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EFFECT OF SMALL DEFORMATION DUE TO MODERATE EARTHQUAKES ON THE SHEAR PERFORMANCE OF SHEAR RESISTING WALL

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ABSTRACT: In order to confirm how cyclic deformation due to moderate earthquakes during the use period of a wooden house affects the shear resisting wall, in-plane shear experiments with cyclic deformation on the walls using plywood and gypsum board were conducted. As a result, it was found that the maximum load and the yield load are not significantly affected even if the wall received repeatedly small deformation. The load reduction due to repeated deformation of gypsum board wall was larger than plywood wall. Additionally, the stiffness of repeated specimens was reduced accordingly. The calculated load reduction trend of sheathed walls subjected to repeated small deformations from the experimental results of nailed joints was found to be generally expressible. It was found that the response deformation of wooden houses during the major earthquake may increase as the stiffness of shear resisting walls decreases.

KEYWORDS: Cyclic deformation, Plywood wall, Gypsum board wall, Moderate earthquake, Shear performance

1 INTRODUCTION

Increasing the continuous use of wooden houses after the major earthquake is important not only for maintaining the assets, but also for early city reconstruction. For the purpose, it is necessary to build high seismic performance house and/or to appropriately evaluate the residual seismic performance at the time of seismic diagnosis after moderate earthquakes.

Cyclic deformations due to small and medium-class earthquakes may reduce seismic performance in existing houses. Especially in large deformations, it is known that the deterioration of shear performance due to multiple cyclic deformations. It has been reported that when the amount of repeated deformation is large, such as during a large earthquake, the deterioration of the shear performance is large [1]. In addition, some examples have shown the effect of cyclic loading on the structural performance of shear resisting walls [2].

However, these existing reports are mainly aimed at improving the accuracy of response prediction during large earthquakes and the prediction of seismic behaviour of wooden houses. They are targeted at large deformation for large earthquakes. Therefore, there are very few examples of studies of large numbers of small deformation repetitions, and the effects of such repetitions have not been clarified. In Japan, small and medium earthquakes often occur. For example, in Ibaraki Prefecture, for the past 30 years, there have been about 300 earthquakes of intensity 3 [3]. It is important to understand to what extent the accumulation of small deformation caused by such earthquakes affects the seismic performance of wooden houses and their response deformation during large earthquakes.

Therefore, in the previous report [4], single shear tests in which nailed joints using plywood, OSB, MDF, and gypsum board were repeatedly displaced many times assuming small and medium earthquakes were conducted. As a result, it was clarified that plywood, OSB, and MDF showed almost the same load reduction tendency. And gypsum board had a particularly large load reduction compared to other boards.

In this report, in-plane shear experiments on the walls were conducted to confirm the effect of repeated small deformation on the shear performance of plywood walls and gypsum board walls.

Table 1: *List of specimens*

	SC	NC
Frame only	-	1
Plywood wall	1	2
Gypsum board wall	1	3

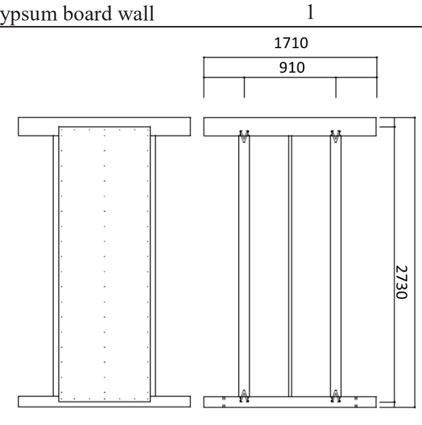

Figure 1: *Configurations of specimens (Unit: mm)*

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2 OUTLINE OF EXPERIMENT

Table 1 shows a list of specimens, and Figure 1 shows the configurations of specimens. The specimen was 1P (b=910, h=2730 mm) wall. Two kinds of panels, plywood (t=9mm) and gypsum board (t=12.5mm) were used. A 105 x 180 mm hybrid beam (E105-F300, Japan Agricultural Standards) was used for the beam. A 105 x 105 mm Sugi glulam lumber (E65-F225, JAS) was used for the columns and base. The base-column and base-beam were joined by two N90 nails and VP plate with a short tenon. Plywood and gypsum board were fastened with N50 nails @ 150mm. There are two types of loading schedules; SC (Standard cyclic schedule) and NC (Numerous cyclic schedule). The SC was set to pull up to 1/15 rad after repeatedly deforming of ± 1/450, ± 1/300, ± 1/200, ± 1/150, ± 1/100, ± 1/75, ± 1/50 and 1/30 rad. For NC specimens, after the loading schedule shown in Table 2, additional loading was performed according to the same schedule as the SC specimen. The target deformation of multiple repetition was set assuming the maximum inter-story deformation of a wooden house during an earthquake with a seismic intensity of 3 to lower 5. The number of repetitions in each step was set by examining the number of observations at each prefectural office location for each seismic intensity from the Seismic Intensity Database [3] and using the maximum number. The loading was performed by displacement control, and the load was applied using a 300 kN jack. Figure 2 shows the test set up and transducer position. Experiments were conducted using a tie-rod system that restrained the column legs from lifting. Loading was displacement-controlled using the true deformation angle (Equation 1). It is obtained by subtracting the slip of the base and vertical displacement of the columns from the top deformation of wall. In equation 1, 2730 mm is the specimen height and 910 mm is the specimen width.

$$\gamma_0 = (\delta_1 - \delta_2)/2730 - (\delta_3 - \delta_4)/910 \qquad (1)$$

γ_0: True deformation angle (rad)
δ_1: Top deformation of wall (mm)
δ_2: Slip of the base (mm)
δ_3, δ_4: Vertical displacement of the columns (mm)

Table 2: *Loading schedule of multiple repetitions*

Seismic intensity	Story deformation (rad)	Target deformation (mm)	Number of repetitions
3	1/2000	±1.4	200
	1/1000	±2.7	200
4	1/450	±6.1	50
	1/300	±9.1	50
4~lower 5	1/200	±13.7	10

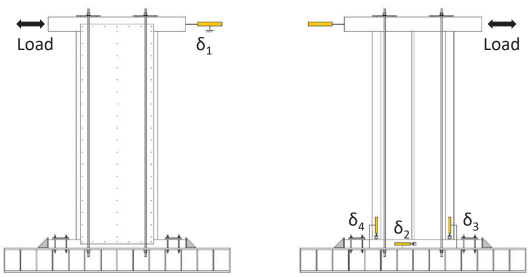

Figure 2: *Test setup and transducer position*

Table 3: *Strength characteristic values*

Plywood	P_{max} (kN)	K (kN/mm)	P_u (kN)	P_y (kN)	$0.2P_u\sqrt{2\mu-1}$ (kN)	$2/3P_{max}$ (kN)	P_{150} (kN)	P_a (kN)	Wall multiplier
SC	7.35	0.92	6.61	4.16	5.34	4.90	5.61	4.16	2.3
NC-1	7.07	1.07	6.42	4.32	4.92	4.71	5.39	4.32	2.4
NC-2	6.42	0.54	5.61	3.91	4.99	4.28	4.61	3.91	2.1
NC-3	7.00	0.66	5.99	3.97	5.42	4.67	4.68	3.97	2.2
NC Mean (CV)	6.83 (0.29)	0.76 (0.22)	6.01 (0.33)	4.06 (0.18)	5.11 (0.22)	4.55 (0.19)	4.89 (0.35)	4.06 (0.18)	2.2 (0.10)
TL	5.91	0.65	4.95	3.49	4.41	3.94	3.78	3.49	1.96
NC / SC	0.93	0.82	0.91	0.98	0.96	0.93	0.87	0.98	0.98

Gypsum board	P_{max} (kN)	K (kN/mm)	P_u (kN)	P_y (kN)	$0.2P_u\sqrt{2\mu-1}$ (kN)	$2/3P_{max}$ (kN)	P_{150} (kN)	P_a (kN)	Wall multiplier
SC	3.93	0.49	3.60	2.55	3.49	2.65	2.82	2.55	1.4
NC-1	4.01	0.91	3.64	2.50	4.62	2.97	3.19	2.50	1.4
NC-2	3.61	0.43	3.13	1.90	3.25	2.41	2.44	1.90	1.0
NC-3	4.59	0.30	4.06	2.91	3.10	3.06	3.29	2.91	1.6
NC Mean (CV)	4.07 (0.40)	0.55 (0.26)	3.61 (0.38)	2.44 (0.41)	3.66 (0.68)	2.71 (0.27)	2.97 (0.38)	2.44 (0.41)	1.3 (0.23)
TL	2.80	0.43	2.41	1.13	1.51	1.87	1.77	1.13	0.63
NC / SC	1.02	1.13	1.00	0.96	1.05	1.02	1.05	0.96	0.96

*Lower tolerance limit value (TL).
P_{max}, P_y, P_u: 95% lower tolerance limit at 75% confidence level.
K: 50% lower tolerance limit at 75% confidence level.

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3 RESULT OF EXPERIMENT

Figure 3 shows the load-displacement envelope as the mean of each specimen group. Table 3 shows the strength characteristic values calculated by the perfect elasto-plasticity model [5]. The stiffness calculated using the slope between 0.1 P_{max} and 0.4P_{max}. The ductility factor μ is the ratio of δ_u to δ_y. The short-term allowable shear capacity P_a is the minimum value among P_y, 2/3P_{max}, $0.2P_u\sqrt{(2\mu-1)}$, and P_{150} (load at 1/150 rad). The wall multiplier is the short-term allowable shear capacity divided by 1.96 kN and the width of the wall (0.91 m in this case), and is an index used in wall amount calculations (a common design method for wooden houses in Japan).

In both cases of plywood and gypsum board, repeated small deformations had no clear effect on the envelope curve of load-deformation relationships and ductility. In addition, comparing the mean values, it was found that there was no significant difference in maximum, yield and ultimate load between the SC and NC specimens regardless of whether the panel was plywood or gypsum board. There was also no difference in wall multiplier, indicating that even when subjected to repeated small deformations, the design performance can be expected to be similar to the shear performance of the sound condition. Furthermore, there was no difference in failure properties (Photo 1) between SC and NC specimen.

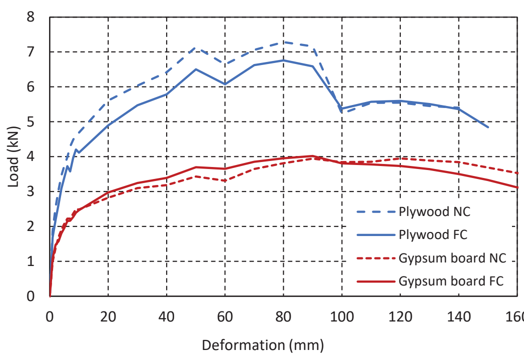

Figure 3: *Load-displacement envelope curve*

Photo 1: *Failure of specimen*
(Right: Gypsum board wall, Left: Plywood wall)

Figure 4 shows the transition of the load residual rate at the target displacement of 1/2000, 1/1000, 1/450, 1/300 and 1/200 rad. Here, the first load for each step is shown as 100%. Similar to the experiment of nailed joint [4], it

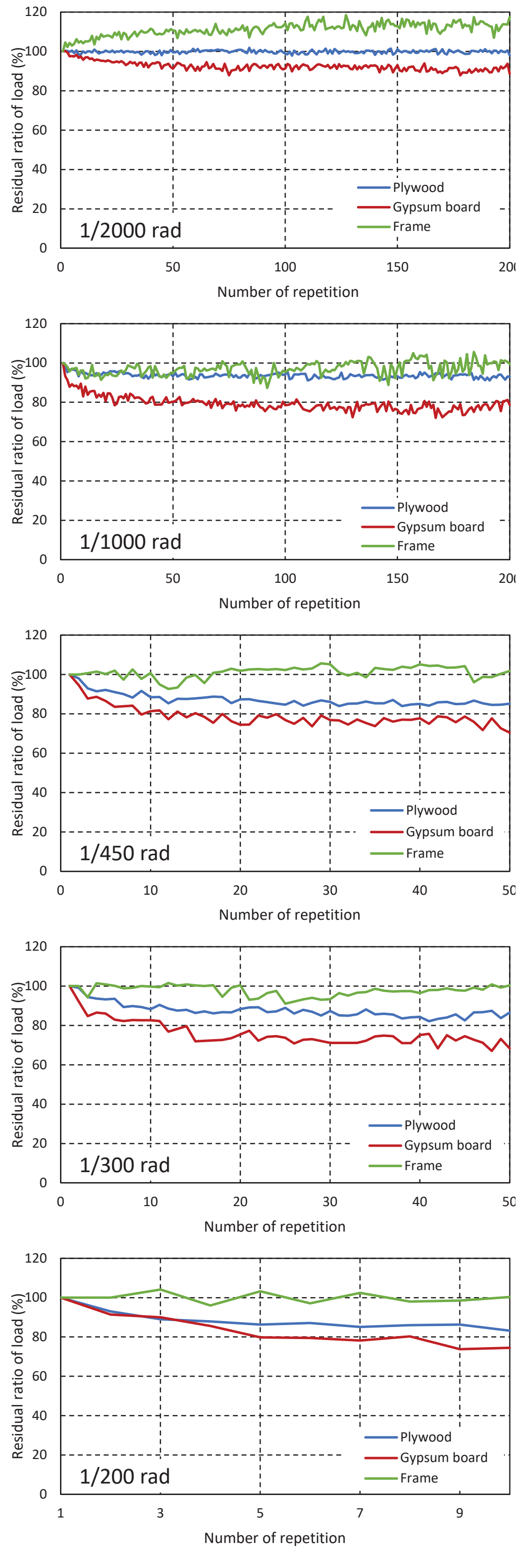

Figure 4: *Transition of the load residual rate*

was found that the load reduction of the gypsum board wall was larger than the plywood wall. In the nailed joint experiment, for example, the load residual ratio at the end of the repetition assuming 1/1000 rad was about 80% for plywood and about 70% for gypsum board. However, in the wall experiment, the load was maintained about 90% on the plywood wall even at the same deformation angle, and the load was maintained about 80% even on the gypsum board. In other words, the load reduction tendency was gradual. It is considered that this is because the target deformation in the nailed joint experiment was set assuming the nail with the largest amount of deformation in the wall, and the amount of deformation of the nail was smaller than expected. No significant tendency for the load to decrease was observed in the range of the number of repetitions of this experiment in the frame only specimen at any deformation angle.

Figure 5 shows the transition of equivalent stiffness and equivalent damping factor obtained by the equivalent linearization method. As with the load reduction, both equivalent stiffness and equivalent damping factor decreased after 5 to 10 repetitions at the beginning of each step, confirming that even small deformations have an effect. However, in subsequent repetitions, a convergence trend was observed, with a gradual decrease or levelling off, and no sudden decrease was observed.

4 PREDICTION AND DISCUSSIONS

The experimental results of the nailed joints [4] are used to examine whether the load residual ratio obtained in the wall experiments can be explained. For the plywood-sugi-N50 nailed joints, the relationship between load residual ratio and number of repetitions at each deformation (step) obtained in the previous report is expressed in both logarithms as shown in Figure 6. The load residual ratio-number of repetition relationship was considered as a proportional relationship, and the slope was calculated for each deformation by linear regression. The intercept of the approximate line was set to 2, since the residual load percentage for the new deformation was 100%. The slopes obtained for each deformation were plotted side by side for each deformation as shown in Figure 7. The larger the deformation, the larger the slope of the approximate straight line, indicating a larger load degradation. Here, it was determined that there is a roughly proportional relationship between the amount of repeated deformation and the slope of the approximate line. Since no load degradation occurs when the deformation is 0, the slope was obtained by linear regression with the intercept set to 0. Using the obtained slope, the equation for residual load at any deformation and any number of repetitions was derived as in Equation 2. The same procedure was performed for gypsum board wall, and the equation for residual load was obtained from Figure 7.

$$\text{Load residual ratio (\%)} = 10^2 \cdot N^a \qquad (2)$$

where a=deceleration index
Plywood: a = -0.047x, gypsum board: a = -0.077x
x: deformation (mm),
N: number of iterations (times)

Several models have been proposed to calculate the load-deformation relationship of sheathed walls using experimental results of nailed joints; Tuomi [6] et al. proposed a relatively simple method to estimate the

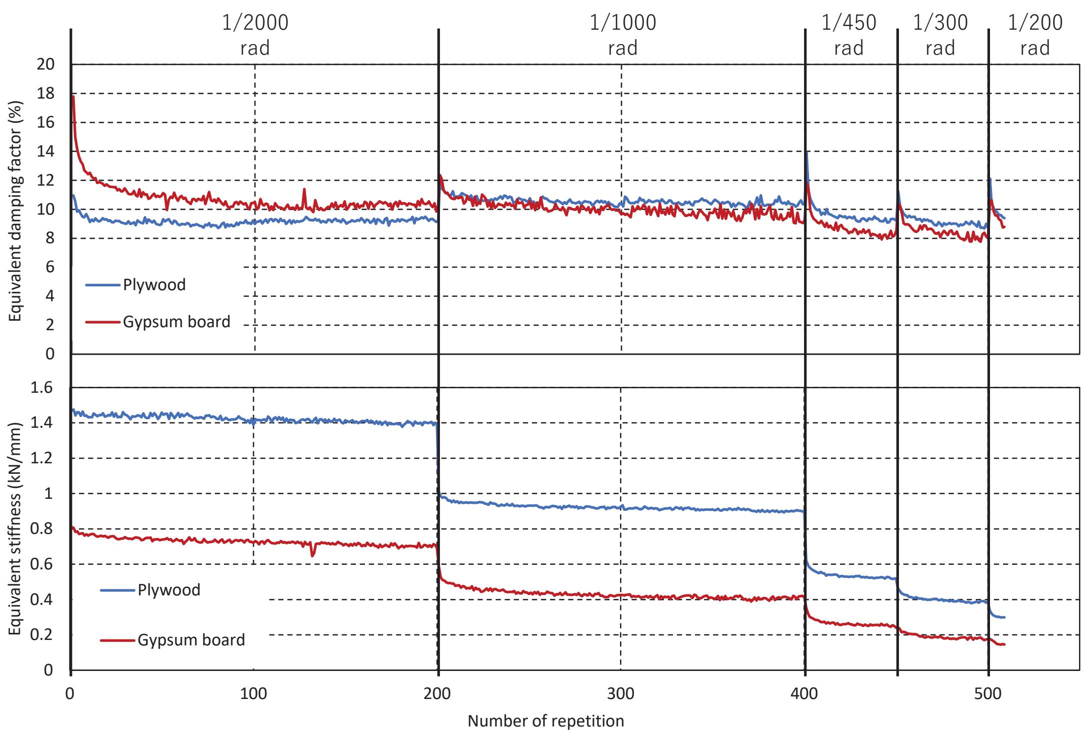

Figure 5: *Transition of equivalent stiffness and damping factor*

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deformation behavior based on the assumption that nails driven into the four corners are displaced in the diagonal direction. Kamiya [7] and Murakami [8] proposed a model that determines the direction of rotation of a face material based on the equilibrium of forces.
Furthermore, Toda et al [9] have modified the equation to adapt to the case where part of the nailed joint has deteriorated due to biodeterioration, and where nails with different load-displacement relationships are mixed within the wall. The calculation method is cited from reference [9] as Equation 3 – 14. Since the equations used in the calculations were proposed with the intention of being used in design, the calculated results of load are slightly lower than the experimental results. The distance from the origin of the coordinates to the neutral axis is expressed by Equation 3 and 4, where i is the serial number of each nail and the load by each nail is considered.

$$x_0 = \frac{\sum x_i \times p_i}{\sum p_i} \quad (3)$$
$$y_0 = \frac{\sum y_i \times p_i}{\sum p_i} \quad (4)$$

x_0: Distance from the coordinate origin to the neutral axis in the x direction (mm)
x_i: x-coordinate of nail with number i (mm)
p_i: Load by the nail with number i (mm)
y_0: Distance from the coordinate origin to the neutral axis in the y direction (mm)
y_i: y-coordinate of nail with number i (mm)

The moment-rotation angle relationships in the x- and y-directions are given in Equation 5 – 7, respectively. And the relationship between the deformation angle of the wall and the rotation angle in the x- and y-directions is given in Equation 8.

$$M_x = K_x \times \theta_x \quad (5)$$
$$M_y = K_y \times \theta_y \quad (6)$$
$$M_x = M_y \quad (7)$$
$$R = \theta_x \times \theta_y \quad (8)$$

M_x: Moment in x direction (Nmm)
K_x: Rotational stiffness in x direction (Nmm/rad)
θ_x: Rotation angle in x direction (rad)
M_y: Moment in y direction (Nmm)
K_y: Rotational stiffness in y direction (Nmm/rad)
θ_y: Rotation angle in y direction (rad)
R: Deformation angle of the wall (rad)

Considering the secant stiffness of each nail, the rotational stiffness is shown in Equation 9 and 10. The deformation of each nail is expressed in Equation 13 using Equation 11 and 12.

$$K_x = \sum K_i \times (y_i - y_0)^2 \quad (9)$$
$$K_y = \sum K_i \times (x_i - x_0)^2 \quad (10)$$
$$\delta_{ix} = (y_i - y_0) \times \theta_x \quad (11)$$
$$\delta_{iy} = (x_i - x_0) \times \theta_y \quad (12)$$
$$\delta_i = \sqrt{{\delta_{ix}}^2 + {\delta_{iy}}^2} \quad (13)$$

K_i: Secant stiffness of nail with number i (N/mm)
δ_{ix}: x-direction displacement of nail with number i (mm)
δ_{iy}: y-direction displacement of nail with number i (mm)
δ_i: Displacement of nail with number i (mm)

Equation 3 – 12 can be obtained by convergence calculations, and the relationship between any given deformation angle of the wall and the corresponding shear force can be obtained using Equation 14.

$$P \times H = M_x = M_y = \frac{K_x \times K_y}{K_x + K_y} \times R \quad (14)$$

H: Height of the wall (mm)

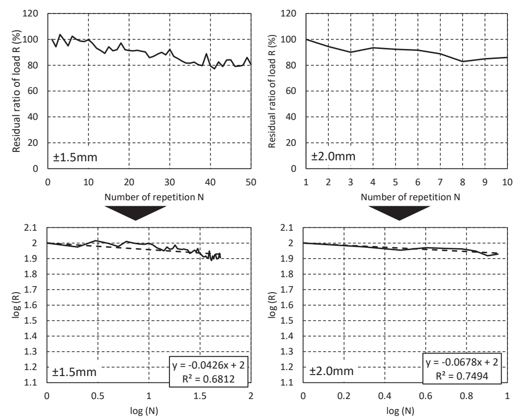

Figure 6: *Relationship between logarithmic load residual ratio and number of repetitions*

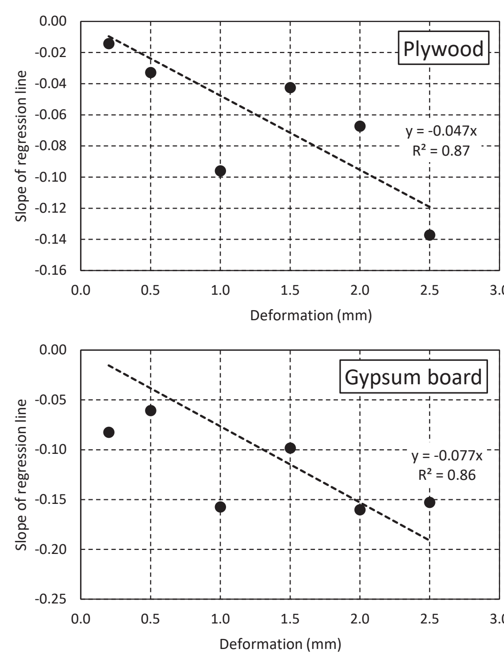

Figure 7: *Relationship between deformation and slope of regression line*

In this study, based on this calculation method, the load residual ratio corresponding to the amount of deformation and repetition for each nail was calculated from Equation 2 and multiplied by the load of each nail to calculate the load on the wall. Then, the load residual ratio of the entire wall was calculated. Comparison of the estimated results with the experimental values is shown in Figure 8. The experimental results are shown up to 1/200 rad, which was the subject of the repeated experiments, and the estimated values are shown up to 1/200 rad with a lower limit of 30% load residual.
For the plywood walls, the load reduction due to the 1/2000 rad repetitions is evaluated somewhat larger, but it can be said that the load reduction trend in the shear experiments of wall can be expressed. For gypsum board, the estimated value at 1/1000 rad repetitions was evaluated to be on the dangerous side compared to the experimental value. The reason for this is unknown. However, for the other deformation repetitions, it can be concluded that the experimental results are well represented. In conclusion, it was confirmed that the load-reducing tendency of shear resisting walls using face materials due to repeated small deformations can be generally estimated by repeated experiments on nailed joints.

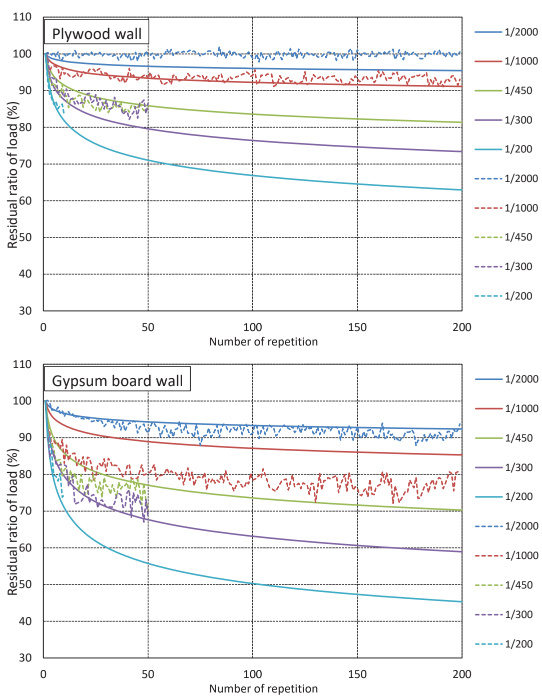

Figure 8: Comparison between estimated value and test result of load residual ratio
(*Solid line: test result, dotted line: prediction*)

5 CONCLUSIONS

In-plane shear experiments on the walls were conducted to confirm the effect of repeated small deformation due to moderate earthquakes on the shear performance of plywood walls and gypsum board walls.
As a result, it was found that the load reduction and equivalent stiffness reduction due to repetition of the same deformation were observed even in the case of repeated small deformations for the sheathed wall. Furthermore, the rate of load reduction due to repeated deformation in the gypsum board wall was larger than that in the plywood wall.
On the other hands, it was found that the maximum load and yield load are not significantly affected even if the wall received repeatedly small deformation.
The calculated load reduction trend of sheathed walls subjected to repeated small deformations from the experimental results from nailed joints was found to be generally expressible.

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