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# EFFECT OF SPRAY-APPLIED RIGID POLYURETHANE FOAM ON SEISMIC PERFORMANCE OF TIMBER HOUSE

Tomoki Furuta[1], Masato Nakao[2]

**ABSTRACT:** Rigid Polyurethane Foam (RPF) is widely used as insulation in Japan. Though the RPF is a non-structural member, it had been said that there was a possibility it increases the seismic performance of plywood shear walls. To clarify the effect of RPF, a static shear loading test of two plywood shear wall specimens was conducted, where one specimen was sprayed with RPF. Compared with the non-RPF plywood specimen, it was found that RPF confines the rotation of plywood. With the confining effect of RPF, the shear stiffness and the maximum shear force of the plywood specimen increased to approximately 170% and 130%, respectively. To estimate the effect of RPF in timber houses, using the static shear loading test result, the earthquake response of a two-story timber house was calculated by the time history response analysis. It was found that RPF may decrease the maximum response drift angle of timber houses in the case with a large number of shear walls or the case with only a plywood shear wall. On further study, it is needed to estimate the influence of the thickness and density of RPF.

**KEYWORDS:** rigid polyurethane foam, plywood shear wall, static shear loading test, time history response analysis

## 1 – INTRODUCTION

As thermal insulation for timber houses in Japan, fiber-type insulation such as glass wool is commonly used to fill it between columns. On the other hand, Rigid Polyurethane Foam (RPF) is also used as a high-grade insulation. For timber houses, RPF is sprayed onto the back of plywood on the external walls. It realizes higher heart insulation properties and air tightness.

Chen et al. [1], [2] reported on the material strengths of RPF and conducted a static shear loading test of two plywood shear walls, where one specimen was sprayed with RPF, and found that RPF carried a diagonal compressive force.

Authors had considered that as the sprayed RPF sticks to columns and plywood, the RPF confines a wood frame and plywood, improving the seismic capacity of timber houses. To verify the confining effect, a static shear loading test of a nailed plywood specimen with the RPF was conducted. Comparing a test result of a plywood only specimen, the effect of RPF on seismic performance was examined. Moreover, to estimate the influence on timber houses' seismic performance, a time history response analysis was conducted.

## 2 –SPECIMENS FOR STATIC LOADING TEST

Two nailed plywood shear wall specimens were constructed. The wall length was 910 mm, and the height was 2730mm as shown in Fig.1. The Plywood size was 2730 mm ×910 mm ×9 mm, nailed by N50 nails spacing of 150 mm. RPF, which conformed to Japan Industrial Standard (JIS) A-2H [3], was applied with a thickness of 70 mm on one nailed plywood specimen as shown in Picture 1.

The specimens were subjected to three repeated shear loads on each loading stage: 1/300 rad, 1/200 rad, 1/150 rad, 1/120 rad, 1/100 rad, 1/75 rad, 1/50 rad, and 1/30 rad. Additionally, one repeated load on 1/20 rad was applied. During the loading, the uplift of the specimen beam was constrained.

In parallel to the static loading test of the shear wall specimen, bending and tension tests of RPF were also conducted to understand the material properties. A three-

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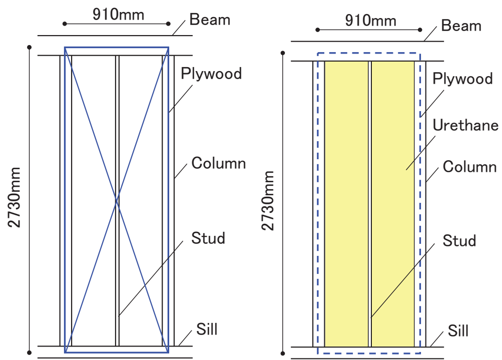
point bending test was conducted using specimens measuring 350 mm x 100 mm x 25 mm, following JIS K 7221-2: 2006. The tension test using 50 mm x 50 mm x 30 mm specimens was conducted following JIS A 9526: 2022 to determine the bonding strength. Fig. 2 shows the result of the bending and tension test. The bending elastic modulus and the bending strength of the RPF were 2.55 N/mm$^2$ and 0.163 N/mm$^2$, respectively, while the bonding strength was 0.354 N/mm$^2$, as shown in Tables 1 and 2.




*(a) Without RPF* *(b) With RPF*

*Figure 1. Plywood shear wall specimen*

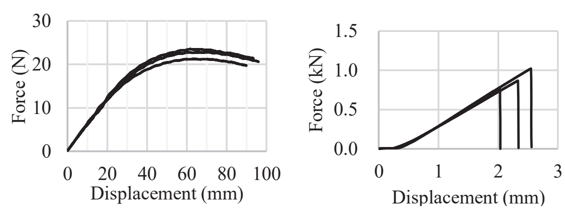
## 3 –RESULT OF STATIC LOADING TEST

### 3.1 FAILURE MODE AND SHEAR STRENGTH

In the plywood specimen without RPF, the plywood rotated as shown in Picture 2, and nails were pulled out gradually as the drift angle proceeded. Finally, fractures of nails and punching out of nails were observed.

In the RPF-applied specimen, the plywood rotated, and nails were pulled out in the same way as the plywood specimen. RPF was peeled off from one column, and shear cracks were observed on the RPF near another column at a relatively large drift angle, as shown in Picture 3.

*Picture 1. Spraying RPF*




*(a) Bending test* *(b) Tension test*

*Figure 2. Material test result*

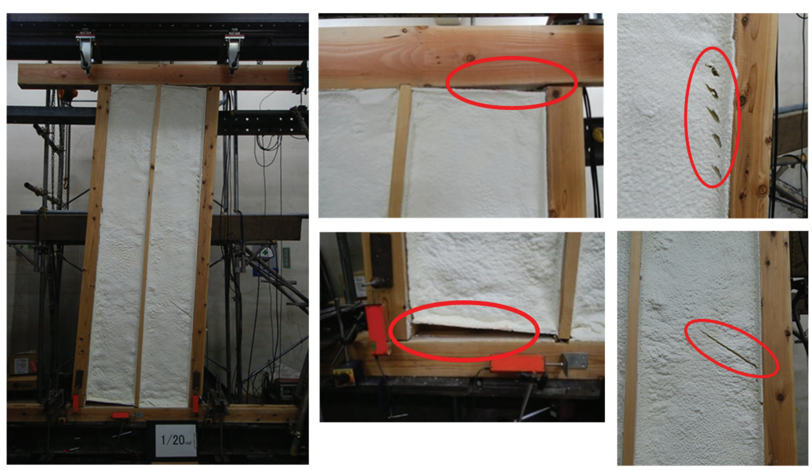
*Table 1. Bending elastic modulus and strength*

| | $E_b$ (N/mm$^2$) | $\sigma_b$ (N/mm$^2$) |
|---|---|---|
| 1 | 2.47 | 0.167 |
| 2 | 2.56 | 0.156 |
| 3 | 2.62 | 0.166 |
| Ave. | 2.55 | 0.163 |

*Table 2. Bonding strength*

| | $\sigma_t$ (N/mm$^2$) |
|---|---|
| 1 | 0.409 |
| 2 | 0.348 |
| 3 | 0.305 |
| Ave. | 0.354 |

*Picture 2. Specimen without RPF*



*Picture 3. Specimen with RPF*


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Fig. 3 shows the shear force-drift angle relationships of the shear wall specimens. Fig. 4 shows a comparison of the skeleton curves of the two specimens. With the RPF, it is found that the shear force on 0.0067 rad and the maximum shear force increase to approximately 170% and 130%, respectively, compared to the non-RPF specimen, while a degradation of shear force is seen after 0.013 rad. The allowable shear strengths of the two specimens were calculated. The one with the RPF was 6.5 kN/m, which was 140% of the one without RPF. The ultimate drift angles were 0.02 rad for the specimen with RPF, while 0.033 rad for the one without RPF.

## 3.2 SHEAR STIFFNESS AND DAMPING RATIO

Fig. 5 shows the shear stiffness of the two specimens. It is a secant shear stiffness calculated using the two points, a maximum point and a minimum point in shear force in one loop. The shear stiffness decreases as the drift angle increases. The stiffness of the specimen with RPF is higher than that without RPF. During a small drift angle range, it is approximately 140 % of the one without RPF, and almost the same level over approximately 0.02 rad range.

Fig. 6 shows the equivalent damping ratio (Heq) of the specimens during loading. Heq tends to increase as the drift angle increases on both specimens and decreases during repeated loading at the same drift angle. The Heq of the specimen with RPF at a small drift angle is approximately 7 %, and 20 % at a large drift angle. The ones without RPF are larger than approximately 11 %

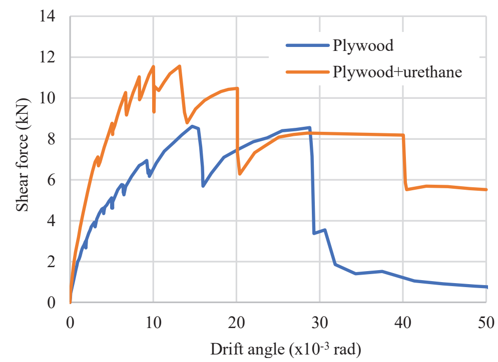



*Figure 4. Skeleton curves of shear force-drift angle relationship*

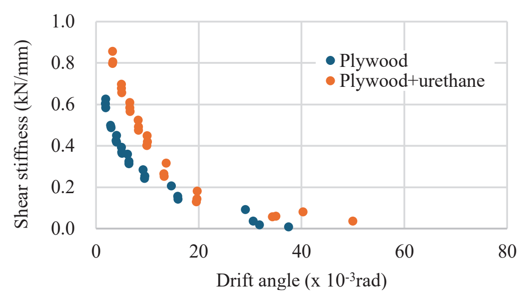



*Figure 5. Shear stiffnenn of wall specimens*

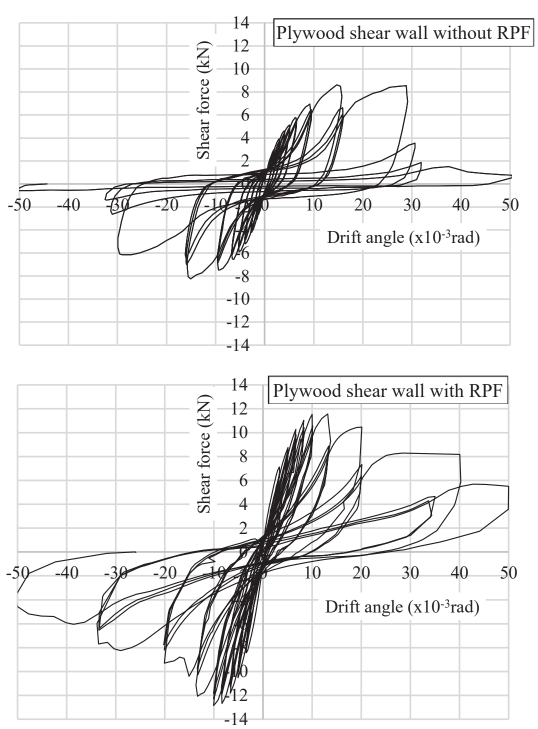
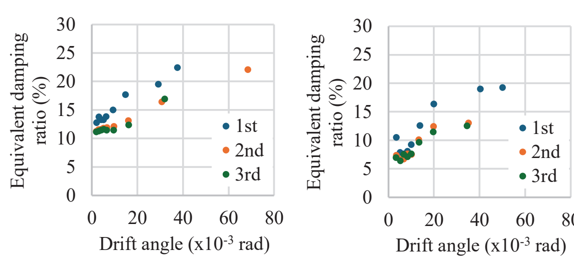



*Figure 3. Shear force-drift angle relationship of shear wall specimen*




*(a) Without RPF* *(a) With RPF*

*Figure 6. Equivalent damping ratio of plywood shear wall specimens*

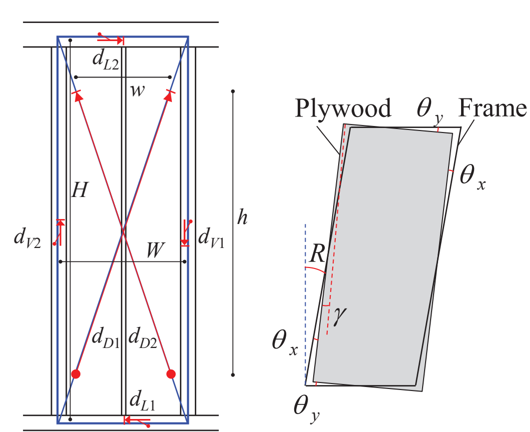



*Figure 7. Measurement of deformation*

even at a small drift angle. From these results, it is found that RPF increases shear stiffness and decreases Heq.

### 3.3 DEFORMATION CHARACTERISTICS

From the data of the displacement transduces attached to the specimens as shown in Fig. 7, relative rotation angles, $\theta_x$ and $\theta_y$, and a shear deformation angle of a plywood $\gamma$ were calculated, where $\theta_x$ is the relative rotation angle of the plywood to the columns, and $\theta_y$ is the one to the lateral members.

Fig. 8 shows ratios of the relative rotation angles and the shear deformation angle to the whole deformation at each drift angle. For the specimen without RPF, the rotation angle $\theta_y$ ranges from approximately 60 % to 80 %. On the other hand, $\theta_x$ and the shear deformation angle $\gamma$ remain below 20 % from a small deformation angle to the end of loading. And the difference between $\theta_y$ and the others increased as the deformation proceeded.

For the specimen with the RPF, $\theta_y$ was approximately 20 % at a small deformation angle, and $\gamma$ was approximately 75 %, on the contrary. It implies that the RPF confined the plywood's rotation and enlarged the shear deformation of the plywood. That led to the higher stiffness of the plywood shear wall. After that, due to the peel-off of the RPF from the column and the shear cracks on the RPF, the confining effect of the RPF disappeared. At 0.05 rad of drift angle, $\theta_y$ and $\gamma$ were almost at the same level as the specimen without RPF. And the shear force of the specimen with RPF was also at the same level as the specimen without RPF.

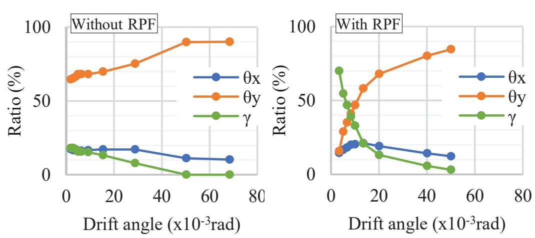


*Figure 8. Ratio of relative rotation angle and shear deformation angle to whole deformation*

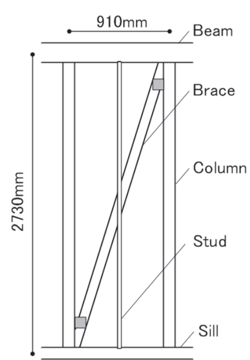


*Figure 9. Braced shear wall*

*Table 3. Number of shear wall on each floor*

| Model | | 1a | 1b | 2a | 2b | 3a | 3b |
|---|---|---|---|---|---|---|---|
| 1st floor | Plywood | 8 | 8 | 8 | 8 | 12 | 18 |
| | Brace | 5 | 13 | 5 | 13 | 0 | 0 |
| 2nd floor | Plywood | 6.5 | 7.5 | 6.5 | 7.5 | 6.5 | 10 |
| | Brace | 0 | 3 | 2 | 6 | 0 | 0 |

## 4 –EFFECT OF RPF ON SEISMIC PERFORMANCE OF TIMBER HOUSE

### 4.1 ANALYSIS MODEL AND METHOD

To evaluate the effect of RPF on two-story timber houses built by Japanese post-and-beam construction, we conducted a time history response analysis.

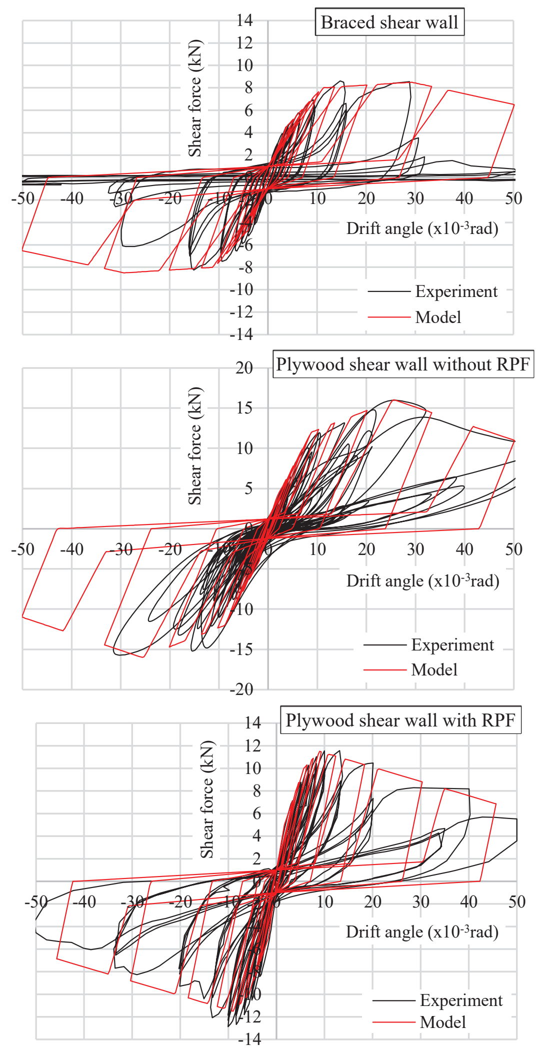


*Figure 10. Hysteresis model of shear wall*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For shear walls, plywood shear walls and braced shear walls, as shown in Fig. 9, were adopted. The size of the plywood is 910 mm x 2730 mm, and the thickness is 9mm. It is fastened to the wood frame with a 50 mm long nail (N50), spacing of 150 mm. The cross-section of the brace is 90 mm x 45 mm, its ends are connected to both sides of the columns with designated brace connectors.

The first and second floor areas are 69.2 $m^2$ and 53 $m^2$, respectively, and the corresponding weights are 167 kN and 104 kN. A number of the shear walls on each floor is listed in Table 3.

A number of shear walls of Model 1 were set properly according to the weight. For model 2, a number of shear walls on the second floor was relatively large. Model 2 was set because most real houses are expected to have a relatively large number of shear walls on the second floor. The Model 3 has no braced shear wall. On each model, Model #a has a minimum number of shear walls as the building standard law in Japan requires, while Model #b has 1.5 times the minimum number, except for the second floor of Model 2.

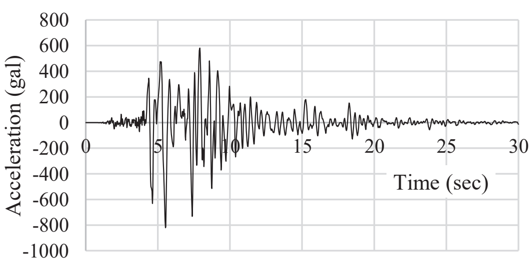


*Figure 11. JMA Kobe NS wave (100%)*

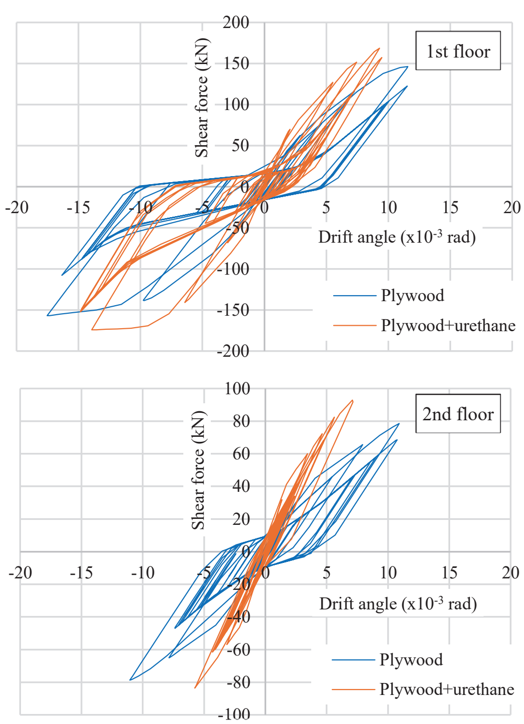


*Figure 12. Shear force-drift angle relationship of 1b model*

Hysteresis models of the shear walls are shown in Fig. 10. They were set considering the static shear loading test result.

Earthquake response analysis of the models was conducted using 50 % of JMA Kobe NS wave as shown in Fig. 11, an earthquake wave observed at Kobe in 1995, where the damping ratio was 5 %. All models were analyzed in two ways, one was with RPF to all plywood shear walls and another was plywood-only shear walls (non-RPF).

## 4.2 ANALYSIS RESULT

Fig. 12 shows the shear force-drift angle relationship of Model 1b. There is a tendency for the RPF to decrease the earthquake response of the models because RPF increases the shear stiffness of plywood shear walls.

Fig. 13 shows the maximum response drift angles derived from the analysis. It can be seen that there is an irregular behavior in Models 1a and 2a, the response drift angle increases with RPF. The reason is expected that the shear stiffness of the second floor of the models increased more

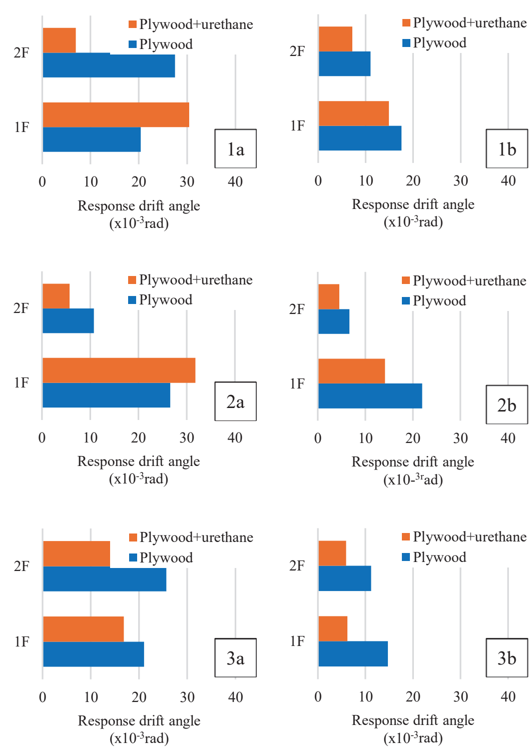


*Figure 13. maximum response drift angle*

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than that of the first floor by adding RPF, and the shear deformation of the models was concentrated on the first floor. Additionally, the drift angle at the maximum shear force of the plywood shear wall with RPF is smaller than that without RDF, and a negative stiffness of the skeleton curves starts at 0.01 rad. This might cause a larger response drift in the model with a small number of shear walls. This is obvious in models 1b and 2b, which have a large number of shear walls; the response drift angles are found to decrease with RPF even on the first floor.

As for Models 3a and 3b, which have plywood shear walls only, the shear stiffness increases at the same rate on the first and second floors. Therefore, a steady decrease in the response drift angle could be found with RPF.

In Model 3b with a large number of shear walls, the response drift angle decreased to approximately 50 % with RPF.

From the above analysis results, it is concluded that RPF may decrease the drift angle of timber houses in the case with a large number of shear walls or the case with only plywood shear walls as shear walls.

## 5 – CONCLUSION

To clarify the effect of Rigid Polyurethane Foam (RPF) on the seismic performance of plywood shear walls, a static shear loading test of nailed plywood specimens with RPF and without RPF was conducted.

It was found that RPF confines the rotation of plywood and increases the shear stiffness of plywood shear walls. Moreover, to estimate the effect of RPF on the earthquake response of timber houses, time history earthquake response analysis was conducted. It was found that RPF may decrease the drift angle of timber houses in the case with a large number of shear walls or the case with only plywood shear walls as shear walls.

In further study, the influence of the thickness and density of RPF would be studied.

## 6 – REFERENCES

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