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INFLUENCE OF THE NUMBER OF PLIES ON THE STIFFNESS OF LAMINATED VENEER LUMBER

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Keywords: Tensile Tests, Laminated Veneer Lumber, Poplar, Young’s Modulus, Longitudinal, Transverse

Abstract
This research paper studies how changing the number of plies affects the mechanical properties, such as stiffness, in poplar Laminated Veneer Lumber (LVL) through tensile testing. Various configurations of LVL poplar specimens were manufactured and tested under uniaxial tensile test to assess both longitudinal and transverse stiffness. The findings reveal that the arrangement of plies significantly impacts mechanical properties. These outcomes offer crucial insights for enhancing the design and efficiency of laminated wood structures.

1. Introduction

The use of wood in transportation is not a recent development, yet it presents an encouraging solution to contemporary environmental challenges thanks to its affordability, minimal carbon emissions and lightweight nature [1,2]. Laminated Veneer Lumber (LVL) and plywood, both wood composites constructed from thin wood plies bonded with adhesive, exhibit mechanical properties comparable to or even surpassing those of solid wood. Recent research underscores LVL's potential in crash and impact scenarios [3,4]. However, these wood composites, and more generally, wood ply, exhibit heterogeneity, resulting in dispersion and variability in mechanical properties. Thus, a detailed analysis is imperative to consider their suitability as structural materials in transportation.

Studies indicate that the number of plies, within a fixed thickness of LVL, influences stiffness and strength [5]. This phenomenon is observed across shear, compression, tensile, and bending tests, with thinner plies yielding higher breaking strength and rigidity in LVL. Nonetheless, only limited research has explored the impact of the number of constant thickness plies on LVL properties [6]. In the case of Carbon Fiber Reinforced Polymer, the laminate theory model does not predict an increase in composite stiffness as the number of plies increases whereas experiments exhibit contradictory results[7].

The present study aims to continue the work carried out by ICA members since 2014 [8]. LVL made up of different poplar plies are being characterized through a series of uniaxial tensile tests. The aim of this campaign is to understand and identify the mechanical properties of poplar LVL and the influence of the number of plies on its behavior

2. Material and Methods

Tensile tests on 1-, 2-, 3-, 5-, 7-, and 9-ply of Koster poplar (*Populus x canadensis*) LVL were carried out to characterize the transverse and longitudinal stiffnesses of these laminates and the influence of the number of plies. Each ply used for the manufacturing of the tensile specimens was 1 mm thick. The

wood veneers were bonded together using Kleiberit 510 PUR 1C FIBERBOND adhesive, stacked, and subjected to a pressure of 10 bars at 25°C for 5 hours to form the LVL. The amount of adhesive applied, as per the manufacturer's recommendation, was 250 g/m^2. The density of the poplar veneers was 355 kg/m^3, with a Standard Deviation (SD) of 21 kg/m^3.
Six 0° unidirectional specimen configurations were used for this study: [0°], $[0°]_2$, $[0°]_3$, $[0°]_5$, $[0°]_7$, and $[0°]_9$. Three 90° unidirectional specimen configurations were also studied: $[90°]_3$, $[90°]_5$, and $[90°]_9$. These series were used to evaluate the effect of the number of plies on the transverse stiffness of LVL. A total of 15 specimens, with rectangular geometry, were manufactured per configuration. The tensile specimens had nominal dimensions of 250×25×thickness of LVL mm^3. Tabs, 50 mm long, were added at each end to limit stress concentrations, and therefore breakage, in the jaws of the testing machine

Tensile testing was conducted under standard ambient conditions of temperature and humidity (23.6°C and 64.6% RH). Prior to testing, the wood samples were conditioned to achieve a moisture content of 9.8% (SD: 0.28%). The tests were performed using an Instron 5900 machine equipped with a 50 kN force cell, providing a measurement accuracy of 0.5 N. A cross-head displacement rate of 2 mm/min was applied during testing. Stereo Digital Image Correlation (DIC) was employed to monitor sample deformation, for which the specimens were coated with speckles to allow image correlation. The size of the speckle patterns was adjusted according to the experimental setup to ensure a minimum size of 3 pixels for each spot [9].

3. Results

3.1. Study of $[0°]_n$ specimens

Figure 1 illustrates the distribution of the mean Young's modulus for the $[0°]_n$ specimens. The variability in the longitudinal Young's modulus of the $[0°]_n$ specimens tends to diminish as the number of plies increases (Figure 1 (a)). Furthermore, there is an evident trend of stiffening in the LVL corresponding to the number of plies. A comparison among 2-, 3-, 5-, 7-, and 9-ply specimens reveals that the Young's modulus tends to escalate with an increase in the number of plies. However, the considerable variability observed in the $[0°]_1$ series precludes a direct comparison with the other series. This inclination towards increased stiffness is noteworthy and aligns with findings from Lechner and colleagues, who observed a similar trend in tensile tests involving 1-, 2-, and 4-ply specimens [6].

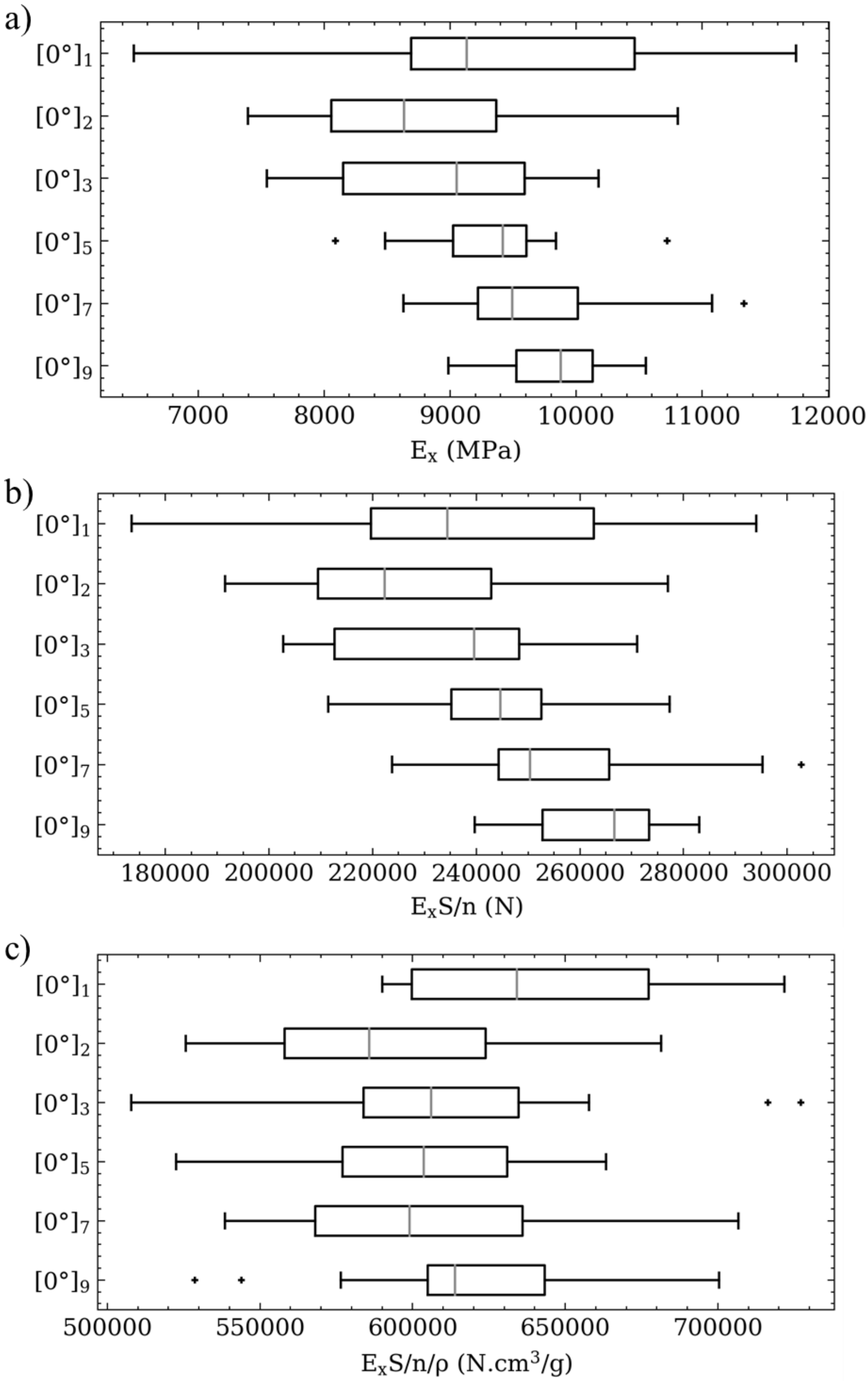

Figure 1. Distribution of the longitudinal Young's modulus by series (a), the Young's modulus multiplied by the cross-section and relative to the number of plies (b), and the specific Young's modulus multiplied by the cross-section and related to the number of plies (c)

It's important to acknowledge that when calculating the stress for determining LVLs stiffness, the cross-section measured on the tensile specimens is taken into account. However, the manufacturing process alters this cross-section (such as compression of the veneers during LVL plate pressing) and this change affects the specimen's cross-section, it may influence stress calculations too. To address this issue, comparing the Young's modulus of the specimens involves adjusting it by multiplying with the specimen's cross-section and dividing by the number of plies (for cross-series comparisons). Figure 1 (b) illustrates this distribution across different series. Despite this adjustment, a stiffening effect remains evident when comparing 2-, 3-, 5-, 7-, and 9-ply specimens.

To assess the impact of density on the results, the wood density of each specimen can be determined using the theoretical density of the wood it comprises. This density is calculated by subtracting the mass of glue from the total mass of the manufactured specimen and relating this to the specimen's volume, excluding the glue joints. It is assumed that the glue is uniformly distributed across all specimens within the same series.

Figure 1 (c) indicates that the distribution of the specific longitudinal Young's modulus, multiplied by the cross-section, relative to the number of plies in the specimens tends to follow a consistent trend with the number of plies. This observed increase in properties with the number of plies can be attributed to the phenomenon of densification associated with the LVL manufacturing process [10]. Consequently, the role of glue in this stiffness enhancement appears to be secondary.

However, as noted by some authors [5,11], the thinner the LVL veneers, the greater the relative amount of glue used to manufacture the LVL. For 2-ply specimens, glue represents 25% of the LVL mass, and it rise up to 37% for 9-ply specimens.

The ply number does not appear to affect the experimentally measured Poisson’s ratio (ν_{lt}) values. However, there is a trend where increasing the number of plies decreases the variability in Poisson’s ratio measurements, though it does not affect the mean values obtained. This decrease in variation can be attributed to the enhanced plane stability resulting from the increased number of plies, which in turn mitigates the occurrence of cupping in specimens [12].

3.2. Study of $[90°]_n$ specimens

The Young’s moduli of the $[90°]_n$ specimens is also an increasing function of the number of plies. This stiffening is more marked than for $[0°]_n$ specimens. Figure 2 shows that, in contrast to the $[0°]_n$ series, specific transverse Young’s moduli multiplied by the cross-section relative to the number of plies of the specimens is always an increasing function of the number of plies. The increase observed in properties with the increasing number of plies can then be explained by the presence of glue in the LVL. In this configuration, the glue has a non-negligible effect on the stiffening of the specimens.

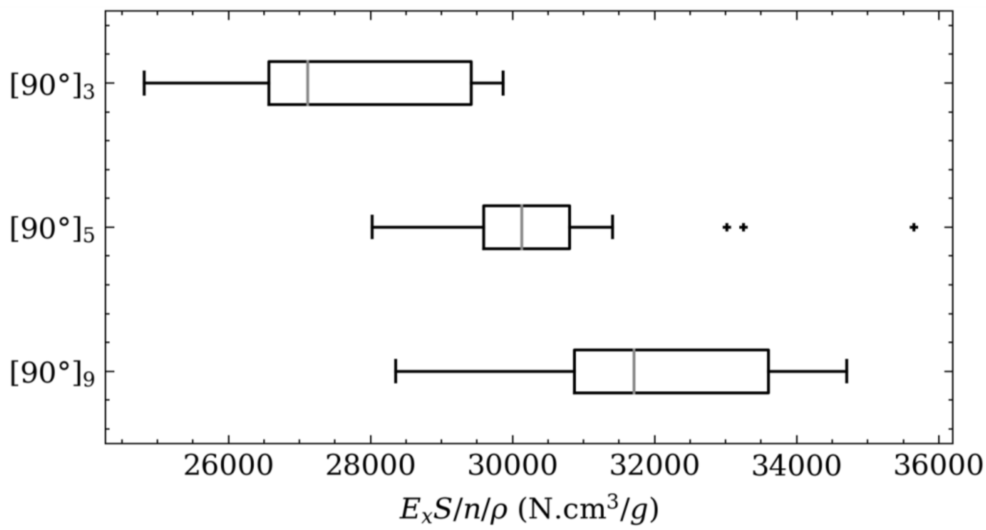

Figure 2. Distribution of specific transverse Young's modulus times the cross-section and relative to the number of plies per series

Since the transverse stiffness of poplar veneers is lower than the longitudinal stiffness, the stiffness of the glue added during the manufacture of LVLs plays a more important role in the total stiffness of the laminate.

4. Discussion and Conclusions

Tensile tests on 1-, 2-, 3-, 5-, 7-, and 9-ply poplar LVLs were carried out to characterize the transverse and longitudinal stiffnesses of these laminates and the influence of the number of plies. The results show that stiffness tends to increase when the laminate is composed of a sufficient number of plies. This observation is valid, not only for longitudinal stiffness but also for transverse stiffness, where the effect is even greater. Although Lechner et al. [6] had already been able to observe this phenomenon, they did not explain it. The explanations on the increase in stiffness put forward during this work are based on the LVL manufacturing process: when the number of plies is increased, the relative amount of glue in the laminate increases. For the $[0°]_n$ specimens, it's interesting to note that the more plies there were in an LVL, the more the variation of the elastic modulus seemed to decrease. The stiffness observed on tensile tests was more homogeneous.

Nevertheless, based on the findings presented, it's important to recognize that wood density, and consequently the densification of wood veneer during manufacturing, can also impact this phenomenon. However, measuring the densification of veneer during manufacturing poses considerable challenges. The stiffness of the adhesive, can also affect the analysis performed. However, the phenomenon of interaction between glue and wood is still considered complex, so it remains an area of active research even today.

Moreover, it's worth noting that the stiffness of the adhesive used is approximately 1.8 GPa (as identified in other studies not presented here). This stiffness of 1.8 GPa may help elucidate why the adhesive has a more pronounced effect on stiffening $[90°]_n$ specimens compared to $[0°]_n$ specimens. In the case of $[90°]_n$ specimens, the adhesive is nearly 12 times stiffer than the 90° plies, whereas for the $[0°]_n$ series, the 0° plies are 5 times stiffer than the adhesive.

Examining the stiffness of LVL based on the number of plies offers a deeper comprehension of the connection between manufacturing processes and the material's mechanical characteristics. This data appears pertinent for establishing an analytical or digital model for wood-based composites. Nonetheless, further investigation is warranted to discern the impact of the number of ply across diverse orientations, materials, and adhesives. Incorporating factors such as local density or veneers' lathe checks could potentially elucidate some of the observed variability in these tests. Moreover, exploring different wood resources could corroborate the observed behavior in species beyond poplar.

Acknowledgments
The research that led to the results presented received funds from the French National Research Agency under the BOOST project (ANR-21-CE43-0008-01). The authors thank the LaBoMaP Laboratory, Cluny, France for providing the Poplar veneers used in this study, through the research project ANR BOOST.

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