J Wood Sci (2006) 52:63–68
DOI 10.1007/s10086-005-0728-5

ORIGINAL ARTICLE

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Pseudodynamic tests and earthquake response analysis of timber structures I: plywood-sheathed conventional wooden walls with opening

Received: April 19, 2004 / Accepted: March 22, 2005 /

Abstract Pseudodynamic (PSD) lateral loading tests were conducted on conventional post and beam timber frames with plywood-sheathed shear walls to validate the dynamic model of wall panels, each with an opening of a different configuration. The lateral forces were applied step by step at the top of the wooden frames by the computer-controlled actuator, and the displacement response for the next step was computed on the basis of the input accelerogram of the 1940 El Centro earthquake scaled up to $0.4g$. The test results were compared with those of the lumped mass time–history earthquake response analysis using the hysteresis model with pinching. The results of the dynamic analysis with this global model consisting of the envelope curves, unloading and reloading with pinching agreed well with the experimental results of the PSD tests of this type of earthquake record. Some parametric studies may be necessary, however, to validate the model with different earthquake records. The hysteretical parameters obtained in this study showed similar values for each of the wall panels with different opening configurations. This makes it possible to use the model and parameters for the plywood-sheathed shear walls to estimate the dynamic behavior of entire structures without conducting expensive PSD tests or shaking table tests.

Key words Computer on-line control · Lumped mass model · Dynamic analysis · Hysteresis model · Opening walls

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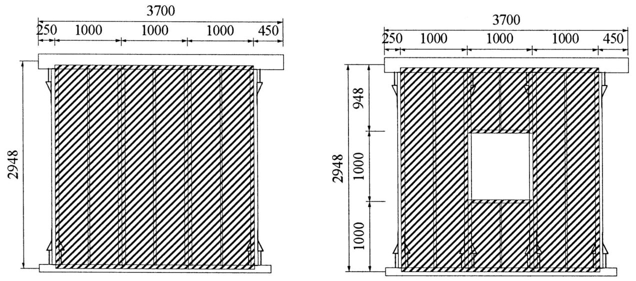
Part of this article was presented at the 53rd Annual Meeting of the Japan Wood Research Society, Fukuoka, March 2003, the 2003 Annual Meeting of the Architectural Institute of Japan, Nagoya, September 2003, and meeting thirty-six of CIB-W18, Colorado, August 2003

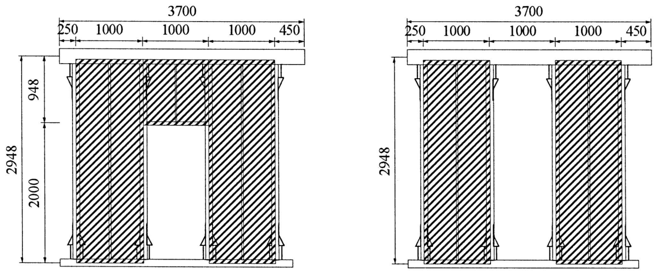
Introduction

Recently shear walls sheathed with panel products such as plywood and oriented strand board (OSB), have been used more frequently in conventional post and beam timber construction. Because the seismic performance of timber structures composed of shear walls is mainly governed by the mechanical properties of shear walls,[1] the evaluation of seismic performance of shear walls is essential for the seismic design of timber structures. The lateral resistance of shear walls is generally determined by four criteria based on the reversed cyclic lateral loading test,[2] i.e., initial stiffness, yield strength, ultimate strength, and ductility.[3] Although these criteria are indispensable for the evaluation of shear walls, they do not predict the actual behavior of structures during earthquakes. The shaking table test may be a useful test method to evaluate the dynamic performance of timber structures;[4–6] however, it is also an expensive test method.

Dynamic properties of shear walls can be easily estimated by the time–history earthquake response analysis if an appropriate model for the hysteretic behavior of shear walls is determined. In this study, the hysteresis model with pinching[7] was applied to conventional timber structures with plywood-sheathed shear walls and the parameters for the hysteresis model were determined from the reversed cyclic lateral loading tests of the wall system. The earthquake response of shear walls calculated by using this model and parameters were compared with the pseudodynamic (PSD) test results to validate the model. The PSD test is a step-by-step quasi-static test that simulates the dynamic response of structures caused by seismic action.[8,9] It is a useful test method to estimate the seismic response of timber structures caused by either actual or virtual ground motions and to validate the hysteresis model for seismic resisting elements. Therefore, the PSD tests were conducted on conventional post and beam timber frames with plywood-sheathed shear walls with various opening configurations.[10] The simulation with the proposed hysteresis model predicted comparatively well the earth-



Specimen B **Specimen W**



Specimen D **Specimen S**

Fig. 1. Schematic representation of specimens

quake response of wall systems that were subjected to the PSD tests, and it was shown that the hysteresis model is useful for the time–history earthquake response analysis of conventional post and beam timber frames with plywood-sheathed shear walls. By using this model and parameters obtained from the reversed cyclic tests of shear walls, it will be possible to predict the dynamic behavior of plywood-sheathed shear walls without conducting either shaking table tests or PSD tests that are expensive to carry out.

Materials and methods

Specimens

The specimens consisted of plywood-sheathed shear walls with conventional post and beam frames of 3000 mm width on center and 2948 mm height as shown in Fig. 1. The specimens consisted of 105 × 105 mm posts and a sill and a 105 × 210 mm beam of spruce (*Picea* spp.) glued laminated timber of which the modulus of elasticity (MOE) and density were 14200 N/mm^2 and 500 kg/m^3, respectively. Posts placed at every 1000 mm were connected to the sill and the beam with a steel pipe of 26.5 mm diameter and hold-down connections (HD-B15).[11] Two hold-down connections were attached to the foot of the posts with three bolts of 12 mm diameter and connected to the steel base frame with a 16-mm-diameter bolt. A single hold-down connection (HD-B15) was attached to the top of the posts and the beam, and they were connected to each other with a 16-mm-diameter bolt. Five-ply lauan plywood (JAS Grade I), 7.5 mm thick, was nailed on one side of the wooden frame with N50 common nails with diameters of 2.75 mm. The spacing of fasteners was 150 mm on both the perimeter and intermediate locations of the sheathings. The specimens had an opening of three different configurations at the center of the wall panel except for specimen B. Specimen W had an opening of 1000 mm width and 1000 mm height, specimen D had an opening that was 1000 mm wide and 2000 mm high, and specimen S had an opening that was 1000 mm wide and continued from the sill to the top beam. Specimen B had no opening. Twelve specimens were prepared for three types of loading, i.e., monotonic, reversed cyclic, and PSD loading and four types of walls.

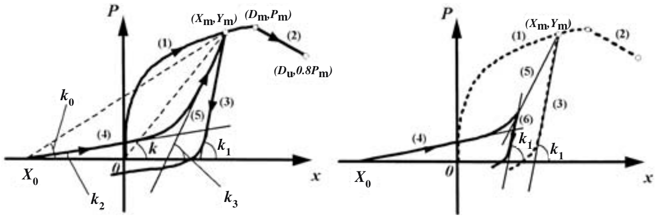


Fig. 2. Hysteresis model of wall system

Test methods

Monotonic and reversed cyclic loading tests were conducted on each wall system to determine the parameters to model the load–displacement relationships. The loading protocol used for the reversed cyclic loading was based on ISO 16670.[12] The lateral loads were measured by a load cell (capacity of ±50 kN, Tokyo Sokki Kenkyujo, Tokyo) and the horizontal displacement at the top of the wall and the vertical displacements of each post were measured by electronic transducers. Pseudodynamic tests were then conducted on each specimen with a computer on-line system (Shimadzu 48000). The accelerogram used for the PSD tests were based on the North-South (NS) components of the 1940 El Centro earthquake linearly scaled to have a maximum ground acceleration of 0.4*g*. The mass of 2.5 t per meter of shear wall length was assumed from the lateral resistance of 4.9 kN/m for the plywood-sheathed shear walls with the wall coefficient of 2.5.[13] Thus, the mass taken for the PSD tests were 5 t for specimens W, D, and S, and 7.5 t for specimen B. A damping factor of 2% was assumed for all the specimens.

Dynamic analysis

Time–history earthquake response analysis with a single degree of freedom (SDOF) lumped mass model was conducted on each type of wall panel. Among the hysteresis models already known,[14] the hysteresis model as shown in Fig. 2[7] was used for the analysis. This model has a feature that the hysteretical parameters are easily determined from the reversed cyclic tests of the element as shown in this study, and it follows the force–displacement relationships precisely. It includes:

1. Loading on the primary curves up to the maximum load
2. Loading on the primary curves over the maximum load
3. Unloading from the peak on the primary curve
4. Reloading with soft spring
5. Reloading toward the previous peak with hard spring
6. Unloading from the inner peak

The primary curves up to the maximum load (1) and those over the maximum load (2), are expressed as follows:

$$P = \left(P_0 + C_2 x\right)\left(1 - e^{-\frac{C_1 x}{P_0}}\right) \tag{1}$$

$$P = P_\mathrm{m} - C_3\left|x - D_\mathrm{m}\right| \tag{2}$$

where, P_m and D_m are the maximum load and displacement, and P_0, C_1, and C_2 are the constants obtained from the enveloped curves of the load–displacement relationships in the reversed cyclic loading tests of wall panel. The primary curves over the maximum load were obtained as the straight line drawn through the points corresponding to the maximum load and the 80% of the maximum load.

Unloading stiffness (3) and the reloading stiffness toward the previous peak (5) were based on the inclination of the straight line obtained by drawing through the origin and the peak on the primary curve (k). Reloading stiffness with soft spring (4) was based on the inclination of the straight line drawn through the peak on the primary curve and the crossing point of the X-axis (k_0).

$$k_1/k = C_4 X_\mathrm{m}^{C_5} + 1 \tag{3}$$

$$k_2/k_0 = 1 - C_6\left|X_\mathrm{m} - X_0\right|^{C_7} \tag{4}$$

$$k_3/k = C_8 X_\mathrm{m}^{C_9} + 1 \tag{5}$$

The parameters C_4, C_5, C_8, and C_9 are determined by approximating the relationships between k_1/k or k_3/k and the peak displacements of each cycle in the reversed cyclic tests (in the case of C_6 and C_7, the relationships between k_2/k_0 and $X_\mathrm{m} - X_0$). Unloading stiffness from the inner peak (6) is assumed to be the same as that of the previous unloading stiffness.

Results and discussion

Parameters

Hysteresis parameters of each wall system were determined from the load–displacement relationships in reversed cyclic loading tests as shown in Fig. 3. Figure 4 shows the approximation of the envelope curves (a), the unloading stiffness (b), reloading stiffness with soft spring (c), and hard spring (d) of each specimen. They show that the fitted envelope curves by Eq. 1 and 2 approximate well the experimental results. The values of k_1/k and k_3/k increased almost linearly from 1 to values between 4 and 6 and from 1 to values between 2.5 and 3, respectively, as the horizontal displacement increased to 100 mm, and those of k_2/k_0 decreased from 1 to between 0.3 and 0.4 as the horizontal displacement ($X_\mathrm{m} - X_0$) increased to 160 mm. The parameters obtained from the reversed cyclic tests for all the specimens are shown in Table 1. The parameters C_4 to C_9 show close values for specimens W, D, and S regardless of the

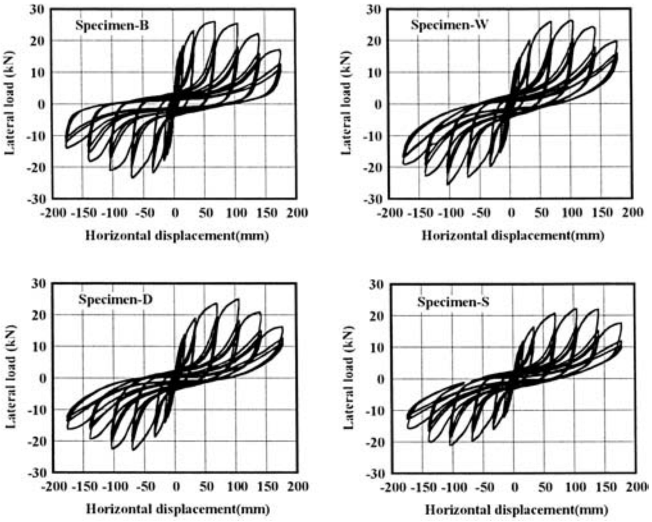


Fig. 3. Load–displacement relationships in reversed cyclic loading tests

Table 1. Hysteresis parameters of wall systems

	Specimen			
Parameter	B	W	D	S
P_0 (N)	16700	17500	17300	16100
C_1 (N/mm)	3470	1810	1660	1360
C_2 (N/mm)	158.5	99.2	74.6	47.4
C_3 (N/mm)	72.5	76.5	96.1	49.0
C_4	0.177	0.204	0.253	0.206
C_5	0.716	0.633	0.536	0.628
C_6	0.109	0.117	0.136	0.116
C_7	0.349	0.325	0.302	0.319
C_8	0.0175	0.0133	0.0148	0.0092
C_9	0.978	1.00	0.980	1.12
D_m (mm)	65	100	100	100

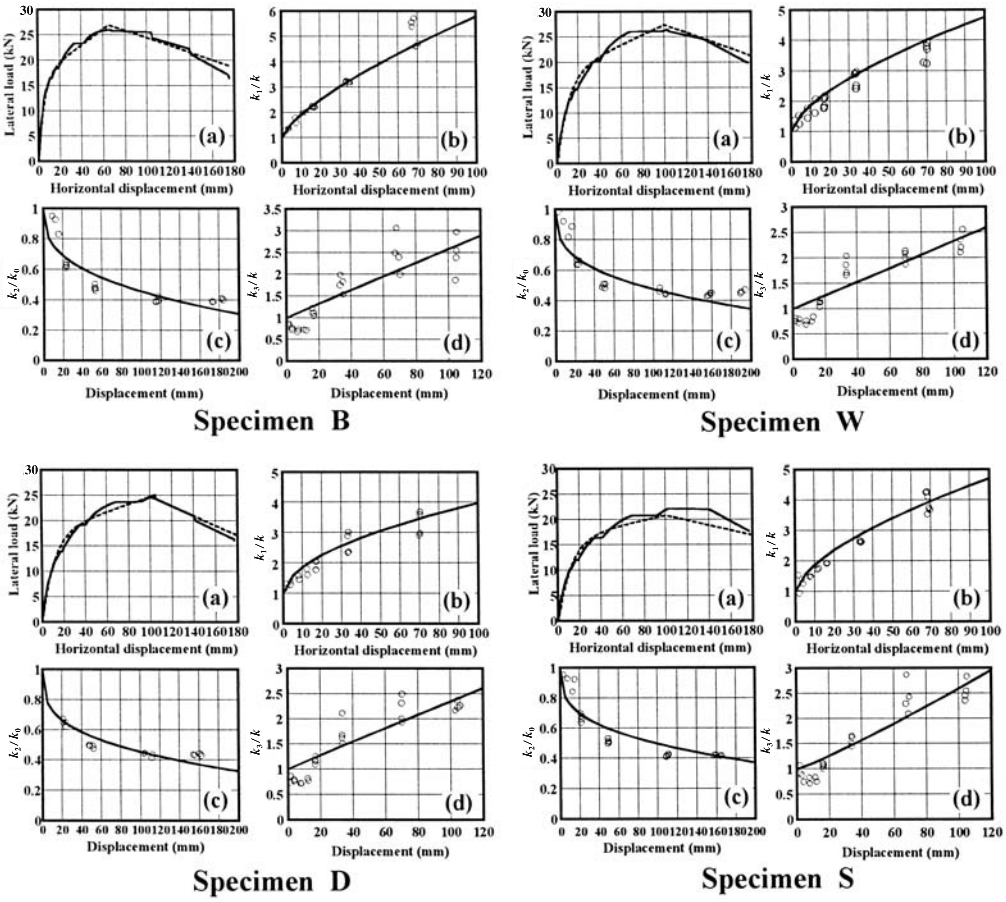


Fig. 4. Determination of the hysteresis parameters from the experimental results. *Plots a*, approximation of the envelope curves by Eqs. 1 and 2; *solid lines*, experimental results; *broken lines*, approximation. *Plots b*, unloading stiffness ratio by Eq. 3. *Plots c*, reloading stiffness ratio with soft spring by Eq. 4. *Plots d*, reloading stiffness ratio with hard spring by Eq. 5. *Circles*, experimental results; *solid lines*, approximation

configuration of the openings and characterize the load–displacement relationships of the conventional post and beam frames with plywood-sheathed shear walls with openings. The parameters of specimen B are, however, slightly different from those with openings.

Comparison of simulation and experimental results

Figures 5 and 6 show the comparison between the simulated time–history displacement response at the top of the wall obtained from the SDOF model time–history analysis and the experimental results obtained from the PSD tests, and that between the simulated lateral force–displacement relationships and the experimental results, respectively. They show that the simulated displacement responses slightly underestimated the response of specimen B and tended to overestimate that of specimen W. These conflicts came probably from the variation of the specimens as only one specimen was tested for each type of wall. The simulation agreed quite well with the experimental results for specimens D and S. As a whole it seems that the simulation follows the response of the PSD tests quite closely. Table 2 shows the comparison of the simulated maximum displacement responses with experimental results. The parenthetic value under each response in the table is the time in seconds when the maximum or peak displacement response occurred. In specimens B and W, the maximum displacement responses of the simulation occurred at times different from that of the PSD tests. Therefore, the simulated peak displacement responses at the same peak where the maximum displacement responses occurred in the PSD tests are also shown in Table 2. In specimens D and S, the simulated

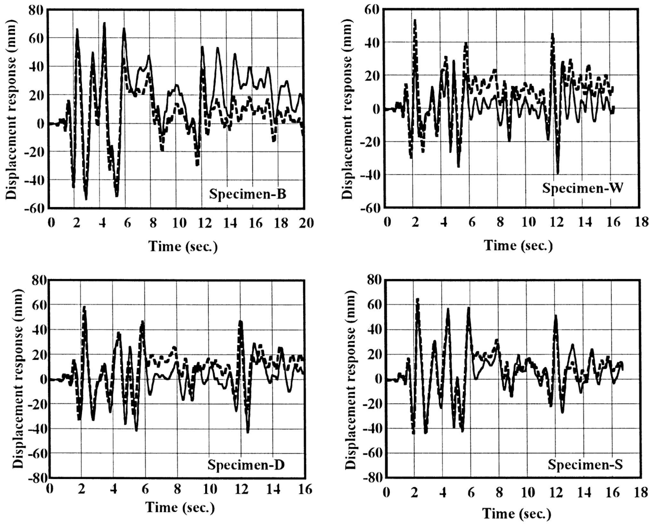


Fig. 5. Comparison of the simulated time–history displacement responses with the experimental results. *Solid lines*, experimental results; *broken lines*, simulation

Table 2. Comparison of the simulated maximum and peak displacement responses with experimental results

Specimen	Experimental	Simulation			
	Maximum displacement (mm)	Peak displacement (mm)[a]	Ratio[b]	Maximum displacement (mm)	Ratio[b]
B	70.62 (4.44)	57.92 (4.40)	1.22	59.79 (2.28)	1.18
W	–39.09 (12.26)	–28.77 (12.32)	1.36	53.17 (2.22)	0.74
D	52.09 (2.28)	58.04 (2.22)	0.90	58.04 (2.22)	0.90
S	60.01 (2.26)	64.72 (2.26)	0.93	64.72 (2.26)	0.93

Values shown in parentheses are the time occurrences of the maximum or peak displacements (units: s)

[a] Simulated peak displacement responses are those that occurred in the same peak when the maximum displacement response occurred

[b] Ratio of experimental maximum displacement to simulated displacement

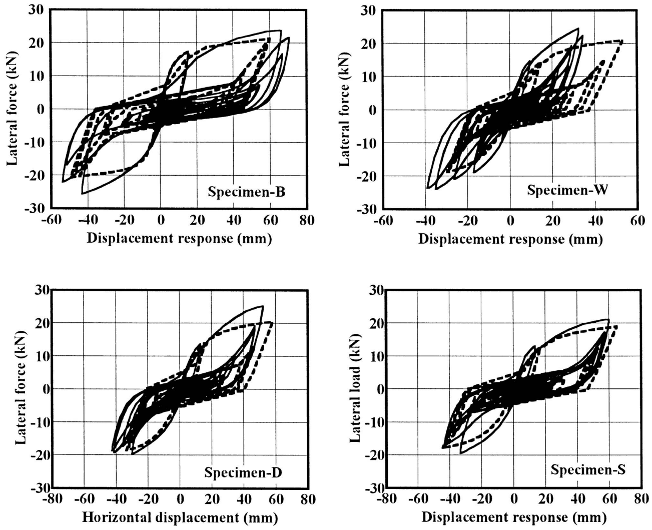


Fig. 6. Comparison of the simulated force–displacement relationships with the experimental results. *Solid lines*, experimental results; *broken lines*, simulation

maximum displacement responses occurred at almost the same time as the PSD tests and the errors between the simulation and the experiments were within 10%. In specimen W the maximum displacement response occurred at 2.22s in the simulation, while it occurred at 12.26s in the experiment. This difference caused a 26% error in the maximum displacement response and a 36% error at the peak of 12s.

It seems difficult to conclude that error came from the variation of the specimens in PSD tests. Further consideration may be necessary on the accuracy of the PSD tests and simulation.

Conclusions

SDOF lumped mass time–history earthquake response analysis by using the global hysteresis model agreed comparatively well with the experimental results of the PSD tests of this type of earthquake record. Because only one type of accelerogram was used for the PSD tests, some parametric studies may be necessary to validate the model with different earthquake records. In addition, the shear walls tested in this study were limited to those with typical opening configurations. However, it is noted that the hysteretical parameters obtained in this study showed similar values among the wall systems with different opening configurations. This shows the possibility of using this model and parameters for plywood-sheathed shear walls to estimate the dynamic behavior of entire structures if the envelope curves of each wall system that make up the structure can be estimated. In this study, the SDOF lumped mass model was used for the analysis. The model is simple and predicts well the earthquake response of the shear walls. However, more sophisticated finite element models[15,16] should be used to predict the stress and deformation of each structural element during the earthquake, because the lumped mass model predicts only the global responses.

Acknowledgments This research was supported by Grants-in-Aid for Scientific Research "Category C" of Monbu Kagakusho and Japan Society for the Promotion of Science.

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