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EXPERIMENTAL STUDY OF FULL-SCALE STEEL-WOOD HYBRID SHEAR WALLS

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ABSTRACT

Cyclic loading tests were performed on three conventional Japanese wooden frames 1820 mm long and 2730 mm high. One was fabricated from pure wood and the other two were reinforced with a new type of seismic element consisting of steel shear walls with slits and out-of-plane stiffening. Two units of steel shear walls 803 mm long, 1288 mm high, and 1.2 mm thick were arranged along the middle of the wooden frame. The steel plate segments between the slits acted as a series of flexural columns, which increased the deformation capacity and enabled the steel shear wall to behave in harmony with the surrounding wooden frame. Moreover, the strength and rigidity of the steel shear walls with slits could be easily controlled by controlling the distance between the slits, the length of the slit, and the number of layers of the slit. The values of the experimental parameter M_{cr}/M were selected as 0.7 and 1.0, where M_{cr} is the lateral torsion buckling moment of the flexural columns between the stiffening plates and M is the maximum moment of the flexural columns between the stiffening plates for when full plastic moments occur at the top and bottom of the flexural columns. Compared to previous 910-mm-long specimens, the present specimens exhibited greater stability without strength degradation up to a drift angle of 6%. However, in the specimen with an M_{cr}/M value of 1.0, slight damage was observed in the columns and the sill before the deformation of the steel flexural columns. The load-carrying capacities and wall strength ratios of the specimens with M_{cr}/M values of 0.7 and 1.0 were almost the same.

Keywords: Steel shear wall with slits, cyclic loading, stiffener, drift angle, wooden frame

1. INTRODUCTION

Previous studies on small 910 mm × 910 mm steel-wood hybrid shear walls have revealed that steel shear walls with slits and out-of-plane stiffening perform excellently when subjected to repeated horizontal loads (Li, 2004, 2008, 2011). The shear strength and rigidity of a steel shear wall with slits can be calculated from the full plastic moments at the upper and lower ends of the flexural columns (i.e., the steel plate between the slits). Moreover, these properties can be easily controlled by the design specifications of the slits, including the interval between the slits (b), the slit length (l), and the number of layers of the slit (m) (Li, 2004).

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In one of the previous studies on full-scale steel-wood hybrid shear walls 910 mm long and 1820 mm high (known as P805 specimens), the author showed that these walls were stable when two units of steel plates and a connection member were used and the wall strength ratios were greater than 3.79 (Li, 2012). However, significant cracks occurred in the sills due to the high tensile forces in the columns during loading. The P805 specimens were tested under loading conditions that were much more severe than those of shear walls in real wooden structures. To reduce the tension in the sill during a cyclic loading test, Li proposed the use of 2P805 specimens 1820 mm long and 2730 mm high because their loading conditions are closer to those in real life. The parameters in Li's work (2012) included the design specifications of the slits, strength of the stiffening plates, connection method of the edge stiffener, number of loading cycles, workability of the construction, and effects of seismic strengthening (i.e., the value of M_{cr}/M). Based on the test results of this previous study, the present study used the following design specifications of the slits and connection member between the two units of steel plates: $b = 25$ mm, $l = 250$ mm, $m = 2$, and connection member cross section of 45 mm $\times$ 105 mm. Only one parameter was considered, namely, M_{cr}/M , which could be adjusted by changing the width of the stiffening plates as shown in Table 1.

In conventional Japanese wooden frames, the wall elements are embedded in the frame to persevere the aesthetics of the wood columns: a concept that is known in Japanese as "Sinkabe." In this study, three full-scale frame specimens were fabricated; one was purely wooden, and the other two were reinforced with steel shear walls with slits and out-of-plane stiffening. The strengths and deformation capacities of the specimens were investigated under cyclic horizontal loads.

2. CYCLIC TESTS

As shown in Figure 1, the wooden frame was 1820 mm long and 2730 mm high. Each steel plate was 803 mm long, 1288 mm high, and 1.2 mm thick. For reasons of workability, the plates were kept 2 mm smaller than the inner dimensions of the wooden frames. The design specifications of the slit were as follows: $b = 25$ mm, $l = 350$ mm, and $m = 2$. The stiffening wood plates measured 18 mm $\times$ 67 mm and 18 mm $\times$ 86 mm, and had M_{cr}/M values of 0.7 and 1.0 at the top and the bottom of the flexural columns, respectively. The wooden edge stiffeners around the circumference of a steel plate had 45 mm $\times$ 45 mm cross sections and were fixed to the steel plate by M6 bolts. End lap joints were used to connect the edge stiffeners. Screws were used to fix the steel plate with the stiffeners to the wooden frame. Figure 1 shows the details of specimen 2P805-25-350-2-T45S-W. Table 1 lists the details of the specimens, and Table 2 presents the mechanical properties of the steel.

Figure 2 shows the setup of the fixed-end loading method. A horizontal load was applied by an oil jack using a displacement-controlled procedure and repeated at storey drift angle amplitudes of 1/600, 1/450, 1/300, 1/200, 1/150, 1/100, 1/75, 1/50, 1/30, and 1/15 rad. Thereafter, a monotonic load was applied up to about 1/13 rad. The loading program is shown in Figure 3.

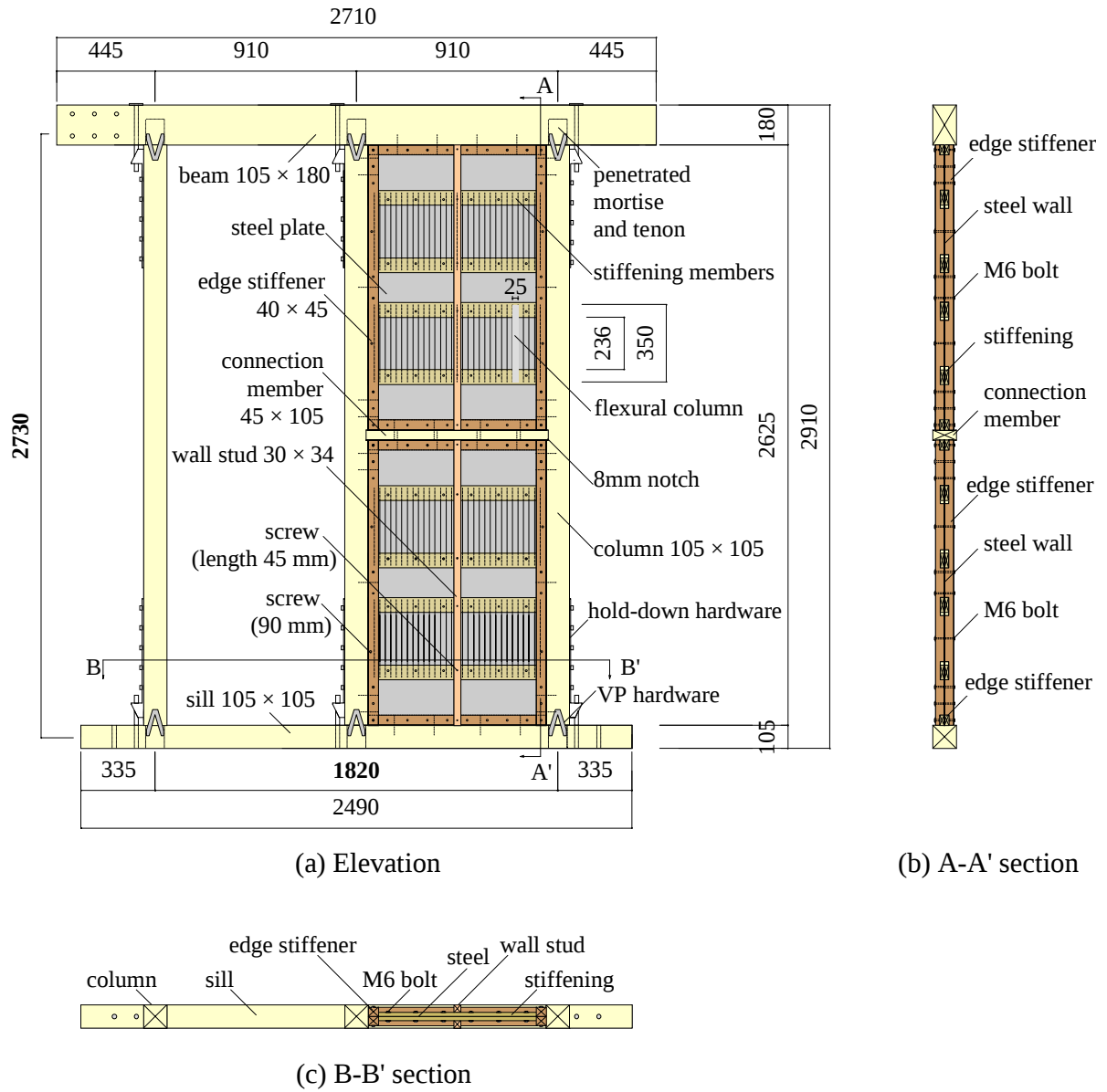


Figure 1: Details of specimen 2P805-25-350-2-T45W.

Table 1: Details of Specimens

Specimen Name	Slit				Stiffening		
	Interval (mm)	Length (mm)	Length after Stiffening (mm)	Layer	Thickness (mm)	Width (mm)	M_{cr}/M
2PFW-T45S	--	--	--	--	18	67	--
2P805-25-350-2-T45S-W	25	350	236	2	18	67	0.7
2P805-25-350-2-T45S-S	25	350	198	2	18	86	1.0

Table 2: Mechanical Properties of Steel

Young's Modulus (N/mm ²)	Yield Stress (N/mm ²)	Tensile Strength (N/mm ²)	Yield Ratio	Throttle (%)	Elongation (%)
1.95×10^5	343.7	395.3	0.87	27.1	32.3

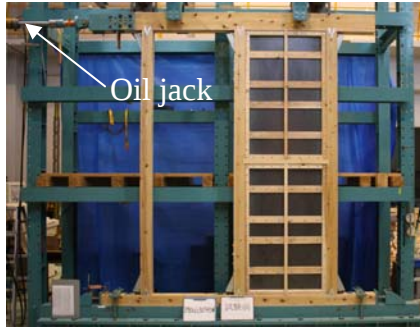


Figure 2: Loading setup.

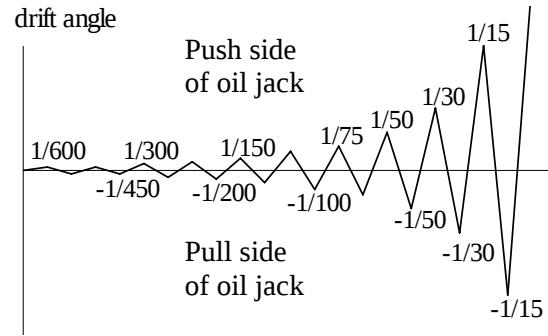


Figure 3: Loading program.

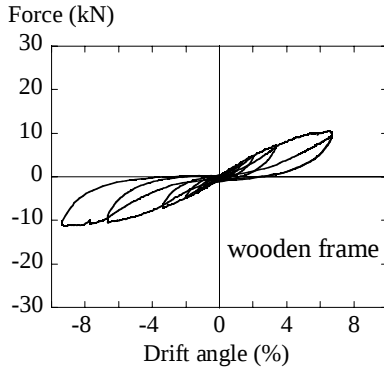
3. TEST RESULTS AND DISCUSSION

3.1. Lateral force-drift angle relationship

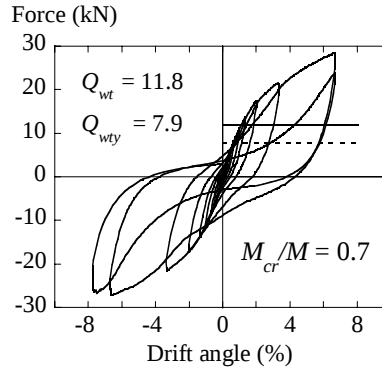
The relationships between the lateral force and the drift angle of the specimens are shown in Figure 4. The drift angle relative to the transverse axis was calculated by subtracting the rotation angle of column bases from the storey drift angle. From Figure 4(a), it is clear that the wooden frame specimen with edge stiffeners and stiffening plates exhibited ductility beyond 6% drift without strength degradation and that the relationships between the lateral force and the drift angle are of the slip type. The maximum force of specimen 2PFW-T45S was 10.5 kN. In Figures 4(b) and 4(c), the horizontal solid lines and dashed lines indicate the calculated ultimate shear strength Q_{wt} and calculated yield shear force Q_{wyt} ($=2/3Q_{wt}$), respectively (Li, 2004). From these two figures, it is clear that the maximum strength of a 2P805 specimen is greater than twice the calculated ultimate shear strength (Q_{wt}). In addition, the relationship between the lateral force and the drift angle of the 2P805 specimens is almost spindle-like, and the specimens have a high energy absorption ability. Table 3 lists the ratio of the test result to the calculation result for the different specimens. The ratio of the strength of the steel wall ($P_{max} - P_f$) to the calculated ultimate shear strength (Q_{wt}) for each specimen is about 1.4.

3.2. Failure modes

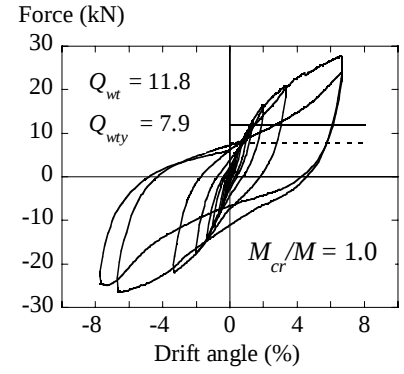
In specimen 2PFW-T45S, which exhibited structural stability, only a small crack was observed in the column at a drift angle of $-1/50$ rad and in the sill at a drift angle of $-1/15$ rad. Figure 5 shows the deformations of the flexural columns for a drift angle of $1/15$ rad. During the test of specimen 2P805-25-350-2-T45S-W, flexural deformations occurred in some flexural columns at a drift angle of $-1/300$ rad, and in all flexural columns at $-1/75$ rad. The plastic deformations of the flexural columns were pronounced at $-1/30$ rad, and cracks appeared in the sill and tenons of the columns at $-1/13$ rad. Conversely, flexural deformations began to be observed in some flexural columns of 2P805-25-350-2-T45S-S specimen at $-1/150$ rad. However, instead of further deformation of the flexural columns, cracks subsequently formed in the sill at the joints between the sills and the columns. The destruction of the sill occurred earlier than the deformation of the steel shear walls with slits when out-of-plane stiffening used an M_{cr}/M value of 1.0.



(a) 2PFW-T45S



(b) 2P805-25-350-2-T45S-W



(c) 2P805-25-350-2-T45S-S

Figure 4: Test results.



(a) 2P805-25-350-2-T45S-W



(b) 2P805-25-350-2-T45S-S

Figure 5: Deformation of flexural columns at 1/15rad.

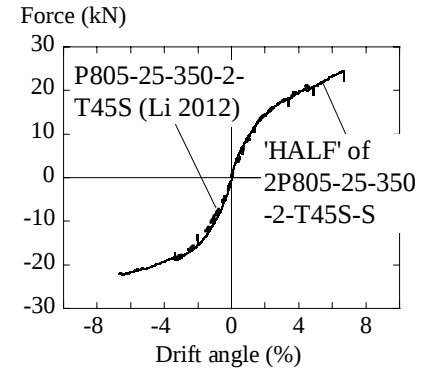


Figure 6: Comparisons of results.

3.3. Wall strength ratios

The technical term “wall strength ratio” is used to express the strength of a shear wall in wooden frames, and is especially important in wooden structures designed according to specifications. It can be calculated using the following equation:

$$\text{Wall strength ratio} = \frac{\min\{P_{1/120}, P_y, \frac{2}{3}P_{max}, 0.2P_u / D_s\}}{1.96L} \alpha \quad (1)$$

where L is the length of the shear wall in meters (in this research, $L = 1.82$ m), α is the reduction factor of the construction and permanence (in this research, $\alpha = 1.0$), and 1.96 is the horizontal strength in kN/m when the wall strength ratio is 1.0. The other terms are defined in the notation list below Table 3.

Table 3 gives the wall strength ratios obtained from the test results up to a drift angle of 1/15rad. The wall strength ratio was calculated using the average forces on the pull and push sides of the oil jack. As shown in Table 3, the wall strength ratios of the 2P805 specimens were about 2.7, and the effects of the values of M_{cr}/M (0.7 and 1.0) were not as significant as those observed in small-scale specimens (Li, 2011). The wall strength ratios given in parentheses are about 4.8, and were the results for “HALF” of the 2P805 specimens. The “HALF” results were obtained by subtracting the lateral load–drift angle relationships of 2PFW-T45S from each 2P805 specimen and then adding

that of the previous wooden frame PFW-T45S ($L = 0.91$ m; Li, 2012). From the comparison of the “HALF” results with those of P805-25-350-2-T45S in Figure 6, it can be seen that the envelopes of the lateral load-drift angle relationships are almost the same. However, the test of P805-25-350-2-T45S had to be terminated at about $1/22.5$ rad owing to the significant crack of the sill; hence, the wall strength ratio was lower, i.e., 3.79.

Table 3: Test results

Specimen Name	Q_{wty} (kN)	Q_{wt} (kN)	$P_{1/120}$ (kN)	P_y (kN)	P_u (kN)	D_s	P_{max} (kN)	P_a (kN)	Strength Ratio	$\frac{P_y}{Q_{wty}}$	$\frac{P_u}{Q_{wt}}$	$\frac{P_{max}-P_f}{Q_{wt}}$	Remarks
2PFW-T45S	--	--	2.4	5.5	9.4	0.66	10.5	2.4	0.67	--	--	--	$P_f =$ 10.50 kN (this paper)
2P805-25-350-2-T45S-W	7.9	11.8	9.9	15.4	23.7	0.48	27.7	9.9	2.77 (4.85)	1.95	2.01	1.46	
2P805-25-350-2-T45S-S	7.9	11.8	9.7	15.1	23.6	0.48	27.1	9.7	2.72 (4.80)	1.91	2.00	1.41	
PFW-T45S	--	--	1.5	3.7	6.0	0.65	7.1	1.5	0.84	--	--	--	$P_f = 7.1$ kN (Li, 2012)
P805-25-350-2-T45S	6.8	10.1	7.8	12.4	18.8	0.56	21.1	6.8	3.79	1.82	1.86	1.39	

Notations in Table 3:

Q_{wty} = yield shear force of steel plate with slits

Q_{wt} = ultimate shear strength of steel plate with slits calculated from full plastic moments of flexural columns; $Q_{wt} = 1.5Q_{wty}$

$P_{1/120}$ = force at drift angle of $1/120$ rad

P_y = yield strength of elastic-plastic model based on test results up to $1/15$ rad

P_u = ultimate strength of elastic-plastic model

D_s = structural characteristic factor

P_{max} = maximum force between drift angles of 0 and $1/15$ rad

$P_a = \min\{P_{1/120}, P_y, \frac{2}{3}P_{max}, 0.2P_u / D_s\}$

P_f = maximum force of wooden frame

4. CONCLUSIONS

All three specimens of this study exhibited stability up to a drift angle of $1/15$ rad. The load-carrying capacity and wall strength ratio for M_{cr}/M values of 0.7 and 1.0 were almost the same for all the specimens, and the load-carrying capacity was about 1.4 times the calculated ultimate strength. The wall strength ratio of “HALF” of the 2P805 specimens was 4.8 that was 1.0 greater than that of the previous P805 specimen, even though the envelopes of lateral load-drift angle relationships of the “HALF” of the 2P805 and the P805 specimens are almost the same. Based on the findings of this research, it is clear that the cracking of sills in real wooden constructions can be prevented when steel shear walls with slits are used. This is especially applicable when shear walls of high strength ratio are necessary in design specifications.

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