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Study on half-scale model test for light-frame shear wall

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Abstract A half-scale model of a light-frame shear wall was developed to evaluate the racking performance of a full-scale shear wall (prototype). The effect of nail size on the performance of the shear wall was also investigated using models constructed with three types of nail. Materials for the model were determined through experimental methods, which included nail-head push-through, stud-to-sheathing nail connection, and static bending tests. Materials with which the model was made to be "in similarity" to the prototype were three-layer 4.8-mm plywood, 39.72-mm long nails, and 1 × 2 lumber cut from 2 × 4 studs. In accordance with ASTM E 72 and ASTM E 564, racking resistance tests were conducted on 20 shear walls. The results showed that the maximum load capacities of the prototype walls could be evaluated by the model without significantly different failure modes. Tests on the effect of nail size revealed that increasing the nail head diameter may improve the performance of shear walls.

Key words Half-scale model · Light-frame shear wall · Similarity · Racking resistance

Introduction

For several decades the racking performance of light-frame shear walls against lateral forces have been evaluated by various methods,[1–5] and the accumulated data have been used as the basic criteria in many fields of wooden construction. Most of the data, however, were based on the results of 2.4 × 2.4 m test specimens, illustrated in ASTM E 72.[6] In recent years wooden structures are becoming multistoried and larger in scale by the aid of construction technologies and structural engineered wooden products. Thus, shear walls are becoming larger along with the introduction of openings in various shapes. Therefore, there is an increasing need to investigate the performance of large shear walls.[7–10] The performance of the shear walls longer or higher than 2.4 m have been evaluated by simulation and full-scale testing that requires not only huge test facilities but also much time, manpower, and cost. These tests are not sufficient because of the specimen sizes and the testing facilities.[11] Also, neither analytical nor numerical models can give precise results on the failure loads, load deformation relations, or failure modes. This kind of information can be achieved only by conducting tests on modeled test specimens.

In this study, to obtain the desired results and also to avoid these disadvantages, a half-scale model test was adopted to evaluate the performance of light-frame shear walls. The model walls were developed by means of experimental methods, and the racking resistance tests were performed on the model and the prototype. During the process of determining the most advantageous materials for the model, the effects of nail length, head diameter, and shank diameter on the performance of a shear wall were investigated.

Though small-scale model tests for the light-frame shear wall have been studied previously, similarities between the model and the prototype have not yet been examined. Patton-Mallory et al.[2] evaluated the racking performance of sheathing panels using only small-scale sheathing panels that were scaled down linearly to about one-fourth. No attempt was made to correlate the small-scale model to the full-scale walls. Serrette et al.[12] performed full-scale static racking tests and small-scale lateral shear tests on various sheathings attached to the metal frames. Based on the normalized data from lateral shear connection resistance tests, they proposed that small-scale connection tests be used as a reliable predictor of the behavior of full-scale walls.

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Theoretical background

The small-scale model is a test specimen reduced in size to investigate the full-scale structure. The small-scale model test is defined as experimental analysis of the actual structural system through use of a miniature manufactured so it has similarity (similitude) to the prototype. The term "similarity" accounts for the relation between model and prototype. The similarity can be checked by comparing each value of the variables involved in the dimensionless parameters of the model and the prototype (Eq. 3). Based on the Buckingham pi (π) theorem, the dimensionless parameter is derived from dimensional analysis with the variables related to a behavior of a structure. When the involved model values of variables can equate the model parameter to the prototype parameter, the model is regarded as being in similarity to the prototype.

Because the dimension of the governing equation for a physical phenomenon is identical in model and prototype, physical variables x_i can be expressed by the following equation.

$$F(x_1, x_2, x_3 \ldots x_n) = 0 \tag{1}$$

Applying the Buckingham π theorem, this equation can be rewritten using the dimensionless π parameters as follows.

$$G(\pi_1, \pi_2, \pi_3 \ldots \pi_m) = 0 \tag{2}$$

where π_i is the dimensionless parameter containing n physical variables (x_i); m is $n - r$; and r is the number of fundamental dimensions: for the static condition, force (F) and length (L) are involved; for the dynamic condition, force (F), length (L), and time (T) are involved.

In a small-scale model test for structures, the variables involved in static behaviors of a structure are force (Q), length (L), and modulus of elasticity (E). Using the dimensionless parameter for Q, π_Q can be found with the following equation.

$$\left(\frac{Q}{EL^2}\right)_P = \left(\frac{Q}{EL^2}\right)_m \tag{3}$$

where P is the prototype; and m is the small-scale model.

Therefore, according to the scale ratio, the force involved in the model can be derived from Eqs. (4), (5), and (6).

$$\frac{Q_p}{Q_m} = S_Q \tag{4}$$

where S_Q is the scale ratio for force.

$$\frac{E_p l_p^2}{E_m l_m^2} = S_E S_l^2 \tag{5}$$

where S_E is the scale ratio for the modulus of elasticity; and S_l is the scale ratio for the length.

Assuming that both moduli of elasticity are identical ($S_E = 1$)

$$Q_m = \frac{Q_p}{S_Q} = \frac{Q_p}{S_E S_l^2} \tag{6}$$

It therefore can be concluded that the force of the model is the force of the prototype divided by the square of the linear scale ratio. For example, if the linear scale ratio is 2, as in this study, to compare the model with the prototype directly, the values of the half-scale model test results should be multiplied by 4 for force and 2 for length.

Determination of materials for half-scale model

Scale ratio

Because wood as a structural material has many defects, such as knots, grain, and anisotropic properties, it is difficult to manufacture small-scale materials of wooden structures artificially and retain the required properties. Furthermore, over-downscaling may create many problems, such as amplifying the effect of wood defects, splitting of wood in connections, and deformation of the members caused by drying stress. To minimize these problems, a half-linear downscale ratio was selected for this study.

Materials

Table 1 shows the details for the materials used in the half-scale model and the prototype. In plywood-sheathed shear walls previously studied by other investigators, the failure modes of racking resistance tests were pronounced, manifesting primarily as nail slip, nail-head pull-through, and panel edges breaking off.[1,3,8] On the basis of these results, the experimental methods to determine the small-scale materials were established: the nail-head push-through test[13] and the stud-to-sheathing nail connection test.[14] Commercially available materials were used tentatively for the model because it was impossible to adjust the properties of

Table 1. Materials for the prototype and tentative materials for the half-scale model

Material	Prototype	Half-scale model
Plywood	11.1 mm exterior CSP	3-Layer lauan 7.4 mm 3-Layer lauan 4.8 mm
Nail	8d Common nail 59.6 mm length 6.8 mm head diameter 2.8 mm shank diameter	Type A 39.2 mm length 4.6 mm head diameter 2.2 mm shank diameter Type B 37.9 mm length 3.9 mm head diameter 2.0 mm shank diameter Type C 39.7 mm length 3.1 mm head diameter 1.9 mm shank diameter
Framing	2 × 4 (38 × 89 mm): SPS S-dry nos. 1 and 2	1 × 2 (18.0 × 43.5 mm): SPF S-dry nos. 1 and 2

the solid wood, and in the case of nails the manufacturing cost was too high to make a special order.

Two types of plywood (7.4 and 4.8 mm thick) and three types of nail (Fig. 1) were selected as tentative materials for the model according to their geometric similarity. The combination (or assembly) of nail and plywood in a model showing the most similarity to that of the prototypes was determined as the small-scale materials based on the maximum load capacity resulted from the nail-head push-through test and the stud-to-sheathing nail connection test. Small-scale studs were manufactured from the 1 × 2 lumbers cut from 2 × 4 studs. Then the small-scale studs were checked for their suitability through the static bending test with five replications.[15]

Materials for the model

The results from the above two tests showed that the type C nail and 4.8 mm thick plywood (combination 5-C) were the most appropriate materials for the model (Table 2). The results of the static bending test revealed that there was no significant difference in the modulus of elasticity (MOE) between 2 × 4 studs and 1 × 2 studs (average MOE 112 000 and 108 000 kg/cm^2, respectively). The 16d common nail connecting the plate to the stud was excluded from the model material-determining tests because its contribution to the shear wall capacity is relatively small compared to the other materials. Furthermore, because of the difficulty manufacturing a small-scale model, such as splitting of the plates induced by nail driving, only the small-scale nails used for stud-to-sheathing connections were driven in all connections of model walls. Note that in Table 2 the listed values of the combination of tentative models were four times the measured values.

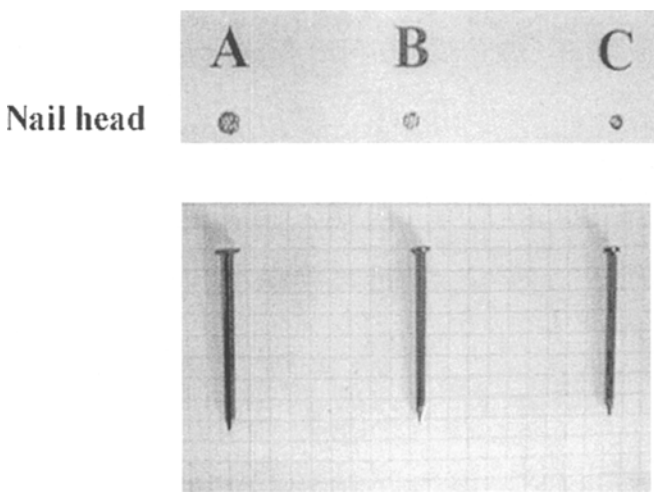


Fig. 1. Three tentatively chosen nails for the model

Shear wall construction

Figure 2 illustrates the four wall configurations (1PLY-F, 2PLY-F, 3PLY-F, 2PLY-O) studied. Based on the geometric similarities the wall sizes, nail spacings, and stud spacings in the models were downscaled by exactly one-half. Two or three test specimens were prepared for each wall configuration; 4.8 mm thick plywood panels and type C nails were used to construct the model. It should be noted that only one type of small-scale nail was used for all connections of the model. All panels used in the prototype were 1.2 × 2.4 m (length × height) and were attached vertically to the frame. All nails, in the model and the prototype, were hand-driven. Table 3 gives the specifications of the wall constructions. Additionally, to investigate the effects of nail sizes, small-scale 2PLY-F walls were constructed using type A, B, and C nails.

Racking resistance test

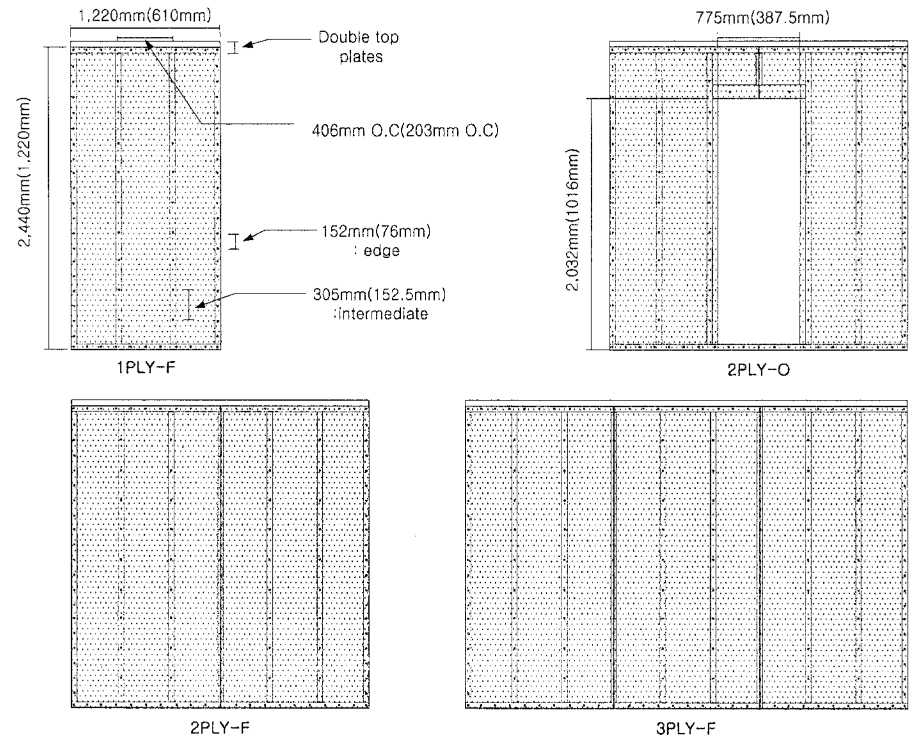
To simplify boundary conditions, test facilities were prepared in accordance with ASTM E 72 (Fig. 3).[6] Using a hydraulic loader, a static monotonic load as described in ASTM E 564[16] was applied to the timber loader, which was bolted on the top plate of the wall. The load rate was

Table 2. Comparison of maximum load capacity from the two tests used to determine materials for the model

Specimen	Repetitions	Maximum load (kN)[a]	
		Nail-head push-through test	Stud-to-sheathing nail connection test
Prototype	**5**	**1.31**	**2.91**
Combination of tentative models[b]			
5-A	5	2.03	5.97
5-B	5	1.72	3.90
5-C	**5**	**1.50**	**2.71**
7-A	5	3.46	6.82
7-B	5	2.53	5.37
7-C	5	1.69	4.27

[a] Maximum load values of models are listed as four times the measured value
[b] Numbers 5 and 7 in combinations refers to 4.8 and 7.4 mm thick plywood, respectively

Fig. 2. Light-frame shear wall configurations



* The values in blanks are sizes of 1/2 small-scale model.
* Note that two nails are driven in each connection of stud-to-bottom plate, and four nails consisting of 2 layers, in each connection of stud-to-double top plates.

Table 3. Framing, sheathing, and nails for shear walls

Materials Prototype	Half-scale model
Framing	
Stud, plate 2 × 4 SPF S-dry nos. 1 and 2	1 × 2 Cut from prototype stud
Double top plate/single bottom plate	Double top plate/single bottom plate
Stud at 406 mm O.C	Stud at 203 mm O.C
Sheathings	
11.1 mm Exterior CSP (1.2 m × 2.4 m)	4.8 mm plywood (0.6 × 1.2 m)
Nail	
8 d common nail (stud-to-sheathing)	All half-scale nails (stud-to-sheathing, plate)
16 d common nail (stud-to-plate)	
Nail schedule: 152/305 mm (edge/field)	Nail schedule: 76.0/152.5 mm (edge/field)

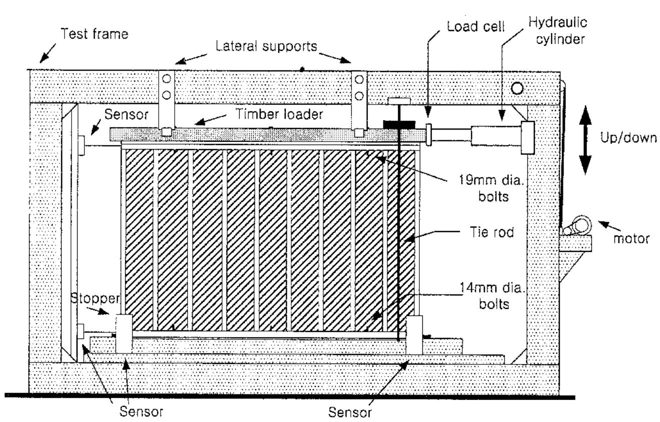


Fig. 3. Racking resistance test setup

0.2 mm/s. Four strain gauges based on transducers were positioned to monitor the horizontal displacement, bottom slip, uplift, and vertical displacement automatically at 0.5-s intervals.

Results and discussion

Similarity error of materials

Similarity error was calculated with the following equation.

$$\text{Similarity error} = \frac{(\text{value of model} \times \text{corresponding scale ratio}) - (\text{value of prototype})}{\text{value of prototype}} \times 100(\%) \quad (7)$$

Table 4. Similarity errors in part sizes of three nail types and maximum load capacity from two material-determining tests

Nail type	Length	Head diameter	Shank diameter	Nail-head push-through test		Stud-to-sheathing connection test	
				With 4.8 mm ply.	With 7.4 mm ply.	With 4.8 mm ply.	With 7.4 mm ply.
A	+32%	+35%	+57%	+55%	+164%	+105%	+134%
B	+27%	+15%	+43%	+31%	+93%	+34%	+85%
C	**+33%**	**−9%**	**+36%**	**+15%**	+29%	**−7%**	+47%

ply., plywood

Table 5. Results of racking resistance tests for models constructed with type A, B, and C nails

Wall type	Repetition	Maximum load (kN)	Primal failure mode
2PLY-F-A	1	13.21	Panel breaking off, nail pull-out
2PLY-F-B	1	10.04	Panel breaking off, nail pull-out, two nail-head pull-through
2PLY-F-C	1	4.78	Nail-head pull-through, panel breaking off, nail pull-out

Table 4 shows the geometric similarity errors in part sizes of the three nail types and similarity errors of maximum load capacities resulting from the nail-head push-through test and stud-to-sheathing nail connection test. Nail type C showed the least geometric similarity errors: −9% in head diameter and +36% in shank diameter, but +33% in length. The combination of nail type C and 4.8 mm thick plywood also gave the least similarity error in the performance of the nail. The major difference between the three nail types lies in the nail-head diameter. It revealed that nail-head size might exert the greatest effect on nail performance for all parts of a nail, though the effects of the other parts of a nail were not negligible. This fact suggests that increasing the nail-head diameter may improve performance of a panel-frame assembly subject to failure of nail-head pull-through, such as a light-frame shear wall assembled with nails.

Effect of nail-head size on racking resistance of the shear wall in the model

Maximum load capacities and failure modes of the three model walls (2PLY-F-A, 2PLY-F-B, 2PLY-F-C) constructed with nail types A, B, and C, respectively, are summarized in Table 5. The maximum load capacities of 2PLY-F-A wall (13.21 kN) and 2PLY-F-B wall (10.04 kN) were 176% and 110% greater than that of 2PLY-F-C (4.78 kN), respectively. In the primal failure type, 2PLY-F-A failed by panel tearing and nail pull-out from the stud. However, nail-head pull-through did not occur in the wall. The reason for failure of 2PLY-F-B was similar to that of 2PLY-F-A except for two nail-head pull-throughs in the right upper corner of the left panel. The failure mode of 2PLY-F-C was a combination of panel tearing, nail pull-out, and nail pull-through, as reported previously. It shows that the wall constructed with 4.8 mm thick plywood and the type C nail is a good model for the prototype. Furthermore, these model tests indicate that the nail-head diameter has a considerable effect on the performance of a shear wall. When the racking load was applied, nail-head bearing on the panel commenced; then the nail head dug inside the panel, gradually crushing the panel. Finally, nail-head pull-through occurred. Therefore, it is thought that increasing the nail head diameter may improve the performance of a shear wall. However, further studies on the contribution of nail head size on the performance of a prototype shear wall are needed owing to the size effect and the relation between the applied load and the nail connection capacity in the prototype.

Checking similarity between shear walls

The results of the racking resistance tests for small-scale models and prototypes are presented in Table 6 and Figs. 4, 5, 6, and 7. To compare the small-scale model with the prototype directly, the values from the half-scale model tests were multiplied by 4. Similarity errors of the maximum load capacities were −3.6%, +6.5%, −4.2%, and −12.8% for 1PLY-F, 2PLY-O, 2PLY-F, and 3PLY-F, respectively. All values were within the 15% limitation set by ASTM E 564 for the condition of the additional test. Failure modes were nail pull-through followed by nail slip, nail pull-out, and panel edges tearing, as expected. No significantly different failure mode was observed between them. However, the full load-deformation curves did not match those of the prototype satisfactorily except for the initial region (or the initial stiffness). It was also observed that the models failed more abruptly than the prototypes. Thus the deformations at maximum loads were smaller in the model than in the prototype. This means that the models have a lower capacity for energy absorption than the prototypes. The reason for this result may be that when determining the materials of the model the main criteria focused on maximum load capacity, and the stiffness and energy ab-

Table 6. Test results of prototypes and half-scale models[a]

Type of shear walls	No. of specimens	Average maximum load (kN)	Load capacity at each deformation (radian)				
			1/500	1/250	1/125	1/60	1/30
1PLY-F (model/prototype)	3/2	11.87/12.31	2.19/1.49	3.30/2.79	5.45/5.13	10.39/8.12	11.89/11.89
2PLY-O (model/prototype)	2/2	16.38/15.38	2.97/2.83	4.81/4.44	8.53/7.06	14.52/10.94	Failure/14.72
2PLY-F (model/prototype)	3/2	20.62/21.53	6.44/6.64	9.58/8.83	14.68/12.50	20.21/17.21	Failure/21.34
3PLY-F (model/prototype)	2/2	29.62/33.98	9.36/9.73	14.59/13.90	23.02/19.74	28.95/26.54	Failure/33.96

[a]The listed values for the half-scale model are four times the measured values

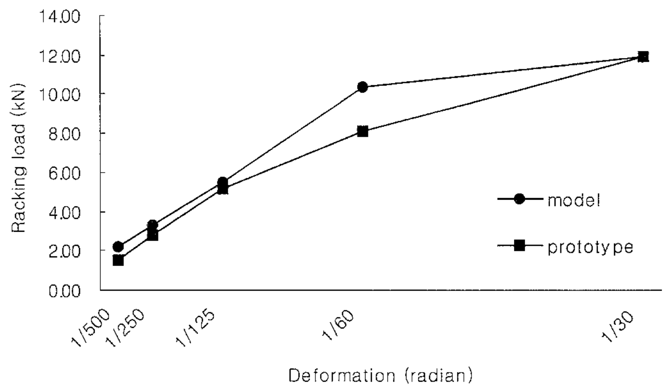


Fig. 4. Load-deformation relations of the model and prototype for 1PLY-F

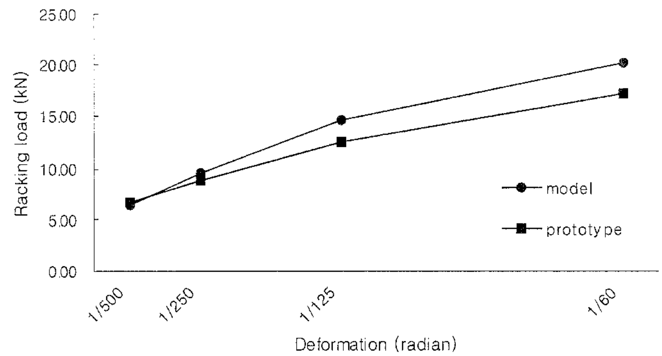


Fig. 6. Load-deformation relations of model and prototype for 2PLY-F

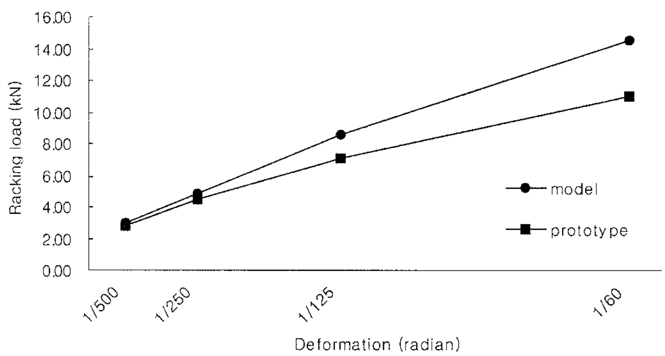


Fig. 5. Load-deformation relations of the model and prototype for 2PLY-O

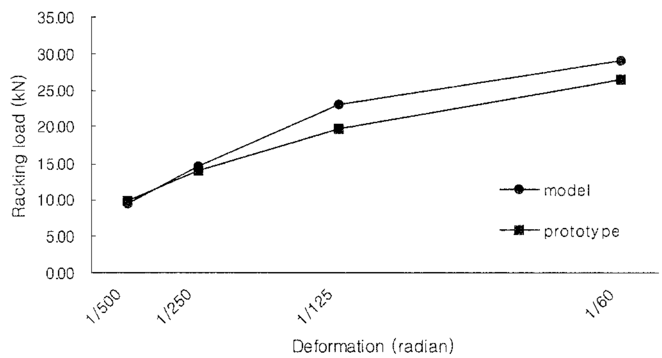


Fig. 7. Load-deformation relations of model and prototype for 3PLY-F

sorption of the nail connection was not considered. If materials with properties identical to those of the prototype were obtained for the model, a whole load-deformation curve of the prototype wall might be predicted through the model. Therefore, more studies on the methodology for obtaining small-scale materials are needed for wooden structures.

Conclusions

The racking performance of light-frame shear walls was evaluated using half-scale models. The effect of nail size on the performance of shear walls was also investigated. Results of this study indicate that the models may be used to predict the maximum load, initial shear stiffness, and failure mode of the prototype wall. However, the entire load-deformation curves derived from racking resistance tests of the model and prototype did not match satisfactorily. Tests on the effect of nail size revealed that using nails with a large head diameter to connect the sheathing panels to the framing members may be a good method for improving the performance of full-scale shear walls.

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