Effect of Testing Methods on the Mechanical Behaviors of Shear Walls composed of Wooden Plates

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Summary

The differences in mechanical behaviors of wooden shear walls were examined using three different methods, namely, no-dead-load type (leg-fixed type), dead-load type and tie-rod type. The experiments were performed on wooden plate walls. The resisting force ratios of various wooden shear walls (multiplier) of different types were compared. The shear walls used in this study were so-called “wooden plates shear wall” which had been used in traditional wooden structures as shear walls in Japan.

The key findings in this study are: (1) The multiplier of no-dead-load type (leg-fixed type) is the strongest among three testing types. (2) It is possible to calculate the initial stiffness of the shear wall by taking six elements such as the slip displacement between adjacent wall plates and embedment deformation of the wall plate to the beam into consideration.

1. Introduction

In Japan, there are three testing methods to evaluate the resisting force ratios of wooden walls (multiplier), namely no-dead-load type (leg-fixed type), dead-load type, and tie-rod type. The restraining conditions of the three testing methods are different and therefore, the effect of each method on the mechanical behaviors of the shear walls composed of wooden plates is of importance. The objective of this study is to investigate whether if there are existing different resistance mechanisms among these three testing methods.

2. Materials and Methods

2.1 Materials

Figure 1 shows a wooden plate wall specimen. The specimen was fabricated using Sugi (Cryptomeria japonica D.Don) wood, except the dowels which were made of Cypress (Chamaecyparis obtusa Endl.). The dowels for plate-plate interface joints were 18 x 18 mm in cross section. The dowels to joining a column to the base or a beam were 12 x 12 mm in...
cross section. All dowels were inserted tightly into the leading holes. The plates were slid along the grooves previously cut in the two columns. Nine specimens were hand-made by a traditional carpenter and set-up on the site for testing.

2.2 Methods

Three replications (specimens) were prepared for one testing methods. There were three methods in total as abovementioned, i.e. no-dead-load type (leg-fixed type), dead-load type, and tie-rod type. The no-dead-load testing method fixes columns directly to the base of the testing frame using hold-down plates as shown in Figure 2 a). Other testing methods fix the sill to the base of the testing frame with anchor bolts. The dead-load testing method applied a pair of vertical load on the top beam of the shear wall to simulate the dead-loads by using so-called pulley and wire loading system as shown in Figure 2 b). The tie-rod testing method places a pair of tie-rods between the base of testing jig and the top beam of the specimen to restrict the up-lift of the specimen as shown in Figure 2 c).

In this study there were three types of dead-load. In the first type, the dead-load was 1.96kN/m as specified in the “Allowable stress design of the post and beam wooden housing” [1]. The loads in the second and third types were set at 3.92kN/m and 7.84kN/m, respectively. In the first type of no-dead-load method, the anchor bolts were not used to connect the column to the beam.

A shear wall specimen was subjected to cyclic loads. Each cycle was repeated three times following the same schedule. The shear deformation angle was controlled up of 1/30 radian. After that the specimen was pulled out to the limit of the hydraulic jack’s stroke. All the specimens were anchored to the base of the testing frame.

Fig. 2. Three testing methods.

3. Results and Discussion

3.1 Results of the shear wall tests and comparison of the testing methods

Figure 3 shows the curve of load-deformation angle with the results of each testing method. These curves vary a lot among three testing methods in terms of the shear deformation angle. The resisting
force ratio of wooden walls (multiplier) was calculated for each testing method using a ‘perfect bi-linear approximation’ [2]. As the automatic evaluation method by using computer based on the elasto-plastic approximation did not give correct values, we evaluated each multiplier by using shear forces recorded at 1/120 or/and 1/150 rad. Table 1 gives the results. The no-dead-load type (leg-fixed type) exhibits the largest multiplier among the three methods. The dead-load has little influence on the multipliers. The tie-rod type shows intermediate values between the no-dead-load and the dead-load types. Due to the use of anchor bolts in the tie-rod type and the dead-load type is slightly looser than the hold-down anchors.

Additionally, Table 1 shows the multiplier of excludes the influence of axial force in the dead-load type and the tie-rod type. These methods accompanied axial forces due to dead load or/and the restricted stress by tie-bar. It was found that the axial force did not give a significant influence on the tie-rod type, but gave a strong impact on the dead-load type.

The failure modes are different among three testing methods. Photographs 1 to 3 show the common failure modes of shear walls using each testing method. The no-dead-load type of the walls shows a tensile failure of the hold-down steel plate. The dead-load type of walls experiences a failure between the tenon and the dowel. The tie-rod type of walls does not fail.

Table 1. The results of the resisting force ratio of various wooden walls.

<table>
<thead>
<tr>
<th></th>
<th>Dead Load</th>
<th>No Dead Load</th>
<th>Tie-rod</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.96kN/m</td>
<td>3.92kN/m</td>
<td>7.84kN/m</td>
</tr>
<tr>
<td>Multiplier</td>
<td>1.2</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Average</td>
<td>1.3</td>
<td>2.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Multiplier (excluded the influence of axial force)</td>
<td>1.0</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Average</td>
<td>1.0</td>
<td>1.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Fig. 3. Load-deformation angle relationship of shear walls tested.

Photo 1. No-dead-load type.  
Photo 2. Dead-load type  
Photo 3. Tie-rod type did not fail.
3.2 Contributions of each element to the total deformation of the shear wall

The deformation mechanisms of a wooden plate shear wall is considered by taking six elements into account, which include the slip displacement between adjacent wall plates, embedment deformation of the wall plate to the beam, and so on. Inayama (2003)[3] indicated that these six elements are important because the deformation of a wooden plate shear wall can be calculated as the sum of displacements of these elements. Figure 4 illustrates these elements and the corresponding formulas are as follows.

(1) The initial slip displacement due to the space between the column and the wall plates.
(2) The slip displacement between adjacent wall plates.
(3) The shear deformation of the wall plates.
(4) The embedment deformation of the compressive zone.
(5) The embedment deformation between the wall plates and the column.
(6) The embedment deformation between the wall plates and the beam or the sill.

![Fig. 4. Deformation elements of a shear plate wall](image)

The following formulas were derived empirically.

\[
K_d = a \times n_d \times k_d
\]

\[
K_s = G \times L \times t
\]

\[
K_a = \frac{E_0 \times L \times t}{2\log(L \cos \theta) + \left(\frac{1}{\cos^2 \theta}\right) - 2}, \quad \theta = \tan^{-1}\frac{H}{L}, \quad E_\theta = \frac{E_o}{50 \sin^2 \theta + \cos^2 \theta}
\]

\[
K_e = \frac{a \times H \times t \times C_{yc} \times E_{\perp c}}{4d_c}
\]

\[
K_b = \frac{L^3 \times t \times C_{yb} \times E_{\perp b}}{15Hdb}
\]

\[
C_{yc} = 1 + \frac{4d_c}{3nt} \left(1 - e^{-\frac{3n(B-t)}{4d_c}}\right), \quad C_{yb} = 1 + \frac{4d_c}{3nt} \left(1 - e^{-\frac{3n(B-t)}{4db}}\right)
\]

Legends:

- \(L\): inner size width of wooden plate of the wall
- \(H\): inner size height of wooden plate of the wall
- \(a\): width of the wooden plate, \(t\): thickness of the wooden plate
- \(d_c\): column width, \(d_b\): beam height
- \(B\): depth of the column and the beam
- \(E_\parallel\): Young’s modulus parallel to the grain of the wooden plate
- \(G\): modulus of shearing elasticity
- \(k_d\): shearing stiffness of a single dowel
- \(n_d\): number of dowels on the each layer
- \(E_{\perp c}\), \(E_{\perp b}\): Young’s modulus perpendicular to the grain of the wooden plate, the column, and the beam, respectively
3.3 Shear deformation of connection between plates

It was found that the slip deformation has a strong impact on the total deformation of a shear wall. Therefore it is deduced that the axial force might influence the shearing stiffness, which can be examined by partial tests of connection between plates. Figure 6 illustrates the testing method. The specimen was taken from a wooden plate shear wall test specimen.

Three different axial forces were pre-loaded by jigs up to 0.00N/mm², 0.18 N/mm², and 0.36 N/mm², representing no stress, stress of the maximum dead load by dead-load type, and stress of restricted tie-bar when 1/60rad by tie-rod type, respectively.

Figure 7 shows the relationship between load and displacement of the partial shearing tests. It was found that the preload had an influence on the static friction, but gave little influence on the stiffness after relative displacement occurred along the connecting part between plates. Generally, the coefficient of dynamic friction is increase by increasing the preload or the weight. However, such a relation has not been found prior to this study.

Table 2 shows the results on initial stiffness between wooden plates based on the partial tests and the slip stiffness between the adjacent wall plates observed in the full scale tests. In this case, the slip stiffness between adjacent wall plates is calculated as the secant stiffness from 10% to 40% of the maximum load on Figures 5 and 7. As a result, the initial stiffness from the partial shearing tests without the preload in the dead-load type (7.84kN/m) is smaller. But it is shown influence the dead
load has an on the preload for the adjacent wall plates by comparison of initial stiffness for each dead load. Therefore, it is thought that the slip stiffness based on full scale tests is influenced by the other slipping elements. In no-dead-load type, it is estimated that the tightening axial force of the hold-down plates and bolts is almost 0.32 kN/mm², if relationship between the partial shearing tests initial stiffness and the preload are liner.

It can be seen that there exist an excellent agreements between calculated values based on partial shearing tests and observed values in full scale tests for the no-dead-load type (leg-fixed type) and the tie-rod type. Especially in the no-dead-load type, the stiffness between adjacent wall plates is very close to the initial stiffness calculated from partial tests. In the tie-rod type, it is possible to explain the difference in stiffness between calculated values and test results by subtracting the initial slip displacement due to the space between the column and the wall plates. But in the

**Table 2. Comparison of initial stiffness between full scale tests and partial tests.**

<table>
<thead>
<tr>
<th>Dead Load</th>
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<tbody>
<tr>
<td>1.96 kN/m²</td>
<td>3.92 kN/m²</td>
<td>7.84 kN/m²</td>
</tr>
<tr>
<td>0.91</td>
<td>0.96</td>
<td>1.27</td>
</tr>
<tr>
<td>0.00 N/mm²</td>
<td>0.18 N/mm²</td>
<td>0.36 N/mm²</td>
</tr>
<tr>
<td>1.55</td>
<td>2.03</td>
<td>2.73</td>
</tr>
</tbody>
</table>

unit: kN/mm

Figure 8 compares the calculated initial stiffness values based on the preload testing results and the full scale tests. The continuous grey curves show the load-deformation relationship from full scale tests and linear lines indicate the calculated stiffness values based on the partial shearing tests shown in Fig. 6 (The preload ranges from right to left side 0.00 N/mm², 0.18 N/mm², and 0.36 N/mm²).

Figure 8 shows the calculated initial stiffness values based on the preload testing results and the full scale tests. The continuous grey curves show the load-deformation relationship from full scale tests and linear lines indicate the calculated stiffness values based on the partial shearing tests shown in Fig. 6 (The preload ranges from right to left side 0.00 N/mm², 0.18 N/mm², and 0.36 N/mm²).

It can be seen that there exist an excellent agreements between calculated values based on partial shearing tests and observed values in full scale tests for the no-dead-load type (leg-fixed type) and the tie-rod type. Especially in the no-dead-load type, the stiffness between adjacent wall plates is very close to the initial stiffness calculated from partial tests. In the tie-rod type, it is possible to explain the difference in stiffness between calculated values and test results by subtracting the initial slip displacement due to the space between the column and the wall plates. But in the
dead-load type, it is difficult to explain this disagreement using the same assumption as that of tie-rod type, because there was a large initial slip displacement and the deformation of the up-lift between the column and sill.

It is clear that the behavior of the shear wall composed of the wooden plates is dependent on the testing method. The firm restriction of the up-lift between the column and the sill is important. It is in plan to develop a new calculation model including the up-lift of the column and the sill.

4. Conclusion

Based on the above results and discussion, the following conclusions would be drawn:

(1) The no-dead-load type (leg-fixed type) exhibits the largest multiplier (2.1) among the three methods and the dead-load type has a slight influence on the multipliers.

(2) The slip displacement between adjacent wall plates differs for each testing method.

(3) The partial shearing tests of the plate to plate connection give different results at different preload levels.

(4) The preload has influence on the static friction, but it has little influence on the stiffness after relative displacement occurred along the connection between plates.

(5) It shows a good agreement between the calculated initial stiffness of the full scale shear wall tests and partial shearing tests, with only exception from the dead-load type.

5. References


Acknowledgements

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