.745	1.000
	SW1.5-4	1.00	10.08	30.02	2.978	0.741	1.335
	SW1.5-6	1.00	7.70	27.12	3.522	0.702	1.579
third (λ_3=2.0) (n_3=0.2)	SW2.2-1	1.06	12.17	57.61	4.73	1.000	1.000
	SW2.2-3	1.18	12.26	76.11	6.21	1.000	1.312
	SW2.2-5	1.06	12.12	76.22	6.29	1.000	1.330
fourth (λ_4=2.0) (n_4=0.5)	SW2.2-2	1.20	8.09	55.04	6.80	1.438	1.000
	SW2.2-4	1.32	8.20	60.54	7.38	1.188	1.085
	SW2.2-6	1.26	8.31	61.57	7.41	1.178	1.090

The following observations can be made from Table 3:

(1)For the groups with the same axial compression ratio, the cracking displacements of the specimens showed closed. The data indicate that cracking displacements is determined not only by concrete strength and specimen’s dimensions but also the value of axial compression ratio.

(2)The ductility ratios for the groups which axial compression ratio equal to 0.5 show a significant reduce over that for the groups which axial compression ratio equal to 0.2. The ductility ratio for SW1.5-2 was reduced respectively by25.5% in comparison with specimen SW1.5-1. The ductility ratio for SW1.5-4 was reduced respectively by25.9% in comparison with specimen SW1.5-3. The ductility ratio for SW1.5-6 was reduced respectively by29.8% in comparison with specimen SW1.5-5.

(3)When the axial compression ratio equal to 0.2, the ductility ratios for SW1.5-3 and SW1.5-5 were increased respectively by34.2% and 67.4% in comparison with specimen SW1.5-1 and the ductility ratios for SW2.2-3 and SW2.2-5 were increased respectively by31.2% and 33.0% in comparison with specimen SW1.5-1which indicated that the ductility ratios of the shear wall with concealed steel frame and concealed steel truss were greatly improved.

(4)When the axial compression ratio equal to 0.5, the ductility ratios for SW1.5-4 and SW1.5-6 were increased respectively by 33.5% and 57.9% in comparison with specimen SW1.5-2 and the ductility ratios for SW2.2-4 and SW2.2-6 were increased respectively by 8.5% and 9.0% in comparison with specimen SW2.2-2 which indicated that the ductility ratios of the shear wall with concealed steel frame and concealed steel truss were greatly improved. The increase extent shows a small difference over those for the specimens with smaller axial compression ratio.

2.4 Hysteretic Behavior

The measured load-displacement hysteresis loops for the specimens are shown in Figure 3. The load-carrying capacity and energy dissipation of the Specimens can be showed by hysteresis loops. It can be seen that the hysteric loops of shear walls with concealed steel frame and concealed steel truss were plumper than that of normal mid-rise and high-rise shear walls and pinching of middle part were lighter than that of normal mid-rise and high-rise shear walls. The bearing capacity of the shear wall with bigger axial compression ratio is higher than that with smaller axial compression ratio while the ductility and energy dissipation are lower.

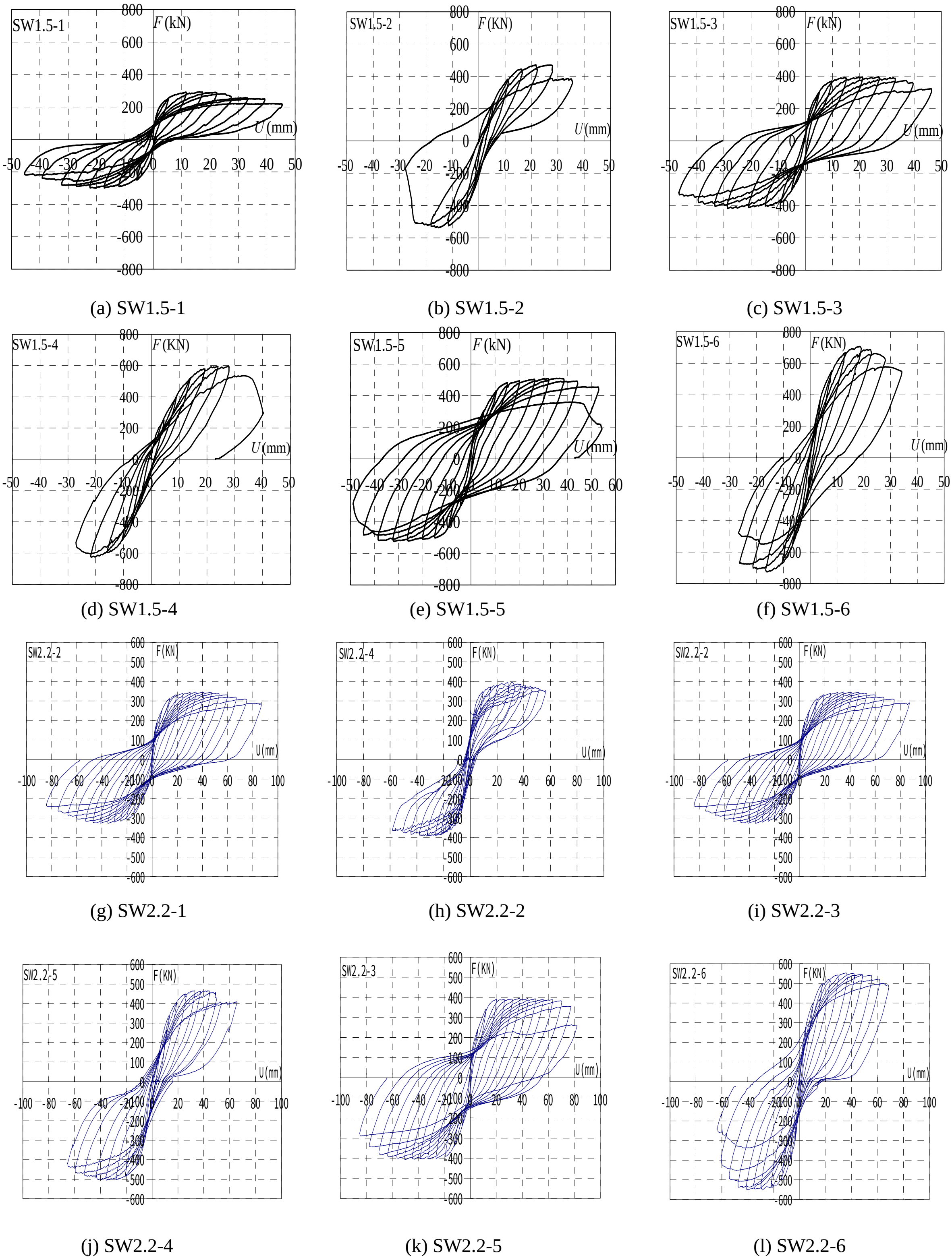
2.5 Energy Dissipation Capacity

Energy dissipation is an important detection index for evaluation of Seismic Performance. Equivalent viscous damping coefficient is used to differentiate the energy dissipation of the structure in engineering. The calculated formula of equivalent viscous damping coefficient is $h_e = S_{(ABCD)}/2\pi S_{(OBE+ODF)}$. The calculating mechanical model is shown in Figure 4. $S_{(ABCD)}$ is area of hysteresis loops ABCD. $S_{(OBE+ODF)}$ is sum area of triangle OBE and triangle ODF. The calculating results are listed in Table 4.

The following observations can be made from Table 4:

(1) The equivalent viscous damping coefficients for the groups which axial compression ratio equal to 0.5 show a significant reduce over that for the groups which axial compression ratio equal to 0.2. The equivalent viscous damping coefficient for SW1.5-2 was reduced respectively by44.6% in comparison with specimen SW1.5-1. The equivalent viscous damping coefficient for SW1.5-4 was reduced respectively by29.4% in comparison with specimen SW1.5-3. The equivalent viscous damping coefficient for SW1.5-6 was reduced respectively by16.8% in comparison with specimen SW1.5-5. The equivalent viscous damping coefficient for SW2.2-2 was reduced

respectively by32.9% in comparison with specimen SW2.2-1. The equivalent viscous damping coefficient for SW2.2-4 was reduced respectively by38.6% in comparison with specimen SW2.2-3. The equivalent viscous damping coefficient for SW2.2-6 was reduced respectively by37.9% in comparison with specimen SW2.2-5. The energy dissipation is reduced while the axial compression ratio is increased.



(a) SW1.5-1 (b) SW1.5-2 (c) SW1.5-3

(d) SW1.5-4 (e) SW1.5-5 (f) SW1.5-6

(g) SW2.2-1 (h) SW2.2-2 (i) SW2.2-3

(j) SW2.2-4 (k) SW2.2-5 (l) SW2.2-6

Figure 3 Hysteretic curves of “load-displacement” of specimens

(2) When the axial compression ratio equal to 0.2, the equivalent viscous damping coefficients for SW1.5-3 and SW1.5-5 were increased respectively by21.6% and 34.3% in comparison with specimen SW1.5-1 and the equivalent viscous damping coefficients for SW2.2-3 and SW2.2-5 were increased respectively by18.8% and 45.9% in comparison with specimen SW2.2-1 which indicated that the equivalent viscous damping coefficients of the shear wall with concealed steel frame and concealed steel truss were greatly improved.

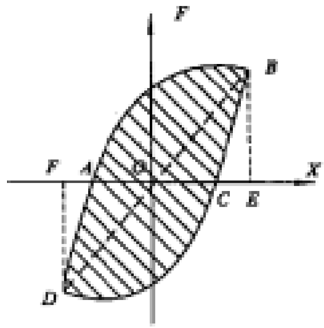


Figure 4 Equivalent viscous damping coefficients of capacity

(3) When the axial compression ratio equal to 0.5, the equivalent viscous damping coefficients for SW1.5-4 and SW1.5-6 were increased respectively by54.9% and 101.4% in comparison with specimen SW1.5-2 and the equivalent viscous damping coefficients for SW2.2-4 and SW2.2-6 were increased respectively by8.8% and 35.1% in comparison with specimen SW2.2-2 which indicated that the equivalent viscous damping coefficients of the shear wall with concealed steel frame and concealed steel truss were greatly improved.

Table 4 Equivalent viscous damping coefficient

Group	Specimen	h_e	h_e Relative value of the two groups	h_e Relative value of the same group
first	SW1.5-1	0.204	1.000	1.000
(λ_1=1.5)	SW1.5-3	0.248	1.000	1.216
(n_1=0.2)	SW1.5-5	0.274	1.000	1.343
second	SW1.5-2	0.113	0.554	1.000
(λ_2=1.5)	SW1.5-4	0.175	0.706	1.549
(n_2=0.5)	SW1.5-6	0.228	0.832	2.014
third	SW2.2-1	0.085	1.000	1.000
(λ_3=2.0)	SW2.2-3	0.101	1.000	1.188
(n_3=0.2)	SW2.2-5	0.124	1.000	1.459
fourth	SW2.2-2	0.057	0.671	1.000
(λ_4=2.0)	SW2.2-4	0.062	0.614	1.088
(n_4=0.5)	SW2.2-6	0.077	0.621	1.351

2.6 Failure Patterns

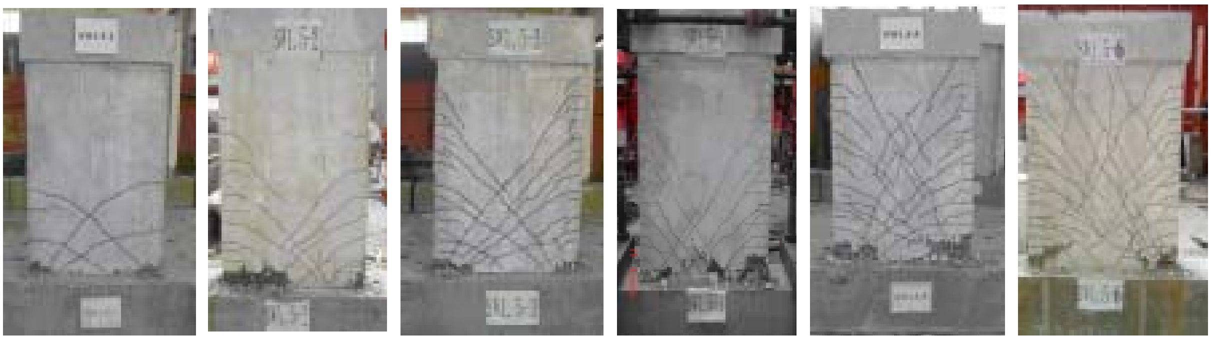
Photos of the specimens at failure are shown in Figure 5.

The failure patterns have characteristic as follows:

(1)The concrete cracks in the traditional reinforced concrete shear wall were relatively tiny. Diagonal cracks appeared early and grew quickly. When the axial compression ratio equal to 0.2, a clear diagonal crack on top developed a 45 angle was showed at both plus direction and negative direction .Later, root concrete in two side of shear wall was crushed and shed. Main bars of hidden columns were bared and bended. The last failure modes were flexural failures. When the axial compression ratio equal to 0.5, the cracks were more than that of smaller axial compression ratio, while the ductility is reduced and the specimen lost bearing capacity early. The last failure modes belonged to flexural failures.

(2) There were many cracks more widely distributed in the shear walls with concealed steel frame. Firstly, a few horizontal cracks appeared, and then the cracks became inclined and wider. Later, root concrete in two side of shear wall was crushed and shed. Main bars of hidden columns were bared and bended and wall roots run-through crack appeared. The last failure modes belonged to flexural failures.

(3)There were many cracks distributed almost over the entire shear walls with concealed steel truss. The main inclined cracks appeared later and slower which indicated that the concealed steel truss defer the cracks and made the complete exertion of energy dissipation of concrete cracks, so that the stiffness and capacity of specimens were improved. Later, root concrete in two side of shear wall was crushed and shed. Main bars of hidden columns were bared and bended and wall roots run-through crack appeared. The last failure modes belonged to flexural failures.



(a) SW1.5-1 (b) SW1.5-2 (c) SW1.5-3 (d) SW1.5-4 (e) SW1.5-5 (f) SW1.5-6

(a) SW2.2-1 (b) SW2.2-2 (c) SW2.2-3 (d) SW2.2-4 (e) SW2.2-5 (f) SW2.2-6

Figure 5 Photos of the specimens at failure

3 CONCLUSIONS

(1) When the axial compression ratio is smaller, both mid-rise shear wall and high-rise shear wall have good ductility and energy dissipation. When the axial compression ratio is bigger, the load-carrying capacity is obviously increased, while the ductility and energy dissipation are reduced.

(2) Whether the axial compression ratio lager or not, the load-carrying capacity, later stiffness, ductility and energy dissipation are obviously increased in the shear walls with concealed steel frame and truss. Especially, the concealed steel truss restrict the expanding of concrete cracks and make the internal force redistributing, then make the distributing areas of cracks broader, which enhance the capacity of energy dissipation.

(3) Whether the axial compression ratio lager or not, the seismic performance is obviously increased in the shear walls with concealed steel truss which can be applied in the high-rise buildings.

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