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A STUDY ON DISPLACEMENT ESTIMATION OF LATH-MORTAR UNDER EARTHQUAKE

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ABSTRACT: The lath-mortar as an external facing member is to be constructed onto several overlapping members, such as plywood, furring strips, and wooden laths, where these members are attached to a timber frame by nails. Therefore, there was an issue that made it complicated to evaluate the differential displacement between a lath-mortar and a timber frame under earthquakes. The goal of this study was set to establish a structural model of the external wall with lath-mortar for enabling FEM analysis. Firstly, static shear loading tests of lath-mortar external wall specimens were conducted to understand the behavior of a lath-mortar under earthquakes, where it was found that plywood between a timber framework and a lath-mortar increases the maximum shear force remarkably. Next, the analysis of a joint, which consists of several overlapping members attached by some nails, was carried out, and the shear force-displacement relationship of the combined nail joint was clarified. Finally, the shear force-drift angle relationships of the lath-mortal external wall specimens could be estimated successfully by FEM analysis using the shear force-displacement relationships of the combined nail joint.

KEYWORDS: lath-mortar, external wall, nail joint, static shear loading test, FEM analysis

1 – INTRODUCTION

Lath-mortar is constructed outside an external wall to protect the timber framework from rain, sunshine, wind, fire, etc. Lath-mortar is also known to contribute seismic performance of timber buildings. Authors have investigated the seismic performance of the lath-mortar wall experimentally and analytically[1], [2], [3].

To make use of such lath-mortar's performance, the lath-mortar is required not to fall off even under earthquakes. To verify that the lath-mortar does not fall off under earthquakes, it is needed to consider the real specification of timber buildings accurately.

For retaining durability, the lath-mortar is normally constructed on furring strips, moreover, the furring strips are often fastened with nails on plywood shear walls these days. Consequently, the lath-mortar is to be constructed on several overlapping members, which made it complicated to evaluate the lath-mortar's displacement under earthquakes. Additionally, the orthogonal wall of the lath-mortar affects the behavior of the front lath-mortar greatly, though only a few studies exist that examine the effect of the orthogonal wall on seismic performance.

In this study, to establish a structural model of the external wall with lath-mortar and to allow for estimation of the lath-mortar's behavior under earthquakes, static shear loading tests of lath-mortar external wall specimens with plywood and orthogonal walls were conducted first. And considering the results of the loading tests, the FEM structural model of the external wall with lath-mortar was tried to build.

2 – SPECIMENS

For higher durability, a ventilation space is required between the wood frame and the exterior wall. To keep the ventilation space, vertical furring strips 15 mm thick are attached to the outer face of columns and studs. As a shear wall, plywood is installed before the vertical furring strips are attached in some cases.

There are two systems in lath-mortar, one is a "double-layer system" and another is a "single-layer system" as shown in Fig. 1 and Fig. 2. In the double-layer system, onto the furring strips, wooden laths are fastened with 50 mm long nails (N50). Asphaltic felt (sheathing membrane) is applied on the wooden laths. Thereafter, a wavy metal lath is fixed with 19mm long staples (1019J) spaced 100mm apart.

For the single-layer system, ribbed metal lath (155RC800-05) is fixed to the furring strips with a 25-mm-long staple (L925T) at the rib, which is spaced 155 mm. Because duplex asphalt paper is fixed to the back of

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the ribbed lath by staples, no wooden lath and asphaltic felt are needed.

External wall specimens with lath-mortar were constructed by a Japanese post-and-beam construction system as shown in Fig. 3 and Fig. 4. The specimen's height was 1820mm, and its wall lengths were also 1820mm. It has three columns, and its cross-section is 105 mm x 105 mm. The species of the specimen's members is Douglas-fir for the beam and Japanese cedar for the other members.

All specimens are listed in Table 1, and the cross-sections of the specimens with the lath-mortar are shown in Fig. 5. The specimen's name "p" represents plywood nailed on columns as a shear wall. The letters "D" and "S" in the specimen's name represent the double-layer system and single-layer system, respectively. Therefore, "pD" means double-layer system lath-mortar having plywood between a wood frame and a furring strip. The specimen "Dm" has the minimum nails in length for furring strips and wooden laths, and "Dn" has no furring strip nails. The "Dt" has thicker furring strips. To estimate the effect of a lath-mortar, specimens without lath-mortar were also prepared. The specimen "p-fs" had plywood and furring strip only, and the specimen "p-fs-wl" had wooden laths on the furring strips.

In all lath-mortar specimens, orthogonal walls were constructed. Though its wall length is just 120 mm, they were expected to constrain the rotation of the lathe-mortar.

Static repeated shear load was applied to the beam of the specimen. Three repeated loads in 1/450 rad, 1/300 rad, 1/200 rad, 1/150 rad, 1/120 rad, 1/100 rad, 1/75 rad, 1/50 rad, and 1/30rad in drift angle, while one repeated load in 1/20 rad and 1/15 rad.

During the loading test, hold-down connectors were applied to the joints of the lateral members and the columns.

To understand the motion of each member of the specimen, markers were attached to each member, and the X, Y, Z coordinates of the markers were recorded by a motion capture system.

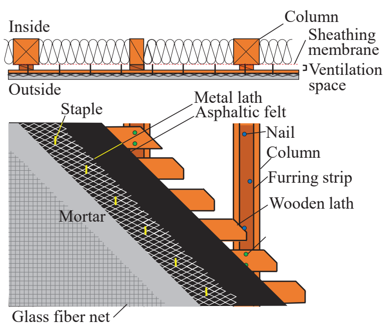

Figure 1. Double-layer system of lath-mortar external wall

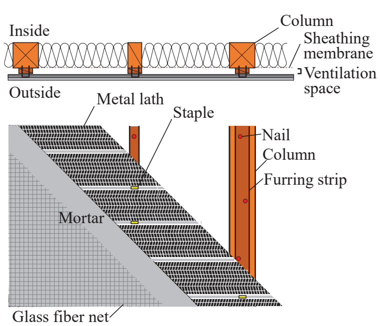

Figure 2. Single-layer system of lath-mortar external wall

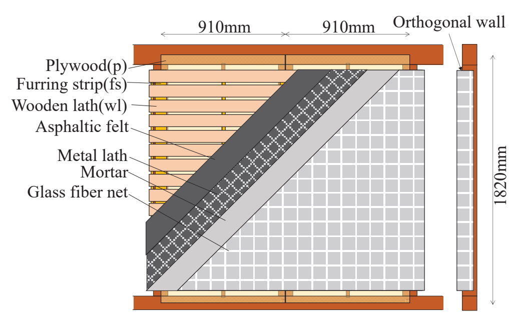

Figure 3. Double-layer system specimen with plywood (pD)

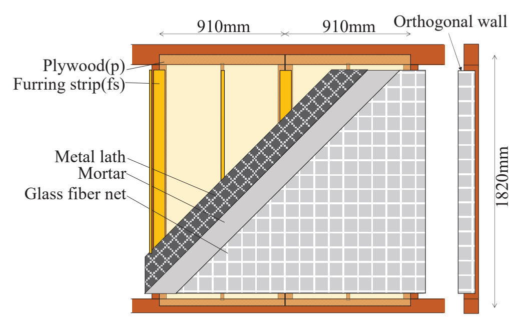

Figure 4. Single-layer system specimen (pS)

Table 1. List of lath-mortar specimen

<table>
<tr><th rowspan="2">Specimen</th><th rowspan="2">Plywood</th><th colspan="2">Furring strip</th><th colspan="2">Wooden lath</th><th rowspan="2">Lath-mortar</th></tr>
<tr><th>Thickness</th><th>Nail</th><th>Thickness</th><th>Nail</th></tr>
<tr><td>p</td><td rowspan="3">○</td><td>—</td><td>—</td><td rowspan="2">—</td><td rowspan="2">—</td><td rowspan="3">—</td></tr>
<tr><td>p-fs</td><td rowspan="7">15mm</td><td rowspan="5">N65</td></tr>
<tr><td>p-fs-wl</td><td rowspan="3">13mm</td><td rowspan="3">N50</td></tr>
<tr><td>D</td><td>—</td><td rowspan="6">○</td></tr>
<tr><td>pD</td><td rowspan="2">○</td></tr>
<tr><td>pS</td><td>—</td><td>—</td></tr>
<tr><td>Dm</td><td rowspan="3">—</td><td>N45</td><td rowspan="3">13mm</td><td>N38</td></tr>
<tr><td>Dn</td><td>—</td><td>N65</td></tr>
<tr><td>Dt</td><td>21mm</td><td>N65</td><td>N50</td></tr>
</table>

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3 – STATIC SHEAR LOADING TEST RESULT

3.1 LOAD-CARRYING CHARACTERISTICS

Fig. 6 shows the shear force-drift angle relationships of all specimens. Specimen p-fs-wl, pD, and pS show over 30 kN in maximum shear force. It suggests that plywood worked effectively in rising shear forces.

Fig. 7 shows skeleton curves of shear force-drift angle relationships of the specimens. The Specimens, p, D, Dn, and Dt show a maximum shear force of about 15 kN. In the specimen Dm, though the shorter length of the nails on the furring strips and wooden laths decreased the maximum shear force slightly, there was no remarkable drop in shear force until 1/15 rad.

Comparing the specimens p and p-fs, it is found that nailing the furring strips through the plywood increases the maximum shear force to 24 kN, 1.5 times as much as the p specimen. Moreover, nailing the wooden laths on the furring strips, the maximum shear force rose to 34 kN, which is as much as the specimen pS.

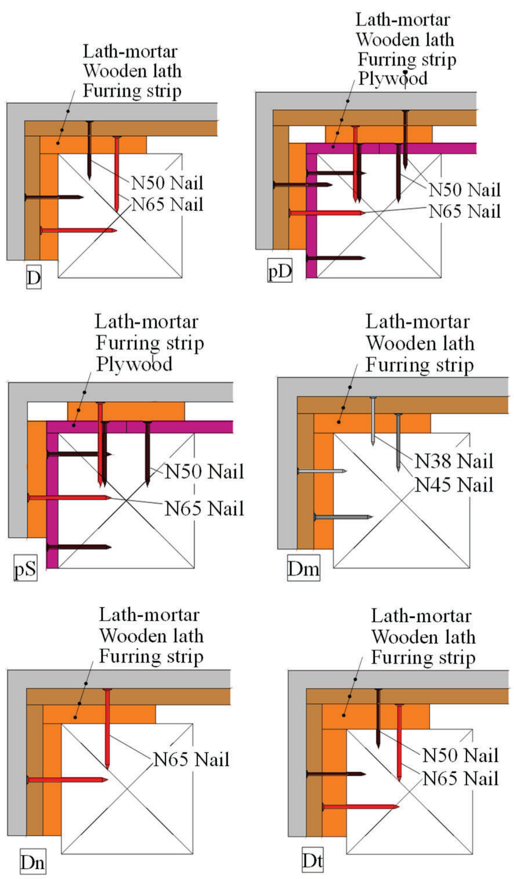

Figure 5. Cross-section of lath-mortar specimen.

The maximum shear force of the specimen pD, which was applied lath-mortar on the wooden laths, reached 38 kN, the effect of lath-mortar was estimated to be 4 kN. In the specimens p-fs-wl and pD, the columns broke at the lower hold-down connector during loading of 1/20 rad.

3.2 DAMAGES ON SPECIMENS

Using a motion capture system, the X, Y, Z coordinates of markers attached to each member were recorded. And then, from the coordinates, the rotation angles of each member were calculated as shown in Fig. 8.

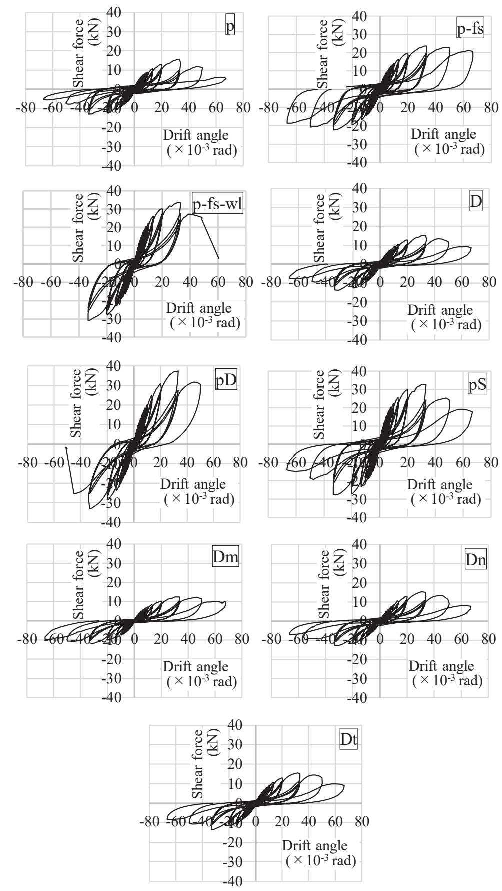

Figure 6. Shear force-drift angle relationship.

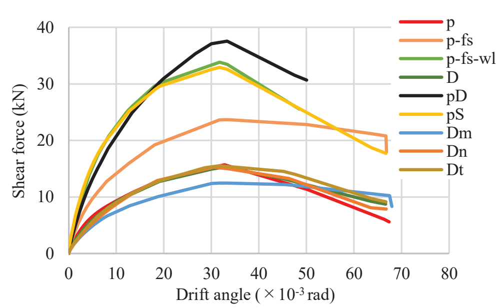

Figure 7. Skeleton curves of shear force-drift angle relationship.

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The rotation angle of p specimen was almost the same level as the drift angle. In specimen D, the lath-mortar's rotation angle was only 0.013 rad (1/75 rad) at 1/15 rad because the orthogonal walls constrained the rotation. However, the rotation angles of the other components were significantly larger than those of the lath-mortar, causing the staples fastening the lath-mortar to the wooden laths to either withdraw or break. Specimens Dn and Dt exhibited the same trend as specimen D.

In specimens pD and pS, the rotation of the plywood, the furring strips, the wooden laths, and the lath-mortar was constrained by the orthogonal walls. Consequently, the nails fastening the plywood to the timber frame withdrew or broke.

In specimen Dm, there were gaps in the rotation angles between the wood frame and the furring strips, as well as between the furring strips and the wooden laths. In the specimen, it was observed that the nails at both boundaries withdrew.

4 – FEM ANALYSIS

4.1 OUTLINE OF FEM MODELING

To predict a shear force-drift angle relationship and failure mode of the lath-mortar, FEM is one of the helpful tools. One major issue for building FEM model of lath-mortar wall is to estimate shear force-displacement relationship of nail joints of layered members. In the specimen pD, for example, the nail fastening a furring strip passes through not only a furring strip but also plywood and reaches a column. Moreover, the nail fastening a wooden lath also passes through a wooden lath, a furring strip, and a plywood, as shown in Fig. 5.

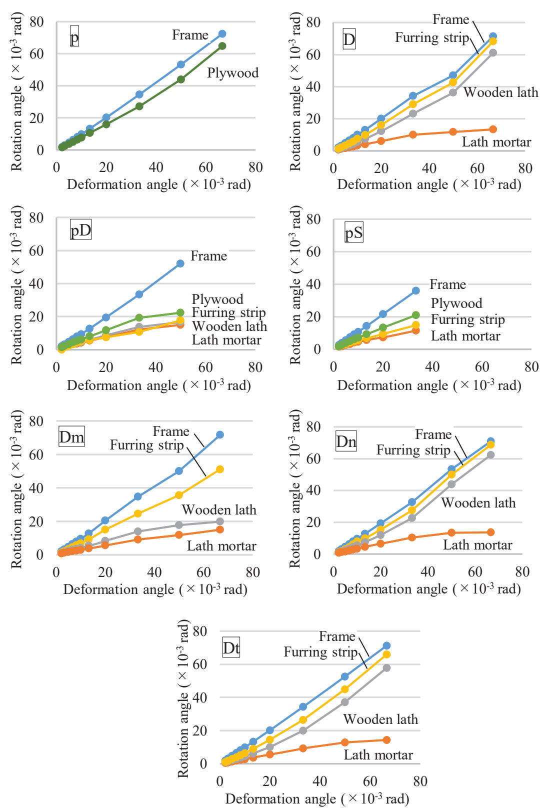

Figure 8. Rotation angle of each member

For this issue, an analysis model of the combined nail joint was built first, and then a static incremental analysis of the layered nail joint was conducted. Fig. 9 shows the analysis model in the specimen pD. For the pD specimen, one combined nail joint consists of 1.47-N50 nails fastening plywood, 0.44-N65 nails fastening a furring strip, and two-N50 nails fastening a wooden lath.

The shear force-displacement relationship derived from the combined nail analysis could be assumed to be of one joint. The analysis model of the lath-mortar wall would be simple by using the shear force-displacement relationship.

4.2 ANALYSIS MODEL

In the analysis model shown in Fig. 9, each nail has a sectional property of a designated number. Springs contain the bearing stiffness and yield stress of wood. The bearing stiffness was calculated by Equation (1), [4], while the yield stress was calculated by Equation (2) [4]. The second bearing stiffness after the yield was assumed to be 1/8 times as much as the initial bearing stiffness.

$$k_0 = E_0 / (31.6+10.9d) \tag{1}$$

$$\sigma_{y0} = 82(1-0.01d)\rho \tag{2}$$

where k_0 is the bearing stiffness parallel to the grain. E_0 is Young's modulus, and d is the diameter of the nail. σ_{y0} is the bearing yield stress parallel to the grain. ρ is specific gravity.

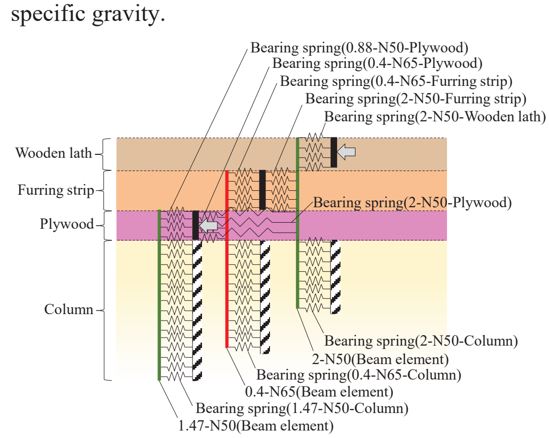

Figure 9. Rotation angle of each member

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The calculation assumed that E_0 = 7000 N/mm^2 and ρ = 0.4 for Japanese cedar, and E_0 = 10000 N/mm^2 and ρ = 0.5 for plywood. The Young's modulus of the nail was 205000 N/mm^2, and the bending yield stress was assumed to be 690 N/mm^2. Table 2 shows the calculated values.

Table 3 shows the number of nails composing the combined nail models of each wall specimen. In the pS specimen model, the springs and the nails related to wooden laths were eliminated from the pD specimen model.

The shear force-displacement relationships shown in Fig.10 are derived from a static incremental analysis of the combined nail models. Most of the results show yield points between about 1 to 2 mm. It was found that pD shows remarkably higher shear force than the other specimens. The shear force-displacement relationships were modeled into quadrilinear models for the next step, lath-mortar wall analysis.

As for a lath-mortar wall analysis model, as shown in Fig. 11(a), is composed of column elements representing a column and a lath-mortar, and non-linear springs representing the combined nail joints and staples. The combined nail joint springs adopted the quadrilinear models derived from the static incremental analysis of the combined nail joint. The lath-mortal was assumed to be rigid, and no rotation was considered due to the presence of the orthogonal wall.

In the specimens with plywood, such as pD and pS, a column element representing plywood was inserted between the combined nail spring and the staple spring as shown in Fig. 11(b).

With the lath-mortar wall analysis model, static incremental analysis was conducted. The shear force derived from the analysis was tripled for a comparison with the experimental result because the experimental specimen had three columns.

Table 2. Calculated bearing stiffness and yield stress

Nail	N38	N45	N50	N65	N50	N65
l (mm)	38	45	50	65	50	65
d (mm)	2.1	2.3	2.5	2.8	2.5	2.8
Sugi or Plywood	Sugi				Plywood	
E_0 (N/mm^2)	7000	7000	7000	7000	10000	10000
ρ	0.4	0.4	0.4	0.4	0.5	0.5
k_0 (N/mm^3)	128.5	123.5	118.9	112.7	169.9	161.0
σ_{y0} (N/mm^2)	32.1	32.0	32.0	31.9	40.0	39.9

l: Length of nail, d: Diameter of nail, E_0: Young's modulus of Sugi or plywood,
ρ: Specific gravity, k_0: Bearing stiffness parallel to the grain,
σ_{y0}: Bearing yield stress parallel to the grain,

Table 3. Number of nails composing combined nail joint

Specimen	Plywood	Furring strip	Wooden lath
D	–	0.4-N65	2-N50
pD	1.47-N50		
pS			–
Dm	–	0.4-N45	2-N38
Dn	–	–	2-N65
Dt	–	0.4-N65	2-N50

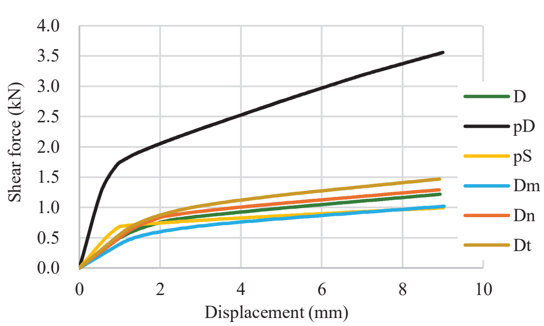
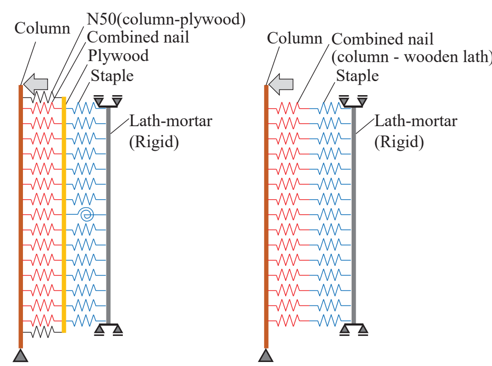


Figure 10. Shear force-displacement relationship of combined nail model



(a) D, Dm, Dn, Dt *(b) pD, pS*

Figure 11. Shear force-displacement relationship of combined nail model

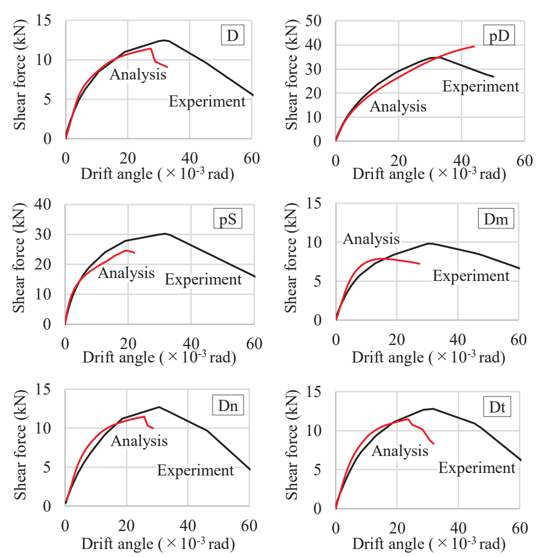


Figure 12. Shear force-drift angle relationship of analysis and experiment

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4.3 ANALYSIS RESULT AND DISCUSSION

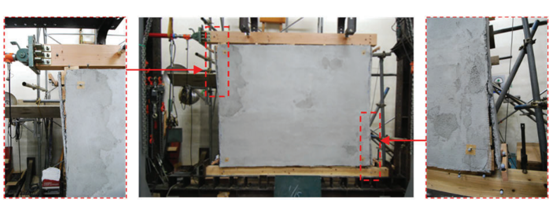
Fig. 12 shows the result of the static incremental analysis and the experimental result. The initial shear stiffness from the analysis is similar to that of the experiment in most of the specimens. However, the analytical maximum shear force was lower than the experimental value. It is considered that the reason was to adopt a low bearing stiffness and yield strength. They were derived using the equations for design that give conservative values. Another reason is that the confining effect of the orthogonal walls is not considered. During the loading in the experiment, the orthogonal wall rotated and was damaged as shown in Picture 1. It implies that the orthogonal wall confined the shear deformation of the lath-mortar wall.

As for the shear stiffness, though it was shown to be well estimated by the analysis, it is expected that the use of experimental bearing stiffness raises the shear stiffness. On the contrary, though the rotation of the lath-mortar was constrained in the analysis, using the realistic rotation stiffness lowers the shear stiffness. These facts cancel each other and show a good estimation. This shows a limitation of the simple one-column model. For further accurate analysis results, a more detailed analysis model considering the width of a wall is needed.

5 – CONCLUSIONS

This study was conducted to establish a structural model of the external wall with lath-mortar for FEM analysis. In static shear loading tests of lath-mortar external wall specimens, it was found that plywood between a timber framework and a lath-mortar increases the maximum shear force remarkably. And it was confirmed that the orthogonal wall constrained the rotation of the lath-mortar.

Before the lath-mortar wall analysis, combined nail joints were analyzed, and the shear force-displacement relationship of the combined nail joint was derived. Using the shear force-displacement relationship, a simple analysis model of the lath-mortar wall was able to be built. The analysis showed close initial shear stiffness to the experimental value in most specimens, however, lower maximum shear forces were shown than the experimental values.



Picture 1. Failure mode of orthogonal wall

6 – ACKNOWLEDGEMENT

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7 – REFERENCES

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