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OPTIMIZED LUMBER ARRANGEMENT IN NLT SUBJECT TO IN-PLANE SHEAR FORCE

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ABSTRACT: Nail-Laminated Timber (NLT) is a wooden panel utilizing lumbers fastened with nails, traditionally used in Canada and the United States. Despite its widespread use, the effects of lumber grade, length, placement, and nail stiffness on structural performance during in-plane deformation are not well understood. This study employs numerical analysis to investigate the effect of member arrangement on the structural performance of NLT panels, particularly for a continuous wall. The analysis focused on optimized lumber arrangement to improve shear stiffness while reducing material usage. Results indicate that a volume ratio of α = 0.80 retains 82% of the shear stiffness of a full volume wall (α = 1.0). Additionally, the lumber arrangement evolves into a diamond shape as the volume decreases, with each side functioning like a brace. This study provides insights into more economical and structurally efficient NLT panel designs.

KEYWORDS: Nail-Laminated-Timber, topology optimization, numerical analysis, shearing load, continuous wall

1 – INTRODUCTION

1.1 BACKGROUND

In recent years, the growing use of timber structures has been driven by their potential to reduce environmental impact. As part of this trend, research on Nail-Laminated Timber (NLT) has become increasingly active. NLT has been traditionally used in Canada and the United States for over half a century[1][2]. Unlike Cross-Laminated Timber (CLT), NLT is assembled using nails, eliminating the need for specialized manufacturing equipment. This allows for on-site assembly, reducing the need to transport long-span prefabricated panels and providing greater flexibility in construction.

Various studies have been conducted on NLT. For example, Feng et al. have investigated experimentally the out-of-plane stiffness and strength of NLT[3][4]. Yeh et al. examined how the mechanical performance of NLT changes when using screws driven diagonally instead of conventional nails[5]. Additionally, studies have explored the use of fast-growing eucalyptus[6] or bamboo-reinforced NLT[7], adapting the material to regional forestry resources. In terms of numerical analysis, Krämer proposed an FEM model to simulate out-of-plane deformation of NLT panel [8]. Xie et al. propose attempted to calculate the in-plane shear rigidity of NLT panels based on the shear rigidity of nails. [9]. In addition, Paroissien et al. developed a detailed finite element model (FEM) for Dowel-Laminated Timber (DLT), which shares structural similarities with NLT [10]. However, the effects of key design parameters such as lumber grade, length, placement, and nail stiffness on structural performance have not been fully investigated.

1.2 CONTINUOUS WALL METHOD FOR JAPANESE WOODEN HOUSE

In Japan, the continuous wall has been proposed as a construction method to prevent soft- first-story collapse in wooden houses[11]. As shown in Fig. 1, this method requires long-span panels that cover the entire height of two floors, and CLT is commonly used for this purpose. However, applying NLT in this method could enable on-site assembly of long-span panels, reducing transportation costs and improving production efficiency. Furthermore, lightweight NLT could enhance ease of construction. In actual experiments using CLT for continuous wall panels, a crane was used to lift the CLT panels during installation. However, in typical Japanese wooden house construction

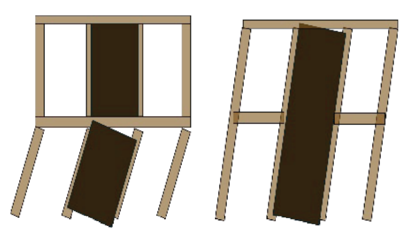

Figure 1. Effect of continuous wall

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sites, it is uncommon to use cranes capable of lifting 6-meter-long panels, which poses practical challenges for implementation.

This study explores the feasibility of replacing CLT with NLT in the continuous wall method. Specifically, it investigates the potential for NLT weight reduction by optimizing lumber placement while maintaining structural performance, using numerical analysis. Additionally, shear tests on nails were conducted to refine the accuracy of the numerical model.

2 – SHEAR TESTS ON NAIL

A standard push-out test was conducted to evaluate the shear stiffness of nails for the numerical model. The shear stiffness of nails plays a crucial role in determining the in-plane deformation of NLT, as it affects the load transfer between individual lumber layers.

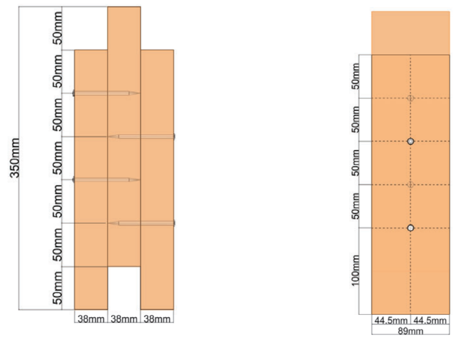
2.1 SPECIMEN

The specimens were prepared using spruce-pine-fir (SPF) lumber with a 2×4 size and cross-section of 38mm ×89mm. Commercially available nails called CN75 in Japan were used for the test, with dimensions of 76.5 mm (length) × 3.76 mm (diameter). The test specimen was designed to simulate an NLT joint, consisting of three layers of lumber with a nail inserted between them as shown in Fig. 2. The nails are driven in from both sides toward the center lumber. The nails are spaced at 50 mm intervals, with a 50 mm distance form top and bottome nails to the edge of the wood. To account for variability, loading tests were performed on three specimens(No.1-No.3).

2.2 TEST SETUP

The test was conducted using a Shimadzu AG-Xplus 50kN Universal Testing Machine (Shimadzu Corporation, Japan) with a maximum load capacity of 50 kN. Fig. 3 illustrates the specimen set in the testing machine. The specimen was not clamped or otherwise rigidly fixed to the testing machine. However, it remained stable due to the frictional force generated by the reaction force during loading. Push-out load is measured at the top part of the specimen and relative displacement betwtoeen the central lumber and side lumbers was measured using a CDP-50 displacement gauge. Additional testing conditions are as follows.

- Nails are driven in by hand
- Loading was stopped after maximum load
- Loading speed is 2 mm/min.



(a). front *(b). right side*

Figure 2. Specimens size and shape

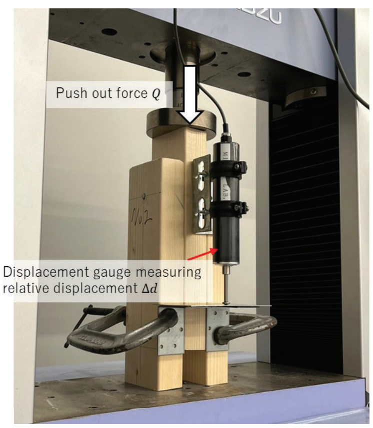


Figure 3. Test setup and measuring method

- Data were collected every 3 seconds.

2.3 RESULTS

As shown in Fig. 4, Specimen No.1 exhibited wood cracking at the bottom section of the specimen, indicating brittle failure in the lumber. In contrast, Specimens No.2 and No.3 did not show any wood cracks. Instead, the nails plastically deformed at the joints, indicating nail shear yielding. This difference of failure mode effect the maximum load as shown in Fig 5. However, the initial stiffness was nearly consistent across all three specimens. Table 1 presents the results of the maximum load and initial stiffness per one nail. The initial stiffness was calculated as the slope of the line connecting the load at zero displacement and the load at a displacement of 1 mm.

Table 1: Result of all specimen

	Initial stiffness (kN/mm)	Maximum load (kN)
No.1	1.196	
No.2	1.042	1.847
No.3	1.105	1.803
average	1.114	1.825

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(a). Bottom part of specimen No.1 (b). Specimen No.3

Figure 4. the condition of specimens after push-out test

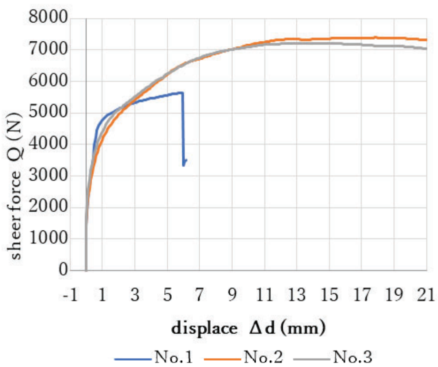

Figure 5. Load deformation curve

An average stiffness of 1.114 kN/mm was adopted for the numerical model.

3 – NUMERICAL ANALYSIS

This study conducts numerical analysis assuming the placement of NLT panels, as shown in Fig. 6, in the continuous wall. Each layer of lumber has two member arrangements, with Layer 1 consists of three 2m lumbers and Layer 2 consists of two 1m lumbers at the top and bottom ends, and two 2m lumbers. To achieve a lightweight NLT structure, gradual reduction of lumber is examined to identify the optimal arrangement that efficiently maximizes stiffness. Since NLT tends to have insufficient stiffness, various reinforcement methods have been proposed. However, optimizing lumber arrangement provides essential information for developing new reinforcement strategies for NLT panel with butt joint.

3.1 LUMBER ARRANGEMENT METHOD

To reduce the number of members used in the continuous wall a lumber arrangement that provides efficient shear stiffness with fewer members is explored. The ratio of the volume of each arrangement to the arrangement with no missing members is α. The efficiency of each arrangement is evaluated by the relationship between α and shear stiffness. Symmetrical shapes are desirable for seismic

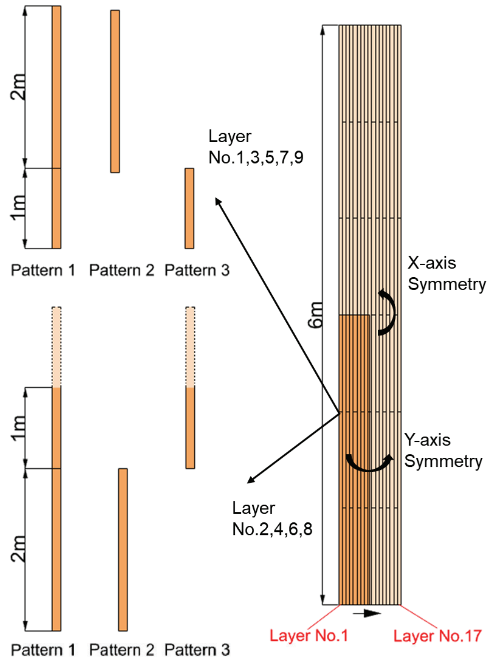

Figure 6. Lumber arrangement method

forces. Therefore, as shown in Fig. 6, the design area is set to 1/4 of the continuous wall and the shape is restricted to be symmetrical vertically and horizontally. By ensuring symmetry in the horizontal direction, only nine layers need to be considered for the actual placement. Additionally, for each layer, three different placement configurations are examined. In this method, it is ensured that no layer is completely devoid of lumber, as the absence of members in a layer would clearly disrupt stress transmission, leading to extremely low stiffness. Numerical analysis was carried out for all patterns, as this method limits the number of placement patterns to 19683 patterns (3 to the nine power).

3.2 NUMERICAL MODEL

Fig. 7 illustrates the numerical model of NLT. This model is constructed by replacing the lumber with beam elements, the nails with shear springs in the y-direction, and the stress transfers due to the contact between lumber pieces in each layer with springs in the x-direction. Additionally, at nail positions, rigid springs extend in the x-direction from the beam elements, allowing for y-direction displacement when the lumber tilts. Each element is an elastic material and has equal stiffness in both positive and negative strain. The stiffness values for each component are shown in Tabel 2. Young's module for lumber is 10500 MPa and stiffness for y-direction shear spring (K_y) is 1.114 kN/mm from experience. In reality, the springs in the x-direction act only in compression due to contact interactions, and at nail locations, withdrawal stiffness

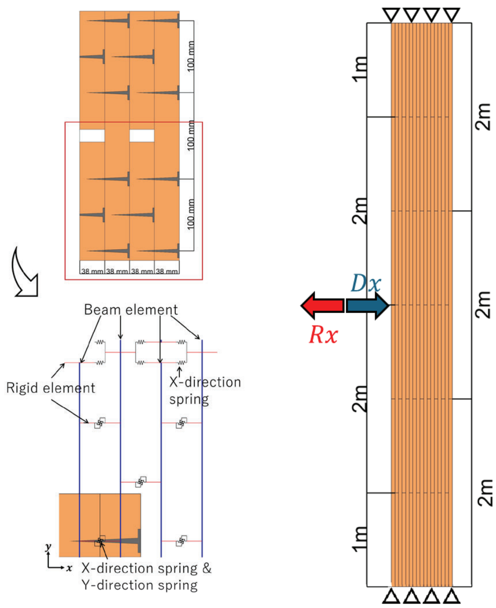

Table 2: Material property

Beam Element		Spring Element	
MPa		kN/mm	
E	G_{12}	K_x	K_y
10500	3600	1000	1.114

must also be considered. However, since the primary focus of this study is to examine the influence of lumber placement, a sufficiently high stiffness was assigned to the x-direction springs (K_x) to ensure the integrity of lumbers in panel.

3.3 ANALYSIS CONDITION

The support conditions fix the x-directional displacements of the upper and lower nodes. A forced displacement *Dx*=30mm is applied at the position shown in Fig. 8 and the shear stiffness of the continuous wall is evaluated by the x-directional reaction force *Rx* at this point. Additionally, due to the instability of certain members resulting from the placement method, all nodes are connected to the origin by springs with a stiffness of 1.0×10^{-6} kN/mm. It has been confirmed that the effect of this spring is no more than 1.0×10^{-4} kN at *Rx*. The numerical analysis was conducted using *Karamba3D*[12], a plug-in for *Rhinoceros* 3D CAD software. Although the calculations were performed on a three-dimensional model, all nodal displacements in the z-direction were constrained to replicate the conditions of a two-dimensional analysis.

3.4 RESULTS

Analysis results are shown in Fig. 9. The maximum values of Rx at each volume ratio and their arrangement are presented. The Rx ratio is defined as the ratio of Rx to Rx at α = 1.0. The comparison of α = 0.52 and α = 1.0 reveals that the volume is halved, while Rx is reduced by up to 22%. The configurations at α = 0.96 and α = 0.80 are observed to carry 99% and 82% of the load compared to α = 1.0, respectively. As α decreased from 1.00 to 0.84, members near the four corners were gradually removed. When α decreased from 0.80 to 0.73, the central members were reduced. Further reduction of α below 0.73 led to the progressive elimination of both central and corner members, resulting in a diamond-shaped configuration with each side functioning like diagonal braces.

Fig. 10 illustrates the bending stress distribution in the beams, while Fig. 11 shows the load on the shear springs in the y-direction, simulating the nails. In Fig. 11, the placement with black circles indicates maximum shear force Qmax. The states presented include: α = 1.0; α = 0.80, where the four corner members are reduced; α = 0.73, where the central members are reduced; and α = 0.54, representing a state with lower load. At α = 1.0 and 0.80, the central part exhibits consistent and high bending stress. The bending stress is lower at the center and increases towards the top and bottom, which is characteristic of a simply supported beam. When α = 0.73, the removal of central members increases the bending stress in the left-side members. At α = 0.57, minimal bending deformation occurs in the right-side members at the center, while

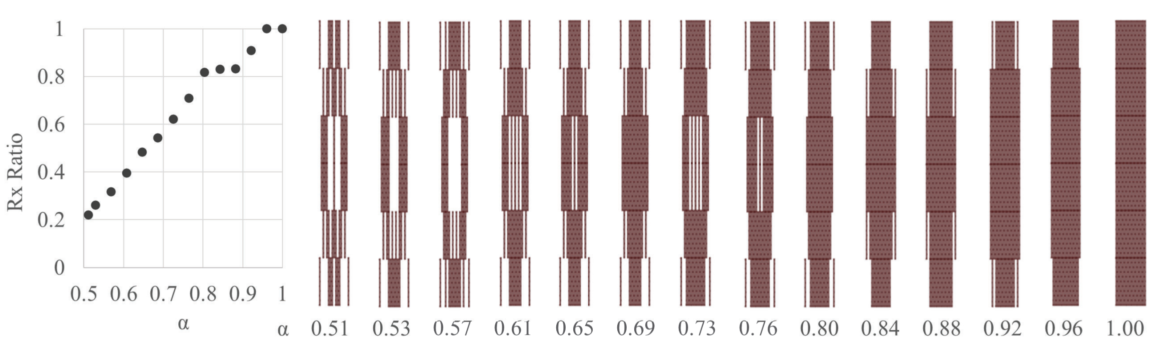

Figure 9. Lumber arrangement on each α

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deformation is observed only on the left side. The maximum shear force of the nails, Qmax, is at most 0.71 kN, confirming that it does not exceed the maximum load observed in the experiment.

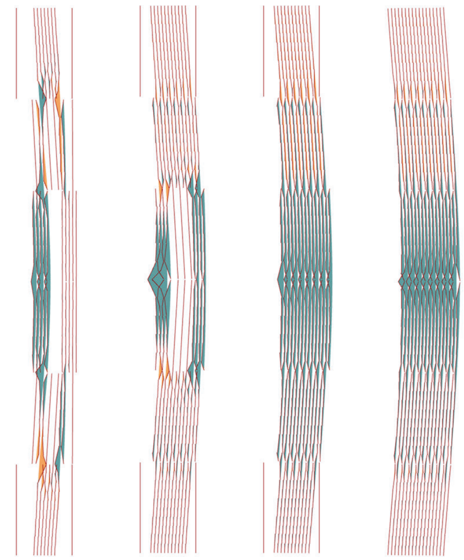
4 – DISCUSSION

The analysis results indicate that the structural efficiency is significantly influenced by the configuration of the members. When comparing α = 0.52 and α = 1.0, the reduction in Rx by up to 22% despite the volume being halved suggests an inefficient arrangement. This can be attributed to the fact that critical structural members are removed when reducing α, compromising load-bearing capacity. Relatively efficient configurations are observed at α = 0.96 and α = 0.80, where the system retains 99% and 82% of the load capacity of the full structure (α = 1.0). This implies that the structural integrity remains largely intact until α approaches 0.73. The transition from α = 1.00 to 0.84 is characterized by the removal of members near the four corners. As α decreases further from 0.80 to 0.73, the removal of central members suggests that these components are less critical for overall structural stability. However, the further reduction below α = 0.73, which results in the elimination of both central and corner members, drastically reduces structural integrity, transforming the configuration into a diamond shape. The efficiency of this diamond shape can be explained by its resemblance to a diagonal brace system, which effectively transfers loads along the diagonals.

Regarding the bending stress distribution, the results at α = 1.0 and 0.80 show typical characteristics of a simply supported beam, where stress is higher towards the top and bottom. When central members are removed (α = 0.73), the stress distribution shifts, increasing the load on the left-side members, which indicates a redistribution of force paths. Furthermore, the shear force distribution at α = 0.57 shows that the load applied to the left side is not effectively transmitted to the right side, suggesting an inefficient load path. The maximum shear force of the nails, Qmax, is within a safe limit (0.71 kN), indicating that the connection method is adequately designed under the tested conditions. However, the results suggest that for lower α values, further optimization of member placement and connection design is necessary to improve load transfer efficiency.

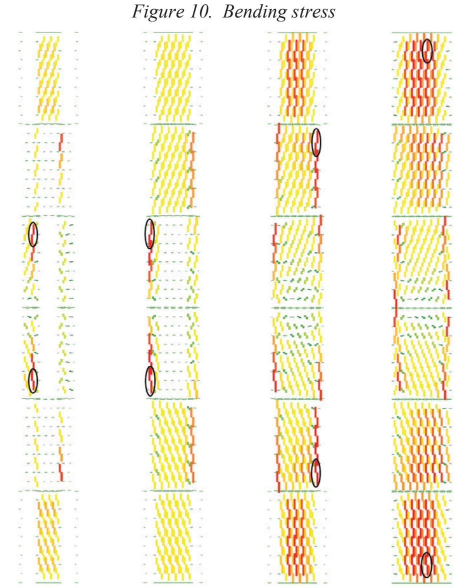
5 – CONCLUSION

This study investigated the optimal arrangement of lumber in Nail-Laminated Timber (NLT) panels under in-plane shear forces using numerical analysis. The results revealed that a volume ratio of α = 0.81 retains 83% of the



(a). α=0.57 (b). α=0.73 (c). α=0.80 (d). α=1.00

Figure 10. Bending stress



(a). α=0.54 Q_{max}=0.52kN (b). α=0.73 Q_{max}=0.71kN (c). α=0.80 Q_{max}=0.66kN (d). α=1.00 Q_{max}=0.58kN

Figure 11. Sheer force distribution

shear stiffness of a full-volume wall (α = 1.0). As the volume ratio decreased, the lumber arrangement evolved into a diamond shape, where each side functions as a brace.

The findings of this study contribute to a better understanding of how optimized lumber placement can enhance the structural performance of NLT while reducing material usage. This insight is particularly valuable for the application of NLT in tall wall with butt joint, where lightweight structures can improve ease of installation.

However, this study is based on numerical simulations. Experimental validation is required to confirm the accuracy of the proposed model. Additionally, the maximum load capacity with nonlinear analysis and response to sesmic load remains an open question for future research. Further investigations should also explore different nail configurations and connection methods to optimize joint performance.

In conclusion, optimizing lumber placement in NLT can lead to more economical and structurally efficient designs. Future research should focus on experimental verification, dynamic analysis, and connection optimization to further enhance the applicability of NLT in modern construction.

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