Glue laminated timber beams in pinus: analytical and experimental study of flexural stiffness

Vigas de madeira laminada de cola em pinus: estudo analítico e experimental da rigidez flexural

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ABSTRACT
In the current global scenario, where demand for sustainable development is paramount, the prestige associated with the applicability of wood as a primary structural element on a scale never before achieved characterizes it as the building material of the 21st century. This is due to its structural, economic, energetic, and environmental principles, and abundant availability in nature. Among the new wood-based products, significant attention is directed toward the Glued Laminated Timber (Glulam) structural system, owing to its enhanced strength characteristics. As this construction system gains momentum in the Brazilian Civil Engineering sector, the technological classification of mechanical properties becomes a critical point for the effectiveness of its implementation, both in terms of quality control and compatibility with the resistance parameters mandated by prevailing regulations. Thus, the objective of this present study is to investigate, through statistical analyses, the characterization of the mechanical parameter of the Elastic Modulus of eight Glulam beams, fabricated using Pinus conifer wood and monocomponent polyurethane adhesive material. This investigation is conducted via non-destructive experimental flexural and static tests, considering a predefined maximum displacement as the stopping criterion, along with the analytical method of transformed section, as proposed by the Brazilian standard ABNT NBR 7190:2011. The results of experimental characterization in structural dimensions and analytical predictions exhibit a high statistical agreement, with a strong correlation of approximately 79.0%.
Keywords: glued laminated timber, characterization, flexural stiffness, non-destructive evaluation, analytical prediction.

RESUMO
No atual cenário global, em que a demanda por desenvolvimento sustentável é primordial, o prestígio associado à aplicabilidade da madeira como elemento estrutural primário em uma escala nunca antes alcançada a caracteriza como o material de construção do século 21. Isso se deve aos seus princípios estruturais, econômicos, energéticos e ambientais, e à disponibilidade abundante na natureza. Entre os novos produtos à base de madeira, a atenção significativa é direcionada para o sistema estrutural de madeira laminada colada (Glulam), devido às suas características de resistência melhoradas. À medida que esse sistema de construção ganha força no setor de Engenharia Civil, a classificação tecnológica das propriedades mecânicas torna-se um ponto crítico para a eficácia de sua implementação, tanto em termos de controle de qualidade quanto de compatibilidade com os parâmetros de resistência determinados pela regulamentação vigente. Assim, o objetivo do presente estudo é investigar, por meio de análises estatísticas, a caracterização do parâmetro mecânico do Módulo Elástico de oito feixes de Glulam, fabricados com madeira de Pinus conifer e material adesivo monocomponente de poliuretano. Esta investigação é realizada por meio de testes experimentais não destrutivos de flexão e estática, considerando o deslocamento máximo predefinido como critério de parada, juntamente com o método analítico de seção transformada, conforme proposto pelo padrão brasileiro ABNT NBR 7190:2011. Os resultados da caracterização experimental em dimensões estruturais e previsões analíticas exibem uma elevada concordância estatística, com forte correlação de aproximadamente 79,0%.

Palavras-chave: madeira laminada colada, caracterização, rigidez flexível, avaliação não destrutiva, previsão analítica.

1 INTRODUCTION
Roundwood, originating from tree trunks, and its traditional derivative products like sawn timber, have stood out since the dawn of civilizations as the oldest construction materials employed by humanity. This is due to wood's natural origin and abundant availability in nature, rendering it a resource of renewable nature (PFEIL; PFEIL, 2003). In current scenarios, given the global philosophy of sustainable development, the use of wood brings forth robust structural, social, environmental, and economic values, positioning it as the construction material of the 21st century (WOODARD; MILNER, 2016; ZMIJEWKI; WOJTOWICZ-JANKOWSKA, 2017).
Being a highly complex biological material (BRAZ et al., 2013), wood can present defects linked to anisotropic and heterogeneous properties, owing to its composition of woody material in fibers distributed along three principal axes—longitudinal, radial, and tangential—perpendicular to each other and with distinct resistant and mechanical properties (DACKERMANN et al., 2016). In order to achieve a more isotropic and homogeneous behavior for structural application, highly industrial procedures for altering wood characteristics have been developed. Consequently, wood-based products, internationally known as Wood Engineering Products (WOODARD; MILNER, 2016), have been introduced to the Construction industry.

The fundamental matrix for manufacturing these wood-based composites is directly related to the utilization of adhesive bonding technologies in layers of essential elements such as laminates, veneers, and wood fibers or chips. This manufacturing context enhances dimensional stability, durability, and homogenization of mechanical properties of structural elements (RAMAGE et al., 2017; ZMIJEWKI; WOJTOWICZ-JANKOWSKA, 2017). Consequently, elements such as Glued Laminated Timber (Glulam), suited for robust and complex linear constructions, laminated veneer laminated veneer lumber and oriented strand board (LVL and OSB), used as secondary cladding and protection materials for structures, and Cross-Laminated Timber (CLT), designed for walls and floors, have gained significant prominence in the construction sector (JELEČ; VAREVAC; RAJČIĆ, 2018).

Due to the implementation of adhesive bonding methodology for wood artifacts, responsible for the reliability of structural elements by distributing and transferring forces among its constituent woody materials, coupled with the variability of properties of tree species employed in the design of engineered wood products, the manufacturing process requires stringent quality control levels and assessment of mechanical properties (TEREZO; SZŰCS, 2010). This is essential to ensure compliance with the requirements set forth in prevailing regulations.

In this context, aiming to expand the applicability and utilization of wood as a fundamental element in Construction, on a scale never before achieved, technological and non-destructive characterization of stiffness properties, which define material behavior
under specific loads in terms of load-bearing capacity and ability to absorb and transfer it, for all wood-based composite elements in structural dimensions, prior to structural installation, serves as a critical foundation for rational and optimized use of this material (LAHR et al., 2016; SALES; CANDIAN; CARDIN, 2011). Furthermore, it facilitates safe and efficient design.

Therefore, through the application of statistical analyses, the present study aims to investigate the equivalence of Elastic Modulus of eight Glued Laminated Timber beams in Pinus. This characterization is achieved experimentally through non-destructive three-point static bending tests and analytically through the transformed section method proposed by the Brazilian standard ABNT NBR 7190:2011, which regulates timber structure design in Brazil. The standard is currently under revision. The goal is to enhance the classification of wood elements in structural dimensions, leading to improved and optimized mechanical properties and widespread adoption of wood-based composite elements.

2 LITERATURE REVIEW

Among the composite wood-based products that utilize laminated components throughout their production process, Glued Laminated Timber stands out as the oldest class of structural elements designed in wood employed in the Construction Industry (USDA, 2010; ZMIJEWKI; WOJTOWICZ-JANKOWSKA, 2017). The first patent for this structural system was registered in competent Swiss authorities in the year 1901 by the German Otto Karl Friedrich Hetzer (1846-1911). It concerned a straight beam consisting of several layers of wood, glued together with a casein adhesive, a natural protein found in milk (RHUDE, 1996; USDA, 2010).

Categorized as a lightweight prefabricated material, Glulam is produced through an industrial pressure bonding strategy using durable structural adhesives that resist moisture, water, temperature, and biological agents (KUZMAN; OBLAK; VRATUŠA, 2010). It involves two or more thin layers of wood with significant length, with the wood fibers parallel to the longitudinal axis of the elements, allowing for the creation of pieces with various shapes and dimensions (RAMAGE et al., 2017; TEREZO; SZÜCS, 2010).
These characteristics are guided solely by the available space for manufacturing and transportation (CUNHA; MATOS, 2010), as well as by high resistance properties resulting from the homogenization of the properties of the laminates, achieved by distributing potential defects and excessive inclinations of the wood fibers among the adjacent lamellae, providing alternate and effective paths for stress distribution.

For the purpose of using materials such as wood, steel, and concrete as structural elements, knowledge of specific strength properties is necessary to optimize, make efficient, and ensure the quality of designs in service. In the case of Engineered Wood Products (EWPs), knowledge of their elastic mechanical properties is of paramount importance, as these are closely linked to the characterization of the Modulus of Elasticity (MOE), which represents the material’s stiffness under a given loading condition without permanent deformation (BRAZ et al., 2013; DACKERMANN et al., 2016; ETTELAEI et al., 2019; GARCÍA-IRUELA et al., 2016).

Traditionally, tests to determine the Modulus of Elasticity for structural elements are mostly conducted through static experimental tests, regulated by current normative documents, including mechanical testing methods involving bending, compression, and tension, aiming to destructively evaluate small-sized specimens sampled specifically from the structural pieces (CUNHA; MATOS, 2010; DACKERMANN et al., 2016). This scenario can lead to changes in the physical shape, strength, and stiffness of the material (ETTELAEI et al., 2019).

In this context, effective mechanical characterization of wood structural elements can be achieved through non-destructive evaluation methodologies, internationally known as Non-Destructive Testing (NDT). These procedures identify the mechanical parameters of wooden components in their structural integrity without causing detrimental effects to the object’s capacity for use and maintenance, as the assessment is performed directly on the object without extracting specimens (CHRISTOFORO et al., 2013; DACKERMANN et al., 2016; ETTELAEI et al., 2019; GARCÍA-IRUELA et al., 2016; SALES; CANDIAN; CARDIN, 2011).

Among the non-destructive classification techniques, the following are noteworthy: (1) Visual classification; (II) Static bending test; (III) Machine Stress Rating;
(IV) Transverse vibration; (V) Ultrasonic. Method (I) involves the visual classification of wooden elements by an examiner to limit the location, size, and type of defects present in the wood, which could negatively affect structural strength (CUNHA; MATOS, 2010). Methodology (II) entails a static test where elements are subjected to bending conditions, with a concentrated load applied at the center of the span between two supports in simply supported conditions, measuring the displacement in the middle of the span. Procedure (III) utilizes mechanical stress equipment to compute the Modulus of Elasticity, as the deflection of structural elements caused by a light load, typically applied by a pressure cylinder associated with a load cell, is measured by sensors (CHRISTOFORO et al., 2013).

Method (IV) involves impacting one end of wooden elements placed on a dual support system, with a load cell at the other end identifying the representative value of the natural frequency of vibration, correlating it with the Modulus of Elasticity. In process (V), the correlation of the Modulus of Elasticity of the structural piece occurs with the propagation time of ultrasonic waves through the wood, detected by a transducer that emits and another that receives the wave (SALES; CANDIAN; CARIDIN, 2011).

3 MATERIALS AND METHODS
3.1 STRUCTURES UNDER ANALYSIS

The research development involved the fabrication of eight Glued Laminated Timber beams, each measuring 4.0 meters in length, within the premises of the Laboratory of Structural Systems Testing (LESE) at the University of Passo Fundo (UPF), Passo Fundo/RS. The cross-sectional profile of each beam consisted of eight Pine wood laminates with nominal dimensions of 2.0 cm thickness, 7.0 cm height, and 400.0 cm length. These laminates were visually inspected and only those devoid of knot defects and excessive wood fiber inclinations were selected. Consequently, the laminates chosen at random were used to create the eight Glulam beams.

Given that the entire process, encompassing design and fabrication of the beams, adhered to the specifications of the Brazilian norm NBR 7190:2011 – Design of Timber Structures, it is evident that due to the significant importance accorded to the lamination
technique by this code, the composition of the Glulam beam's cross-sectional profile was achieved by arranging the laminates based on their Modulus of Elasticity values. Laminates with a lower Modulus of Elasticity value \( E_{M,i} \) were positioned in the central half of the structural element's cross-section, while those with higher values \( E_{M,s} \) were allocated to the outermost quarters from the neutral axis \((x)\) (ABNT, 2011), as illustrated in Figure 1.

Figure 1– Illustrative section showing the combination of laminates with different Moduli of Elasticity.

To this end, the constituent laminates of each beam were individually characterized regarding their Modulus of Elasticity through a non-destructive bending test. This characterization was essential to conclude the process of cross-sectional composition and initiate the gluing stage. In this phase, a one-component polyurethane adhesive, PUR-501, was applied to the contact surfaces of the laminates to form the layers of the beam laminates. This choice was made due to the advantages associated with its application temperature limit and minimal curing time. The bonding pressure was achieved through the use of 8” C-clamps.

3.2 EXPERIMENTAL METHOD

The non-destructive experimental characterization of the Glued Laminated Timber beams' Modulus of Elasticity parameter \((MOE_Y)\) employed the three-point bending stiffness test, following the configuration illustrated in Figure 2. In this arrangement, the structural elements are subjected to a specific concentrated load \((P)\) applied at the midpoint of the free span, under the assumption of bi-supported conditions.
This setup is aimed at acquiring the vertical displacement data at the midpoint of the span (deflection \( \delta \)).

Figure 2 – Configuration of the bending stiffness test for the beams \( (MOE_v) \).

Due to the assumed bending stress configuration for the aforementioned test, as outlined by Equation 1, the vertical displacement parameter \( (\delta) \) is calculated. As the collected data primarily involves vertical displacements and considering the unfamiliarity with the components’ stiffness parameter, the initial equation is redefined as Equation 2. This alteration enables the determination of the Modulus of Elasticity for the elements.

\[
\delta = \frac{P * L^3}{48 * E * I}
\]

\[
MOE_v = \frac{P * L^3}{48 * \delta * I}
\]

Where:

- \( \delta \) – Deformation of the element, in meters;
- \( P \) – Applied load, in \( kN \);
- \( L \) – Free span, in meters;
- \( E \) – Bending stiffness of the structural element, in \( kN/m^2 \);
- \( I \) – Moment of inertia of the cross-sectional element, in \( m^4 \);
**MOE**$_V$ – Modulus of Elasticity of the beams, in $\frac{KN}{m^2}$.

In conducting the three-point bending stiffness test depicted in Figure 3, a free span of 3.47 meters was employed for all beams. This choice was guided by the limitations imposed by the spacing between supports within the utilized framework and the adoption of simply supported conditions at both beam ends. To apply the concentrated load ($P$) at the midpoint of the span, a hydraulic jack was employed, in conjunction with a load cell possessing a maximum capacity of 5.0 tons. A digital reader was integrated with the load cell to meticulously document the magnitude of the applied load. Meanwhile, the resultant vertical displacement ($\delta$) was meticulously measured utilizing a dial indicator featuring a 0.50 mm range. This dial indicator was meticulously positioned with the aid of a magnetic base, strategically placed just beneath the lower surface of the beams.

Figure 3 – Performing the Modulus of Elasticity test for the beams.

Source: Author (2023).
For each beam element, three repetitions of the aforementioned test were conducted, with the prescribed stopping criterion being the predetermined maximum displacement, as defined in Equation 3.

\[ \delta_{\text{máx}} = \frac{l}{250} \]  

(3)

Where:

- \( \delta_{\text{máx}} \) – Maximum vertical displacement, in millimeters;
- \( l \) – Free span considered for the structure, in millimeters.

The accepted limit for the maximum displacement was 13.88 millimeters. It is noteworthy that this value surpasses the specified maximum displacement value set by the Serviceability Limit State stipulated in NBR 7190:2011 (ABNT, 2011) by 19.96%, based on the limit condition of \( l/300 \) (11.57 millimeters). This circumstance was introduced to evaluate the load-displacement relationship’s behavior once the threshold established by the Serviceability Limit State was exceeded. However, it’s important to note that this specific aspect is not within the scope of the current research.

3.3 ANALYTICAL METHOD

The analytical prediction of the beams' Modulus of Elasticity \( (MOE_A) \) involves considering the calculation of the transformed section for Glued Laminated Timber components, as outlined by Equation 4. This equation is recommended by the Brazilian standard NBR 7190:2011 (ABNT, 2011).

\[ MOE_A = \frac{2 \times E_{M,S} \times I_{(\frac{1}{4})} + E_{M,i} \times I_{(\frac{1}{2})}}{l} \]  

(4)

Where:
- $I$ – Moment of inertia of the cross-sectional element, in m$^4$;
- $E_{M,s}$ – Average value of the modulus of elasticity for the upper range of values, in $\frac{KN}{m^2}$;
- $E_{M,i}$ – Average value of the modulus of elasticity for the lower range of values, in $\frac{KN}{m^2}$;
- $I_{(\frac{1}{4})}$ – Moment of inertia of the fourth quarter furthest from the cross-sectional centroid ($x$), in millimeters;
- $I_{(\frac{1}{2})}$ – Moment of inertia of the central half of the cross-section relative to the centroid ($x$), in millimeters.

4 RESULTS AND DISCUSSION

For both methodologies discussed in the section above, Table 1 and Table 2 respectively present the resulting data collected from experimental measurements of the Modulus of Elasticity for the Glued Laminated Timber beams ($MOE_V$) and from the analytical prediction of the transformed section ($MOE_A$), as proposed by ABNT NBR 7190:2011.

### Table 1 – Experimental Modulus of Elasticity of Beams ($MOE_V$).

<table>
<thead>
<tr>
<th>Beams</th>
<th>Measurement 1 (MPa)</th>
<th>Measurement 2 (MPa)</th>
<th>Measurement 3 (MPa)</th>
<th>Average $MOE_V$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB1</td>
<td>15.638,27</td>
<td>15.702,98</td>
<td>15.702,98</td>
<td>15.739,05</td>
</tr>
<tr>
<td>TB2</td>
<td>14.891,47</td>
<td>15.058,56</td>
<td>14.975,02</td>
<td>14.975,02</td>
</tr>
<tr>
<td>TB5</td>
<td>13.821,75</td>
<td>13.923,38</td>
<td>13.872,56</td>
<td>13.872,56</td>
</tr>
<tr>
<td>TB8</td>
<td>15.447,84</td>
<td>15.549,47</td>
<td>15.574,88</td>
<td>15.524,06</td>
</tr>
</tbody>
</table>

Source: Author (2023).

### Table 2 – Analytical Modulus of Elasticity of Beams ($MOE_A$).

<table>
<thead>
<tr>
<th>Beams</th>
<th>Average $MOE_A$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB1</td>
<td>18.565,34</td>
</tr>
<tr>
<td>TB2</td>
<td>16.475,81</td>
</tr>
<tr>
<td>TB3</td>
<td>15.453,12</td>
</tr>
<tr>
<td>TB4</td>
<td>14.929,10</td>
</tr>
<tr>
<td>TB5</td>
<td>14.138,78</td>
</tr>
<tr>
<td>TB6</td>
<td>15.814,35</td>
</tr>
</tbody>
</table>
Considering the primary aim of this research, which involves investigating the equivalence of the Modulus of Elasticity among eight Glued Laminated Timber beams crafted from Pine, through both experimental and analytical characterization, an analysis of variance (ANOVA) was executed at a significance level of 5.0%. This analysis aimed to assess their comparability based on the compiled datasets mentioned earlier. To achieve this objective, the results obtained from this analysis are visually presented in the graph of Figure 4. Additionally, a statistical regression analysis was performed, as depicted in the graph of Figure 5, to establish a regression line accompanied by the determination coefficient $R^2$. This coefficient serves as a valuable tool for illustrating the distribution and behavior of datasets in terms of their correlation.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TB7</td>
<td>15.866,93</td>
</tr>
<tr>
<td>TB8</td>
<td>16.174,53</td>
</tr>
</tbody>
</table>

Source: Author (2023).

Figure 4 – Results of the ANOVA analysis.

Source: Author (2023).
Figure 5 – Results of the Regression Analysis.

Upon examining the graphical presentations provided above, it is evident that both sets of analyzed data demonstrate normal distribution and homogeneity. This assessment confirms that the relationship between the experimental and analytical methodologies, used to characterize the Modulus of Elasticity of the fabricated Glued Laminated Timber beams, holds significant importance. This categorizes the collected datasets as statistically valid and comparable. Moreover, the regression line depicted in the second graphical representation underscores a robust correlation between the estimated experimental data and the data derived from analytical prediction. This is further supported by the Determination Coefficient $R^2$, which boasts a notable value of 79.0%.

It's important to highlight that the 21.0% portion not accounted for by the Determination Coefficient $R^2$ arises from specific characteristics of the interaction between laminates and adhesive materials, the quality control protocols in beam manufacturing processes, as well as inherent physical attributes of wood's biological nature. These aspects are not encompassed within the analytical characterization. This situation underscores the significance of non-destructive characterization of engineered
wood elements within structural dimensions. Despite the strong correlation achieved between the datasets, analytical prediction serves specifically as an indicator of flexural stiffness, as it uniquely considers the dimensional attributes of cross-sectional elements and the characteristic mechanical properties of each constituent laminate. Conversely, experimental characterization delves into the true properties of the structural component, leading to a more efficient use of wood and enhanced structural reliability throughout its service life.

5 CONCLUSIONS

Regarding the technological characterization of structural beams made from Glued Laminated Timber in Pine, specifically in terms of the mechanical parameter of the Modulus of Elasticity, achieved through the application of non-destructive experimental flexural rigidity tests and the analytical estimation proposed by the Brazilian standard NBR 7190:2011, it is deduced that both measurement methodologies are statistically equivalent, exhibiting a correlation of approximately 79.0%.

Contrasting this scenario, it's noteworthy that certain pertinent variables considered during the development of non-destructive and experimental characterizations of wooden components within structural dimensions are not adequately addressed by the analytical determination. This analytical approach exclusively serves as an indicator of an essential mechanical property, pivotal in the development of wood-based composite element projects.

Hence, the non-destructive technological characterization of structural components not only optimizes wood utilization but also amplifies the reliability of wood structures within the context of Brazil.
REFERENCES


