Stiffening Methods for Enhancement of Hysteretic Performance of Slitted Steel Shear Walls

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SUMMARY:
Investigated are the steel shear walls that have slits and are stiffened by wood panels. To examine the effects of various design parameters on the performance of the walls, a series of tests consisting of twelve specimens are conducted. Material of stiffening panels, number and initial torque of bolts to restrain the stiffening panels, and end detail of the slits are adopted as the test parameters. It is disclosed that the stiffness of the stiffening panels affects the degree of pinching in the cyclic behavior and the initiation and propagation of cracks initiated from the slit end controls the maximum strength. A good balance between the crack growth and out-of-plane deformation is found to be the key to achieve good performance of the walls as the shear resisting elements, and those stiffened by wood panels are more effective than those stiffened by steel panels.

Keywords: Slitted steel plate, Wood panel, Buckling-restraining, Shear wall

1. INTRODUCTION

We have been studying a type of hysteretic damper that consists of a thin steel plate with vertical slits. This damper is suited to earthquake retrofit for mid or low-rise buildings with many windows or door openings. Each steel plate segment separated by the slits behaves as a flexural link arranged in parallel, which undergoes larger flexural deformation than its shear deformation. Moreover, both the strength and stiffness of the damper are adjustable independently by changing the arrangement of slits. To obtain large damping, stiffening by panels is adopted in this study, in which the panels cover the entire steel plate and are fastened by bolts (Fig.1). As the material of the stiffening panels, plywood is adopted. The proposed damper is thinner than those using stiffener ribs, and light and easy to construct and join with beams. However, the stiffness inclined to the grain of wood is small, so it is a concern that wood would possess the desired effect of stiffening and the steel plate stiffened by woods would achieve stable behavior up to a large drift angle.

In this study, a series of tests using twelve specimens are conducted to examine the effectiveness of wood panels as the stiffening material, effects of bolts to restrain the out-of-plane deformations of the steel plate, and performance of the damper at large drift angles.

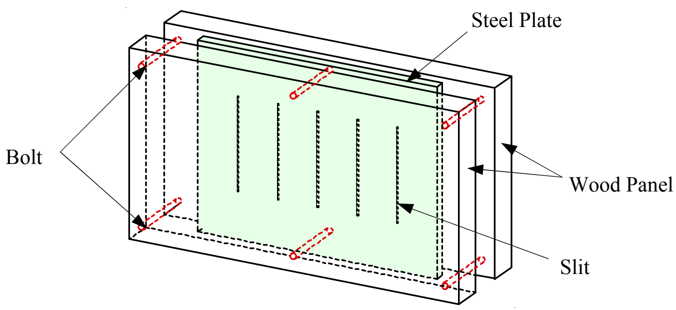


Figure 1. Slitted steel shear wall stiffened by wood panels

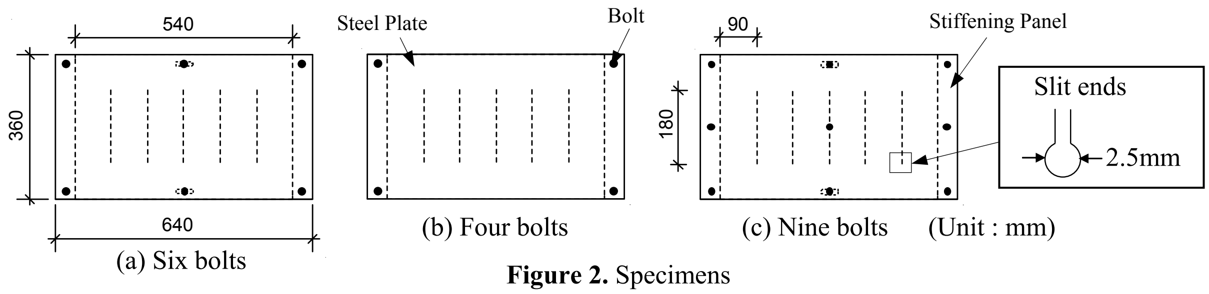


Figure 2. Specimens

Table 1. Specimen list

	Steel plate	stiffening panel				Loading protocol
	Slit end	Material	Thickness (mm)	Number of bolts	Initial Torque (Nm)	
S1	$\phi 2.5$	No stiffening				2 cycles up to 0.08rad
S2		Wood	24	6	0.5	
S3		Wood	24	6	3	
S4		Wood	24	6	10	
S5	No trim	Wood	24	6	0.5	
S6	$\phi 2.5$	Steel	6	6	0.5	
S7		Wood	24	4	0.5	
S8		Wood	24	9	0.5	
S9		Wood	24	6	0.5	2 cycles up to 0.02rad, 10 times at 0.04rad
S10		Steel	6	6	0.5	
S11		Steel	10	6	0.5	2 cycles up to 0.08rad
S12		Steel with treatment	10	6	0.5	

2. TEST PROGRAM

2.1 Test specimens

Fig. 2 shows the configuration of the specimens. The slitted steel plate is about 1/3 in scale of the prototype and uses SS400 steel. The plate has one layer of five slits. The slit ends were trimmed in a circular arc to minimize stress concentration for all specimens except for S5. The diameter of the arc is set to the minimum size for laser processing for 2.3 mm thick steel plate, and the arc is made to avoid the degradation of strength. The slit ends of S5 were shaped in arc with a diameter of 0.5 mm instead of 2.5 mm. Table 1 shows the list of specimens. S2 is the base specimen whose stiffening consists of 24mm thick wood panels fastened by the initial torque of 0.5Nm using six bolts. The plywood consists of seven plies of 24 mm thickness (wood panel, hereafter). The steel panel of 6 mm thickness is also used, which has the bending stiffness equal to that of the wood panel. We examined the differences of performance between wood and steel stiffening by the comparison of S2 and S6. The material properties of stiffening panels are shown in Table 2. The wood panel weighs 3 kg, while the steel panel is 3.5 times heavier than wood panel. The effect of friction between the steel plate and stiffening panel is studied in comparison with S11 stiffened by the normal steel panels and S12 stiffened by the surface-treated steel panels. The panels are coated by teflon of 30-50 μm to reduce the friction coefficient to about 1/4 (0.05-0.1). The effect of the number of stiffening bolts, six (S2), four (S7), and nine (S8) shown in Fig. 2 on energy dissipation are examined. The initial torque of bolts, 0.5 Nm (S2) tightened by hands, 3 Nm (S3) and 10 Nm (S4) clenched by wrench, are adopted to study the effect of torque on energy dissipation. Bolt holes of steel plate used for stiffening are enlarged in the loading direction to avoid the shear force to the stiffening panels. Large washers with a diameter of 45 mm are used not to dent in the wood.

Table 2. Material property

		Thickness (mm)	E (N/mm^2)	σ_y (N/mm^2)	σ_u (N/mm^2)	Weight (kg)
Slitted steel plate		2.29	198000	278	424	3.5
Stiffening panel	Wood	24.1	6045	-	-	3.0
	Steel	5.68	206000	279	400	11

2.2 Loading set-up and measurement

The loading setup is shown in Fig. 3. Two specimens are loaded at the same time. The slitted steel plate is sandwiched by steel angles (L-65x65) at both ends and connected by high tension bolts, and these angles in turn are bolted to loading columns. The center column is connected to 2MN oil jack and the slitted steel plate is subjected to shear force by displacement control of the jack. Rollers were connected to the center column at the bottom and near the joint part of the jack to maintain the plumbness of the column. Cyclic loading up to 0.08 rad with 2 times at each shear angle is adopted except for S9 and S10, for which the loading of 0.04 rad are repeated for 10 times after the cyclic loading up to 0.02 rad to check the change in damping performance when subjected to many cycles of shear force. The shear angle of 0.04 rad corresponds to the story drift angle of 0.015-0.02 rad. This story drift angle is 3-4 times the limit angle for the Japanese seismic design, 0.005 rad.

The measuring points are shown in Fig.3. The elastic strain gauges are set in the center of both flanges of the loaded columns. The force of each specimen is obtained by dividing the jack force in the ratio of the gauge values measured for right and left columns. We also measure the out-of-plane deformations of the stiffening panels at points far from bolts and points of contact with the steel plate of four corners (Fig.3).

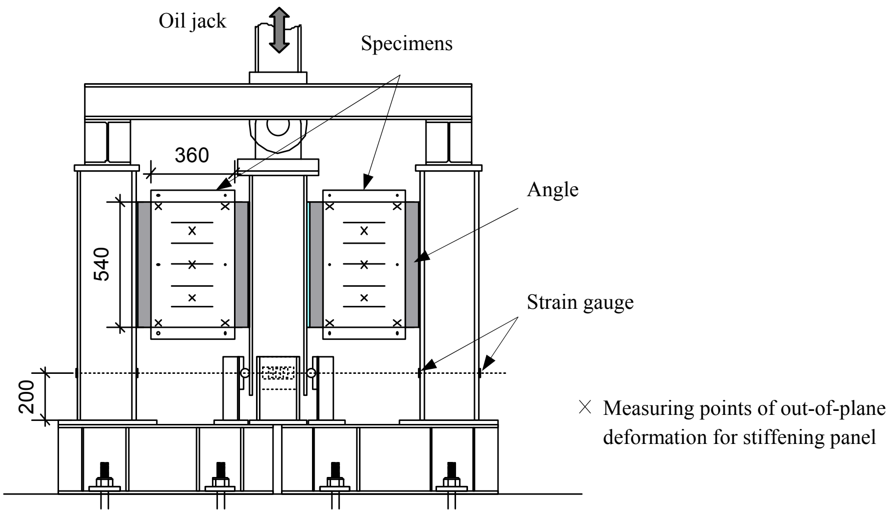


Figure 3. Loading setup used in test

3. TEST RESULTS

Fig. 4 shows the relationships between the shear force and shear angle obtained from the tests.

3.1 Behavior of basic specimen and effect of arc for slit ends

The base specimen, S2, shows stable behavior up to the shear angle of 0.08 rad. The first cycle strength reached to the maximum value at 0.06 rad and the strength kept in the same level up to 0.08 rad. The loops show little pinching up to the second cycle of 0.04 rad and after that the second cycle becomes smaller than the first cycle. Within the serviceable range from 0.005 rad to 0.01 rad, buckling of the steel plate or pinching behavior did not occur. Cracks of S5 without trim at slit ends are 1.5

times as large as those of S2; therefore the rate of strength reduction is larger. It is confirmed that the trim of arc, whose diameter is about the same as the thickness of the steel plate, can suppress the stress concentration at slit ends and propagation of cracks.

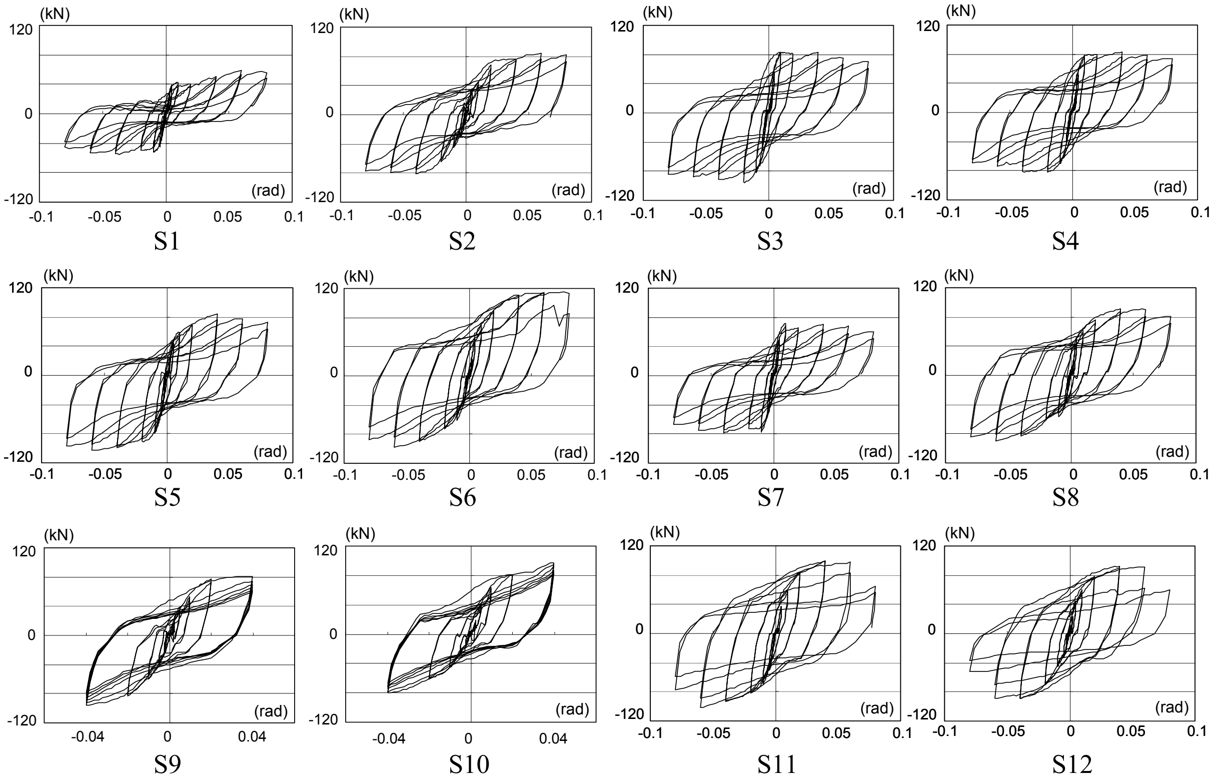


Figure 4. Hysteretic loops obtained from tests
(horizontal axis : shear angle (rad), vertical axis : shear force (kN))

3.2 Differences of stiffening materials

The differences of stiffening materials are described here in comparison with the specimen without stiffening (S1), the specimen stiffened by wood panels (S2), and the specimen stiffened by steel panels (S6). Test results are shown in Fig.5. The crack length in Fig.5(c) is the average value obtained by dividing the sum of the grand total crack length by the number of cracks, i.e., 20. For the specimens stiffened by wood panels, the out-of-plane deformation of the steel plate is defined as the sum of the maximum deflection of stiffening panel at the shear angle of 0.08 rad and the depth of scratches into the wood generated by steel plate. The maximum strength is the average of absolute values of maximum and minimum strengths, and the dashed line in Fig.5(a) represents the design strength[1)] (85.9 kN). The ratio of strength reduction is obtained by dividing the differences between the maximum strength and the strength at 0.08 rad by the maximum strength. S2 stiffened by wood panels has stable behavior up to the shear angle of 0.08 rad, but for S6 stiffened by steel panels, a center bolt jammed against the bottom edge in the long hole of the steel plate and fractured at the second cycle of 0.08 rad. By stiffening the slitted steel plate using panels, the strength is raised by 1.4, and energy dissipation increased as shown in Fig. 5(a). The maximum strength of S2 is in good agreement with the design strength. For S6 stiffened by steel panels, the strength increases by 15 % relative to S2, because the stiffening panel touched the mounting angle and it generated additional resistance force against loading. S2 and S6 are the same in equivalent viscous damping (h_{eq} hereafter), and it is 1.5 times larger than that of S1 without stiffening. Fig. 6 shows photos of slitted steel plates after loading. The out-of-plane deformations distributed at slit ends for all specimens. For S1 without stiffening, large lateral buckling occurs in shear links and cracks progress from slit ends. The maximum out-of-plane deformation of S1 is 33 mm, and it decreases to less than 1/5 by stiffening. Among them, the out-of-plane deformation of S6 is smaller than that of S2, and the curvature of S6 is larger than that of S2 near the slit ends. Large cracks occur at slit ends for S6 because the slitted steel plate could not deform toward out-of-plane and the stress was concentrated in plane. In contrast, the crack length for S2 is half of the others. It is attributed that the slitted steel plate can cut into woods and the stress in plane turns small. Thus, the strength degradation of S2 is made small as shown in Fig. 5(b). The inner sides of wood panels had the trail of the slitted steel plate and deep scratches at the slit ends. The depth of scratch is nearly the same for all points and is an average of 0.9 mm. The inner sides of steel panels have trails but no deep scratches.

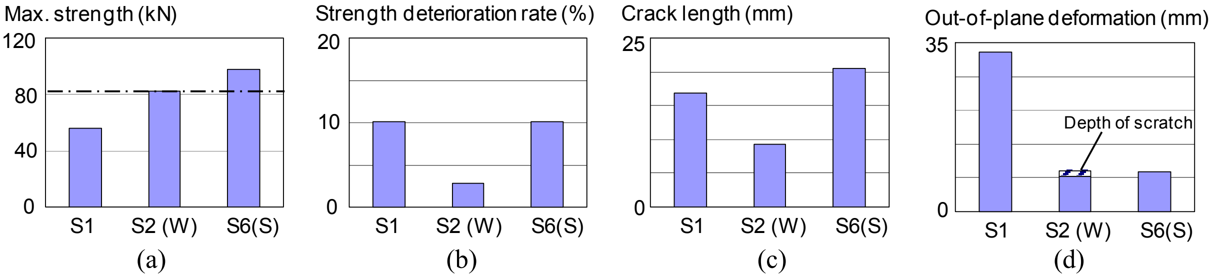
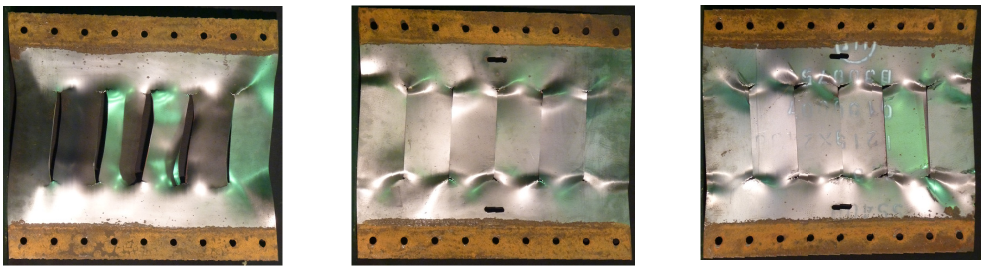


Figure 5. Comparison of stiffening materials



(a) S1 (No stiffening) (b) S2 (Wood stiffening) (c) S3 (Steel stiffening)

Figure 6. Slitted steel plates after loading

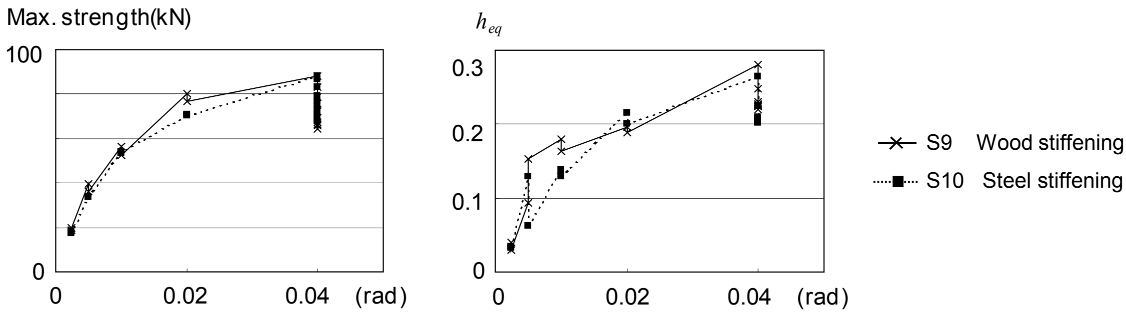


Figure 7. Maximum strength and equivalent damping ratio of S9 and S10

3.3 Effect of repeated loading

The maximum strength and h_{eq} of S9 and S10 are shown in Fig. 7. Though S9 stiffened by wood panels has a slightly smaller strength than S10 stiffened by steel panels, S9 has a larger h_{eq} from the small drift angle and reaches 0.15 of h_{eq} at the angle of 0.005 rad. The strength of the tenth cycle decreases to 75 % relative to the first cycle. The h_{eq} of the tenth cycle decreases to 70% of the first cycle, but it remains 0.2. It is considered that the specimen has sufficient damping, because shear walls that had been studied in previous research had 0.15-0.3 of h_{eq}. Cracks did not occur at slit ends for S9 and S10, thus both specimens maintain sufficient ductility to the shear angle of 0.04 rad. Therefore, the stiffening effect of wood panels and steel panels are found to be almost the same at 0.04 rad, which is a value that is considered as the maximum shear angle in conventional seismic design.

3.4 Influences of out-of-plane deformation of steel plate and crack on hysteretic behavior

Fig.8 represents the influences of out-of-plane deformation of steel plate and cracks at slit ends to the hysteretic behavior. The strength degrades with the increase of crack length regardless of the material used in the stiffening panel as shown in Fig.8 (a). When the stiffening panel that has large bending stiffness or large stiffness inclined to the grain are used or many bolts are arranged, the in-plane stress is concentrated at slit ends and cracks occur from slit ends. In contrast, when the stiffening panels are not used or a few bolts are used, each shear link sustains large lateral buckling and cracks occur from slit ends. Comparing the initial torque of bolts (S2, S3 and S4), S2 with the torque of 0.5 Nm has the smallest cracks with the smallest strength deterioration rate, so it is more efficient for the reduction of cracks by turning the bolts by loose fastening than by tight fastening. Fig.8(b) shows that the maximum strength increases with the suppression of out-of-plane deformation of steel plate. For the specimens stiffened by wood panels, out-of-plane deformations are larger than the specimens stiffened by steel panels but the difference in strength remains 15 % at most. Increasing the number of bolts for wood stiffening helps the out-of-plane deformations of steel plate suppressed and the maximum strength increased. It is found that the smaller out-of-plane deformation and crack length the specimen experiences, the higher performance is achieved as the damper. “Zero” in Fig.8 (c) represents the desired performance as the shear wall, thus stiffening by wood panels is considered to be more effective than stiffening by steel panels.

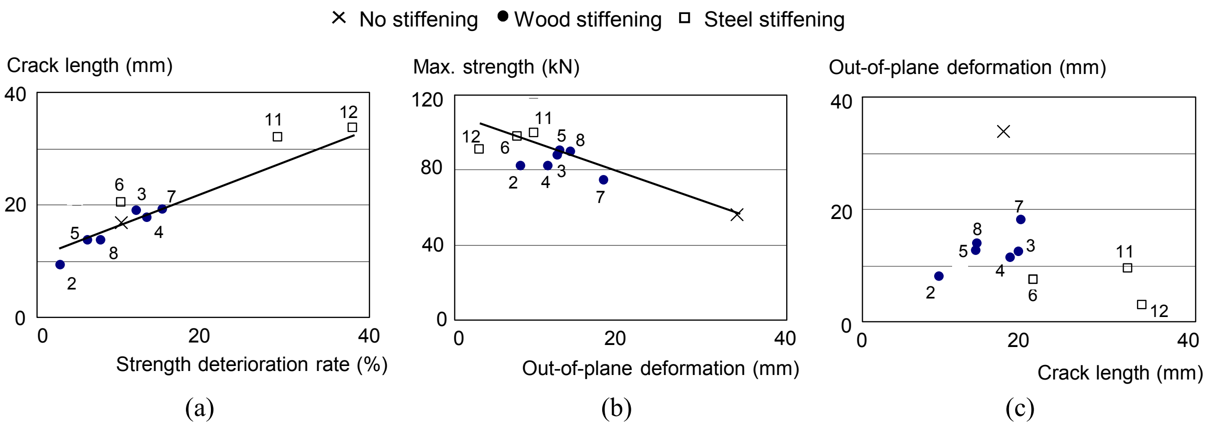


Figure 8. Influences of out-of-plane deformation of steel plate and crack on hysteretic behavior

4. CONCLUSIONS

A series of tests using twelve specimens are conducted to examine the effects of various design parameters on the performances of the slitted steel shear wall. Major findings from these studies are as follows.

1. By suppressing out-of-plane deformations of the slitted steel plate, both the strength and dissipated energy increase.
2. The stiffening panels provide similar energy dissipation regardless of the material of stiffening panels as long as they have the same bending stiffness.
3. Buckling and the succeeding out-of-plane deformations of the steel plate affect the maximum strength, and propagation of cracks initiated from slit ends leads to the degradation of the maximum strength.
4. Good balance between the crack growth and out-of-plane deformation is found to be the key to achieve higher performance of the shear wall as the shear resisting element, and stiffening by wood panels is found more effective than stiffening by steel panels.

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