World Conference on
Timber Engineering
Oslo 2023

STUDY ON THE RELATIONSHIP BETWEEN INTERLAYER DEFORMATION ANGLE AND TORN WALLPAPER OF WOODEN HOUSES

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ABSTRACT: The purpose of this study is to clarify the elongation rate of wallpaper required to prevent wallpaper from breaking in wooden houses due to medium earthquakes. For this purpose, it is necessary to clarify the relationship between the elongation rate of wallpaper and the interlaminar deformation angle at which the wallpaper breaks. However, there is no defined method to measure the elongation rate of wallpaper. Therefore, this study first aimed to establish a method to measure the elongation rate of wallpaper and conducted three types of tensile tests. In addition, a shear test was conducted to reproduce the original tearing of the wallpaper, and the results were compared with those of the tensile test to verify which tensile test results are valid as a measurement method.

KEYWORDS: Wooden Houses, Interlayer deformation angle, Wallpaper, Plasterboard

1 INTRODUCTION

There is a problem of wallpaper tearing in houses due to earthquakes and other events. This is because horizontal forces acting on the house cause interlaminar deformation, which rotates the plasterboard, the base of the interior, and causes misalignments and openings between adjacent boards. According to the Japanese Building Standard Law, the angle of interstory deformation generated by a moderate earthquake should be kept within 1/120 rad. if no part of the house is damaged due to deformation of structural members. The interlaminar deformation angle at this point is generally called the damage limit. According to this definition, it can be interpreted that the house can be used continuously without repair if it is within the damage limit. However, previous studies have shown that wallpaper breaks even at interlaminar deformation angles smaller than the damage limit. Therefore, the objective of this study was to estimate the target elongation rate of wallpaper necessary to prevent the wallpaper from tearing within the damage limit.

2 SUMMARY OF RESEARCH

To estimate the target value, the relationship between the elongation rate of wallpaper and the interlaminar deformation angle at which breakage occurs is investigated. Since there is no established method for measuring the elongation rate of wallpaper, tensile tests of wallpaper were conducted to establish a measurement method. However, since the tensile test alone does not reproduce the original wallpaper breakage, a shear test of the wallpaper was conducted and compared with the results of the tensile test to confirm the correlation.

3 STANDARD TENSILE TESTS

3.1 SPECIMEN SPECIFICATIONS

The test specimens were made by cutting wallpaper into strips 15 mm wide and 280 mm long (Fig.1,2). The gripping position was set at 50 mm from both ends, and the center 180 mm was set as the elongation allowance. Six types of vinyl wallpaper, which are frequently used in Japan, were used for the test specimens. Six types of vinyl wallpaper with different surface shapes, foam amounts, and elasticity were used (Table 1). The first letter of the test specimen name is derived from the surface shape, and the second letter from a word indicating the characteristics of each specimen. A total of 36 specimens, six of each specification, were used.

Table 1 List of specimen specifications

Specimen name	Surface form	Thickness [mm]	Feature
SN	Stone	0.42	Normal vinyl cloth
SF	Stone	0.60	Foamed to increase thickness
SF’	Stone	0.55	Foamed to increase thickness
SS	Stone	0.58	Stretch performance
FF	Fabric	0.60	Foamed to increase thickness
FL	Fabric	0.72	Used for a long time

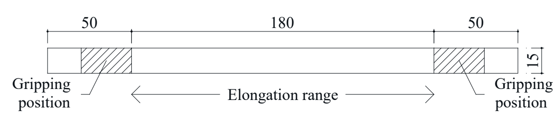

Figure 1. *Tensile specimen dimensions*

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https://doi.org/10.52202/069179-0040

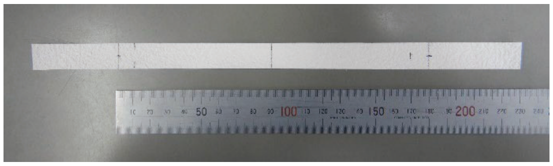

Figure 2. *Tensile specimen shape*

3.2 SUMMARY OF EXPERIMENTS

Tensile tests were conducted to measure the elongation rate of wallpaper. For the test, tensile force was applied to the specimen using a 1 kN universal testing machine at the Nippon Institute of Technology (Fig. 3). The test was applied at a rate of 20 mm/min until the wallpaper broke. Rupture was determined when the load dropped from the maximum load to half of the maximum load. Elongation was determined by dividing the displacement at break by the elongation threshold and expressed as a percentage.
If the wallpaper broke due to the tightening force when the testing machine gripped the specimen, the correct elongation rate of the wallpaper could not be measured. Therefore, if the specimen broke within 10 mm from the gripping position, the result was considered invalid (Fig. 4, 5).

Figure 3. *Testing machine*

Figure 4. *Specimen installed*

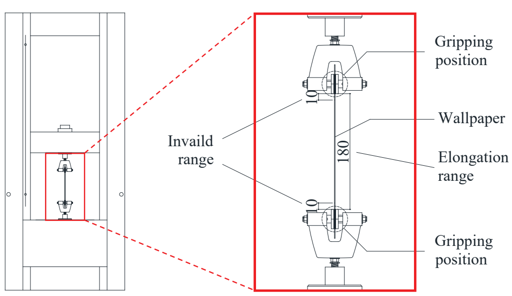

Figure 5. *Specimen installation state and invaild range*

3.3 EXPERIMENTAL RESULT

The test results from the standard tensile test are shown in Table 2 and Fig. 6. Slight differences in elongation rate and maximum proof stress were observed among the wallpaper types. The highest elongation value was obtained with SF, which has a stony surface and a large amount of foam, while SS, which has a stretch performance, showed the third highest elongation value. Fracture behavior was similar for all specifications, with the wallpaper breaking instantaneously at maximum load. One reason for the lack of difference was the shape of the vinyl wallpaper. Vinyl wallpaper is manufactured by coating vinyl chloride resin onto backing paper. Although the backing paper has higher resistance than the vinyl resin, it is not elastic and is therefore prone to rupture. When the backing paper breaks, the vinyl resin also breaks, and it is thought that it was difficult to obtain a difference in results.
However, when vinyl wallpaper is applied, a large amount of water is used to dilute the glue, which may reduce the resistance of the backing paper. Therefore, in the next test, the resistance of the backing paper will be reduced by adding moisture to the wallpaper, and the elongation rate will be measured with the effect reduced.

Table 2 *Standard tensile tests results*

Specimen name	Elongation rate [%]	Pmax [N]
SN (Stone Normal)	1.58	49.82
SF (Stone Foamed)	2.22	66.04
SF' (Stone Foamed)	1.86	70.05
SS (Stone Stretch)	1.89	71.07
FF (Fabric Foamed)	1.60	50.69
FL (Fabric Long)	2.11	62.91

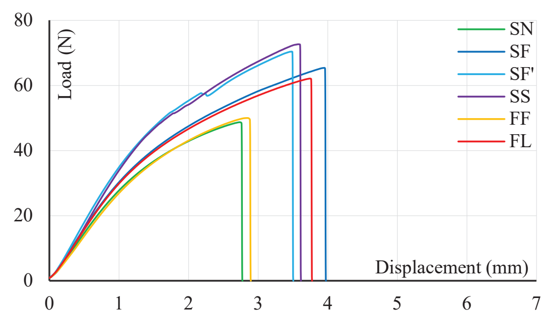

Figure 6. *Std. tensile tests graph*

4 WET TENSILE TESTS

4.1 SPECIMEN SPECIFICATIONS

The shape of the specimen was the same as in the standard tensile test. The same six types of vinyl wallpaper were used as in the standard tensile test. The test specimens were six of each specification, for a total of 36 specimens. The condition of the specimens was also changed to reduce the influence of the backing paper. In order to reproduce the decrease in resistance due to moisture in the glue when applying vinyl wallpaper, the specimens were impregnated with water for 5 minutes, and the excess water droplets were wiped off using tissue paper (Fig. 7,8).

Fig. *7 Impregnating wallpaper*

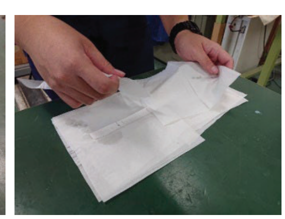

Fig. 8 *Wiping off excess moisture*

4.2 SUMMARY OF EXPERIMENTS

In order to measure the elongation rate of wallpaper with the influence of the backing paper reduced, tensile tests were conducted with the specimens wet. For the test,

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tensile force was applied to the specimens using a 1 kN universal testing machine at the Nippon Institute of Technology. After impregnating the specimen for 5 minutes before applying the force, water droplets on the surface were wiped off and the force was applied immediately. The test was applied at a rate of 20 mm/min until the wallpaper ruptured. Rupture was determined when the load dropped from the maximum load to half of the maximum load. Elongation was calculated by dividing the displacement at break by the elongation threshold and expressed as a percentage.

If the wallpaper broke due to the clamping force when the testing machine gripped the specimen, the correct elongation rate of the wallpaper could not be measured. Therefore, if the specimen broke within 10 mm from the gripping position, the result was considered invalid.

4.3 EXPERIMENTAL RESULT

The test results of the wet tensile test are shown in Table 3 and Fig. 9. As a result of the moisture content in the wallpaper, there were large differences in the maximum proof stress and elongation rate. In addition, the wallpapers exhibited two types of fracture behavior: integrally fractured and plastically deformed. The one-body break type (Fig. 10) is a rupture behavior in which the vinyl resin and the backing paper rupture at the same time, and was observed in SF, SF', FF, and FL, which have large amounts of foam. The plastic deformation type (Fig. 11) is a failure behavior in which the vinyl resin and backing peel off at the maximum proof stress (Fig. 12), and only the backing breaks, causing plastic deformation of the vinyl, and was observed in standard SN and SS with stretch performance. The stretch performance of SS was particularly clear, showing an elongation rate of 8.06 %, more than 60 % higher than the elongation rate of other specifications, which was around 5 %.

We believe that the wet tensile test was able to measure the performance of the vinyl resin itself by wetting the wallpaper and reducing the effect of the backing paper. However, the wallpaper is actually wet only when it is installed, and the glue is considered to have already dried when the earthquake occurs. Therefore, in the next tensile test, we decided to reproduce the wallpaper after it had dried and apply force.

Table 3 *Wet tensile tests results*

Specimen name	Elongation rate [%]	Pmax [N]
SN (Stone Normal)	5.43	16.04
SF (Stone Foamed)	5.24	32.32
SF' (Stone Foamed)	4.95	30.01
SS (Stone Stretch)	8.06	18.93
FF (Fabric Foamed)	5.23	15.23
FL (Fabric Long)	4.83	14.89

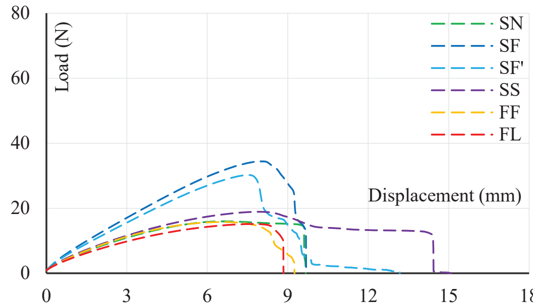

Figure 9. *Wet tensile tests graph*

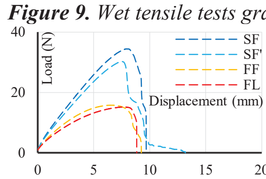

Fig. 10 *One-body break type*

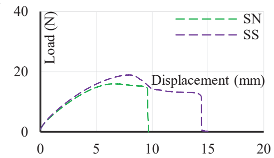

Fig. 11 *Plastic deformation type*

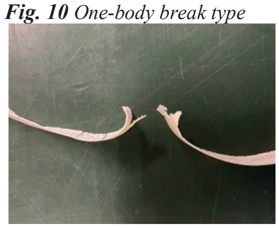

Figure 12. *Peeling of vinyl resin and backing paper*

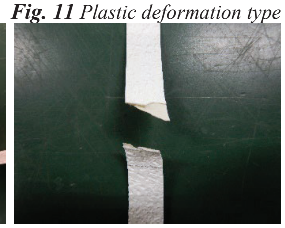

Fig. 13 *Break point of SS*

5 DRY TENSILE TESTS

5.1 SPECIMEN SPECIFICATIONS

The shape of the test specimen was the same as in the standard and wet tensile tests. In this test, three types of vinyl wallpaper (SN, SF, and SS) were tested for verification purposes. A total of 18 specimens were tested, six for each.

After impregnating the specimens under the same conditions as in the wet tensile test, the specimens were allowed to dry for three days (Fig. 14, 15). This reproduced the condition of the wallpaper after drying at the time of the earthquake.

Fig. 14 *Impregnating wallpaper*

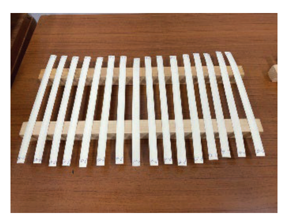

Fig. 15 *Wallpaper drying*

5.2 SUMMARY OF EXPERIMENTS

In order to reproduce the condition after the glue dried and measure the elongation rate of the wallpaper, a tensile test was performed by wetting the specimen and then drying it. For the test, tensile force was applied to the specimens using a 1kN universal testing machine at the Nippon Institute of Technology. After impregnating the specimens for 5 minutes, the force was applied to the specimens that had dried for 3 days. The test was applied at a rate of 20 mm/min until the wallpaper ruptured.

Rupture was determined when the load dropped from the maximum load to half of the maximum load. Elongation was calculated by dividing the displacement at break by the elongation threshold and expressed as a percentage.
If the wallpaper broke due to the tightening force when the testing machine gripped the specimen, the correct elongation rate of the wallpaper could not be measured. Therefore, if the specimen broke within 10 mm from the gripping position, the result was considered invalid.

5.3 EXPERIMENTAL RESULT

The test results of the dry tensile test are shown in Table 4 and Fig. 16. Reproducing the results after the glue dried, the difference in elongation rate caused by the different types of wallpaper was minimal. The highest elongation value was observed for SF, which has the highest amount of foam, followed by SS, which has the highest stretch performance, and standard SN, which had the lowest elongation. The reason for the lack of difference could be due to the effect of the backing paper, as in the standard tensile test. We believe that the moisture absorbed during the impregnation process was dried, and the backing paper's resistance was restored.

***Table 4** Dry tensile tests results*

Specimen name	Elongation rate [%]	Pmax [N]
SN (Stone Normal)	1.66	48.95
SF (Stone Foamed)	2.51	71.37
SS (Stone Stretch)	2.29	71.40

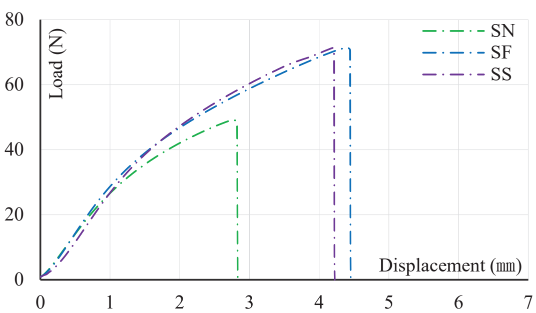

***Fig. 16** Dry tensile tests graph*

6 TENSILE TESTS COMPARISON

The elongation and Pmax obtained for all tensile tests are shown in Table 5.

***Table 5** Tensile tests results*

Specimen name	Tests type	Elongation rate [%]	Pmax [N]
SN (Normal)	Standard	1.58	49.82
	Wet	5.43	16.04
	Dry	1.66	48.95
SF (Foamed)	Standard	2.22	66.04
	Wet	5.24	32.32
	Dry	2.51	71.37
SF' (Foamed)	Standard	1.86	70.05
	Wet	4.95	30.01
SS (Stretch)	Standard	1.89	71.07
	Wet	8.06	18.93
	Dry	2.29	71.40
FF (Foamed)	Standard	1.60	50.69
	Wet	5.23	15.23
FL (Long)	Standard	2.11	62.91
	Wet	4.83	14.89

6.1 STANDARD-WET COMPARISON

A graph comparing standard tensile testing to wet tensile testing is shown in Fig. 17. Wetted wallpaper reduced Pmax by more than half for all specifications, but increased elongation by more than twice. In addition, all exhibited similar fracture behavior in the standard tensile test due to the influence of the backing paper, but differences in fracture behavior were observed when the backing paper was wetted and its bearing capacity was reduced. Based on the above, it can be considered that the standard tensile test almost always measures the performance of the backing paper, while the wet tensile test can measure the performance of the vinyl resin.

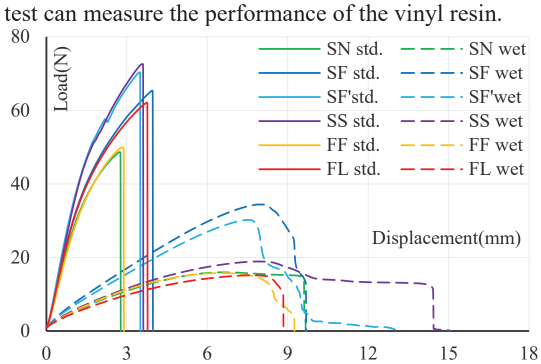

***Figure 17.** Std.-Wet tensile tests comparison graph*

6.2 STANDARD-DRY COMPARISON

A graph comparing standard tensile testing to dry tensile testing is shown in Fig. 18. Compared to the standard wallpaper, the wallpaper that was dried after being moistened showed comparable values for both maximum proof stress and elongation. This is thought to be due to the fact that the backing paper, although once moistened, dried and returned to its original strength. Therefore, it was found that the dried tensile test showed equivalent test results to the standard tensile test.

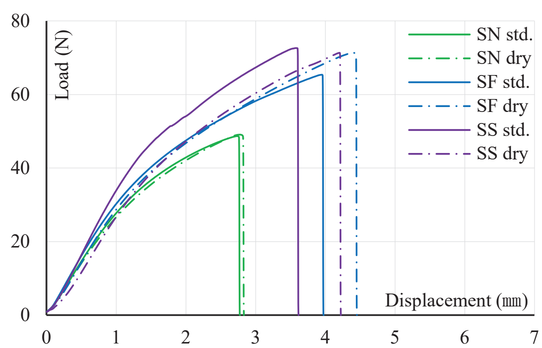

***Fig. 18** Std.-Dry tensile tests comparison graph*

6.3 TENSILE TEST CONCLUSIONS

We have conducted three tensile tests so far, and it is clear that vinyl wallpaper has a higher resistance than backing

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paper, and that no difference can be seen due to the influence of the backing paper when tested in its original state. It is also clear that the effect of the backing paper can be reduced by adding moisture, and the difference in performance of the vinyl resin can be confirmed.
However, the actual cause of wallpaper breakage is the displacement or opening of the plasterboard, not pure tensile fracture. Therefore, we decided to conduct shear tests on wallpaper that reproduced the displacement of the plasterboard to confirm the displacement that causes rupture. The results of the shear test were compared with the results of the respective tensile tests to verify which elongation rate in the tensile test was a reasonable value for evaluating the rupture.

7 SHEAR TESTS

7.1 SPECIMEN SPECIFICATIONS

Since it is difficult to apply shear force to a single piece of wallpaper, we decided to reproduce the original house interior. 3 sheets of plasterboard (70 x 200 mm at both ends and 140 x 230 mm in the center) were lined up and the wallpaper was attached (Fig. 19). The gluing was done in such a way as to straddle all the plasterboards. A curing period of one week was allowed for the glue to dry.
Wooden frames (Fig. 20) were also made to hold the specimens in place. Only the plasterboards at both ends were fastened to the frame with screws; the center board was not fastened (Fig. 21). The frames were secured using a testing machine and bolts.
The wallpapers used were four types of wallpaper with stone surface geometry.

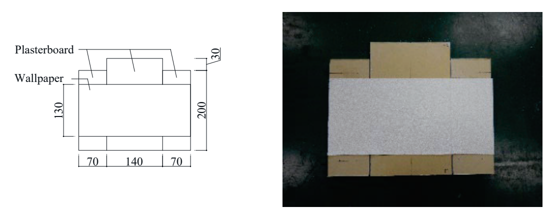

Figure 19. *Wallpaper placement of specimen*

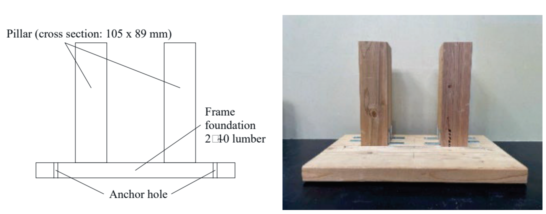

Figure 20. *Frame for specimen fixation*

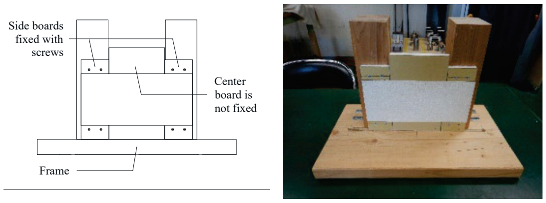

Figure 21. *Specimen fixed to the frame*

7.2 SUMMARY OF EXPERIMENTS

A wallpaper shear test is performed to measure the relative displacement between plasterboards when wallpaper breaks. A 50 kN universal testing machine from the Nippon Institute of Technology was used for the test. After the frame to which the specimen was fastened was fixed to the testing machine, the plasterboard in the center, which was not fastened, was grabbed by the upper jig of the testing machine (Fig. 22, 23), and the displacement of the boards was reproduced by raising only the center board. The force was applied at a rate of 2 mm/min until the wallpaper completely ruptured. Since it was difficult to determine rupture by the decrease in bearing capacity, damage was checked every 0.5 mm of displacement, and rupture was determined when more than half of the wallpaper was ruptured at the top of the joints.

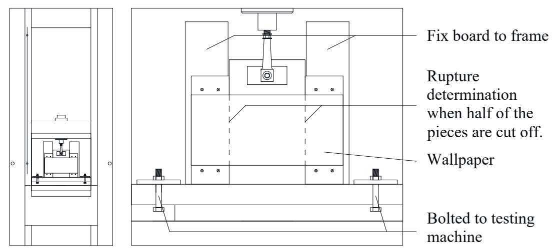

Figure 22. *Specimen installation state and invaild range*

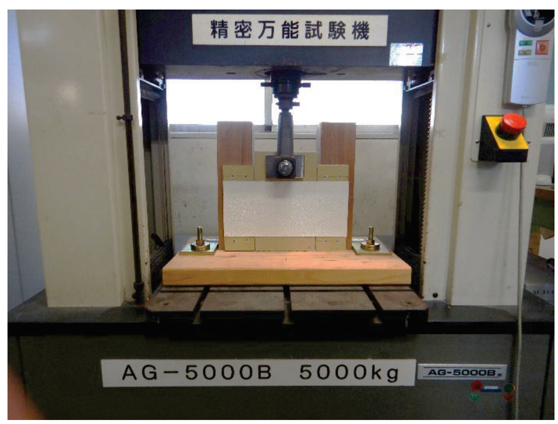

Figure 23. *Specimen installation state*

7.3 EXPERIMENTAL RESULT

The results of the shear test are shown in Table 6. The standard wallpaper, SN, and the wallpapers with high foam content, SF and SF', broke when the displacement was around 3.4 mm. On the other hand, SS, which has a stretch function, failed at a displacement of 4.5 mm at rupture compared to the other specifications (Fig.24). From the above results, it is considered that the stretch function is effective against shear failure.
Assuming that the plasterboard rotates at the same angle as the interlaminar deformation angle, the interlaminar deformation angle can be estimated from the board-to-board misalignment. 4.5mm corresponds to approximately 1/200 rad. However, this is only the case when there is no resistance to rotation of the faceplate, and is not an accurate estimate. It is necessary to actually test

https://doi.org/10.52202/069179-0040

the gypsum board bearing walls and measure the relative displacement between boards and the interlaminar deformation angle, and then re-evaluate the results. In addition, the chamfered edges of the gypsum board and the putty used to fill them were not reproduced in this study, so actual reproduction is also necessary.

***Table 6** Shear tests results*

Specimen name	Board displacement at break [mm]	Estimated interlayer deformation angle at break [rad.]
SN (Normal)	3.18	1/286
SF (Foamed)	3.67	1/247
SF' (Foamed)	3.34	1/272
SF (Foamed)	4.51	1/201

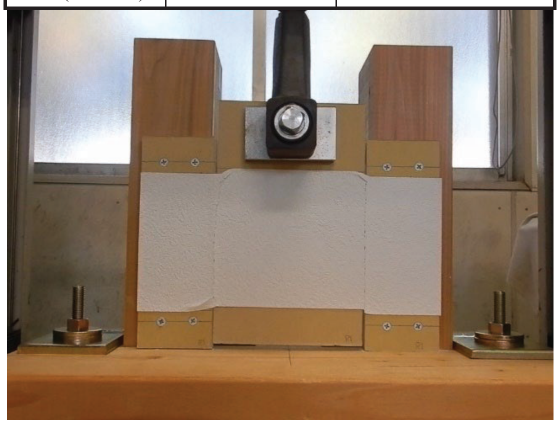

***Figure 24.** Wallpaper at break judgment (SS)*

8 COMPARISON

The relationship between the increase in elongation in the standard tensile test and the rupture displacement in the shear test is shown in Fig. 25, and the relationship between the increase in elongation in the wet tensile test and the rupture displacement in the shear test is shown in Fig. 26. The trend of increasing elongation in the standard tensile test appears to be generally consistent with the trend of increasing rupture displacement in the shear test. However, the SS rupture displacement with stretching performance in the shear test is large and deviates from the trend. The trend of the rupture displacement in the shear test was generally consistent with the trend of the elongation ratio in the wet tensile test. In particular, the values of SS in both tests were very high compared to the other three specifications, which were similar. Therefore, it can be seen that there is a strong relationship between the rupture displacement in the shear test and the elongation rate in the wet tensile test.

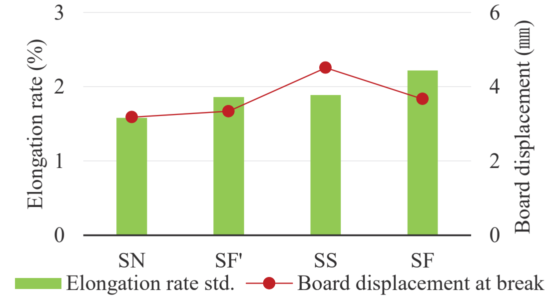

***Figure 25.** Tensile(std.)-shear tests result comparison*

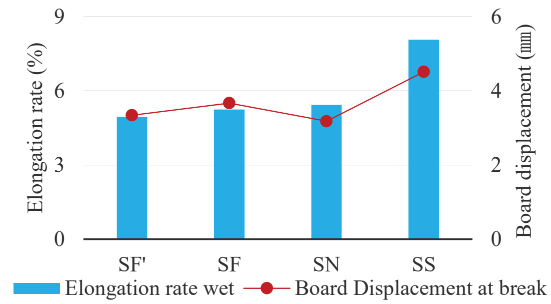

***Figure 26.** Tensile(wet)-shear tests result comparison*

9 CONCLUSIONS

By moistening the wallpaper, the influence of the backing paper was reduced, and the elongation rate could be measured while the performance of the vinyl resin itself was brought out. The fact that the elongation rate in the wet tensile test is strongly related to the breaking displacement in the shear test indicates that there is a relationship between the interlaminar deformation angle at which the wallpaper breaks and the results of the wet tensile test. In the future, we plan to conduct static force tests on full-scale walls actually covered with wallpaper to measure the interlaminar deformation angle at which the wallpaper breaks, and to clarify the relationship with the results of partial tests.

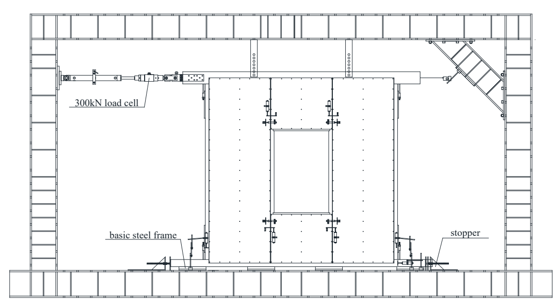

***Figure 27.** Plan for in-plane shear static force test*

ACKNOWLEDGEMENT

The test specimens used in this study were provided by POLUS R&D Center of Life-Style Co., Ltd. I would like to thank all those involved.

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