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DEVELOPMENT OF HYBRID MULTI-ANGLED LAMINATED TIMBER PLATE FOR MITIGATING ORTHOTROPY

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ABSTRACT: Recently, as global efforts intensify against climate change and the pursuit of carbon neutrality gains prominence, timber has been gaining more attention for its carbon-fixing properties. Its recyclability and sustainability make it an attractive construction material. The civil engineering field faces increasing demands to reduce CO_2 emissions, prompting exploration of timber's potential in diverse structural applications such as bridges, mid- to high-rise buildings, and other civil engineering projects. This study focuses on developing timber materials that mitigate the orthotropic effect by laminating thin timber plates with shifted fiber directions. The research aims to compare stiffness and orthotropic reduction between multi-angle laminated timber models and other laminated configurations. As a result, it indicates that multi-angle laminated timber exhibits relatively high stiffness compared to other models and approaches nearly isotropic properties.

KEYWORDS: laminated timber, Multi-angled, orthotropic, sustainable

1 – INTRODUCTION

In recent years, various strategies and technological developments have been proposed to mitigate CO_2 emissions, with several technical reports focusing on emissions related to civil engineering works and structures [1][2][3]. Given the pressing need for efforts within the civil engineering field to reduce CO_2 emissions, there have been growing initiatives to incorporate wood and wood-based materials appropriately in civil engineering structures. These efforts not only aim to reduce environmental impact but also contribute to regional economic revitalization through the increased use of domestic timber, blend better with the surrounding landscape, and offer potential benefits through carbon sequestration.

Moreover, a study by Edazawa, Sawada, and Mizuguchi calculated the CO_2 emissions associated with small-scale structures such as concrete and timber retaining walls, demonstrating the effectiveness of timber use [4]. In contrast, a report concerning bridge replacements in Western Australia—where approximately 30% of the existing bridges are timber—indicates a trend toward selecting steel or concrete bridges over timber alternatives in response to increasing traffic demands [5]. However, given that timber buildings are actively being constructed in Australia, timber bridges should also be viable options for replacement. The reluctance to adopt timber in bridge reconstruction is primarily attributed to concerns regarding durability and load-bearing capacity.

This study focuses on the carbon sequestration characteristic of wood and explores the potential application of timber in civil engineering structures such as bridges, while also taking into account stiffness and strength requirements. Previous studies and developments, including Cross-Laminated Timber (CLT), have sought to mitigate the anisotropic behavior of wood by altering the fiber orientation through lamination. However, the perpendicular layering in CLT can lead to a uniform stiffness that compromises overall structural rigidity [6][7]. Therefore, this research proposes a novel timber component that minimizes the effects of anisotropy by finely varying the fiber orientation, thereby maintaining structural stiffness while improving material performance.

2 – Multi-Directional Laminated Panels

Conventional CLT (cross-laminated timber) panels mitigate the inherent anisotropy of natural wood to a certain extent by laminating layers with orthogonal grain orientations, thereby enabling biaxial bending stiffness. However, this approach simultaneously reduces the stiffness along the principal axis to approximately half of that in the grain direction of solid wood.

To address this issue, the present study proposes a novel panel model aimed at reducing the effects of anisotropy and achieving more uniform stiffness by laminating thin wood veneers at varied angles, as illustrated in Figure 1(a) and Figure 1(b). This model, referred to as the Multi-Angle Laminated Timber (MALT) model, utilizes ultra-thin wood laminae laminated at multiple angles rather than solely orthogonal ones. Specifically, two configurations are examined: one in which the grain direction is rotated by 45 degrees in each successive layer

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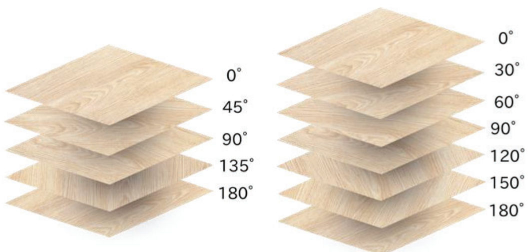
(Figure 1(a)), and another with a 30-degree rotation (Figure 1(b)).

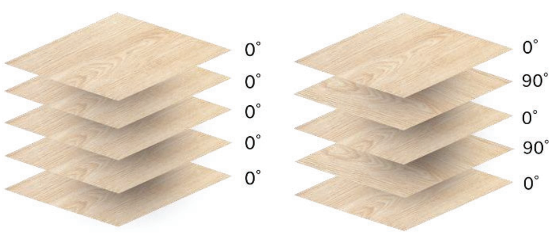
Furthermore, leveraging the sheet-like nature of the laminae, the study envisions the potential to reinforce the MALT model in future applications by inserting multiple fiber sheets between layers, with the goal of developing a wood-based panel material exhibiting enhanced isotropic stiffness.

For comparison, Figure 2(a) presents the structural configuration of conventional laminated veneer lumber (LVL), while Figure 2(b) illustrates cross-laminated timber (CLT).



(a) 45-degree (b) 30-degree

Figure 1. Multi-Angled Timber Plate Models: (a) 45-degree rotation; (b) 30-degree rotation



(a)LVL(Parallel lamination) (b) CLT(orthogonal lamination)

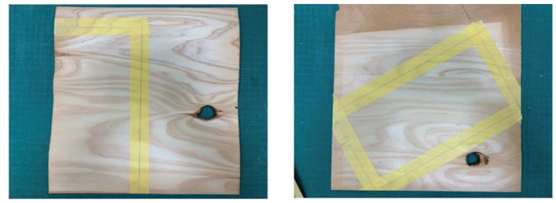
Figure 2. Conventional Laminated Timber Plates: (a) LVL (parallel lamination); (b) CLT (orthogonal lamination)

3 – EXPERIMENTAL OVERVIEW

To investigate the mechanical properties of the MALT panels, bending and tensile tests were conducted on actual specimens.

Specimen preparation

In this experiment, specimens were prepared using two types of MALT panels: one composed of five layers with the grain direction rotated by 45 degrees in each successive layer, and another composed of seven layers with a 30-degree rotation. In addition, two reference panels were fabricated: one with five layers laminated in orthogonal directions, and another with five layers laminated in the same direction. The material used was 1 mm-thick sugi (Japanese cedar) veneer.



(a) 90-degree (b) 30-degree

Figure 3. Material Preparation for Experimental Testing: (a) 90-degree orientation; (b) 30-degree orientation

As shown in Figure 3(a) and Figure 3(b), 30 cm × 30 cm veneers were cut at the required angles for lamination. To prevent cracking during cutting, masking tape was applied along the cut lines. The adhesive used was API (aqueous polymer isocyanate resin adhesive). It was applied at a rate of 200 g/m² per layer and evenly spread using a roller.

To prevent warping during lamination, weights were placed on top of the veneers and aligned with the intended lamination angle. The laminated panels were then pressed using the machine under a pressure of 1 MPa for one hour. After pressing, the specimens were cured for 24 hours to allow the adhesive to fully harden.

Once curing was complete, the laminated panels were cut into test specimens according to the dimensions in accordance with JIS standards. Additionally, moisture content tests were conducted using the leftover veneer pieces. The average moisture content was 9.0%, confirming that the veneers were sufficiently dry and the adhesive performance was not adversely affected.

Bending and Tensile test

Both bending and tensile tests were conducted using a SHIMADZU Autograph AGS-X 50 kN testing machine.

The bending test was performed using a three-point bending method. Span lengths (l) were determined such that $l \geq 25t$ where t is the thickness of the specimen. The span was set to 125 mm for the five-layer specimens (MALT45, cross-laminated, and parallel-laminated), and 175 mm for the seven-layer MALT30 specimens. Load and displacement were recorded at the crosshead, with a loading rate of 1 N/s.

For the tensile test, the grip length was 45 mm on each end, with a span length of 150 mm. In addition to load and displacement from the crosshead, strain was measured using strain gauges affixed to both sides at the center of the span. The loading rate for the tensile test was 15 N/s.

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Test results

The Young's modulus EEE was calculated using the measured load and displacement data from the bending test by substituting into (1)

$$\delta = \frac{Pl^3}{48EI} \quad (1)$$

The results for Young's modulus and maximum load are summarized in Table 1**.** The load–displacement relationships obtained from both the experimental and numerical results for the 45-degree model and 30-degree model are plotted in Figure 5(a) and Figure 5(b).

Table 1. Summary of bending test results

Name of spesimen	Bending strength (Mpa)	Young's moduls (GPa)
45_s1	73.6	5.32
45_s2	65.1	5.00
45_s3	64.0	4.32
45_s4	69.5	5.33
45_s5	79.8	5.00
30_s1	32.9	4.14
30_s2	37.6	4.13
30_s3	42.4	4.37
30_s4	37.2	3.58
30_s5	39.7	4.06
C_s1	54.6	4.49
C_s2	55.8	3.89
C_s3	58.1	4.67
L_s1	51.6	5.59
L_s2	92.2	6.42
L_s3	73.0	6.24

Due to material limitations, five specimens each were tested for MALT45 and MALT30, and three each for the cross-laminated and parallel-laminated panels.

The mechanical test results for four different conditions were analyzed. For the 45-degree, the average value was 70.4 with a standard deviation of 6.49. For the 30-degree orientation, the average was 37.96 with a standard deviation of 3.50. For the 90-degreee orientation, the average measured 56.17 with a standard deviation of 1.78. Finally, for the 0-degree orientation, the average was 72.27 with a standard deviation of 20.31. Among the four cases, the 0-degree orientation exhibited the highest average value, indicating the greatest strength. However, it also showed the largest standard deviation, suggesting considerable scatter in the measurements. In contrast, the 90-degreee orientation showed relatively high strength with the smallest standard deviation, indicating the most consistent behavior and the least scatter among the samples.
The 30-degree orientation had the lowest average value, suggesting that the material is weakest when loaded at this angle.

4 – ANALYTICAL MODEL AND METHODOLOGY

Numerical simulations were conducted using Salome-Meca 2019 for the numerical simulations. In this study, two types of analyses were conducted: one to compare the mechanical behavior of the MALT model with that of conventional unidirectional laminated models such as LVL (Laminated Veneer Lumber) and orthogonally laminated models such as CLT (Cross-Laminated Timber), and another to investigate the extent to which the multi-directional lamination mitigates the effects of anisotropy.

Analysis Model

In all analysis models, the laminated timber layers were modeled as square panels measuring 1000 mm × 1000

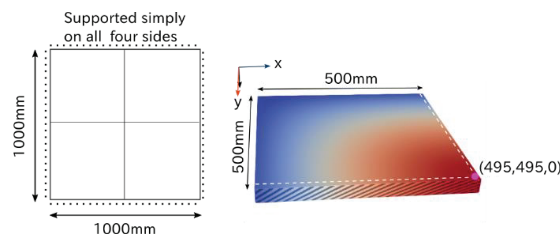

Figure 4. Numerical model Multi-Angle Laminated Timber (MALT) Model

mm with a thickness of 1 mm per layer. Although actual bonding was performed with API adhesive, the numerical models assumed fully bonded layer interfaces. Instead, the interfaces between layers were modeled as fully bonded (rigid connection).

As shown in Figure 4, the boundary conditions consisted of simply supported edges on all four sides, with a uniform surface load of 0.001 N/mm² applied to the top surface. A linear static analysis was conducted under these conditions.

The material properties assumed were based on Japanese cedar (sugi), with the Young's modulus in the grain (strong) direction (Ex) set to 6000 MPa, and the moduli in the transverse directions (Ey and Ez) set to 1/25 of Ex (i.e., 240 MPa)**.** The shear modulus (G) and Poisson's ratio (ν) were assumed to be isotropic in all directions and set to 400 MPa and 0.016, respectively**.**

For assigning fiber orientations in the multi-directional lamination models, Euler angles were used. However, since the models only required two-dimensional in-plane rotation**,** the laminae were rotated about the axis perpendicular to the plane by the necessary angle only.

Analysis Method

The first set of simulations aimed to compare the stiffness of various laminated models by varying two parameters: the lamination angle and the number of layers. For the MALT model, as illustrated in Figure 1, the grain

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direction was rotated by 45 degrees in each successive layer along the two principal axes. Since five layers complete a full 180° cycle (0°–180°), five layers were treated as one set. By increasing the number of such sets, the total panel thickness increased to 5 mm, 10 mm, and 15 mm, respectively.

To ensure consistency in comparison, laminated panels based on other models—including conventional orthogonal lamination and an isotropic model—were constructed with the same total thicknesses and analyzed under the same boundary conditions.

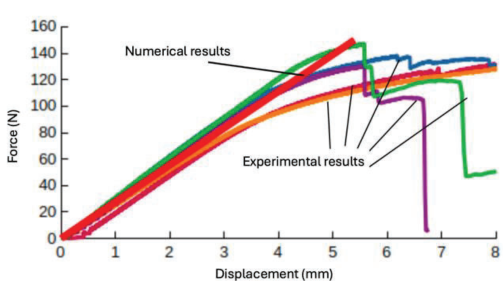
In the second part of the study, which aimed to examine the degree of anisotropy reduction, a model was created in which the grain direction was rotated by 30 degrees per layer. In addition, linear static analysis was performed after rotating the entire model by 15-degree increments. The resulting normal strains in orthogonal directions were compared across each configuration to assess the reduction in anisotropic behavior. Since the 30-degree rotation model completes a full 180° cycle with seven layers (0°, 30°, 60°, 90°, 120°, 150°, and 180°), the total thickness of the panel was set to 35 mm to match the overall thickness of the 45-degree MALT model.

5 – ANALYTICAL RESULTS

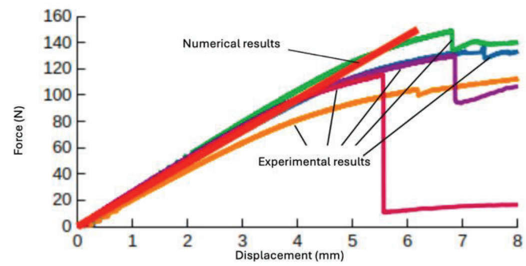
Comparison between experimental model and Numerical Simulation model

The load–displacement relationships obtained from both the experimental and numerical results for 45-degreed model and 30-degree model are plotted **in** Figure 5(a) and (b), with load on the vertical axis and displacement on the horizontal axis. In all models, the simulated behavior showed a strong agreement with the experimental results within the elastic range.

These results confirm the high accuracy and reproducibility of the numerical model. Furthermore, the close correspondence suggests that the effect of the adhesive was negligible, and that the veneer layers acted in a fully bonded (rigidly connected) manner.



(a) 45-degree



(b) 30-degree

Figure 5. Load–Displacement Curves from Experimental and Numerical Results: (a) 45-degree MALT; (b) 30-degree MALT

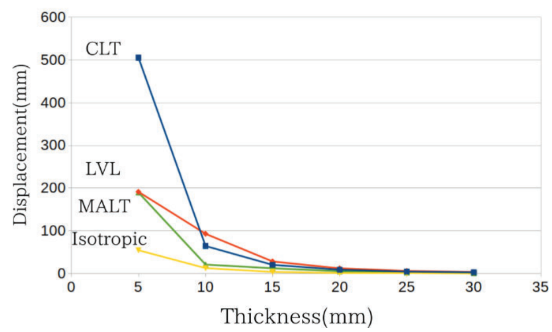


Figure 6. Relationship between displacement and thickness

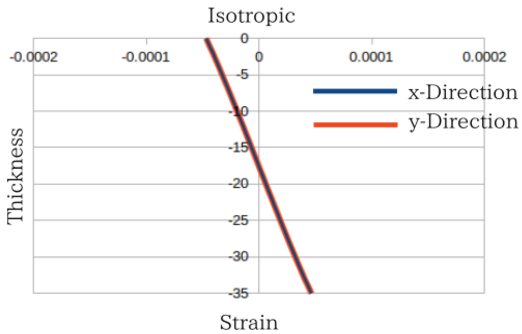
Table 2. Summary of displacement and rate of reduction

Thickness (mm)	Displacement		Rate of reductinon (%)
	CLT	45-degree	
5	505.1	189.5	63
10	64.7	21.3	68
15	20.6	12.6	39
20	9.2	5.6	39
25	4.9	3.0	39
30	3.1	1.9	40

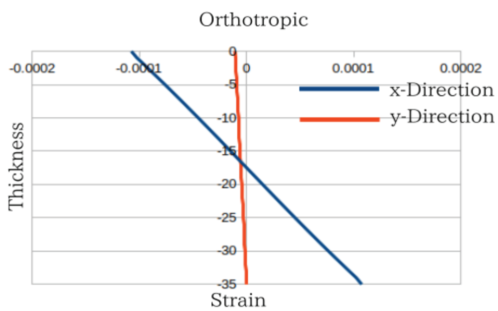
Based on these findings, it can be concluded that the structural response of MALT members under elastic conditions can be accurately captured using the proposed numerical analysis tool.

Comparison of Central Displacement

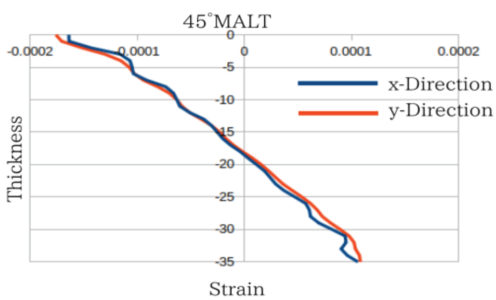
Figure 6 presents the relationship between panel thickness and central displacement, with the horizontal axis representing the panel thickness and the vertical axis representing the central displacement. In this figure, the CLT model refers to the orthogonally laminated model, LVL represents the unidirectionally laminated model, and MALT denotes the model laminated at 45-degree intervals.The results indicate that for panel thicknesses of 5 mm and 10 mm, the displacements of the CLT and MALT models differ significantly. However, as the panel



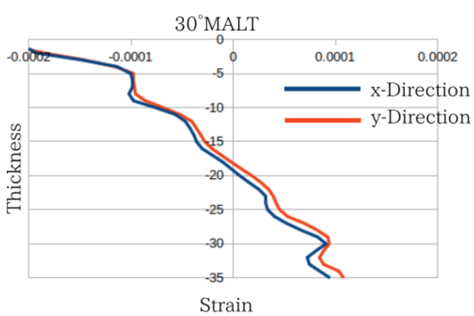
(a) Isotropic model



(b) Orthotropic model



(c) 45-degree



(d) 30-degree

Figure 7. Strain Responses Under Rotation: (a) Isotropic; (b) Orthotropic; (c) 45-degree MALT; (d) 30-degree MALT

Table 3. Summary of Young's modulus for each layers

Angle	x-direction [MPa]	y-direction [MPa]
0	3338.5	2046.6
15	3054.5	2207.0
30	2686.0	2095.1
45	2287.1	2575.9
60	1875.8	2520.2
75	2002.0	2907.2
90	1719.1	3370.2
105	2109.1	2878.1
120	2079.0	2211.5
135	2003.9	2295.2
150	2383.2	2389.1
165	2606.4	2205.2
180	3338.5	2046.6
Avg.	2421.8	2442.1

thickness increases, the displacements appear to converge toward a constant value.

Table 2 summarizes the central displacements for the CLT and MALT models, as well as the reduction rate of MALT displacement relative to the CLT model. For thicknesses of 5 mm and 10 mm, where the differences were most pronounced, the reduction rate exceeded 60%. Even for thicker panels, the reduction rate remained approximately 40%.

These results confirm that, compared to unidirectional and orthogonal laminated models, the MALT model effectively reduces displacement, exhibiting behavior closer to isotropy.

Assessment of Anisotropy Reduction

To evaluate the degree of anisotropy reduction, simulations were conducted for both the 45-degree MALT model and the 30-degree MALT model**,** in which the entire panel was rotated incrementally by 15 degrees between 0° and 180°. The strain responses of these MALT models were compared with those of an isotropic model and an orthotropic model of equivalent thickness, by plotting strain values under identical loading and boundary conditions.

Due to the 15-degree rotation steps, a total of 12 orientations were analyzed for each MALT model. Across all orientations, both MALT45 and MALT30 models exhibited similar behavior in their principal strains, with minimal variation in the strain response between orthogonal directions. This consistency suggests a significant reduction in anisotropic behavior. For clarity, representative results from the simulations where the models were rotated by 15 degrees are presented.

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Specifically, Representative strain results are presented in Figure 7(a) through Figure 7(d)

Strain values were extracted from the point **(**x = 495, y = 495, z = 0–35 mm**)**, as defined in Figure 4, to minimize the influence of boundary conditions.

As shown in Figure 7(a), the isotropic model exhibited equal strain behavior in the x- and y-directions, while the orthotropic model (Figure 7(b)) displayed significantly different behavior between the two directions. In contrast, both the 45-degree and 30-degree MALT models demonstrated similar strain magnitudes in the x- and y-directions, indicating behavior closer to that of the isotropic model.

Furthermore, no significant differences were observed between the 45-degree and 30-degree MALT models in terms of their strain responses.

Stiffness Evaluation

From the nodes where strain results were, the corresponding normal stresses in the orthogonal directions were extracted.

Based on the stress–strain relationships, the Young's modulus for each of the 35 individual layers was calculated. These values were then averaged through the thickness direction to determine the effective Young's modulus for the entire analytical model. Following the same approach used to assess anisotropy via orthogonal strains, the entire model was rotated from 0° to 180° in 15-degree increments, and the corresponding effective Young's moduli in the principal directions were calculated. The results are summarized in Table 2. In this table, the first column indicates the rotation angle (measured clockwise from the original orthogonal coordinate system), and the second and third columns show the calculated Young's moduli in the two orthogonal directions for each angle.

According to the results in Table 3, when averaging the layer-wise Young's moduli both through the thickness and across the plane, the effective Young's modulus in the strong axis direction was 2421.8 MPa, while in the weak axis direction it was 2442.1 MPa, yielding a difference of only 0.8% between the two.

Although these values are less than half of the fiber-direction Young's modulus of 6000 MPa used as the material property input, the results indicate that the MALT model achieved **a** high degree of stiffness uniformity, successfully achieving near-isotropic in-plane stiffness.

5 – Conclusion and Future Work

In this study, numerical analyses were conducted to investigate the behavior of thin laminated timber panels composed of individually rotated layers under a uniform distributed load. The effects of panel thickness were examined by comparing the proposed model with conventional orthogonally laminated (CLT) and unidirectionally laminated (LVL) models.

The results demonstrated that the Multi-Angle Laminated Timber (MALT) model, which utilizes multiple fiber orientations, exhibited significantly reduced deflection and a behavior closer to isotropy compared to traditional CLT and LVL models.

Furthermore, to evaluate the degree of anisotropy reduction, coordinate systems rotated in 15-degree increments were applied to the MALT models, and principal strains in orthogonal directions were analyzed. It was found that in all configurations, the two in-plane strains exhibited nearly identical responses, indicating that the model achieves a considerable degree of anisotropy mitigation.

Based on the strain results, directional Young's moduli were calculated and then averaged across the in-plane directions. The resulting effective moduli showed a high level of isotropy, confirming that in-plane stiffness was well homogenized. However, the overall effective Young's modulus of the model was less than half of the assigned fiber-direction modulus (6000 MPa), indicating a reduction in absolute stiffness.

As a future direction, this study proposes the insertion of high-strength fiber sheets between the thin wood veneers, leveraging the layer-by-layer construction method of the MALT model. This approach aims to retain isotropic stiffness while improving the overall structural rigidity, contributing to the development of high-performance, wood-based structural materials**.**

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