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Flexural Properties of Downscaled Dowel-Type-Fastener Laminated Timber

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Abstract— Use of nail-laminated timber (NLT) in structural buildings has steadily increased in recent years, which calls for a need to optimize the design of its assemblies. This study was aimed at examining the effect of nailing patterns on the flexural properties of unspliced NLT specimens. To reach this, the modulus of elasticity (MOE) of each lumber piece was determined using a long-span centre-point bending test to ensure that all pieces of lumber used were in the same MOE range. A type of downscaled NLT specimen was designed and fabricated using nails, which were 30 mm in thickness, 44 mm in width, and 730 mm in length. The 3D ring shank nails used were 30 mm in length and 2.4 mm in diameter. Three nail spacing (i.e. 60, 85 and 110 mm) were used in fabrication of the NLT. The glue-laminated timber (GLT) specimens of the same dimensions were manufactured for comparison purposes. The specimens were tested under four-point bending. The apparent modulus of elasticity MOE_{app} and apparent modulus of rupture MOR_{app} of each specimen were measured. It was found that the solid group had the highest MOE_{app} of 10,836 MPa, while the NLT group of 60-mm-nail-spacing had MOE_{app} of 10,145 MPa and the NLT group of 110-mm-nail-spacing had the lowest MOE_{app} of 9,254 MPa. As for the MOR_{app}, the GLT group had the highest value of 88 MPa followed by the 60-mm-nail-spacing NLT group (75 MPa) and the 110 mm-nail-spacing NLT group (69 MPa). The 60-mm-nailing NLT group appeared to exhibit the best performance, which was recommended for full-size specimen tests.

Keywords— Nailing pattern, laminated timber, ring shank nail, stiffness, apparent modulus of elasticity, and apparent modulus of rupture

I. INTRODUCTION

In recent years, the percentage of structures built with laminated timber (both nail laminated timber and dowel laminated timber) has increased steadily and this trend can be attributed to the change in raw wood materials such as small diameter logs. On account of the limited size and the heterogeneous nature of trees, the correct assembly of lumber is an important issue in the use of lumber. The technologies of end-to-end connection and face-to-face lamination are widely used to either increase the size or tailor the shape of the pieces or to increase dimensional stability and isotropy [1].

Nail laminated timber (NLT) according to [2] can be defined as a solid wood structural element created by placing dimension lumber (nominal thickness of 51 mm x 76 mm, or 102 mm, and a width ranging from 102 mm to 305 mm) on edge and fastening the individual laminations together with nails. Fig. 1 shows typical NLT.

Fig. 1: Typical Nailed Laminated Panel (Structure craft Builders 2016)

NLT are generally oriented so that the greatest bending loads are applied parallel to the interlayer planes. The significantly different bending properties that a laminated timber can exhibit between strong and weak axes are attributed to interlayer slip. If NLT is subjected to bending about a vertical axis, there is a negligible slip between layers.

However, If the same panel is subject to bending about a horizontal axis, there can be a considerable slip between layers. In some panels, this slip can be so large that for all practical purposes, the individual layers act independently to resist the applied loads. For this reason, laminated timbers are oriented and designed to resist the highest bending moments in bending about a vertical axis. When this is done, they are classified as vertically laminated assemblies [3].

The bending strength and stiffness of laminated timber are dependent on many factors such as interlayer shear transfer capacity, splice arrangement, thickness length ratio and use of butt-joint reinforcement (if such reinforcement is used). The interlayer shear capacity is the amount of load that is transferred by nails per unit area of wood contact while the interlayer shear stiffness is the shear stiffness of the nail connections per unit of the contact area. Both the interlayer shear capacity and interlayer shear stiffness increase with an increase in the number of the fasteners, fastener bending yield, fastener diameter and wood specific gravity [4]. Shear transfer capacity is influenced by type, size, density, and arrangement of fasteners. As a result of the complex interaction of laminated timber variables, there is a need to try different ways of making laminated timbers and to define its structural performance. The laminates, which meet at a butt joint, may not be connected to one another by any means other than through their connection with adjacent laminates. So there may need to use some reinforcement like a galvanized steel sheet. Continuity along the span is provided through butt joints which are staggered, the laminates need to be arranged (splice arrangement) and which in turn depends on the number of layers and an increase in the number of layers (3 or 4 layers) increases the number of ways for arranging the joints [4].

Among these aforementioned factors, research on the effect of nail spacing and pattern which is very important was conducted. Nail spacing must be selected to provide a sufficient amount of interlayer shear capacity because if the interlayer shear capacity is too low, individual connections will be overloaded and fail before design bending and shear stresses are reached in the wood. While increasing the number of fastener will consequently increase interlayer shear capacity, the fastener cannot be increased without bounds, due to the fact that at some points, nailing induced stresses will result in wood splitting and premature panel failure and if not instant failure, on the long run, the nail holes create weakness in the panel and cause failure earlier.

This project describes a study on the mechanical behaviour of NLT, glue-laminated timber (GLT) and solid specimens under flexural tests. The GLT and solid specimens were used as reference groups. The chosen range of parameters such as stiffness and strength encompass those currently employed as the basis of design code, and others that designers might find useful. The evaluation of the effects of nail spacing and nail length are interesting to those working in the wood products industries as shorter nails are easy to use with a nail gun compared to longer ones which might not be able to use with a nail gun. The objective of this chapter was to evaluate the effect of spacing and dowel fastener type on the mechanical behaviour (stiffness and strength properties) of fastener-laminated timber, which was accomplished by experimental testing of NLT and WDLT in comparison with glue-laminated timber and solid wood.

II. RELATED WORK

The primary objective of this project was to investigate the performance of laminated timber panels fabricated using nails and hardwood wooden dowels. This work contributed towards increasing the knowledge of the mechanical behavior of mechanically laminated timber products with the specific objectives shown below:

III. METHODOLOGY

3.1 Lumber

The 2x6 Spruce-Pine-Fir (SPF) lumber of No. 2 and better J Grade was used, which had the dimensions of 38 mm in thickness, 140 mm in width, and 3,600 mm in length. The density of each lumber piece was determined using volume by measurement (using the ratio of the mass of each lumber to the volume). The overall moisture content (MC) of each lumber piece was measured at two different locations randomly selected with a moisture meter (Model: Wagner MMI 1100) to ensure the lumber used had a similar MC. Three-point static bending tests were performed to assess the modulus of elasticity (MOE) for every single lumber piece. Loads were applied using dead weights applied at the mid-span on the wide face of a lumber piece. The span used was 3000 mm. A 50-mm linear variable differential transformer (LVDT) was placed under the lumber at the location of the applied load to measure the deflection at mid-span. After applying a weight (i.e. pre-load) of 22 N (4.9 lbs), the LVDT was zeroed; the deflection was immediately recorded after the second weight of 136 N (30.5 lbs) was applied. To eliminate the influence of annual ring orientation and any warping effect on the stiffness, the deflection of each lumber was measured twice by applying the weight on the two surfaces by turning over the lumber specimen.

3.2 Fabrication of Downscaled NLT Specimens

Lumber pieces were selected in such a way that their densities were within a range of one standard deviation from the mean density of the lumber used as this could minimize the influence of density variation on lumber properties. The MC of lumber at fabrication of specimens was at 12±3%. Each downscaled three-layer NLT specimen used had dimensions of 30 mm thickness, 44 mm width and 730 mm in length. The downscaled specimen has approximately 3.5 in ratio both in width and in thickness to the full size. 3D ring shank nails of 30 mm in length and 2.4 mm in diameter were used. Three nailing spacings were used in the fabrication of the NLT specimens, 60, 85 and 110 mm and these correspond with 250, 350 and 450 mm nail spacing respectively in the full scale. The nails were arranged in a zigzag pattern as shown in Fig. 2. Three-layer downscaled NLT specimens were fabricated. Meanwhile, the downscaled glue-laminated timber (GLT) specimens were also made as a reference and had the same dimensions as the NLT specimen. GLT specimens were bonded with polyurethane adhesive and pressed at a pressure of 0.70 MPa for 8 hours. All the adhesively bonded specimens were then stored in a conditioning chamber (20±2^{o}C and 65±5% Relative Humidity) for about seven days before testing. The laminated specimens were trimmed to the target sizes. There were five groups in this study (Table 1), each of which had 11 replicates, generating a total of 55 specimens. The unfastened lumber group (one piece/no lamination) was prepared for comparison purposes as well.

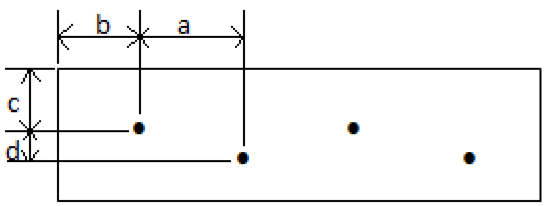


Fig. 2: Nail spacing used (a = 60, 85 or 110 mm; b = 40 mm; c = 18 mm; d = 13 mm)

Table 1: Description of 5 groups tested

Group	Laminating method	Number of nails used per specimen
A	Nailing (60 mm spacing)	24
B	Nailing (85 mm spacing)	18
C	Nailing (110 mm spacing)	14
D	Polyurethane	---
E	Single layer (solid)	---

The four-point static bending tests with a specimen of 630 mm span were conducted using a universal testing machine (Model: MTS 810) in the Wood Science and Technology Centre, the University of New Brunswick, Fredericton, Canada, with reference to ASTM standard [5]. The loading rate was 2 mm/min and the frequency of logging data was 2Hz.

3.3 Calculation of Bending Properties

The MOE of individual lumber piece was calculated using Equation (1). Apparent modulus of elasticity MOE_{app} for each specimen tested was calculated using Equation (2) while apparent modulus of rupture MOR_{app} was calculated using Equation (3).

$$MOE = \frac{PL^3}{4bd^3\Delta} \quad (1)$$

$$MOE_{app} = \frac{23PL^3}{108bd^3\Delta} \quad (2)$$

$$MORapp = \frac{P_{max}L}{bd^2} \quad (3)$$

Where L is the span (mm) b is width (mm), d is depth (mm), P is the load applied (N) in the linear range of load-deflection curve, Δ is the deflection at a given load (P), P_{max} is the ultimate load (N).

IV. RESULTS AND DISCUSSION

4.1 Density, MOE, and MC of Lumber

The average MC of lumber measured was 14% while average density was 440 kg/m^3 and the MOE was 11,165 MPa, Table 2. The lumber used in this study had an MOE value falling in the range of one standard deviation (1,863).

Table 2: Mean values for Density, MOE, and MC of lumber

	MC	Density	MOE
Mean	14%	440 kg/m^3	11,165 MPa
CV (%)	11.8	8.8	20.6
Count	140	140	140

4.2 Mechanical Responses

4.2.1 Response of deflection to load

Fig. 3 plots the average load-deflection curves of all five groups tested. It can be found that all the groups show a linear load-displacement relationship until a certain percentage of the peak load, i.e. the limit of proportionality (PL), followed by an increasing non-linear portion until the peak load. The sharp break shown in the NLT group curve can be attributed to the nail holes present in the specimen. From the load-deflection graph, it can also be seen that there was no abrupt decrease in flexural load capacity after initial cracking which indicates that there was adequate ductility in tension thus flexural strengthening can occur. The graph shows that after initial cracking, there was minimal or slow crack growth, which suggests that the crack propagation has been minimized by the lamination process and the parallel orientation of the grains. Nearly all the load-deflection curves for all the groups look similar apart from group A and this is assumed to be caused by the closed range of the nails to each other, the zigzag in the curves indicates nail propagation failure; The sharp break in the specimen as shown in the load-deflection curve indicates that the specimen failed as a whole but not as an individual for all the groups. This sharp break in the curve is more pronounced in the NLT series and this is attributed to the presence of nails which creates holes and subsequently weakness in the specimen. These three NLT groups also showed a slight difference in peak load with increasing the nail spacing, which could be because the propagation of cracks from nail to nail becomes easier when the nail holes, acting as introduced defects, are located closer to each other.

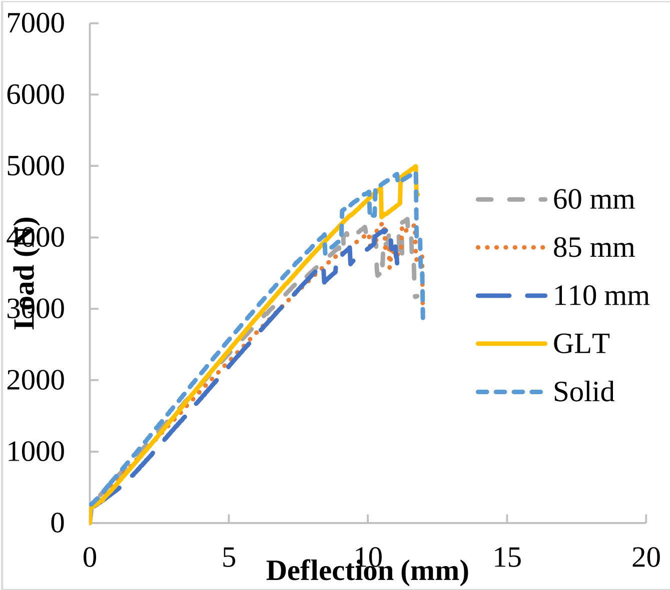


Fig. 3: Load-displacement curves of five groups tested

Table 3: Stiffness, limit of proportion (PL) and peak load values of the five groups

Group	Peak load (kN)	PL (kN)	Stiffness (kN/mm)
A	4.3	2.9	426
B	4.2	2.7	420
C	4.0	2.4	406
D	5.0	3.2	440
E	4.9	3.0	442

Table 3 summarizes the peak load, PL and stiffness values for each group. The peak load of each group, from which it can be found that Group A had the highest peak load of 4.3 kN, Group B among had the peak load of 4.2 kN while Group C had the lowest peak load of 4.0 kN. Group D (i.e. adhesively laminated specimens) had a peak load of 5.0 kN, while group E had a peak load of 4.9 kN. It was not surprising to observe much lower peak load values for nailed panels compared to the glued one because the GLT specimen was bonded together intimately and thereby formed a glue line that helped hold the laminates together strongly compared to the NLT ones which were nailed at intervals. Also, the GLT specimens having reached the yield point still took a substantial amount of load before failure because they behaved as a whole panel. The peak load of the adhesive group (Group D) 16% higher than those of nailing groups and about 2% higher than that of group E (solid lumber).

The PL among groups A, B, C, D, and E varied between 2.4 and 3.2 kN. Among the three NLT groups, group A attained a higher PL very close to the peak load while group B and C took a considerably higher load after reaching PL before attaining the peak load (failure occurred); this large difference between PL and peak load in group B and C could be attributed to the nailing spacing as evidence that no nail propagation occurred in the specimen. Overall, GLT and solid had a very large difference between the PL and the peak load.

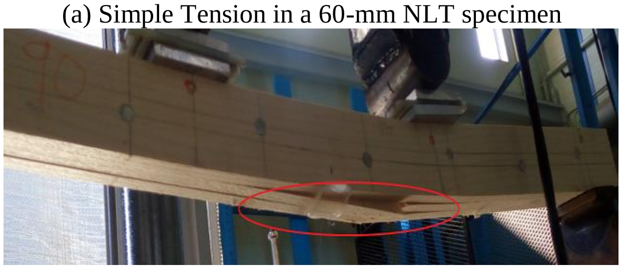
Based on the slope of the graph, it can be concluded that out of the three nailing groups, group A had the highest stiffness value among the NLT group, closely followed by group B while group C had the least stiffness value and when looking at the peak load, group A had a better peak load than C and almost the same as that of B. Group D had higher stiffness value among than the NLT groups; this is as a result of the adhesive used in joining the laminates together. Group D (i.e. GLT group) showed higher stiffness due to the well-compacted wood layers and it also exhibited complete composite action as there was no slip between individual layers when the assembly was loaded. Group E had the highest stiffness value and close to Group D among all the five groups as group E acts as a single laminate. From Fig. 4 and Table 3, it can be found that three NLT groups did increase in stiffness significantly with increasing the nail spacing, however, beyond a certain number of nails the improvement may start to decrease until it ceases all together which could suggest that the composite elements were intimately joined regardless of the number of nails.

4.2.2 Failure Modes

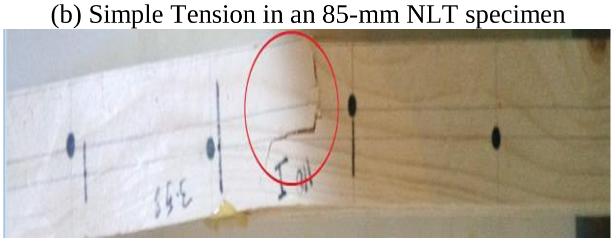
In accordance with ASTM D143 [6], six failure modes were found to occur in small clear wood specimens under bending tests, which are used as a reference to discuss the failure modes occurring in this study. For three NLT groups (Groups A, B, and C), it was observed during testing that the crack(s) propagated in Group A horizontally along a path parallel to the grain axis, resulting in a simple tension failure mode (Fig. 4a). Some propagated along the nailing line, from nail to nail as a result of close the range of the nails to one another. It was observed that there is no evidence of delamination or nail withdrawal in group A. In Groups B and C, the crack(s) did not visibly propagate from nail to nail (Figs. 4b and 4c), which could be due to their relatively wide nail spacing. The crack propagates horizontally to both sides of the specimen where the loads were applied. No delamination or nail withdrawal for group B, the simple tension mode was observed for group B, while simple tension failure mode also occurred in Group C. The crack initiated at the centre of the specimen for the entire groups as shown in Fig. 4. However, some crack propagation in the groups initiated from the knots close to the centre of the specimen and propagated along the grain and thereby led to their prompt failure. There was no physical sign of nail withdrawal or pull out in any of the NLT groups.

Simple tension failure mode occurred the most in group D. One of the group D broke in two due to the presence of knots (Fig. 4d) and this caused failure to occur suddenly without reaching the ultimate load and the specimen broke apart into two separate pieces in a brittle manner; however the GLT specimens remained intact. But for all other replicates, they were able to attain maximum load capacity as one piece even after the maximum load was reached and continued to carry a significant amount of load in the post-maximum load stage. The lamination process thus converts the brittle matrix into a ductile material. The lamination serves as crack arrester in the tension mode. Although the beams had reserved capacity after the first failure, it was felt that the redistribution of stresses in the member after the first bending failure might cause additional difficulties in the interpretation of results. The single lamination (group E) failed in simple tension (Fig. 4e); the crack initiated at the centre and propagated along the horizontal axis.

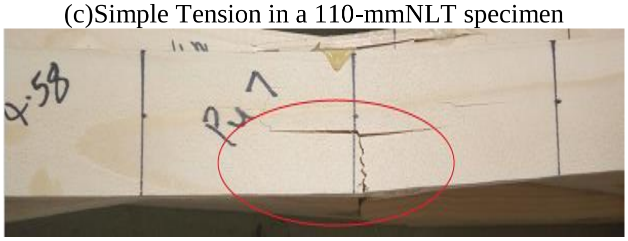
(a) Simple Tension in a 60-mm NLT specimen



(b) Simple Tension in an 85-mm NLT specimen



(c)Simple Tension in a 110-mmNLT specimen



(d) Failure in a GLT specimen

(e) Failure mode in unfastened specimen

Fig. 4: Photography of failure modes of broken specimens

4.2.3 Apparent MOEapp and MORapp

Table 4 shows the average MOEapp and MORapp values of five groups tested while Figs. 5a and 5b illustrate a comparative diagram for the groups for the MOEapp and MOR app respectively. Group A had the highest MOEapp value of 10,145 MPa among the NLT while Group B had MOEapp value of 9941 MPa and Group C had the least MOEapp value of 9254 MPa. Ultimately, it can be found that Group E had the highest MOEapp value of 10,836 MPa closely followed by Group D which had a value of 10,775 MPa. Group A among the NLT specimen had the highest MOEapp of 10,145 MPa, which could be attributed to its having the largest number of nails and lowest nailing spacing, i.e. the nails in this group were closer to each other than in the other groups. However, for MORapp, Group A had 74MPa, while Group B also had the highest value of 75 MPa. Group B had the highest MORapp due to the crack propagation caused by the high number of nails in Group A which led to its failure even without reaching the full capacity of it. Group C showed the least value of 69 MPa. Group D had the highest value of 88 MPa out of the five Groups and then followed by Group E with a value of 84 MPa. All the laminated groups (say A, B, C, and D) were compared to the non-laminated one (Group E, i.e. solid wood group) as reported in Table 4. The ratios of MOEapp or MORapp between a laminated group and Group E were calculated. Group A had the highest percentage ratio to Group E among the NLT for MOEapp while Group C had the lowest percentage ratio. For MORapp, Group A had the highest percentage ratio while Group C had the lowest ratio.

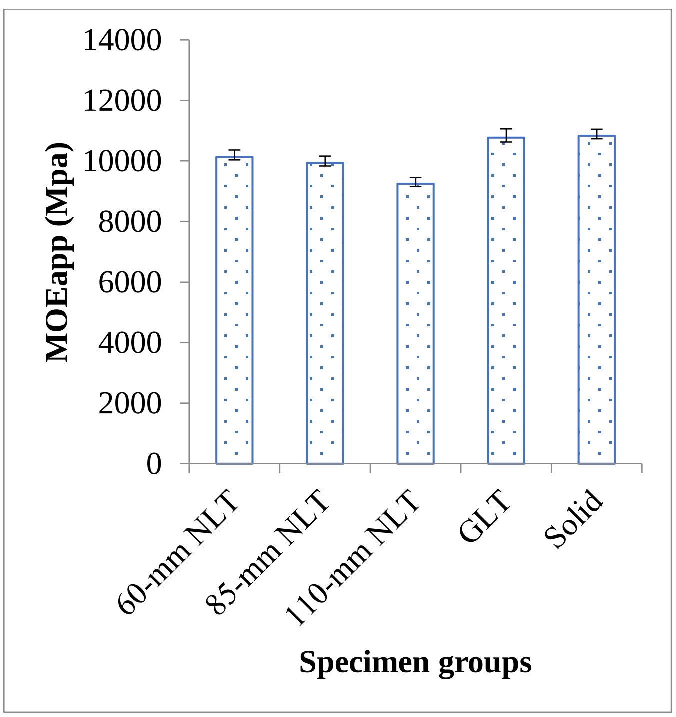
In general, the ratios of MOEapp and MORapp between Group D and Group E showed the highest number, suggesting the use of adhesive is the best for joining laminates together and that adhesives can hold much better than nails as this will eliminate the need to make holes in the timber thereby improve the mechanical strength and stiffness of the panels as creation of holes using nails constitute to the panel weakness with time. Also using adhesive can prevent splitting of the wood as driving nails into the wood can cause splitting especially along the nail line. This is because splitting on its own will limit the ultimate strength of the panel [7].

The CVs of MOEapp of three nail-laminated groups range consistently from 17.3%, 21.9 to 24.2% for Groups A, B, and C, respectively, Group A had the smallest CV value which is an indication that the MOEapp value is more precise and there is less variation in the mean value compared to the other two groups. The CVs for Groups D and E are 13.1% and 23.0%, respectively. CV for Group D is considerably lower compared to other Groups and this shows that there is consistency in the result for Group D than that of the other four groups. For the MORapp, the CV values of Group A, B, and C are 13.2%, 18.4%, and 19.5% respectively, the same trend as the MOEapp; group A had the lowest value while group C had the highest CV for the NLT Group. Group D among all the groups, had the lowest CV of 8.5%, and 22.2% for Groups E.

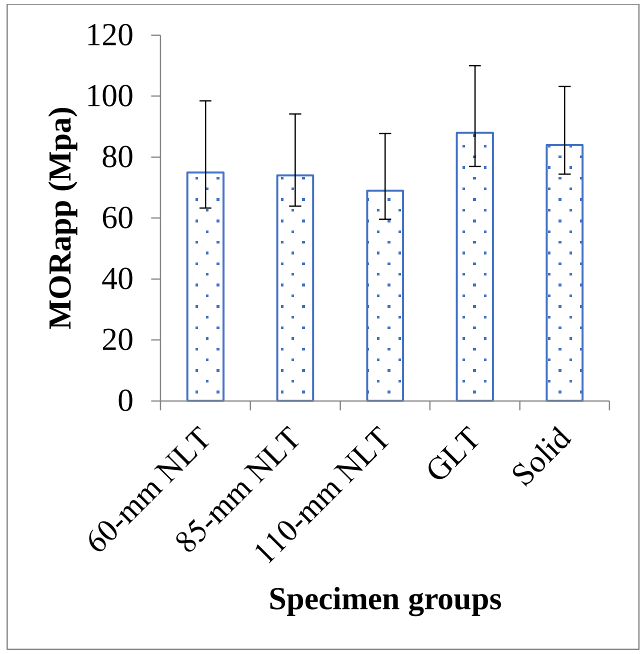
Many studies have shown that vertically laminating members are associated with an increase in design bending stress (i.e., an increase over that which would be assigned to individual members) [8, 9, and 10]. The results in this study have shown that though laminating may not significantly increase the average MORapp of the assembly, the CV for the assembly's MORapp is lower than that of the single members due to load sharing between members. It was established that losses in the strength of nailed laminated timber connections could occur as a result of an increase in the number of nails beyond a certain point [11], though it might improve the strength up to an extent but will ultimately cause failure as the nail holes created weakness with time.

Table 4: Descriptive table for MOEapp and MORapp values

Group	$MOE_{(app)}$ Average (MPa)	Ratio	CV (%)	$MOR_{(app)}$ Average (MPa)	Ratio	CV (%)
A	10,145	0.94	17.3	75	0.89	13.2
B	9,941	0.92	21.9	74	0.88	18.4
C	9,254	0.86	24.2	69	0.82	19.5
D	10,775	0.99	13.1	88	1.05	8.5
E	10,836	-	23.0	84	-	22.2



(a) Comparison between the apparent MOE



(b) Comparison between the apparent MOR

Fig. 6: Comparison between the mechanical properties

4.2.4 ANOVA analysis

Analysis of variance (ANOVA) was carried out at a 5% significance level to test the effect of the nailing pattern on MOEapp and MORapp between the groups. It was discovered that significant difference exists among these groups and the interaction between them, as a result of this, a follow-up analysis was carried out using the Duncan Multiple Range Test (DMRT) to show the level of significant difference among groups. The results in Table 5 shows that there is a significant difference in the MOEapp between the NLT groups and Groups D and E as they both share different alphabets, however, there is no significant difference between Group D and E as they both possess the same alphabet. While for MORapp, a significant difference exists between Group D and all the NLT groups (Groups A, B, and C) as this is an indication that the GLT group (i.e. Group D) has higher strength properties compared to the NLT groups. However, there is no significant difference between groups A, B, and C.

Table 5: Duncan Multiple Range Test

Group	*MOE(app)* (MPa)	*MOR(app)* (MPa)
A	$10{,}145^{ab}$	75^{a}
B	9941^{a}	74^{a}
C	9254^{a}	69^{a}
D	$10{,}775^{b}$	88^{b}
E	$10{,}836^{b}$	84^{ab}

Note: Alphabets with the same letter show that there is no significant difference and alphabets with different letter suggest that there is a significant difference.

V. CONCLUSION AND FUTURE SCOPE

From the above results and discussion, the following could be concluded as follows:

- Whether the nailing spacing (number of nails) controlled the failure or limited the ultimate strength of an assembly could not be stated with any degree of certainty as there was no significant difference in the mechanical properties tested among the groups tested.
- There was no significant difference in MOR_{app} the strength property among the NLT groups, but the stiffness increased to some degree with increasing number of nails: However, beyond a certain number of nails the strength might cease to increase.
- Simple tensile splitting dominated the failure mode for all the groups and that the crack initiated at the centre of a specimen for all the groups.
- The 60-mm-nailing spacing appeared to be optimal for NLT, generating the best performance, which was recommended for the next step research on the verification tests of full-size NLT.

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AUTHORS PROFILE

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