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CALCULATION METHOD FOR IN-PLANE SHEAR PROPERTIES OF NLT

Tianjun XIE[1], Shiro NAKAJIMA[2]

ABSTRACT: Nail Laminated Timber (NLT) was tested to verify its in-plane shear properties and to develop a method for calculating its load-deformation relationship. The NLT test specimens consisted of 20 pieces of Japanese cypress lumber, each with a cross-sectional size of 45 mm × 120 mm and a length of 1900 mm. The pieces were joined using 75 mm-long common nails. Since NLT is composed of lumber connected by nail joints, its load-deformation relationship was derived through incremental displacement analysis, considering the load-deformation behavior of the nail joints. The calculated results closely followed the test results at smaller deformation levels but underestimated the load at larger deformation levels. This underestimation was attributed to the embedment effect of the adjoining lumber. By incorporating this embedment effect into the calculation, the revised model provided accurate estimations across both small and large deformation levels. The findings indicate that the in-plane shear properties of NLT can be effectively evaluated using incremental displacement analysis while accounting for the load-deformation relationship of nail joints and lumber embedment.

KEYWORDS: In-plane shear, NLT, Nail joint, Embedment, Incremental displacement analy

1 – INTRODUCTION

Nail Laminated Timber is a panel-shaped wood member made by laminating sawn lumber and joining them using nails. In recent years, large dimension wood materials made by laminating and joining lumber have been used as structural materials for buildings around the world. Such large-size wood materials include cross laminated timber (CLT), which is collectively called mass timber in Europe and America[1]. Meanwhile, NLT is beginning to be used in Japan as well. Since it can be formed without gluing, it can be produced at lumber mills and other wood processing plants located throughout the country, and it can be manufactured at the construction site.

NLT is used for floor slabs, roof slabs, and load-bearing walls of buildings, but due to its component structure of laminated lumber, when a force that deforms a rectangular panel into a parallelogram (hereinafter referred to as“in-plane shear force”) is applied, the panel is significantly deformed (hereinafter referred to as“in-plane shear deformation”). The in-plane shear stiffness is an indicator of the degree of resistance to in-plane shear deformation when an in-plane shear force is applied. The in-plane shear strength is an indicator of the resistance of a panel to in-plane shear forces (hereinafter referred to as“shear resistance”).

Design guidelines [2] are published and useful engineering knowledge are given. Though there seems to be limited information for how to derive the load deformation curve for in-plane shear of NLT and how to evaluate the in-plane shear characteristic values for NLT without operating full-size tests.

In this study, and for the purpose of determining the in-plane shear stiffness and in-plane shear yield capacity of NLT, we proposed a method to calculate the relationship between load and displacement when in-plane shear force is applied, using the load-displacement relationship of nail joints that constitute the NLT.

[1] Tianjun XIE, Graduate School of Regional Development and Creativity, Utsunomiya University, Utsunomiya, Japan, 842391030@qq.com

[2] Shiro NAKAJIMA, School of Regional Design, Dept. of Architecture and Urban Design, Utsunomiya University, Utsunomiya, Japan, s-nakajima@uu.utsunomiya-u.ac.jp

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2 – EXPERIMENTAL SETUP

Figure 1 gives the assembly and size of the test specimen. The specimen consisted of an NLT 900 mm wide and 1900 mm long attached to a frame consisting of a foundation, load-bearing girder, and vertical load-bearing column. One structural screw was used per lumber piece, and each screw was placed on a different side of the lumber piece and fastened from both sides. For the connections between the vertical load-bearing columns and the foundation and load-bearing girders, beam joint hardware (BX Kaneshin Co. F-SP) was used, and the number of screws to attach the hardware was adjusted so that the column caps and column legs were pinned together. [3]

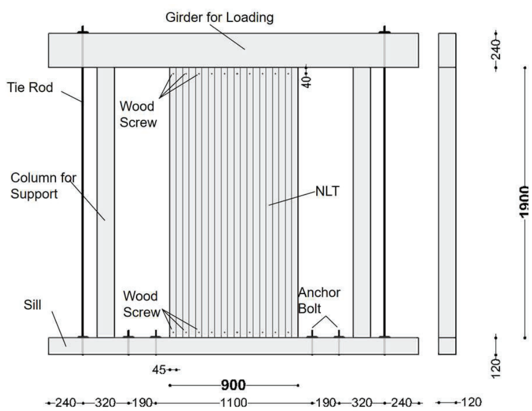

Figure.1 Assembly of the test specimens.

Note: Unit of the numbers in the figure is mm.

The NLT consisted of 20 cypress lumber pieces with a cross section of 45mm×120mm and a length of 1900mm. Lumbers were nailed at double line using CN75 nails (specifications listed in Table 1) at a distance of 20 mm from the edge of the lumber as shown in Figure 2.

Nailing spacing along the length of the lumber was 200 mm.The nailing positions were shifted by 100 mmbetween adjacent layers to prevent overlap of nailing positions.

Table.1 Specifications of the materials that make up the test specimen

Members Composing NLT	Item	Properties and Specifications
Lumber	Species	Japanese Cypress
	Size	45mm×120mm×1900mm
	Density	Average: 446 kg/m^3
	MOE	Average: 11.5 kN/mm^2
Foundation	Species	Japanese Cypress
	Density	Average: 497kg/m^3
	MOE	Average: 10.8 kN/mm^2
Column	Species	Japanese Cypress
	Density	Average: 484 kg/m^3
	MOE	Average: 11.3kN/mm^2
Nail		JIS A5508-2009, CN75

Photo 1 shows the in-plane shear test: horizontal displacements at the top and bottom of the NLT during three cyclic positive/negative shear tests at 1/600rad, 1/450rad, 1/300rad, 1/150rad, 1/100rad, 1/75rad, 1/60rad, and 1/50rad, Vertical displacements at both ends of the NLT were measured, and relative displacements were measured at 10 locations between the lumber members of the NLT.

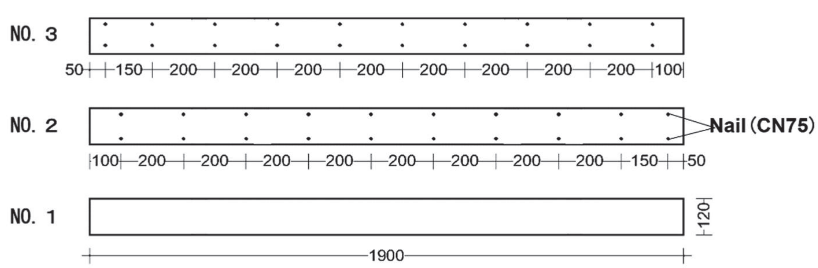

Figure.2 Location of the notches for the nail joints at the lumbers composing NLT.

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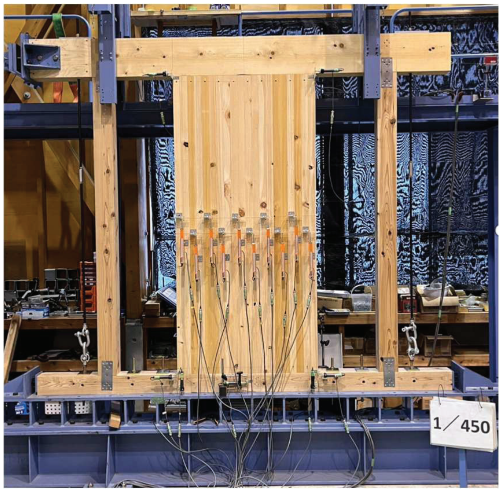

Photo 1 In-plane shear test

3 –EXPERIMENTAL RESULTS

3.1 Load – true shear angle relationship

Figure 3 shows the relationship between the load on the specimen and the true shear deformation angle. The thick line in the figure is the envelope of the positive side (the side that was pulled off during the application of the load). This is thought to be due to the fact that shear deformation is induced in the NLT by pinning the ends of the lumber (no horizontal movement).

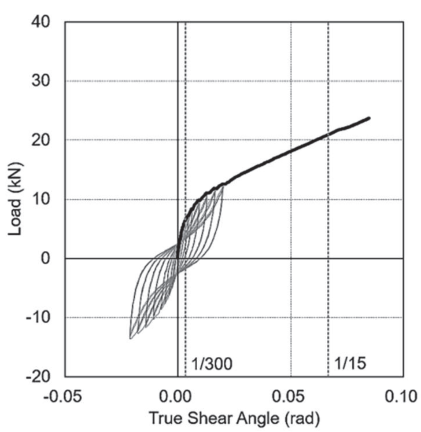

Figure 3 Load – true shear angle relationship of the NLT test specimens.

3.2 Characteristic values

Table 2 shows the characteristic values of the NLT specimen in terms of ultimate load, ultimate displacement, plastic modulus, and initial stiffness, in addition to the four indices for evaluating the wall modulus or bearing capacity of wooden load-bearing walls. The yield capacity of the specimens was determined by the load $P_{1/300}$ when the true shear deformation angle was 1/300rad.The $P_{1/300}$ of NLT specimen was 6.43kN.On the other hand, the initial stiffness k was 0.49kN/mm for the NLT specimen.

Table 2 characteristic values of NLT specimen

$P_y(kN)$	9.73
$2/3P_{max}(kN)$	13.2
$P_{1/300}(kN)$	6.43
$0.2Pu\sqrt{2\mu-1}$	8.28
Pu	15.9
μ	3.91
$k(kN/mm)$	0.490

Note:The ultimate displacement Du is the displacement at a true shear deformation angle of 1/15 rad. The maximum load was defined as the load at a true shear deformation angle of 1/15 rad.

Note 2:For the NLT, the load at a true shear deformation angle of 1/300 rad was adopted because the configuration was judged to be similar to that of frame wall construction.

4 – CALCULATION METHOD FOR LOAD DEFORMATION RELATIONSHIP

The method of calculating the load-deformation angle relationship for unreinforced NLT, which bearing capacity is determined solely by the shear performance of the nail joints, is discussed in this report. The method to calculate the load-deformation angle relationship for NLT with the following characteristics is described below.

Thickness of the lumber that makes up the NLT: b (mm)

Number of pieces of lumber making up the NLT: n (pieces)

Number of nails connecting two pieces of lumber: m (pcs)

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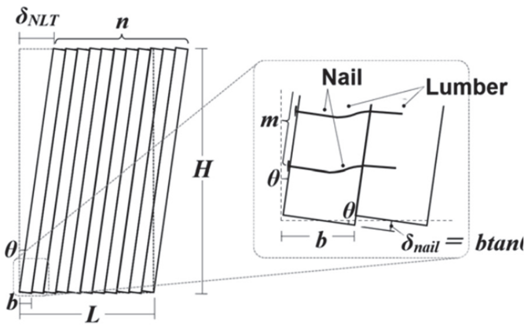

Figure 4 Modeling of Nail Joints of NLT

For the NLT with wall length L (mm) and height H (mm) shown in Figure 4, assuming no deformation other than shear deformation of the NLT such as lifting of the column legs when the top of the NLT is displaced δ_{NLT} (mm) in the horizontal direction, the tilt θ (rad) in the NLT (lumber) is obtained from Equation 1.

$$\theta = \frac{\delta_{\mathrm{NLT}}}{x} \tag{1}$$

The relative displacement (misalignment) δ_{nail} (mm) that occurs between adjacent lumber pieces when the lumber that makes up the NLT is inclined by θ (rad) can be obtained using Equation 2.

$$\delta_{nail} = b\,sin\,\theta \tag{2}$$

The amount of work $w_{nail}(x \to x+\Delta x)$ performed by a nail joint (per nail) in a certain microdisplacement interval x to $x+\Delta x$ can be obtained by Equation 3, where $P_{nail}(x)$ is the load (per nail) when the displacement of the nail joint is x and assuming a linear relationship between load and displacement in the microdisplacement interval Δx.

$$w_{nail} = (x \to x+\Delta x) = \frac{1}{2}\{P_{nail}(x) + P_{nail}(x+\Delta x)\} \cdot \Delta x \tag{3}$$

The displacement (misalignment) δ_{nail} (mm) of the nail joint can be obtained by Equation 4 using the horizontal displacement δ_{wall} (mm) at the top of the NLT.

$$\delta_{nail} = b\,sin(\frac{\delta_{NLT}}{H}) \tag{4}$$

If the top of the NLT is displaced from y to $y+\Delta y$, from Equation 5, the nail joints that make up the NLT will be displaced from the displacement of Equation 1 to that of Equation 4。

$$x = b\,sin(\frac{y}{H})$$

$$x + \Delta x = b\,sin(\frac{y+\Delta y}{H}) \tag{5}$$

From Equations 3, 4, and 5, the amount of work $w_{nail}(x \to x+\Delta x)$ performed by a single nail comprising the NLT when the top of the NLT is displaced from y to $y+\Delta y$ is obtained from Equation 6.

$$w_{nail}(x \triangleright x+\Delta x) = \frac{1}{2}\left[P_{nail}\left\{b\sin\left(\frac{y}{H}\right)\right\} + P_{nail}\left\{b\sin\left(\frac{y+\Delta y}{H}\right)\right\}\right] \times \left\{b\sin\left(\frac{y+\Delta y}{H}\right) - b\sin\left(\frac{y}{H}\right)\right\} \tag{6}$$

Assuming that all nail joints constituting the NLT deform in the same manner and that their load-displacement relationship is the same, the amount of work $W_{nail}(x \to x+\Delta x)$ performed by all nails constituting the NLT when the top of the NLT is displaced y to $y+\Delta y$ is obtained by Equation 7.

$$W_{nail}(x \to x+\Delta x) = s \cdot w_{nail}(x \to x+\Delta x) \tag{7}$$

s is the total number of nails in NLT.

$$s = m \times (n-1) \tag{8}$$

If the horizontal load applied to the top of the NLT to give a horizontal displacement of y to the top of the NLT is $P_{NLT}(y)$, then the amount of work done by the horizontal load W_{NLT} when the top of the NLT is displaced from y to $y+\Delta y$ is obtained by Equation 9.

$$W_{NLT}(y \to y+\Delta y) = \frac{1}{2}\{P_{NLT}(y) + P_{NLT}(y+\Delta y)\} \cdot \Delta y \tag{9}$$

Since the amount of work done by all nail joints and the amount of work done by the horizontal force applied to the top of the NLT are equal in the microdisplacement section, Equation 10 holds.

$$W_{NLT}(y \to y+\Delta y) = s \cdot w_{nail}(x \to x+\Delta x) \tag{10}$$

Organizing the above equations leads to the Equation 11.

$$P_{NLT}(y+\Delta y) = \frac{sb}{\Delta y}\left\{P_{nail}(b\,sin(\frac{y}{H})) + P_{nail}(b\,sin(\frac{y+\Delta y}{H}))\right\} \times \left\{sin(\frac{y+\Delta y}{H}) - sin\left(\frac{y}{H}\right)\right\} - P_{NLT}(y) \quad (11)$$

Assuming $y=0$ and $P_{NLT}(y)=0$, if the load-displacement relationship of the nail joint is known, $P_{NLT}(y+\Delta y)$ can be obtained by determining Δy since all variables on the right side of the equation are known. The same calculation can be repeated with increasing displacement to obtain the load-displacement relationship.

The force caused by the embedment of the lumber $f_{embed}(\theta)$ at the shear deformation angle of θ can be calculated by Equation 12 as modelled in figure 5. Where d is the width of the lumber and K_{embed} is the elastic modulus of embedment of wood.

$$f_{embed}(\theta)=(m-1)\cdot(h\times d)\cdot K_{embed}\cdot(b-b\cos\theta) \quad (12)$$

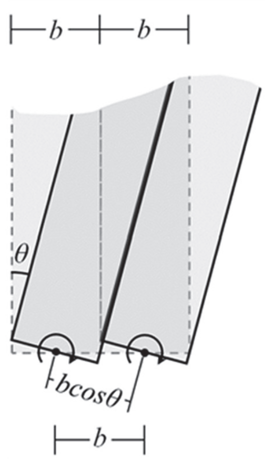

Figure 5 Modeling of Embedment of NLT.

5–CALCULATION RESULTS

Figure 6 gives the test results and the calculated results. The "Calculated Result A" does not take account the internal work done by the embedment of the adjoining lumbers and the load carrying capacity of NLT is underestimated at the larger deformation level. On the other hand the "Calculated Result B" takes account the internal work done by the embedment of the adjoining lumbers and gives a better estimation than "Calculated Result A".

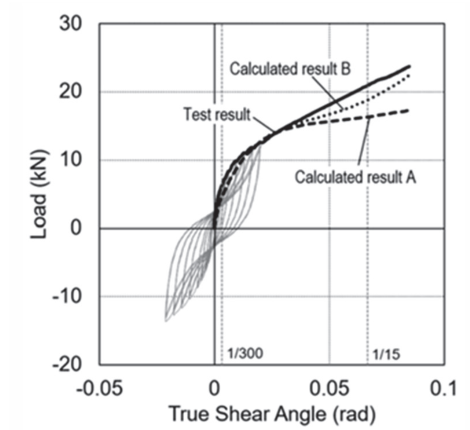

Figure 6 results

6–Linear Calculation Method for In-Plane Shear Stiffness of NLT

In the actual construction calculation, it is too cumbersome to utilize the above calculation method. For the calculation of the rigidity of the NLT endurance wall, a simple calculation method is also proposed. Assuming that the deformation of the NLT is linear, the deformation of the nails at the joint is used to infer the deformation of the NLT as a whole.

The in-plane shear stiffness of the NLT is when two lumber members comprising the NLT are joined by nail joints in one shear plane as shown in Figure 7,

1) The shear stiffness of a single nail joint joining two pieces of lumber comprising an NLT multiplied by the number of joints (n) between the two pieces of lumber,
2) The value is divided by the number of lumber pieces (m) minus one (m-1), which is the number of lumber pieces (m) that make up the NLT.

This leads to Equation 13.

$$K_{NLT} = K_{Joint} \times N_{Joint} \div (N_{Lumber} - 1) \quad (13)$$

K_{NLT} is NLT in-plane shear stiffness.

K_{joint} is Shear stiffness of single nail joint .

N_{joint} is Number of joints between lumber pieces.

$N_{lunmber}$ is Number of lumber joints between lumber pieces.

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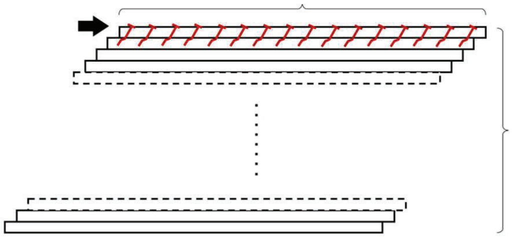

Figure 7 Concept of in-plane shear stiffness of NLT

The shear stiffness of a nail joint subjected to one-plane shear is determined by Equation 14.

$$k_s = \frac{4E_S I_S \mu_1^3}{(1+\omega^2)(\coth \mu_1 t_1 + \omega \coth \mu_2 t_2)} \qquad (14)$$

The tilt θ (rad) that occurs in the lumber when the top of the panel is displaced by x (mm) can be calculated by Equation 15.

$$\theta = \frac{x}{h} \qquad (15)$$

The rigidity of the panel k_{wall} can be calculated by Equation 16.

$$P(x) = k_{wall} \cdot x \qquad (16)$$

P(x) is the load on the top of the NLT.

The amount of work required to deform the top of the NLT from 0 to yield displacement x_{yeild} is obtained by Equation 17.

$$W_{panel} = \int_0^{x_{yeild}} (k_{wall} \cdot x)dx = \frac{1}{2} k_{wall} \cdot x_{yeild}^2 \qquad (17)$$

On the other hand, since n nail joints joining two pieces of lumber are located at m-1 number of lumber stacking points, $n \times (m-1)$ nail joints are deformed when the NLT is deformed in-plane shear. The amount of internal work done by the nail joints at this time can be calculated by Equation 18.

$$\{n \times (m-1)\} \cdot W_{nail} = \{n \times (m-1)\} \int_0^{\delta_{yeild}} (k_{nail} \cdot x_{nail})dx = \{n \times (m-1)\} \cdot \frac{1}{2} k_{nail} \cdot \delta_{yeild}^2 \qquad (18)$$

δ_{yeild} is the shear deformation of the nail joint when the top of the panel x_{yeild}.

The shear deformation of the nail joint and is obtained by Equation 19.

$$\delta_{yeild} = b \times \tan\theta = b \cdot \theta \qquad (19)$$

b is the thickness of the lumber (mm)

The external workload equals the internal workload.

$$W_{panel} = \{n \times (m-1)\} \cdot W_{nail} \qquad (20)$$

Organizing the above equations yields the Equation 21.

$$\frac{1}{2} k_{wall} \cdot x_{yeild}^2 = \{n \times (m-1)\} \cdot \frac{1}{2} k_{nail} \cdot \delta_{yeild}^2 = \{n \times (m-1)\} \cdot \frac{1}{2} k_{nail} \cdot (b \cdot \theta)^2 \qquad (21)$$

Therefore, the in-plane shear stiffness of the NLT k_{wall} can be obtained by Equation 22.

$$k_{wall} = n \cdot k_{nail} (\frac{b \cdot \theta}{x_{yeild}})^2 \qquad (22)$$

7–CONCLUSIONS

The load deformation relationship of in-plane shear of NLT was almost well estimated by the calculation method proposed in this paper. The results indicate that the in-plane shear properties of NLT can be evaluated though incremental displacement analysis with concern of the load deformation relationship of the nail joints and the embedment of the lumbers.

A simple linear calculation method for the presumption of the overall rigidity of the NLT using the dislocation of the pinned joints between the NLT fabricated materials is also proposed. However, the calculation results are only 0.82 of the experimental results. Since the load-displacement relationship is nonlinear from the initial deformation, slight differences in the displacement at which stiffness is evaluated will result in different stiffness, which may be one reason for the difference between the experimental and calculated results.

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