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The Adhesion Performance in Green-Glued Finger Joints Using Different Wood Ring Orientations

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Abstract: Structural lumber is designed to meet the technical standards that ensure safety, cost-effectiveness, and sustainability. However, some tree species face limitations in their growth, which restricts their widespread use. An example of this is *Nothofagus alpina*, which has excellent mechanical properties but is not utilized much due to the challenges in extracting its timber and poor utilization, mainly because of the length of the wood. There is little information concerned with the uses and better management of small pieces using Nothofagus species, but it is still insufficient. This study investigates the adhesion performance of green-glued finger joints with varying wood ring orientations and moisture contents ranging from 21% to 25% using *Nothofagus alpina*. The primary aim is to assess how ring orientation and wet timber affect the green gluing process for creating larger wood pieces than sawn wood. The resulting products could meet the standards for wood serviceability number three for native Chilean wood. The findings indicate that finger joint performance improves with higher timber moisture levels. However, the orientation of the wood fibers did not significantly affect the performance under the tested conditions. It is important to note that this effect may become more significant near the fiber saturation point. These findings emphasize the need for a detailed protocol on the green gluing technique for *Nothofagus alpina* and the associated drying and surface processes in finger joint construction.

Keywords: *Nothofagus alpina*; green gluing; finger joints

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1. Introduction

Wood is a highly competitive material due to its favorable weight-to-strength ratio and sustainability criteria [1]. However, due to its natural growth patterns, wood production faces limitations in size, consistency, and mechanical and physical properties homogeneity. Glued-Laminated Timber (GLT) or glulam is a technique developed to overcome these challenges [2,3]. This technology involves creating structurally Engineered Wood Products (EWPs) by finger-jointing and gluing wood lamellae end-to-end, resulting in a more homogeneous, shape-stable material. GLT allows the production of massive timbers, up to 30 m in length, which would be difficult or impossible to obtain from a single tree [4]. This technique is also valuable for eliminating the natural defects of plain wood, such as knots or any other defect that reduces mechanical properties.

At the same time, Laminated Veneer Lumber (LVL) and Cross-Laminated Timber (CLT) are two popular engineered wood products extensively used in modern construction due to their strength, stability, and sustainability. LVL is mainly used for linear structural elements and provides high strength and stiffness in one direction. On the other hand, CLT is used to create large panels with strength and stability in multiple directions, making it ideal for the walls, floors, and roofs of multi-story buildings. Both LVL and CLT are solid, stable, and sustainable building materials. They offer significant environmental benefits, making them a more eco-friendly choice than traditional construction materials [5,6].

In the same way, glued laminated timber, often called glulam, is an engineered wood product created by bonding layers of wood (known as laminas) with adhesives. This process enables the production of structural elements in different sizes and shapes, including long spans and unique designs that captivate interest and are often challenging to achieve with solid wood [7].

The glulam technique uses moisture above the fiber saturation point (FSP) timber [8]. On the contrary, green gluing is a technique used to bond freshly sawn lumber that has not been through a kiln or air-drying process [9]. Several authors have reported the impact of this technique in protecting and assessing native forests. For instance, Lissouck et al. [10] explained that developing the glulam industrialization of species of wood native from the Congo basin can mitigate their overexploitation, thus protecting them against rarefaction and extinction risk. Similar studies have been developed using different native species worldwide [11–13], a robust background to implement this technique in other species. However, limited information on research on native Chilean species is found [8,14].

In a previous study by Rosales et al., the feasibility of using the green gluing technique with Nothofagus Chilean species was tested [14]. The green gluing with timber near or above the fiber saturation point shows promising results. However, their potential is limited by the standard for laminated wood products, which require kiln-dried wood for manufacturing. Typically, wood products are made by machining and gluing dried timber with a moisture content of around 10%. While manufacturing GLT with green wood and letting it dry as a final product saves time and energy, the wood tends to retract while drying, which can cause shrinkage and internal strain in the material until it ruptures. Hence, the primary challenge of green wood gluing is to ensure that the product can withstand the drying cycle. At the same time, the lack of regulations for using the green gluing technique in hardwoods presents a challenge. As a result, this study intends to push to develop this technique for use in more minor structural elements like pergolas, garages, and playgrounds. If the method's focus shifts to small companies and producers, it could lead to the more sustainable management and production of these types of constructions.

Previously, Sterley and Gustafsson [15] studied the shear fracture properties of one-component polyurethane (PUR) wood-adhesive bonds. Their article examines the impact of moisture content (MC) and pressing conditions during the gluing process. This study aims to improve our understanding of how these factors affect the mechanical performance of adhesive bonds, especially in green gluing where unseasoned wood is used. The findings indicate that the precise control of moisture content and pressing conditions is essential for optimizing the performance of PUR adhesive bonds in wood applications. Additionally, the study highlights the potential of green gluing techniques to enhance wood utilization and energy efficiency in the wood processing industry, potentially leading to more sustainable wood use. These results can serve as a valuable reference for understanding potential outcomes when using the *Nothofagus alpina* species and incorporating finger joints.

The finger joint technique may provide a solution to overcome this issue. Pommier and Elbez demonstrated that finger joints made with green-glued softwood could be more potent than those made with gluing on dry wood [16]. This situation is due to the higher ductility of greenwood, which allows the finger profile to fit up to the tipping point, resulting in a more regular glue line [16]. Despite this information, it is crucial to consider the hygroscopicity of wood, which allows the wood products to endure thermal and hygroscopic variations with the seasons' changes throughout their life. This anisotropic wood swelling with humidity variations provokes internal strain that may harm the beam [4]. Green-glued wood products can suffer swelling while drifting to moisture equilibrium, but pieces with deformations are reduced.

Furthermore, other factors, such as the length and slope of the finger joint, are closely related to the strength of a specimen [17,18]. The applied pressure is also crucial for evaluating the ultimate tensile strength [2,19]. Additionally, the stiffness and thickness of the bond line are essential factors, as emphasized by Groom and Leichti [20]. Therefore, the performance of the wood product is critical in the initial cycle.

Wood's drying process and its direction-dependent shrinkage may be particularly harmful to the finger joint region depending on the relative orientations of wood rings on the two sides of the joint. This information could be crucial to overcoming the structural standard of the norm and implementing green gluing using native Chilean wood. Moreover, equipping small industries with simple tools and procedures is vital, especially considering their access to smaller woods. This action not only protects forests with these species but also reduces the need to replace them with other species (pine or eucalyptus), underlining the practicality of the proposal and its potential to empower small producers. Due to that, this research studied the adhesion performance in green glued finger joints using different wood ring orientations. The results of this research can provide helpful information for understanding the behavior of green-glued wood sections and thus use them in longer sections for construction.

2. Materials and Methods

2.1. Selection, Preparation, and Characterization of Wood

The study used *Nothofagus alpina* (Rauli), a native wood species in Chile with a 500 kg/m^3 oven-dry density. Softwood green-glued finger joints have been shown to have potential by Pommier et al. [16]. Moreover, this study used a one-component polyurethane adhesive (1C-PUR) due to its good mechanical properties and low environmental impact [2,21]. This adhesive is certified for structural use in the traditional dry bonding process (13–18% humidity), that is, on the support of wooden structures (safety data sheet according to Chilean standard NCh2245:2015) [22]. Nonetheless, this product was used in a previous report to carry out the green gluing technique with promising results [14].

At the same time, to reduce the uncertainty and variability of wood, all specimens were made with wood from the same lot, and half of them were dried before gluing. According to the EN 408 standard, the moisture content in the specimen must be stable when tested (less than 0.1% mass variation in 6 h). The modulus of elasticity (MOE) of wood was measured using a FAKOPP Microsecond Timer© (Agfalva, Hungary), designed explicitly for wood measurements by the Hungarian company Fakopp Enterprise (Agfalva, Hungary) [23,24]. Therefore, the green-glued specimens were dried to Equilibrium Moisture Content (EMC) corresponding to 14% moisture content for the Santiago of Chile city before being tested. All specimens were tested at 6–8% moisture content measured with the RDM3 tool by the Delmhorst Instrument Company (Towaco, NJ, USA). To appreciate the effect of relative wood ring orientation, a batch of tests was made for each of these configurations (Figure 1): Tangential–Tangential (T/T): six dry-glued and six green-glued, Radial–Radial (R/R): six dry-glued and seven green-glued, Radial–Tangential (R/T): 11 dry-glued and 11 green-glued. A batch of 10 plain beams without junctions was also tested as a reference. In total, 57 tests were conducted.

Moisture content, reference density (mass and density at moisture content at 14%) and oven-dry density (mass and density at 0% moisture content) were determined for each end of the tested pieces according to Chilean standard NCh 176/1 [25] and NCh 176/2 [26], respectively.

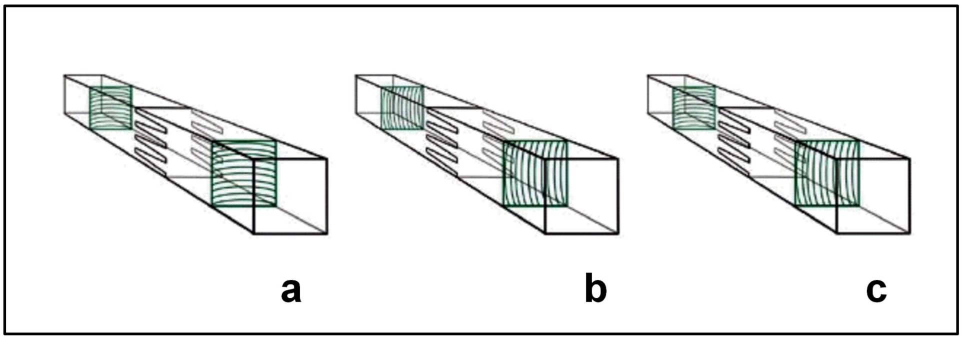

Figure 1. Different orientation ring combinations to build the finger joint samples: (**a**) Tangential–Tangential (T/T); (**b**) Radial–Radial (R/R); and (**c**) Radial–Tangential (R/T).

2.2. Measurement of Moisture

Upon receipt, the sawn board samples measuring 50 mm × 50 mm × 920 mm were observed and separated based on the orientation of the rings concerning the lumber's faces. Only treads with rings tangent to one side (around 20 degrees) were selected for the study. Each lumber's humidity was measured using the RDM3 tool from Delmhorst Instrument Company. To prevent the lumbers from drying, they were kept in plastic bags when not being manipulated for cutting or gluing. All specimens were prepared within a minimum period of approximately two weeks to maintain their humidity at environmental temperature (20 ± 3 °C). These efforts were successful as the moisture content was re-measured for the green-glued specimens and had not changed. The moisture content measures varied between 21% and 25%. The moisture measurements were conducted using the sensor mentioned, which is faster and less intrusive for determining the moisture content. Furthermore, small companies or producers will be able to utilize this method.

2.3. Drying Protocol

When received, the reference lumber and dry-glued specimens were placed in a dry oven at 40 degrees Celsius and kept there for nine days. Afterward, they were moved to laboratory conditions for an additional week before being cut down in a controlled environment of 20 ± 3 °C and less than 60 ± 5% relative moisture. In Chilean standards (NCh 176/1 [25] and NCh 176/2 [26]), it is mandatory to work within the specified range of temperature and moisture to certify the data's value. This protocol helped to achieve a measured moisture content of 6–8%, with very few cracks on the lumber. Most of the cracks were located at the ends of the lumber, which were subsequently removed.

2.4. Finger Joint Profile Cutting Protocol

The green-glued lumbers squared to 46 mm × 46 mm × 920 mm, while the others were left to dry. Then, as shown in Figure 2, a 3-axis CNC machine and a finger joint cutting bit were used to cut the finger joints off. The machine corresponds to Shopbot, the PRSalpha model. The depth of the finger cutting was determined through tip gap adjustment tests to find the optimal depth of 11 mm. The ends of the beams were planned to ensure consistency in the depth of the finger joints, as illustrated in Figure 2. The fingers were cut in four passes, each being 3 mm, except for the last one, which was 2 mm to limit defects during the cutting process.

Support was built to cut the finger profile in half and specimens 12 by 12, using the same CNC machine as the finger profile to guarantee orthogonality between the fingers and the specimen's axis. Slots were machined in plywood boards, and a system blocking the specimens was mounted on top of this board. The slots ensure the position of the specimen on two axes, and the first pass provides the precision on the third axis. The CNC has a 0.01 mm precision on each axis. The cutting speed was set to 18,000 rpm.

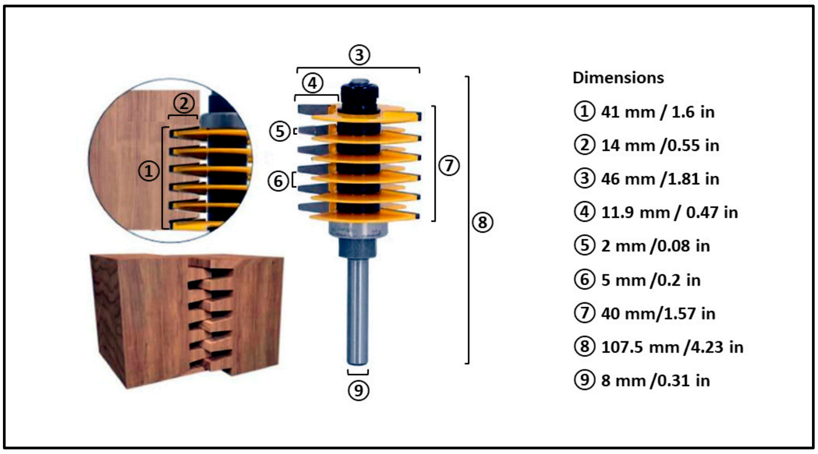

Figure 2. Details of finger joint construction. Each number indicates the position and the length used.

Lastly, the 92 cm lumbers were cut in half just before cutting the finger profile to prevent the finger from drying. The lumbers were immediately covered with plastic film to keep it from drying out.

Forty-eight hours after cutting the parts, they were glued together using Jowapur 685.12 adhesive and pressed at 6 N/mm^2, following Pommier's and Elbez's instructions [10]. The pressure was kept for a few seconds, as recommended by He et al. [27]. The pressure was applied end-to-end without guidance, resulting in a maximum 1-degree misalignment, which was corrected during the following squaring process. After two days for the glue to polymerize, the specimens were dried using the same protocol (nine days in a dry-40 degrees Celsius oven followed by one week at lab conditions).

The reference lumbers were immediately squared and cut to the correct dimensions for the EN 408 four-point bending tests. The dimensions were 36 mm × 36 mm × 800 mm (Figure 3) since the lab's test bench had a 700 mm span. On the other hand, the dry-glued specimens were squared down to 43 mm × 43 mm × 920 mm lumbers. These pieces were cut in half, and the fingers were cut. They were then glued and pressed at 6 N/mm^2. After two days of polymerization, they were cut to 36 mm × 36 mm × 800 mm and made ready for testing. The green-glued specimens were squared again once dry, cut down to the 36 mm × 36 mm × 800 mm dimensions, and prepared for testing. Slices showing the glued zone were kept as much as possible when cutting the specimen to its ultimate size to observe the glue joint and compare it to the mechanical test results.

The green gluing technique described in this research was developed by Rosales et al. (2023) [14]. In this procedure, a spatula is used to apply 150 g/m^2 of adhesive to each contact surface. A clamping pressure of approximately 0.6 MPa is maintained for two hours. The pressing operations were carried out in a controlled environment at 20 ± 3 °C. The NCh 2148 standard [28] sets out the operating range for pressing conditions.

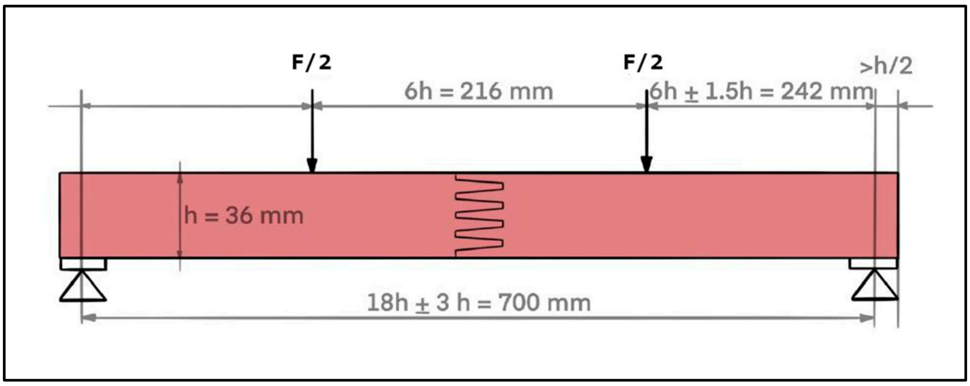

Figure 3. Dimensions of the specimens following the EN 408 standard.

2.5. Mechanical Tests

The bending tests were conducted following the instructions of the EN 408 standard [29]. Although the norm required more specimens, a clear tendency was observed with the specimens used in the study. The study determined each specimen's bending strength and rupture mode (MOR). The determination of the local modulus of elasticity (MOE) in bending for each specimen was subjected to a symmetrical load by being bent at two points throughout 18 times its depth, as illustrated in Figure 3. The lateral restraint was applied as needed to prevent lateral torsional buckling. This action allowed the specimen to deflect with minimal frictional resistance. All the procedures followed the EN 408 standard [29]. The press model was TC10001, and a local manufacturer made it [14].

The two following equations are used to calculate the MOR and MOE of finger wood [30].

$$\text{MOR} = \frac{3 \cdot P \cdot a}{b \cdot h^2} \tag{1}$$

$$\text{MOE} = \alpha \cdot \frac{6 \cdot P \cdot a \cdot L^2}{\delta \cdot b \cdot h^3} \tag{2}$$

where:

$$\alpha = \frac{1}{8} - \frac{1}{6} \cdot \left[\frac{a}{\text{L}}\right]^2 \tag{3}$$

P: applied load (N);
a: distance from one of the supports to the applied load (mm). In this case, 242 mm;
L: span of the tested element (mm). In this case, 700 mm;
b: width of the section of the part (mm);
h: height of the section of the part (mm);
α: coefficient of elastic deformation;
δ: deformation at span center.

In summary, MOR relates to the stress at yield during bending, while breaking strain quantifies the material's deformation capacity before fracture occurs.

2.6. Micro-Computed Tomography (Micro-CT)

A high-resolution Bruker SkyScan 1272 microtomography (Kontich, Belgium) was used to scan the samples. The scanner operated a rotation of 0.4 at 80 kV, 125 mA, and used an aluminum filter of 0.25 mm. The resolution of the analysis was 12 µm. The images were visualized with Nrecon reconstruction software (Version 3.1.1), and three-dimensional scanned images were obtained. The images were repositioned with Data Viewer software v1.5.1.9 to standardize the sample positioning. Quantitative assessments were performed using micro-CT and software analysis in a volume of interest (VOI) of approximately 2 cm^3 in the transversal plane. Images of each sample were obtained using a visualization software, with a pixel size of 24 µm. Voxels with grayscale values between 25 and 255 were considered solid material, while voxels between 24 and 0 were considered void space [14].

The image analysis was similar to that of the research group in [14]. This analysis consisted of processing and analysis with Image J software version 154e (The National Institutes of Health, Bethesda, MD, USA). Images obtained from micro-CT were corrected by removing the background. The corrected image was then converted to a binary black-and-white format for post-processing and parameter estimation. The thresholding procedure used was the iterative selection method. Finally, the percent porosity was calculated by dividing the number of black pixels by the total number of pixels and multiplying by 100 [31].

2.7. Roughness Measurement

The average roughness (Ra) was carefully measured for each piece. Duplicate measurements were taken on each side of the five finger joints of every piece. The fingers on each end were identified and cut with a carpenter's saw. The pieces were then conditioned at 20 ± 3 °C and 55 ± 5% RH for 48 h. Validating the procedure is a critical step. Before registering the value and realizing the measurement, it is essential that the parameters are in the specified range. The average roughness (Ra) was measured using a PCE-RT 1200 roughness tester. This thorough approach involved taking duplicate measurements on both faces of the five finger joints of 30 pieces, resulting in 1200 roughness measurements. This meticulous process ensured a comprehensive and accurate analysis.

2.8. Statistical Analysis

A one-way ANOVA was conducted to compare species under each condition. Significant differences were noted on each graph. An unpaired *t*-test with Welch's correction compared the same orientation wood under different moisture levels. The analysis and the graphics were carried out using the GraphPad Prism 6 program.

3. Results

3.1. Wood Characterizations

Various wood parameters can affect the outcome of the green gluing technique, and density is one such parameter. Table 1 below summarizes this parameter for samples with varying moisture content in finger jointing using the green gluing technique. The values of samples extracted from the finger joint and the opposite side of the finger were obtained.

Table 1. Physical parameters of wood and finger joint tested.

Physical Parameter	Statistical Tests	Finger Joint of Green Gluing	Wet Wood	Finger Joint of Dry Wood	Dry Wood
Oven-dry density (kg/m^3)	Average	0.511	0.534	0.541	0.548
	Standard deviation	0.046	0.045	0.039	0.037
	Size sample	14	14	16	16

The results suggest that the moisture had a low impact on the density using Nothofagus alpina. However, the water gradient into the wood could affect the gluing efficiency. On the other hand, the roughness of the wood (Table 2) showed significative statistical differences in the variance test among the groups (Table 3), which gives evidence of the influence of the roughness on the performance of the green gluing technique.

Table 2. Roughness (µm) values for finger-jointed wood under different treatments were assessed.

Statistical Tests	Finger Joint of Green Gluing	Wet Wood	Finger Joint of Dry Wood	Dry Wood
Average	12.345	8.707	9.650	10.497
Standard deviation	2.900	1.727	2.475	2.709
Size sample	69	70	80	80

Table 3. Analysis of variance for the roughness value.

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	Probability	F Critical
Between groups	3	502.765	167.588	26.847	2.2169×10^{-15} *	2.635
Within groups	295	1841.500	6.242			
Total	298	2344.265				

* significant difference.

In Table 4, Tukey's mean comparison test identified significant differences in the roughness of the finger joint used for the green gluing technique compared to the other conditions. Additionally, there were significant differences in the roughness of dry wood compared to wet wood and the finger joint area used for the green gluing technique.

Table 4. Tukey test of roughness for the conditions tested.

	Finger Joint of Green Gluing	Wet Wood	Finger Joint of Dry Wood	Dry Wood
Finger-joint of green gluing	-	<0.001 *	<0.001 *	<0.001 *
Wet wood		-	0.0988 NS	<0.001 *
Finger-joint of dry wood			-	0.1421 NS
Dry wood				-

NS: non-significative. * significant difference.

3.2. Mechanical Test

The study's results that focused on the orientation effect of wood rings on the green gluing technique are presented in Table 5. The table includes the mean modulus of rupture (MOR), MOR coefficient of variation, mean modulus of elasticity (MOE), MOE coefficient of variation, and the type of failure. The types of failure indicated in Table 5 are presented in Figure 4.

Table 5. Mechanical results of the experimental design.

Condition	Orientation					
	R/T		R/R		T/T	
Dry	Mean MOR (MPa)	23.09	Mean MOR (MPa)	20.10	Mean MOR (MPa)	18.02
	COV	0.175	COV	0.396	COV	0.398
	Type of failure	c (100%)	Type of failure	b (20%) c (80%)	Type of failure	c (100%)
	Mean MOE (Mpa)	10,665.4	Mean MOE (Mpa)	10,319.97	Mean MOE (Mpa)	9842.91
	COV	0.99	COV	0.056	COV	0.148
Green	Mean MOR (MPa)	51.32	Mean MOR (MPa)	50.42	Mean MOR (MPa)	45.80
	COV	0.158	COV	0.074	COV	0.109
	Type of failure	a (25%) b (60%) c (15%)	Type of failure	a (30%) b (40%) c (30%)	Type of failure	a (50%); b (50%)
	Mean MOE (Mpa)	11,151.88	Mean MOE (Mpa)	11,813.25	Mean MOE (Mpa)	11,771.55
	COV	0.126	COV	0.092	COV	0.182

Different combinations of wood fiber orientation: Radial–Tangential (R/T); Radial–Radial (R/R); Tangential–Tangential (T/T).

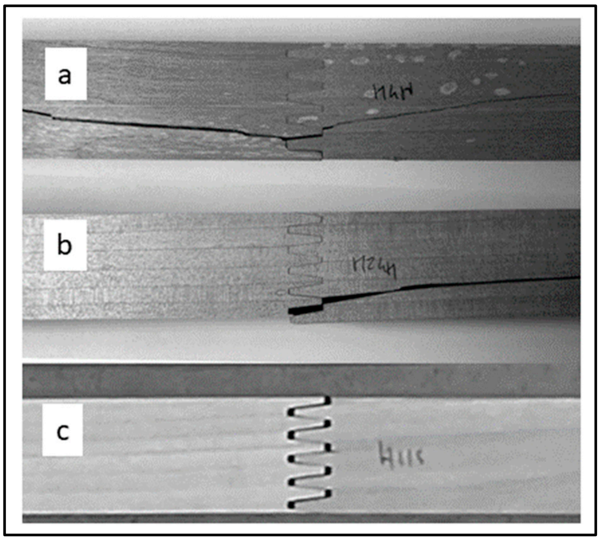

Figure 4. Types of failures observed: (**a**) wood failure crossing the joint zone; (**b**) failure initiated by the fingertip gap; and (**c**) separation of the fingers.

The comparison of the average MOR values supports the fact that the different combinations of orientation did not influence the results. This trend was observed in dry wood specimens and those made with green wood.

However, the ANOVA test noted a significant difference (p-value < 0.0001) when comparing dry and green wood samples. These results suggest that using green wood in the finger joint resulted in superior performance compared to using dry wood. The same conclusion was drawn when comparing the results of each orientation combination using wood with different moisture levels, as determined by an unpaired t-test with Welch's correction. On the other hand, the MOR value of the reference samples (wood of total length of finger joints) showed a much higher value, almost four times more (approximately 84.23 $\pm$ 17.25 MPa). This value confirms the excellent mechanical properties of the wood.

The modulus of elasticity was calculated based on each specimen's ultimate load and strain. This modulus was adjusted for each specimen's linear elastic behavior range. The results showed that the modulus of elasticity of the wet-glued specimens was similar to that of the standard specimen. However, the modulus of elasticity in bending for the wet-glued samples was higher than that of the dry-glued samples, although this difference was not statistically significant.

The variability index of the results indicated low values for both the wet and dry-glued samples, with 10.1% for the dry-glued samples and 13.3% for the wet-glued samples. It was also observed that the stiffness of wooden parts was higher when the gluing was realized using wet timbers, but the difference in stiffness between damp and dry wood was not as significant as the breaking strain.

Furthermore, the analysis of deformations revealed that the tension was proportional to the loads and higher in wet specimens. The tension was significant when comparing wet conditions in the same ring orientations. Additionally, the load that caused a deformation in all specimens exhibited a linear behavior without a range of inelastic behavior, suggesting an extremely brittle behavior.

Regarding the type of failure, the dry-glued specimens unexpectedly broke utterly at the joint (failure type "a") when using the R/T timber orientation with dry timber. This type of failure suggests a possible issue with the adhesion process. On the other hand, the green-glued specimens showed a mix of wood failure crossing the joint zone (B) and failure initiated by the finger gap (C). Some specimens had partial separation of the fingers, but never entirely, and only when other rupture modes occurred. Strain concentration at the tip gap of the fingers caused a rupture that followed the glue joint on the side of the fingers. However, a defective glue joint for the green-glued specimens did not initiate the rupture. The shift in the roughness in the zone of a finger could be responsible for these results.

3.3. Characterization by Microcomputed Tomography (Micro-CT)

Micro-CT was used to examine the internal morphology of finger joint samples made from native wood with varying moisture levels. The analysis revealed a wide range of wood porosity in dry and moist samples, ranging from 50% to 70%, despite being sourced from the same batch of wood (Figure 5). This situation could potentially impact the specimen performance, especially regarding adhesive penetration. However, no significant difference was observed in the thickness of the glued line between the samples with the same orientation but different humidity levels. This comparison was made in the end finger, allowing for better results. The adhesive covered a large surface area in this union zone, using between 75% and 97% of the surface area. All the relevant data are presented in Table 6.

The data on the porosity of the glue line and its thickness indicate that the fiber orientation does not affect the performance of the finger joints made with *Nothofagus alpina*. However, it is important to investigate why finger joints with green wood have better MOR and MOE values.

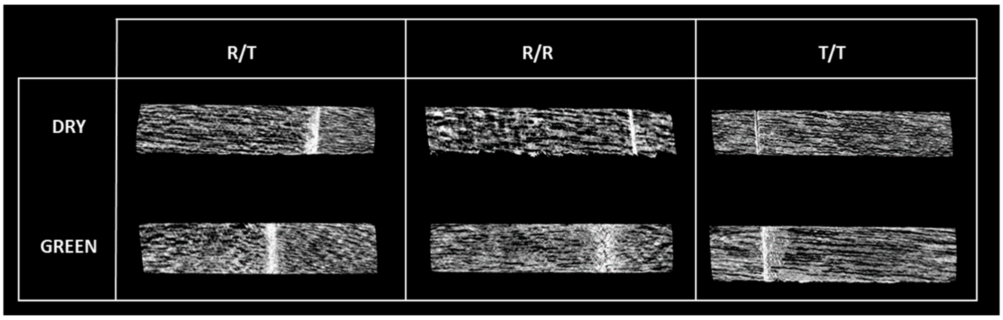

Figure 5. Porosity distribution with different timber orientations in finger joints under different moisture levels.

Table 6. Summarize the influence of different fiber orientations and moisture levels on the average porosity and thickness of the glue line in various types of finger joints.

Sample	Thickness of the Glued Line (µm)	Average Porosity (%)	Average Porosity in Glue Line (%)
Dry R/T	340 ± 72.1	56.7 ± 0.79	13.7
Green R/T	341.3 ± 120.7	59.6 ± 0.33	11.3
Dry R/R	229 ± 63.7	70.7 ± 0.29	9.4
Green R/R	350 ± 55.7	50.2 ± 0.48	1.49
Dry T/T	187.7 ± 51.9	66.3 ± 0.23	6.07
Green T/T	247 ± 61.4	52.5 ± 1.41	7.03

Different combinations of wood fiber orientation: Radial–Tangential (R/T); Radial–Radial (R/R); Tangential/Tangential (T/T).

4. Discussion

This study promotes the use and conservation of *Nothofagus alpina*, a species known for its excellent mechanical properties. However, its potential use is restricted due to the limited availability of specimens in the right size for different applications. The study aims to identify the best techniques to extend the length of the pieces and improve their mechanical response under green gluing conditions.

The wood's characterization showed an MOE and MOR value almost four times higher than the samples with finger joints, indicating good timber quality. However, unexpected results were observed in the finger joints sample.

Using the green gluing technique mixed with finger joints showed better behavior than the samples made with dry timbers (Table 5). According to the research, the green gluing technique effectively produces long-lasting pieces with good mechanical behavior. The data gathered show a significant difference in the MOR and tension values between the samples made with dry wood and those made with wet timber. The use of timber with high moisture content seems to improve the adhesion capacity of glue compared to other factors, as there was almost no difference in the line thickness and porosity between the samples with the same treatment but using timber with a different moisture content. The difference in the average porosity line was more significant in the samples with R/R orientation. Probably, the R/R orientation had a more substantial influence on the glue polymerization than the T/T orientation, where the difference was not noticeable (Table 6).

In a previous study, the samples made with dry wood performed better than those made with higher moisture contents using *Nothofagus alpina* [14]. However, the results of this research are contrary. The finger joint construction probably creates a localized drying effect and a gradient throughout the finger. This assumption is based on the thickness of the glued line between the specimens, which had similar values between dry and wet samples, without the influence of the ring orientations (Table 6). Moreover, previous backgrounds supported the hypothesis since it was demonstrated that the thickness of the glued line was almost double in wet samples compared to dry samples [14].

The study by Jakob et al. highlights the crucial role of fiber orientation in determining the mechanical properties of wood products [32]. The research indicates that unidirectional fiber orientation is necessary for high composite strength and stiffness. However, the present study found that fiber orientation did not significantly affect the MOR and MOE values. In the analysis of the mechanical behavior of the finger joint, we observe that when pure bending is applied, there are no shear stresses in the studied section. However, due to the shape of the connection, tensile stresses appear perpendicular to the fiber. This observation confirms that the bending resistance should be lower when the piece is arranged in the T/T plane than in the R/R arrangement. The tensile strength normal to the signature is higher in the radial plane than in the tangential plane. This finding suggests that fiber orientation would play a more significant role in the mechanical performance of composite materials than solid wood products. In practical applications, a structure such as cross-laminated timber (CTL) could distribute forces over a wide surface area and the wood fibers.

In contrast, finger joints could create rupture points that may concentrate forces and reduce mechanical performance. The fibers' orientation had a more significant impact on how well the adhesive penetrated the body of the finger, where the wood structure could differ from the end of the finger. This situation was shown in a study by Shirmohammadli et al. [33], which demonstrated how the cellular structure of softwoods and hardwoods can affect the penetration of 1C PUR adhesive.

Choosing the correct type of glue is essential for achieving the best results with green gluing. The selection can be a difficult decision because the performance of the glue depends on many factors, including the type of wood, wood density, application process, surface treatment, and the final timber product [8,14,34,35]. In this research, the glue selected had previously been tested with good performance [14], whereby the possibility of a wrong selection was discarded. Despite this, moisture can significantly affect the performance of adhesives in wood bonding, impacting both short-term and long-term bond integrity. In this study, a high moisture content in wood may inhibit adhesive penetration. For example, adhesives like urea-formaldehyde (UF) [36] and polyvinyl acetate (PVA) [37] may not penetrate as deeply into wet wood fibers, resulting in weaker mechanical interlocking and reduced bond strength. Wood's moisture content can affect its mechanical properties, including tensile strength. It can also impact the bonding strength of adhesives and the overall performance of finger-jointed lumber. Generally, wood with higher moisture content tends to have lower mechanical strength due to reduced bonding efficiency and potential for dimensional changes. Therefore, the drying process of the wood influences the bonding and could be relevant to ensure consistent and reliable results in terms of tensile strength under high-temperature conditions [38].

However, the mechanical results may be attributed to changes in roughness in the finger joint area and shifts in pore size, which may have influenced the green gluing performance more than the type of glue used and the moisture content in this study.

To confirm this suggestion, a more thorough study should be carried out that includes various microscopy techniques and adhesives. These considerations will help to determine whether the changes observed could be due to the formation of intra-chain hydrogen bonds at dehydrated crystallite surfaces caused by drying cycles. These bonds may cause conformational changes within the cellulose chains and increase packing density. A similar phenomenon was previously reported by other authors [39,40].

The construction of finger joints was the most relevant action for this research. This step is influenced by the finger's characteristics and the wood's drying process. In this sense, the shape and size of the finger probably helped in the local drying process, triggering a better performance in the wet samples. This behavior was reflected in a higher MOR value compared to the samples made with the dry wood. In the same way, the results in the glue line could support this suggestion because the thickness of the glue line was similar between the samples with the same orientations but with different moisture levels (Table 6, Figure 5). The orientation probably limited the adhesive penetration, but the union capacity was given by the moisture localized in the body of the finger.

The study by González-Prieto et al. [41] reported similar findings. They made green-glued finger joints using Eucalyptus globulus wood and a single-component polyurethane adhesive. The study evaluated the mechanical behavior of the joints and found that the moisture state was a significant factor. The finger joints made in a moist environment showed higher elastic modulus and resistance compared to those made in a dry environment. The results suggest that these joints had resistance to inflection, similarly to solid pieces without finger joints for this species. The authors concluded that using finger joints in green castings is feasible and can improve the quality of the joint for hardwood species.

It should be noted that finger-jointed pieces have reduced bending strength compared to a solid piece of wood. In this case, wet-glued pieces showed an average drop in strength of 41.6%, while dry-glued pieces showed a drop in bending strength of 75.8%. This behavior can be attributed to the discontinuity of the piece, which makes it structurally weaker. However, it should be noted that the green gluing technique combined with finger joints still requires significant improvement. The MOR and MOE values need to be higher than 90% of solid wood in order to be used for structural applications. Creating smaller structures that meet the service class 3 wood standards is more feasible.

Although the wet specimens showed the best results in the mechanical test, there is still a long way to go. The green gluing technique involves various areas of knowledge [8]. One important consideration is the characteristics of wood, where density plays a significant role. Previous research by Alia-Syahirah et al. [42] reported that higher density can harm adhesion in wood products. This finding is consistent with the results of Ahmad et al. [13], who found that denser wood species have worse bonding characteristics than less dense ones. However, the density was not a relevant factor in the finger joint construction using *Eucalyptus globulus* wood with a high moisture content [41]. These findings suggest that the gluing procedure must be adapted depending on the species studied.

This study used a preliminary approach to identify the factors that influence surface roughness. The results of the multiple linear regression model will help control these factors better, thus improving the performance and application of green gluing using finger joints in future projects. It has been reported by Yu et al. [43] that surface roughness can significantly impact the ability of glue to wet wood surfaces. This effect should be evaluated more accurately to determine the best way to apply the green gluing technique to Nothofagus species.

In future studies, it is essential to investigate how moisture levels affect the bending modulus of elasticity and compressive strength of wood. Research has shown that the pliability of treated wood differs significantly depending on its moisture content since the most favorable pliability is achieved when bending the wood at or close to its fiber saturation point [44].

5. Conclusions

Green gluing is a method that could increase the value of various wood species to increase the size of wood pieces. In this study, it was found that the finger joint samples performed best when made with timber that had high moisture levels. Future studies must examine the influence of moisture close to the fiber saturation point on the finger joint, the effect of surface roughness, its mechanical response, and the drying process.

Research and development in this technology will enable us to produce higher-quality components, maximize our use of local wood resources, and encourage improved forest management. This method could create laminated beams and decorative and construction panels. It also has applications in the production of indoor and outdoor furniture.

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