World Conference on Timber Engineering Oslo 2023

EXPERIMENTAL STUDY ON IN-PLANE SHEAR PERFORMANCE OF CROSS-LAMINATED TIMBER

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ABSTRACT: The in-plane shear performance of CLT using the asymmetric four-point bending test method was conducted to examine the test conditions. The parameters of specimens were the span, the height, the layups and the loading direction. As a result, it was found that the bending failure occurred when the span ratio was 1.25 times. This suggests that shear failure may occur reliably below the span ratio was 1.0 times. The shear strength was increased when loaded with the same lamina at the span ratio of less than 0.5 times. Therefore, it is recommended that the span ratio was 0.5 to 1.0 times to adapt for CLT in-plane shear testing method. The shear strength and the percentage of perpendicular layers were positively correlated, suggesting that shear strength may be estimated in a simplified manner. The diagonal measurement of shear modulus is considered to be the easier way to calculate the shear modulus, as it does not require any concern for the grain direction. The shear modulus values ranged from half to four times higher than the design values in Japan. A comparison of the shear strength and shear modulus between values in the reference using other testing methods and the experimental values in this study shows a tendency to show different values. This may be due to the different shear section areas of the specimens depending on the test method and the different restraint conditions.

KEYWORDS: Shear performance, Cross-laminated timber, Asymmetric four-point bending test

1 INTRODUCTION

Currently, the utilization of wood is promoted around the world since the environmental problem became serious. To increase the utilization of timber in buildings, the tall and large-scale wooden buildings are getting important. CLT is attracting attention because it has high shear performance and the usage ability of a large amount of wood. Therefore, CLT is used at walls and floors in wooden large structures. If CLT is used as earthquake-proof walls, the horizontal force applies at the in-plane direction of CLT panel. As the structure becomes larger, the in-plane shear force increase. Therefore, it is important to understand the in-plane shear performance of CLT.

However, the method for evaluating the in-plane shear performance of CLT is not established. We focused on the asymmetric four-point bending test method as shown in Figure 1 from among multiple test methods[1)-4)], because the method has the advantage that the stress control of bending and shear is easy. The span of the method for lumber and glulam is set by Japan Housing and Wood Technology Center (HOWTEC)[5)]. There are also existing studies using this test method for lumber[6),7)], glulam[8)] and MDF[9)], but there are almost no studies using it for CLT have been found[10)]. Therefore, it is not established about CLT, so it needs to investigate to adapt on CLT. Particularly with regard to the in-plane direction of CLT, appropriate test methods are difficult to implement, as bending and embedment failures may occur.

In this study, it was investigated the in-plane shear performance of CLT; the parameters of the targets are the loading span, loading direction and specimen's height. In addition, shear deformation is measured using three different measurement methods, and the simplest and most suitable measurement method is investigated. This study aims to propose the test method and measurement method of in-plane shear for CLT.

2 OUTLINE OF EXPERIMENT

Table 1 shows the specifications of the specimens. As shown in Figure 2, specimen's layups were set to 3 layers 3 plies, 4 layers 4 plies, 5 layers 5 plies. 4 layers 4 plies CLT is not standard used layups, but was used to study the differences in deformation under the same stress, as the front and back sides have different the grain directions. All specimens were made of *Japanese Cedar* (*Sugi*). The 3 layers 3 plies and 5 layers 5 plies have two load directions which are in major axis and minor axis against in-plane bending.

As shown in Figure 1, the testing method was the asymmetric four-point bending test method, the supporting and loading spans were 1 to 2 times as specimen's height. And the span of between supporting and loading span minus loading plate width (S-w_p), divided by specimen's height(d) is called span ratio. Here, it was named the major and the minor axis as shown in

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https://doi.org/10.52202/069179-0017

Table 1: *List of specimens*

Layups	width×height (mm)	{Span(S) – Width of plate(w_p)} / height(d) ratio	Loading direction	Density (kg/m³)	Moisture (%)	Number of specimens
3 layers 3 plies	90×240	0.5	Major	410±50	11.9±1.1	Each 6 Total 12
		0.75	Minor			
4 layers 4 plies	120×240	0.5・0.75・1.0		438±36	11.6±0.7	Each 6 Total 18
5 layers 5 plies	150×120 150×360	0.25・0.5・0.75・1.0・1.25	Major	463±24	10.1±0.6	Each 3 Total 60
		0.5・0.75・1.0・1.25・1.5	Minor			

Figure 3. The major axis outer laminae are grain perpendicular to the loading direction, and the minor axis outer laminae are grain parallel to the loading direction. The width of the loading and supporting plate were set to 3/4 of the specimen's height for the major axis, and 1/2 for minor axis and 4 layers 4 plies in consideration of the compression stress. The loading rate was 1 mm/min and the load was applied until the load dropped to 0.8 P_{max} after the maximum load was reached.

The 4 layers 4 plies have different grain directions on the front and back side. Here, they were named the pe side and pa side as shown in Figure 4. The sides were determined in the loading direction and grain direction. As shown in Figure 5, the shear strain was measured by three ways. The shear modulus values calculated by each measurement methods are called as G_h, G_v and G_d respectively.

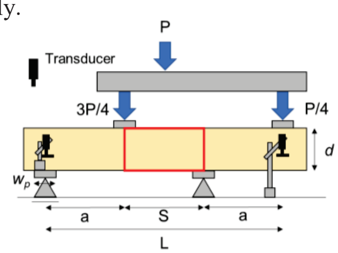


Figure 1: *Test method and measurement*

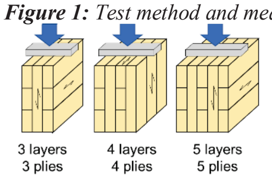


Figure 2: *Layups*

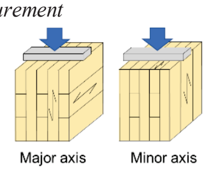


Figure 3: *Loading direction*

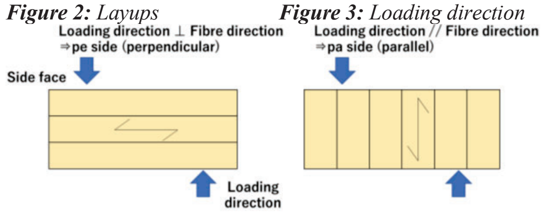


Figure 4: *Loading side of 4 layers 4 plies*

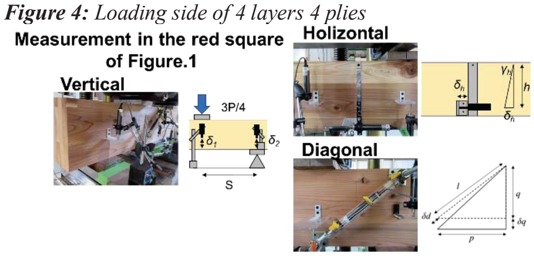


Figure 5: *Measurement of displacement*

3 RESULTS AND DISCUSSIONS

3.1 FAILURE MODES

The mainly failure phenomenon are shown in Figures 6 to 8. As shown in Figure 6, bending failure occurred in a part of the span ratio 1.25*d* and 1.5*d*. Shear failure occurred in the parallel layer as shown in Figures 7 and 8. Mode I failures were common on the major axis and pe side, while Mode III failures were common on the minor side and pa side as shown in Figure 9[11]. In the shear failure specimens, there was no difference in the failure phenomenon depending on the span ratio. Bending failure may occur if the span ratio is 1.25*d* or more, therefore the span ratio must be set to less than 1.0*d*.

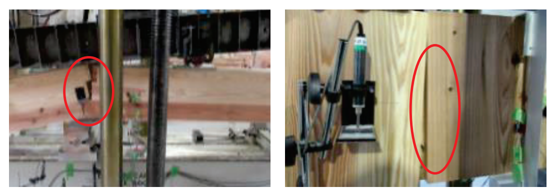


Figure 6: *Bending failure*
(Left: Major axis on 1.25d, Right: Minor axis on 1.5d)

Figure 7: *Shear failure*
(Left: Mode I, Major axis, Right: Mode III Minor axis)

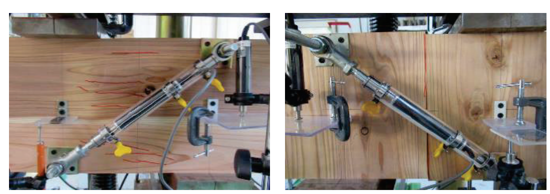


Figure 8: *Shear failure of 4 layers 4 plies*
(Left: Mode I, pe side, Right: Mode III, pa side)

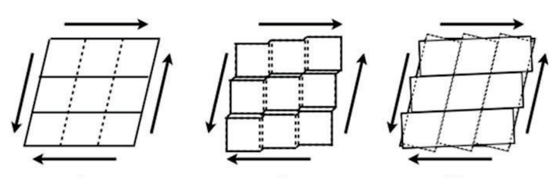


Figure 9: *Definition of shear deformation* [11]

https://doi.org/10.52202/069179-0017

3.2 SHEAR STRENGTH

The relationship between the span ratio and shear strength is shown in Figure 10. The reference value, which is the CLT Construction Manual in Japan (CLT-Manual-J)[12], is also shown in Figure 10. The value of the major axis was higher than that of the minor axis regardless of the span. In addition, the effect of specimen's height was small and the shear strength showed almost the same value in the minor axis of 120mm and 360mm. The experimental value was approximately 1.09 to 3.01 times that of the reference value. In the 120mm specimens, some high values were shown in a small span ratio. In this case, the specimen's height is small, the shear area is also short and there had only one vertical lamina in the shear area as shown in Figure 11. Therefore, the loads were applied to each end of one lamina, and the high struts occurred on one lamina as the vertical compression. Thus, it is necessary to consider the test conditions so that the lamina boundary is within the shear section. For larger heights, a size of 240mm is considered appropriate as the increased volume makes testing more difficult. A span ratio of 0.5 to 1.0*d* is considered a desirable span ratio, where bending failure does not occur and the same lamina is less likely to be loaded. In terms of layups, the major axis was higher than the minor axis in 3 layers 3 plies and 5 layers 5 plies. The factor was considered to be the proportion of perpendicular layers in the total layer thickness.

The relationship between the percentage of perpendicular layers and shear strength is shown in Figure 12. Mode I to III indicate the shear strength of each mode as determined by the shear reference strength calculation formula in the CLT Manual J[12].The calculation formulas for Mode I～III are shown in Equation(1).

$$F_s = min\begin{cases} f_{v,lam} \\ f_{v,lam90}\cdot\dfrac{t_{net}}{t_{gross}} \\ \dfrac{b\cdot n_{ca}}{2t_{gross}}\cdot\dfrac{1}{\dfrac{1}{f_{v,tor}}\cdot\left(1-\dfrac{1}{m^2}\right)+\dfrac{2}{f_R}\cdot\left(\dfrac{1}{m}-\dfrac{1}{m^2}\right)} \end{cases} \quad (1)$$

$f_{v,lam}$:Shear strength of parallel to the grain
$f_{v,lam90}$:Shear strength of perpendicular to the grain
t_{net} :Thickness of perpendicular to the grain
t_{gross} :Thickness of the CLT
b :Width of lamina
n_{ca} :Number of perpendicular bonded layers of CLT
$f_{v,tor}$:Torsional shear strength of the intersecting surfaces of two perpendicular bonded lamina
m :Lowest value out of the number of lamina in each layer in the width direction
f_R :Rolling shear strength

Figure 12 shows that the percentage of perpendicular layers and the experimental values are positively correlated, with a transition close to mode II. The approximate equation y=10x for the proportion of perpendicular layers x, suggesting the possibility of a simple shear strength estimate. Mode II is a failure caused by shear deformation the perpendicular lamina at the edge, but the failure was observed in this study. The calculation formula, experimental values and failure properties show different fracture mode tendencies. The factor is considered to be influenced by the test method and is an issue for further study. The range of perpendicular layer percentages in this study includes the Japanese Agricultural Standard (JAS)[13] for CLTs other than 5 layers 7plies. Further studies should be conducted on 3 layers 4 plies, where the proportion of perpendicular layers is 50% the same as with 4 layers 4 plies. In addition, 5 layers 7 plies should also be considered in the further studies. Figure 14 shows the relationship between shear strength and air-dry density, and Figure 15 shows the relationship between shear strength and moisture content calculated by the oven-dry testing. The approximate straight line, approximate equation and coefficient of determination are shown respectively. Neither showed much correlation and the results were almost unchanged. The slope of the approximate line and the value of the coefficient of determination also indicate that there is no correlation between density and moisture content and shear strength in the results of this study.

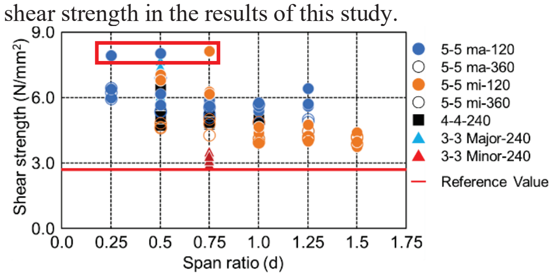


Figure 10: *Relationship between span and shear strength*
Example of notation
5 layers 5 plies, major axis, height is 120mm ⇒ 5-5ma-120

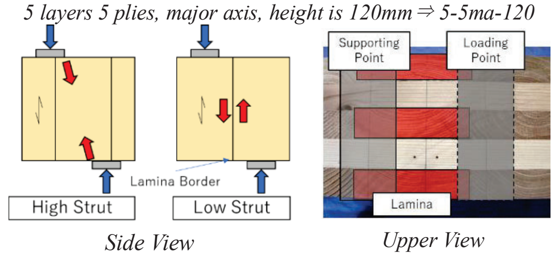


Figure 11: *Loading point and struts*

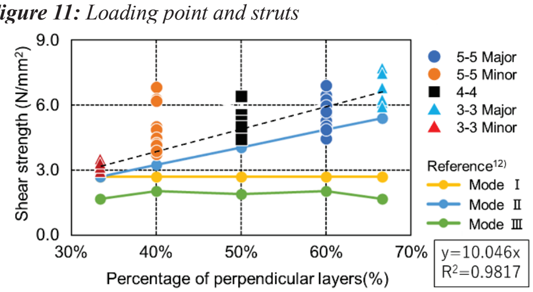


Figure 12: *Relationship between percentage of perpendicular layers and shear strength*

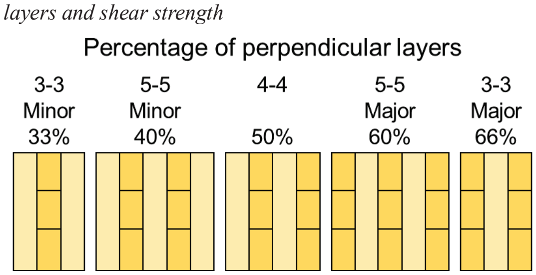


Figure 13: *Image of percentage of perpendicular layers*

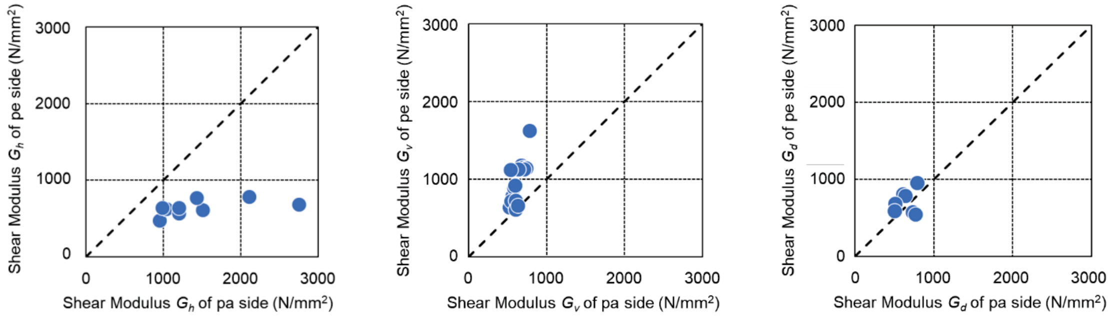
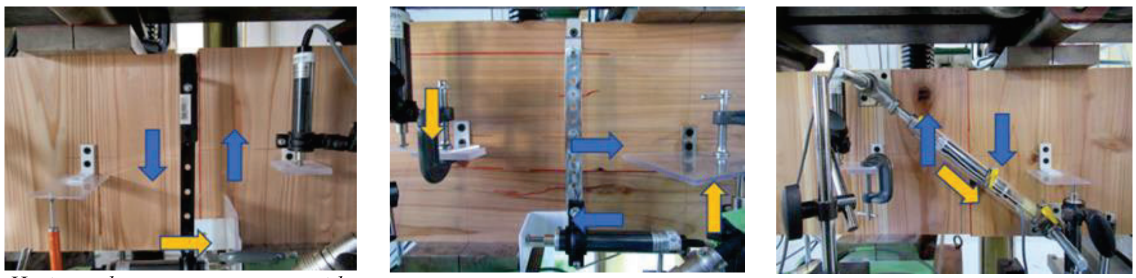


Figure 16: *Relationship between pa side and pe side of shear modulus*



Horizontal measurement on pa side *Vertical measurement on pe side* *Diagonal measurement on pa side*

Blue arrow: grain direction (transformation) Yellow arrow: measurement direction

Figure 17: *Measurement direction of each side*

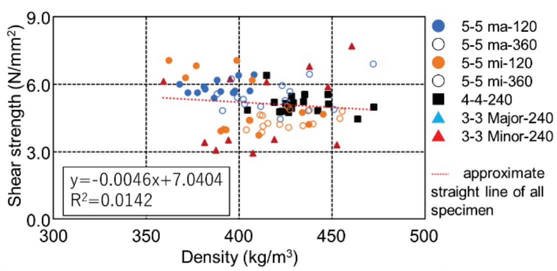


Figure 14: *Relationship between density and shear strength*

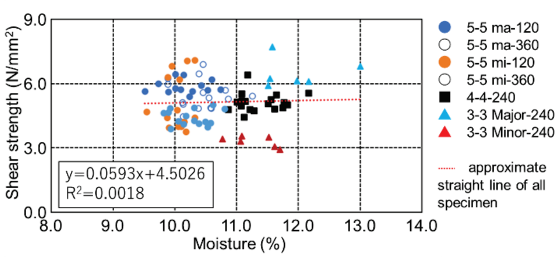


Figure 15: *Relationship between moisture and shear strength*

3.3 DIRECTIONS OF SHEAR MODULUS

Figure 16 shows the shear modulus for the pa side and pe side of 4 layers 4 plies for each measurement method. As the 4 layers 4 plies has different grain directions on the front and back, it was thought possible to study the differences in deformation due to the grain direction under the same stress.

The vertical and horizontal axes are the pe side and pa side, respectively. In G_h shown on the left, the pa side showed higher values than the pa side. In contrast, the pe side showed higher values for G_v shown on the middle. On the side with high values, the measurement direction was perpendicular to the grain direction on each surface as shown in Figure 17. Therefore, the horizontal and vertical measurement should be measured parallel to the grain. In G_d shown on the right, the shear modulus showed 500-1000N/mm^2 with small differences in each side. This is due to the fact that the diagonal measurement has a wider measurement range and can measure deformations in any direction. Therefore, diagonal measurement is less affected by the grain direction and is considered to be an easier measurement method. It is also considered a simple measurement method, as it does not require any concern for the direction of the grain.

3.4 SHEAR MODULUS

The relationships between the span ratio and shear modulus by each measurement methods in Figures 18-20. The legend is the same as in Figure 10. The values indicated in the CLT-Manual-J[12] are called reference values and are compared. The horizontal and vertical measurement methods in the previous section showed high values for the values measured in perpendicular to the grain direction. Therefore, for G_h and G_v in the 4 layers 4 plies, the values measured on the side parallel to the grain direction were used. For G_d, the difference between the values of the two sides was small, so the average value of the two sides was used. Figures 18-20 show that the values for the 4 layers 4 plies were higher than the reference values, ranging from 500-1000 N/mm^2 for all measurement methods. The horizontal measurement method showed a wide range of values, with a particularly large variation in the minor axis. Specimen height had no effect on the shear modulus. For span ratio, a negative correlation is observed for G_v and G_d, suggesting that bending deformation is affected. However, G_v and G_d are

https://doi.org/10.52202/069179-0017

considered to be suitable measurement method for shear deformation, as they show a smaller range of values than G_h. And they are closer to be reference value. In particular, G_d is considered to be a more suitable measurement method because its highest value is around 1000 N/mm^2 and it is easy to measure as mentioned above. A reason for the different variation in values is the difference in the measurement range. G_h is measured at the center of the specimen, whereas G_v and G_d are measured at over a wider area (including more lamina boundaries in parallel and perpendicular layers) between the inner supporting and loading points. Therefore, it is considered that the inclusion of the deformation of the entire CLT is a factor. These results suggest that the shear modulus is negatively correlated with the span ratio, that over test conditions have little influence. And that the diagonal measurement method is close to the reference value and stable because it is measured over a wide range.

3.5 COMPARE WITH OTHER TESTING

Figures 21 and 22 show a comparison with experimental values and reference values for full-scale horizontal loading testing[14)-15)], which are often used as in-plane shear testing for CLT. Only data from the same tree species used in this study were used in the reference. The shear modulus is based on values of diagonal measurement.

In the relationship between shear strength and the percentage of perpendicular layers shown in Figure 21, the values in the reference show a sideways trend that differs from the values in this study. The results of the 3 layers 3 plies (33%) in this study and the reference are also close. However, for the other layups, the divergence of the values according to the test method is greater, with an average difference of approximately 2.3 times the value for the percentage of perpendicular layers of 66%.

In the relationship between shear modulus and the percentage of perpendicular layers shown in Figure 22, the reference values show a slightly negative correlation, whereas the values of this study show a positive correlation. Specimens with 50% of perpendicular layers showed close values regardless of the test method and layups.

Thus, a comparison of the shear strength and shear modulus between values in the reference values using other test methods and the experimental values in this study shows a tendency to show different values. This may be due to the different shear section areas of the specimens depending on the test method and the different restraint conditions. The differences in performance between test methods are a subject for further study.

4 CONCLUSIONS

The asymmetric four-point bending test was conducted on CLT to investigate the effects of layups, span ratio, height and loading direction on shear strength and shear modulus. For shear strength, it was found that the height and span ratio did not have a significant effect. The results for the 4 layers 4 plies showed values around the major and minor axis of 5 layers 5 plies. The difference in between 3 layers 3 plies depending on the loading direction suggests that

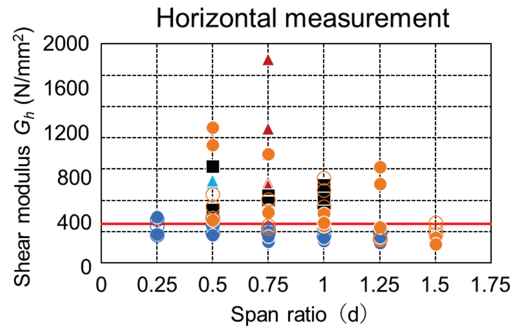


Figure 18: *Relationship between span and shear modulus G_h*

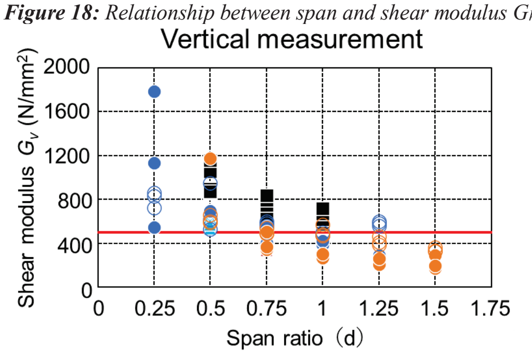


Figure 19: *Relationship between span and shear modulus G_v*

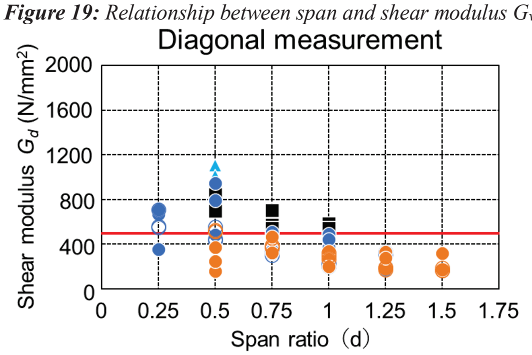


Figure 20: *Relationship between span and shear modulus G_d*

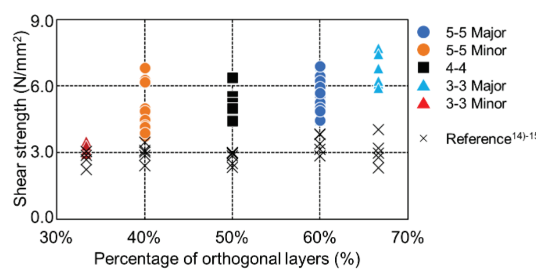


Figure 21: *Comparison with experimental values and reference values of shear strength*

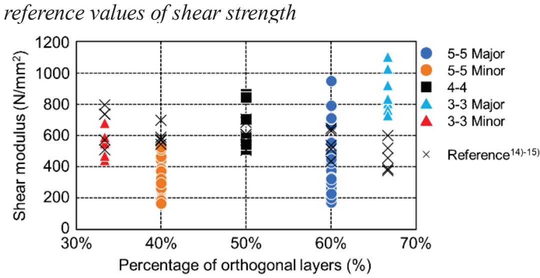


Figure 22: *Comparison with experimental values and reference values of shear modulus*

the percentage of perpendicular layers in the overall thickness may have an effect on shear strength. For shear modulus, the measurement in the diagonal direction (Gd) showed the least variation. In addition, it showed values close to those in the CLT-Manual-J[12] and is considered to be less affected by the grain direction. Based on these results, the method is considered to be an appropriate method for measuring deformation.
Based on the above results, it is considered that the appropriate test conditions are;

- The specimen's height should be 240 mm or more (two or more lamina in the direction of height)
- The span ratio should be in the range of 0.5-1.0*d*, avoiding bending failure and loading with the same lamina
- The layups are influenced by the percentage of perpendicular layers
- The shear strength is positively correlated with the percentage of perpendicular layers, suggesting that shear strength could be estimated in a simplified manner
- The measurement method is recommended because it is easier to measure in the diagonal direction.

Future research should include experiments on specimens with different proportions of perpendicular layers to investigate the relationship with shear strength and failure modes.

ACKNOWLEDGEMENT

We would like to thank all the students in the laboratory for their cooperation in conducting the experiment. Part of this study was based on the Architectural Institute of Japan Chugoku Branch Incentive Research Grants 2022. We would like to express our gratitude for all support.

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