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EXPERIMENTAL EVALUATION OF NORMAL AND SHEAR STRESSES IN GLUED JOINTS OF STRUCTURAL TIMBER

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ABSTRACT
This study investigates the behavior of glued joints in structural timber, focusing on the analysis of normal and shear stresses occurring in the adhesive line. Test specimens of Eucalyptus grandis glued with resorcinol resin adhesive were utilized. The research aimed to compare the shear strength between the Push-out test and the direct shear test, as well as to evaluate the influence of normal stresses, especially tension perpendicular to the fibers, on the failure of glued joints. The results revealed significant differences in shear strength between the testing methods, highlighting the importance of normal stresses, which proved critical for structural failure. The stress distribution along the adhesive line was found to be non-uniform, with concentrations at the extremities in the elastic phase and greater uniformity in the plastic phase. These findings contribute to the under-standing of the behavior of glued timber joints and suggest the need for detailed analysis to optimize structural performance in practical applications.

Keywords: Normal stresses, shear stresses, glued joints, structural timber, Eucalyptus grandis, resorcinol resin, Push-out test.

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INTRODUCTION

Timber is one of the oldest and most versatile building materials used by humans [1, 2]. From the earliest rudimentary constructions to modern large-scale structures, timber has been valued for its mechanical properties, abundance, and ease of handling [3]. However, the true revolution in the use of timber in large-scale structures began in the 19th century with the advent of gluing techniques, which allowed for the creation of larger and more robust structural elements from smaller pieces [4].

The development of timber gluing techniques began with the use of natural adhesives, such as animal and vegetable glues, which were common until the late 19th century. These adhesives, however, had significant limitations, such as low shear strength and poor durability in humid environments or those subject to extreme temperature variations [5]. The Industrial Revolution brought with it the need for more robust and durable construction materials, which drove research and development of synthetic adhesives [6].

In the early 20th century, the creation of phenol-formaldehyde resin marked a turning point in timber engineering. Introduced by Leo Baekeland in 1907, this resin was the first commercialized synthetic plastic and quickly found application in timber bonding. Phenol-formaldehyde resin provided joints with high shear strength and excellent durability, essential characteristics for the construction of more complex and robust timber structures [7].

With the advancement of gluing techniques, innovative products emerged, such as glued laminated timber (glulam) and cross-laminated timber (CLT), which expanded the possibilities for using timber in civil construction [8]. Glulam, for example, was initially developed in Germany in the late 19th century, but its large-scale application began in the 1920s and 1930s, especially in bridges and buildings. These materials allow for the construction of large structures with high mechanical strength, durability, and an attractive aesthetic, characteristics that are increasingly valued in sustainable construction [9, 10].

Parallel to the development of synthetic adhesives and glued materials, there were significant advances in the strength of materials, which provided the theoretical foundations for the analysis of stresses in glued timber joints. The classical theory of strength of materials, formulated by scientists such as Augustin-Louis Cauchy in the 19th century, is important for understanding internal stresses in solid materials, including timber [11]. This theory allowed for the prediction of how materials would behave under different load conditions, but it had limitations when dealing with anisotropic materials such as timber.

Timber, due to its fibrous nature, has mechanical properties that vary significantly in different directions, which complicates the analysis of stresses in glued joints [12].

It was only in the second half of the 20th century that linear mechanical fracture theory began to be systematically applied in the analysis of glued timber structures [13]. Initially developed for metallic materials, this theory allowed for a more detailed understanding of failure mechanisms in glued structures. The application of this theory to timber was pioneered in the work of Leicester in the 1970s, which demonstrated that shear stresses are not linearly distributed along the adhesive line, especially in the elastic phase [14, 15].

These findings were fundamental to modern timber engineering, as they helped establish guidelines for the design of glued joints that consider the non-uniform distribution of stresses. Experimental studies have shown that the ultimate strength of a glued joint is strongly influenced by stress concentrations at the ends of the adhesive line, a factor that can lead to premature failures if not adequately considered in the design [16, 17].

Glued joints play an essential role in the structural integrity of timber elements, especially in applications that require high strength and durability. With the growing demand for more sustainable constructions and the search for renewable materials, timber has stood out as a viable solution for large-scale buildings [1, 9]. However, the complexity of interactions between timber and adhesive requires a detailed understanding of the stresses generated in glued joints [18, 19].

Recent studies have explored various approaches to improve the strength of these joints, including the use of new types of adhesives, chemical treatments of timber, and advanced manufacturing techniques, such as 3D printing of glued timber components [20]. The analysis of normal and shear stresses in glued joints has thus become an essential field of study to ensure the safety and durability of timber structures [18].

This study aims to contribute to the understanding of the behavior of glued joints in timber, investigating the influence of normal and shear stresses on the adhesive line. The choice of Eucalyptus grandis [Eucalyptus grandis] and resorcinol resin-based adhesive was based on their mechanical properties, which are widely recognized in the construction industry [21]. The experimental campaign was carefully planned to simulate real-use conditions, using representative test specimens and measuring deformations along the adhesive line with high-precision electrical strain gauges. Several authors were consulted to define this experimental campaign [22-25].

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The objectives of this study include experimentally verifying that the shear strength of a glued joint, when determined through the Push-out test, is different from the direct shear test on the adhesive line; proving that failure occurs due to normal stresses (tension perpendicular to the fibers); and evaluating how these extremes are distributed along the adhesive line. Additionally, the results will be compared with existing theories to validate or refute the theoretical models currently used in timber engineering. The results will contribute to the improvement of timber engineering practices, offering insights for the development of more rigorous technical standards capable of ensuring the safety and durability of structures built with glued timber.

THEORETICAL ANALYSIS

Glued joints play a decisive role in the structural integrity of timber elements, especially in applications that require high strength and durability. To understand the behavior of these joints under different loading conditions, it is essential to analyze the stresses generated in the adhesive line, considering both normal and shear stresses. This theoretical analysis is based on the fundamentals of strength of materials and linear mechanical fracture theory, providing an in-depth understanding of failure mechanisms in glued structures.

CLASSICAL THEORY OF STRENGTH OF MATERIALS

The classical theory of strength of materials provides the basis for stress analysis in solid materials, including timber. In a glued joint, load transmission occurs predominantly through shear stresses in the adhesive line, as illustrated in Fig. 1. The distribution of these stresses along the adhesive line can be complex, especially in structures with non-linear geometries or subject to variable loads [11].

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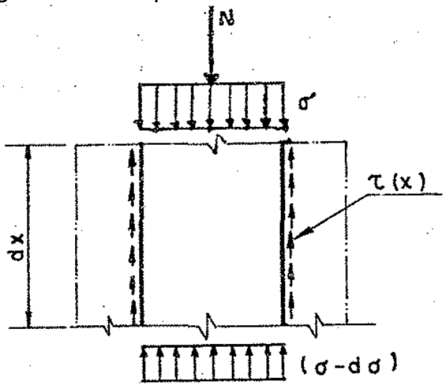
Fig. 1. Force equilibrium in the dx element.



For a glued joint under compression, the maximum shear stress in the adhesive line (τac) can be expressed as a function of the normal soliciting force (N) and the length of the adhesive line (Lc), as per Eq. (1).

$$\tau = \frac{N}{2.a.L_c} = \frac{N}{2.A_c} \quad (1)$$

where Ac=a·Lc is the glued area, with a being the width of the adhesive line.

[14] demonstrated that the shear stress τac varies along the length of the adhesive line. In the elastic phase, the distribution is non-linear, with stress concentrations at the ends of the adhesive line, Fig. 2. In the plastic phase, the distribution becomes more uniform, as per Eq. (2).

$$\tau_{ac} = \frac{\tau_{pl}.L_c}{2} \quad (2)$$

where τpl represents the shear stress in the plastic phase. The uniform distribution in the plastic phase is crucial for predicting failure behavior in glued joints, as the ultimate strength is reached when the soliciting shear stress reaches the value of the yield stress of the adhesive or the timber-adhesive interface.

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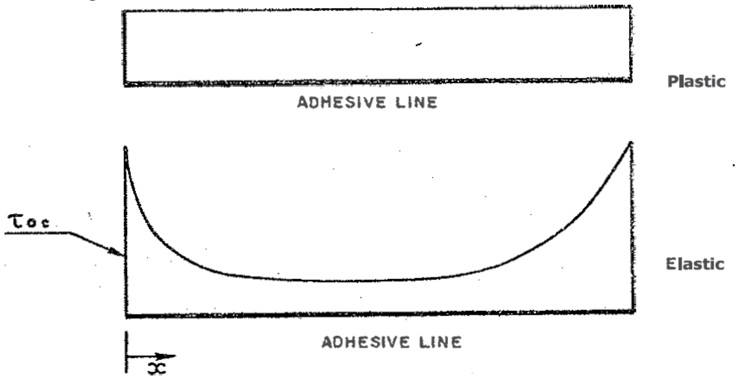
Fig. 2. Shear stress distribution in the adhesive line.



In addition to shear stresses, normal stresses also play a significant role in the strength of glued joints. These stresses arise due to the eccentricity of the soliciting load and can be tensile (σtn) or compressive (σcn) perpendicular to the adhesive line. Fig. 3 presents the distribution of these stresses, which are derived from the bending moment (M) and the couple (F) applied along the adhesive line, described by Eq. (3):

$$\left.\begin{aligned} \sigma_{xn} &= \frac{2.F}{y'.a} = \frac{2.M}{y'.a.z} = \frac{N.c}{y'.a.z} \\ \sigma_{tn} &= \frac{3.F}{2.y''.a} = \frac{3.M}{2.y''.a.z} = \frac{3.N.c}{4.y''.a.z} \end{aligned}\right\} \quad (3)$$

Where z is the lever arm of the couple F, y' is the distance from the upper face of the piece to the neutral line, y" is the distance from the lower face of the piece to the neutral line, σ_{cn} is the normal compressive stress to the adhesive line, and □tn is the normal tensile stress to the adhesive line.

These equations demonstrate that the distribution of normal stresses along the adhesive line can be significantly influenced by the geometry of the joint and the position of the applied load. Joint failure will occur when the soliciting tensile or compressive stress exceeds the shear strength of the timber or adhesive.

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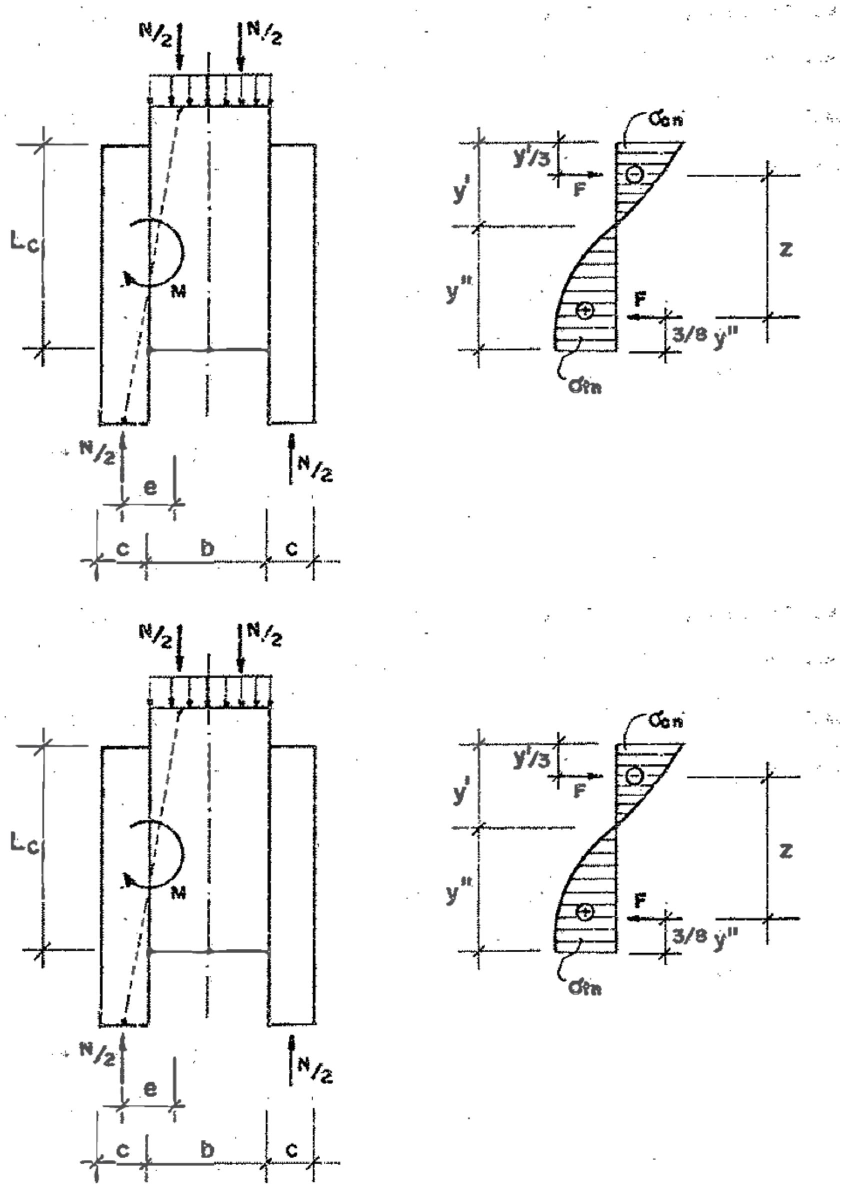
Fig. 3. Static equilibrium of forces and stress distribution.



LINEAR MECHANICAL FRACTURE THEORY

Linear mechanical fracture theory is an essential tool for predicting failure behavior in materials such as glued timber. This theory, applied to glued joints, considers the presence of initial cracks or defects in the adhesive line, which can serve as stress concentration points. Failure occurs when the maximum stress in the joint reaches a critical value, leading to structural collapse, as shown in Fig. 4.

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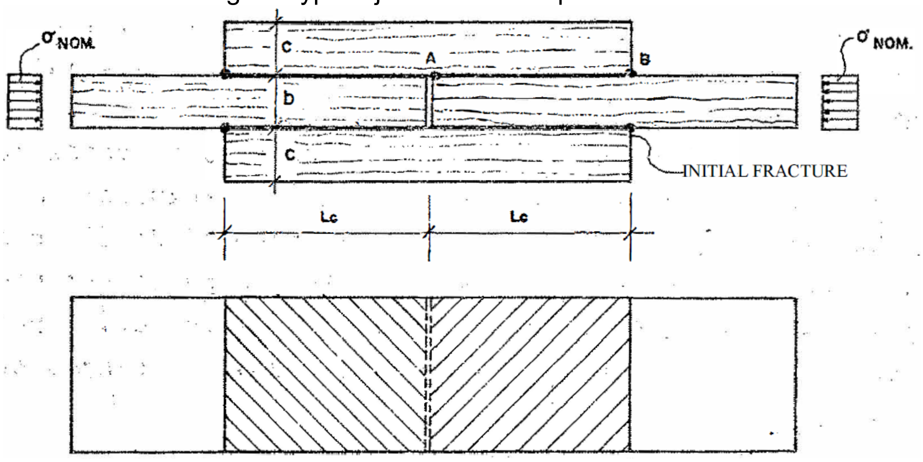
Fig. 4. Typical joint under compressive load.



The application of this theory to structural timber was presented by [14] and complemented by several others [15, 19]. Succinctly, this theory is concerned with the maximum stress that appears in the typical joint, through elastic analysis of a test specimen. The maximum stress belongs to the domain of the stress field limited by the boundary conditions. According to [16], generally, in the vicinity of the joints, there are two types of maximum stress fields. The proportion of these fields is defined by the stress intensity factors (KA and KB), which consider the geometry of the joint and the loading conditions.

The stress σ, in a region close to the typical joint, can be represented by Eq. (4)

$$\sigma = K_A \cdot (2 \cdot \pi \cdot r)^{-0.4502} \cdot f_A(\theta) + K_B \cdot (2 \cdot \pi \cdot r)^{-0.1028} \cdot f_B(\theta) \qquad (4)$$

Where r and θ are the polar coordinates referring to the typical joint. The terms fA(θ) and fB(θ) are functions exclusively of θ. Only the stress intensity factors (KA and KB) influence the load and depend on the structure.

The joint can be visualized as if it were surrounded by a contour in which the stress will be in accordance with equations similar to Eq. (4), having the same format of stress distribution for all similar joints in structural elements. Thus, the strength of the material within this contour can be expressed as a function of KA and KB. In this way, critical collapse will occur when Eq. (5) is reached.

$$f\left(\frac{K_A}{K_{AC}} \cdot \frac{K_B}{K_{BC}}\right) = 1 \qquad (5)$$

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where KAC and KBC are the characteristics of the material's strength properties, analogous to the modulus of rupture or shear strength in a test specimen. KAC is the rupture value of KA when KB is zero, and KBC is defined analogously.

The values of KA and KB are obtained from a two-dimensional elastic stress analysis, using the finite element technique [16, 26]. These values, valid for the joint shown in Fig. 4, are dimensionless. The values of KB are lower than the values of KA and, as r decreases, the stress associated with KA, Eq. (4), increases more rapidly in relation to KB. Consequently, the critical collapse for adhesive joints, according to linear mechanical fracture theory, can be reasonably approximated by Eq. (6).

$$K_A = K_B \qquad (6)$$

In other words, considering the complete plastification of the material, the critical collapse will take the form of equation 1, which was obtained in the analysis from the strength of materials, confirming the validity of its application.

The validity of these theoretical formulations has been extensively tested in experimental studies that used glued timber test specimens to verify the accuracy of theoretical predictions. The results of these studies demonstrated a strong correlation between predicted and experimentally observed stresses, providing a solid basis for the application of these theories in practice [16, 18, 21].

The theory of finite element analysis, which offers a detailed three-dimensional analysis of stress distribution, was not directly applied in this study, although it is a powerful tool in more complex analyses. Similarly, other advanced concepts of computational simulation, such as progressive crack analysis and non-linear modelling of adhesive failure, were only mentioned as possible areas for future research.

It is important to note that while these theoretical models provide valuable insights into the behavior of glued timber joints, they are based on certain simplifications and assumptions. In practice, factors such as wood anisotropy, variations in adhesive properties, and environmental conditions can influence joint behavior in ways that may not be fully captured by these models.

MATERIALS AND METHODS

The experimental campaign was designed with the objective of systematically and controllably evaluating the distribution of normal and shear stresses in the adhesive line of

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glued timber joints, using specially manufactured test specimens to simulate real-use conditions in timber structures. The following sections detail the materials, the methodology for assembling the test specimens, the testing procedures, and the instrumentation employed.

The tests were carried out in the facilities of the Centre of Advanced Research of Wood and New Materials (CPAM3) and the Laboratory of Experimental Analysis of Structures of the School of Engineering of the Federal University of Minas Gerais, Brazil.

MATERIALS

The timber used for manufacturing the test specimens was Eucalyptus grandis [Eucalyptus grandis], a species native to South America, known for its excellent mechanical properties and durability. Eucalyptus grandis has an apparent density ranging between 6.1 kN/m³ and 6.9 kN/m³, depending on the moisture content, which varied between 10.7% and 11.3%.

This timber species was chosen due to its widespread use in glued timber constructions, as well as its characteristics that allow for good adhesion with the adhesive used. The timber boards were selected to minimize defects such as knots and cracks, which could influence the test results.

The adhesive employed was a resorcinol-based resin, commercially known as Cascophen RS-216-M, manufactured by Alba S.A. Resorcinol is an adhesive widely used in structural timber applications, due to its excellent shear strength and durability in humid and outdoor environments.

The preparation of the adhesive strictly followed the manufacturer's recommendations, with the mixing of the liquid resin and powder catalyst in the recommended proportions. The weighing of the components was carried out on an electronic scale of the "Marte" brand, with precision to thousandths of a gram, ensuring the accuracy of the formulation. The adhesive was applied at room temperature, ranging between 20 °C and 30 °C, ideal conditions for the curing of resorcinol.

MANUFACTURE OF TEST SPECIMENS (TSS)

Using the equations of strength of materials, Eq. (2) and (3), the average strengths of Eucalyptus grandis (average tensile strength normal to the fibers 4.10 MPa, average shear strength 15.1 MPa), and considering that the failure of the test specimens occurs indistinctly

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by tension normal to the fibers or by shear in the adhesive line, the dimensions of the test specimens were determined. They were manufactured from timber beams with dimensions of 6 x 16 cm, as specified by the standards, [24, 25], for structural timber joint tests. In order to optimize the use of timber and ensure consistency in the tests, some main dimensions were fixed, Fig. 5.

The test specimens, manufactured according to [25], were divided into three main groups: 3 TSs for Push-out tests, 3 TSs for adhesive line shear tests, 3 TSs for normal compression tests on the adhesive line and 3 TSs for normal tension tests on the adhesive line.

The manufacture of the TSs involved meticulous preparation of the timber surfaces to be glued, ensuring they were smooth and free of dust and contaminants. The adhesive was applied uniformly with a brush, and the pieces were joined under controlled pressure until the adhesive was fully cured, according to the times specified by the manufacturer (pressure of 1 MPa for 4 hours).

INSTRUMENTATION AND EQUIPMENT

To measure the deformations in the adhesive line and evaluate the stresses during the tests, electrical strain gauges (SGs) were installed at strategic locations on the TSs. The SGs were configured in a ¼ Wheatstone bridge circuit, connected to a 12-bit analogue/digital board, controlled by a multiplexer board that allowed readings with a frequency adjusted to 1 Hz, ensuring precise reading of deformations over time.

In the "Push-out" type TSs, five SGs were positioned along the adhesive line, as shown in Fig. 5.

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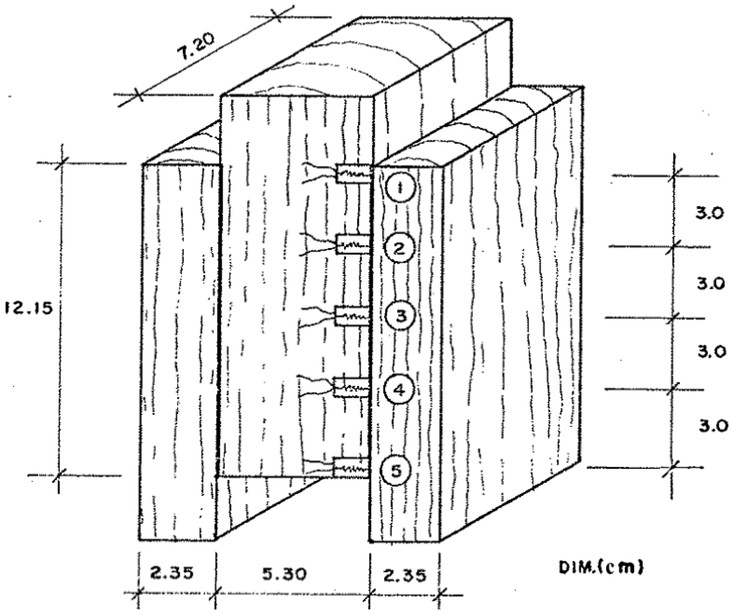
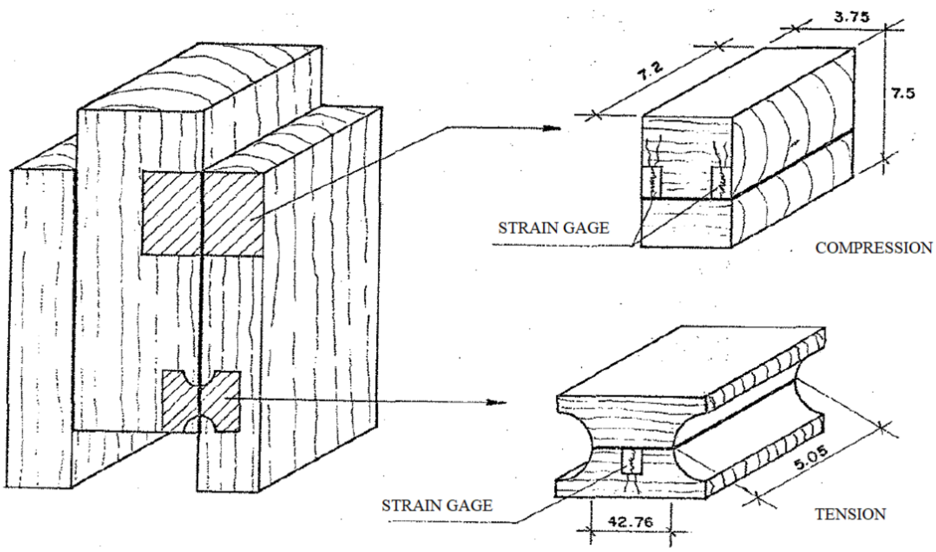
Fig. 5. Test specimen (TS) model and position of electrical strain gauges (SGs).



To determine the modulus of elasticity normal to the fibers in tension and compression, the TSs were taken from the "Push-out" TS, utilizing the SGs, as shown in Fig. 6.

Fig. 6. Tension and compression test specimens.



In the adhesive shear TSs, three SGs were installed on the adhesive line, as schematized in Fig. 7.

Fig. 7. Position of electrical strain gauges (SGs) in the shear TS.

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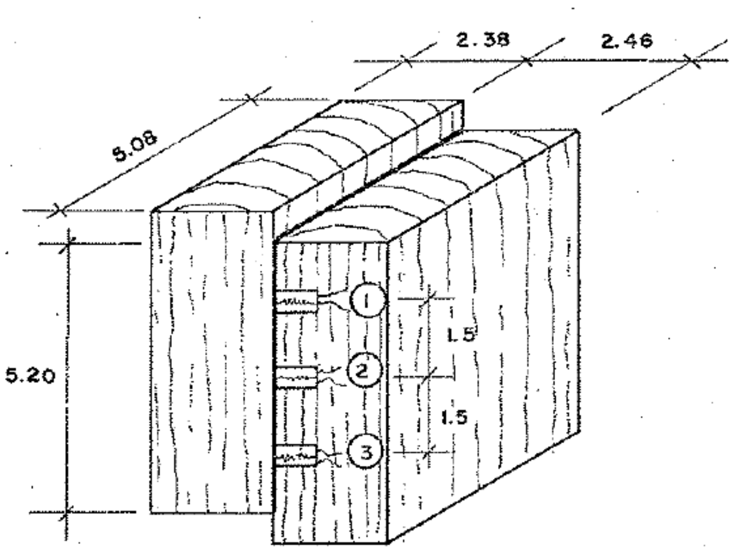

The installation of the SGs followed standard procedures to ensure correct adherence and minimization of measurement noise. System calibration was performed before each test to ensure the accuracy of the collected data.

The compression, tension and shear tests were conducted on an Instron/Emic universal testing machine with a capacity of 300 kN. The machine was configured to apply monotonic load at a rate of 30 MPa per minute. During the tests, the deformations in the SGs were recorded for each load increment, until the TSs ruptured.

TEST METHODOLOGIES

The test methodology was designed to evaluate in detail the shear, tensile and compressive strength of glued timber joints, using specially manufactured TSs. Each type of test followed standardized procedures to ensure reproducibility and precision of results. The use of electrical strain gauges in a ¼ Wheatstone bridge circuit, connected to a high-precision analogue/digital board, allowed for detailed measurements of deformations, essential for the analysis of normal and shear stresses. The use of the universal testing machine ensured controlled application of loads, accurately replicating the service conditions that glued joints would face in real applications.

The choice of load application rates was based on previous studies and recommendations from [25], aiming to minimize the effects of loading rate on the results. These practices ensured that the data obtained were representative of the actual behavior of glued timber joints, providing a solid basis for analysis and comparison with existing theoretical models.

The Push-out test is fundamental for determining the shear strength of glued joints. This test consists of applying an axial force to the TS, pushing a central section of the piece until failure occurs in the adhesive line. The test involved fixing the TSs in the Instron/Emic universal testing machine, with a capacity of 300 kN, configured to apply an increasing monotonic load, at a rate of 25 MPa/min. The load was applied gradually, and the deformations were measured using five electrical strain gauges (SGs) positioned along the adhesive line, as illustrated in Fig. 5. These measurements were recorded at every 5 kN up to the rupture load of 144 kN. The SG readings allowed for the determination of transverse deformations to the adhesive line. The collected data were used to construct stress-strain graphs, which show the material's behavior from the beginning of load application until complete failure. The maximum shear value was calculated based on the maximum applied load, according to [25].

The direct shear test on the adhesive line was designed to compare with the shear strength obtained through the Push-out test and to determine the distribution of normal stresses in the adhesive line and compare it with that determined in the Push-out test. The procedure consisted of fixing the TSs in the universal machine, and the load was applied directly to the adhesive line at a rate of 25 MPa/min. During the test, three SGs were strategically positioned on the adhesive line to monitor transverse deformations, as shown in Fig. 7. The SG readings were analyzed to determine the distribution of normal stresses along the adhesive line.

The normal compression test was performed to determine the modulus of elasticity normal to the fibers. The TSs were subjected to an increasing axial load at a speed of 10 MPa/min, as specified in [25]. The SGs, installed on the TSs, recorded the deformations throughout the test, allowing the determination of the normal compression modulus of elasticity (Ecn). The modulus of elasticity was calculated using Hooke's Law, and the distribution of normal stresses was analyzed to identify possible failures in the adhesive line due to compression.

The normal tension test was performed to evaluate the strength of the glued joint when subjected to tensile forces applied perpendicular to the adhesive line. Similar to the compression test, the TSs were subjected to an increasing axial load, applied at a rate of 25 MPa/min. SGs, previously installed in the regions of interest, monitored the deformations. This test was particularly important for evaluating the joint's resistance to tension perpendicular to the wood fibers, one of the most common causes of failure in glued joints.

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The collected data were used to calculate the modulus of elasticity in normal tension (Etn) from the stress-strain graphs.

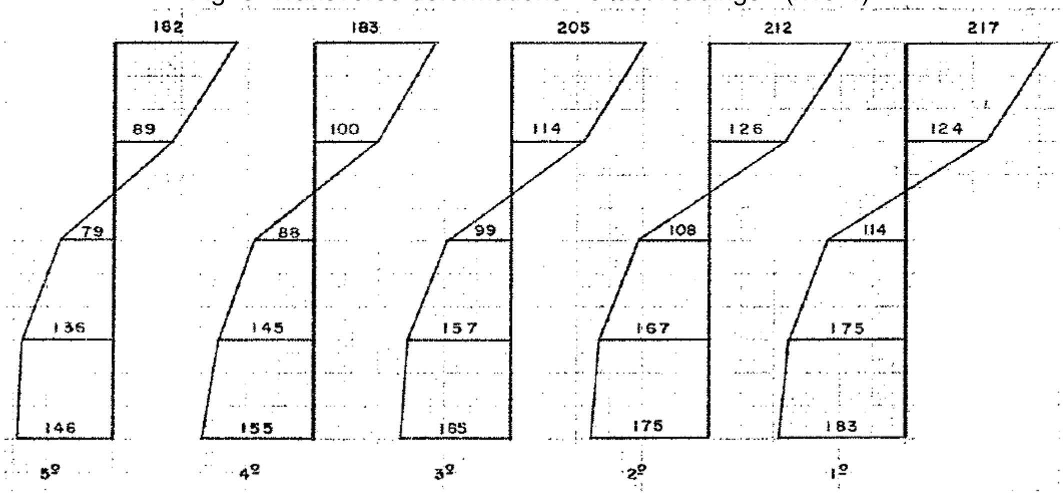
RESULTS AND DISCUSSION

EXPERIMENTAL RESULTS

The experimental tests conducted provided detailed data on the behavior of glued timber joints under different loading conditions. The main results obtained for normal and shear stresses in glued joints, using TSs made of Eucalyptus grandis and resorcinol resin-based adhesive, are presented below.

In the Push-out tests, the applied loads and deformations in the 5 electrical strain gauges were recorded for each of the 3 TSs. Fig. 8 shows the five last readings of transverse deformations (average of the 3 TSs).

Fig. 8. Transverse deformations - 5 last readings - (x10-4).



In the compression and tension tests perpendicular to the grain, with deformations measured by SGs and applied load, stress-strain graphs were obtained as presented in Fig. 9 (average of 3 specimens). The moduli of elasticity calculated from the tests, for compression and tension perpendicular to the grain, were: E_{cn} = 790 MPa and E_{tn} = 60 MPa, respectively.

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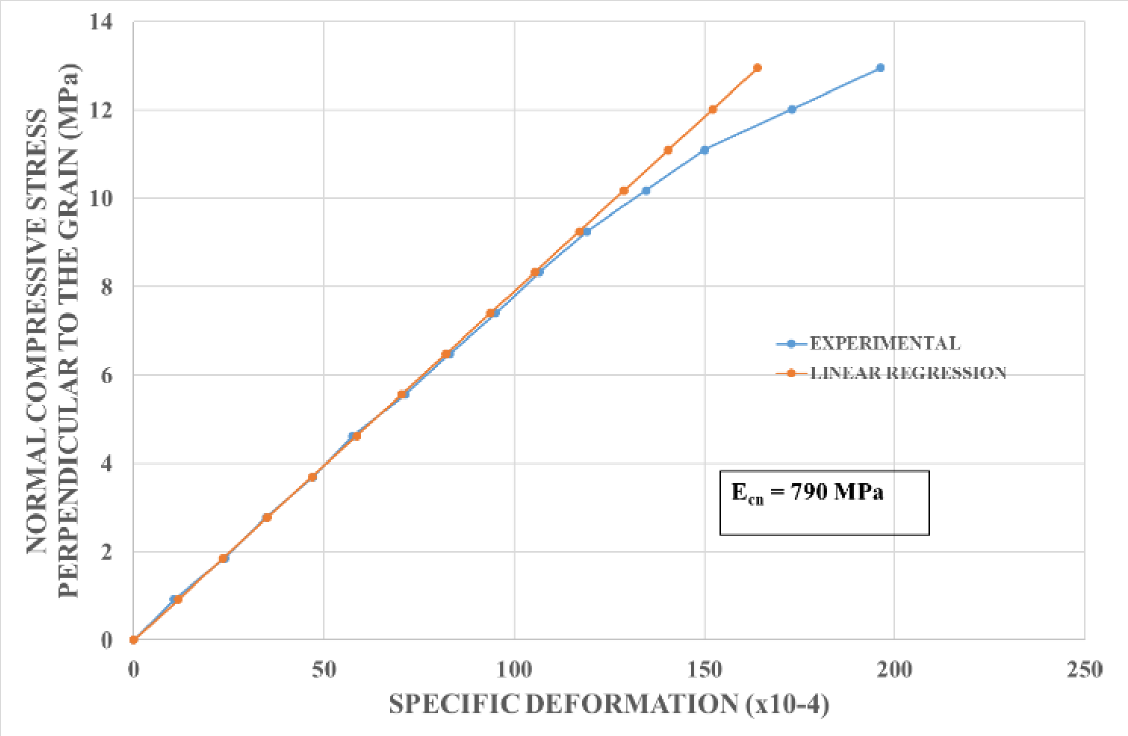
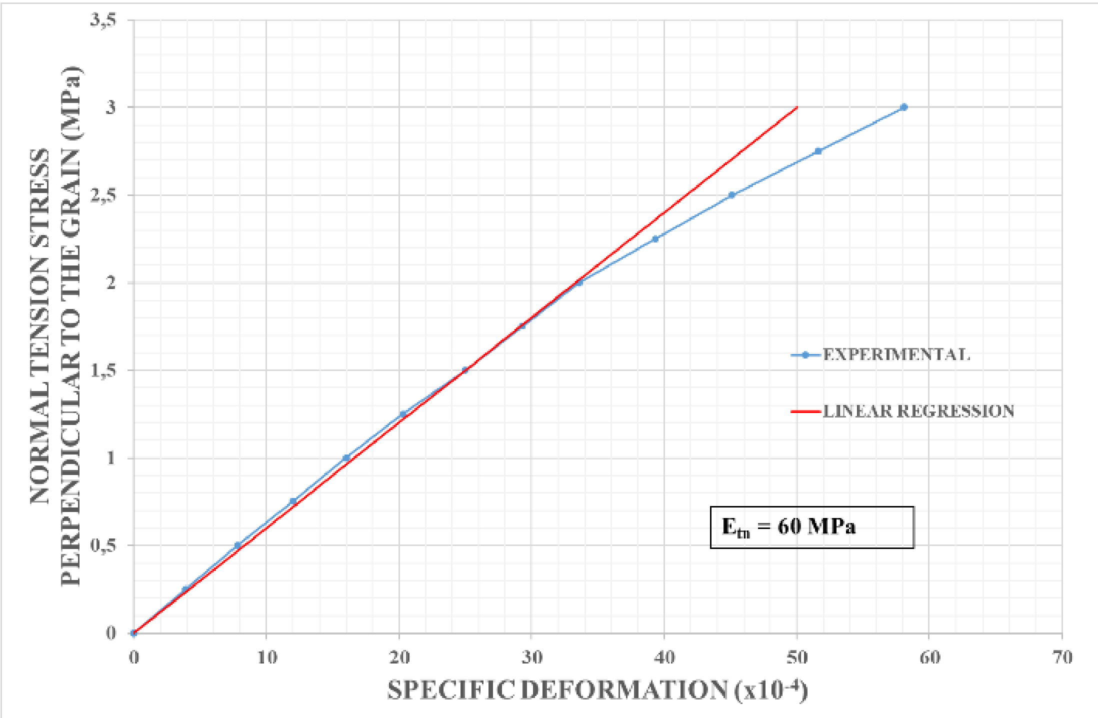
Fig. 9. Stress-strain diagram – a)- normal compression, b)- normal tension.



a)



b)

Applying Hooke's law and disregarding the influence of deformations in other directions, the distribution of transverse stresses can be obtained, as shown in Fig. 10 (average values for the 3 test specimens).

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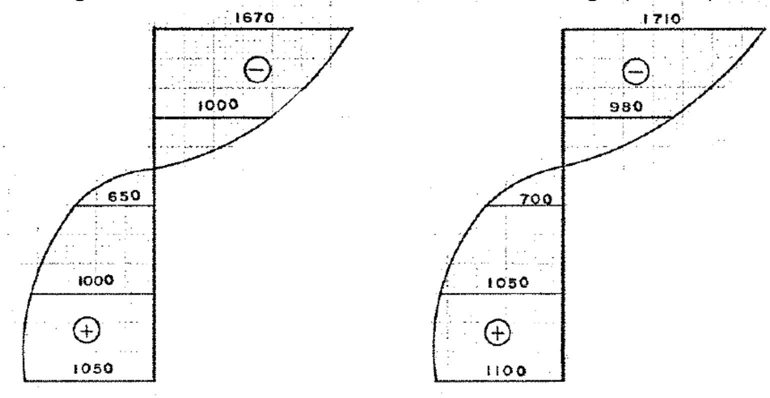
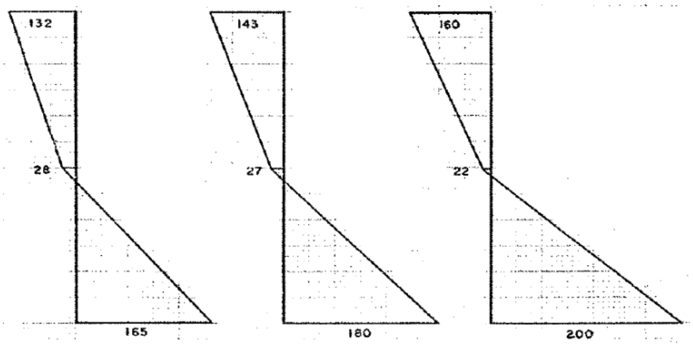
Fig. 10. Stress distribution of the last 2 readings (N/cm2).

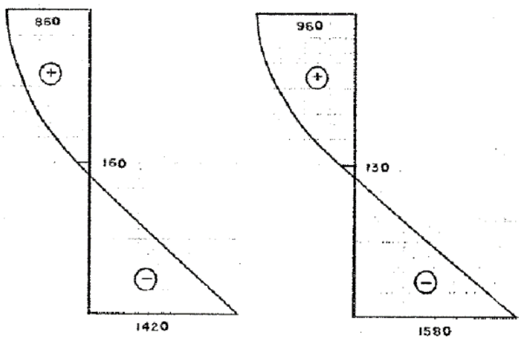


In the direct shear tests of the TSs, Fig. 11.a shows the distribution of deformations for the last three readings (average values of the test specimens). Using the normal compression and tension moduli of elasticity, the distribution of transverse stresses is obtained, as shown in Fig. 11.b.

Fig. 11. a) - Transverse deformations - 5 last readings - (x10-4), b) - Stress distribution of the last 2 readings (N/cm2).

(a)





(b)

DISCUSSION

The experimental results demonstrated complex behavior of glued timber joints, especially regarding the distribution of normal and shear stresses along the adhesive line. The Push-out and direct shear tests revealed significant differences in shear strength, whilst the normal compression and tension tests provided insights into the influence of normal stresses on the strength of the joints.

One of the main objectives of this study was to experimentally verify whether the shear strength determined through the Push-out test differs from that obtained by the direct shear test on the adhesive line. The results indicated that, indeed, there is a significant difference between the two methods. The Push-out test showed a lower shear strength (τac) than that observed in the direct shear test. This difference can be attributed to the high tensile stress in the adhesive line in the Push-out test, where the geometry of the TS influences the stress concentration at the ends of the adhesive line (due to the eccentricity of the load in relation to the adhesive line), as observed by the authors [16, 18, 20].

In contrast, the direct shear test, which applies the load with less eccentricity in relation to the adhesive line, tends to reflect a distribution of lower tensile stresses, resulting in higher shear strength. This can be observed by comparing Fig. 10 (distribution of normal stresses in the adhesive line at the moment of rupture of the Push-out test specimens) and Fig. 11.b (distribution of normal stresses in the adhesive line at the moment of rupture of the direct shear test specimens). In Figure 10, both tensile and compressive stresses normal to the fibers along the adhesive line are in the plastic phase, clearly indicating that the rupture occurred due to normal tension and not shear. In Fig. 11.b, only the normal tensile stresses to the fibers are in the plastic phase, which could indicate that the rupture occurred due to shear of the adhesive line.

These findings corroborate previous studies, such as that of [27], who reported variations in shear strength across different testing methods, emphasizing the importance of considering the geometry of the test specimen and the stress distribution when interpreting the results of glued joint tests. The confirmation that the Push-out test may underestimate shear strength suggests the need for methodological adjustments or correction factors to align the results of different testing methods.

Another crucial objective of the study was to experimentally prove that the failure of glued joints, both in the Push-out test and in the direct shear test, occurs due to normal stresses, especially tension perpendicular to the wood fibers. Failure in glued joints was frequently initiated by cracks originating from tension perpendicular to the fibers, confirming the hypothesis that normal stresses play a critical role in determining the final strength of the joint. This behavior was documented in previous studies, such as that of [22], who highlighted that normal stresses, especially those of perpendicular tension, can cause premature failures in glued joints due to the low strength of wood in this direction.

Furthermore, the comparison of the moduli of elasticity normal to compression (Ecn) and tension (Etn) obtained experimentally with values found in the literature confirmed the consistency of the results. The modulus of elasticity in tension was significantly lower than in compression, which is consistent with the anisotropy of wood, as described by [28]. The lower resistance of wood to tension perpendicular to the fibers explains the propensity of glued joints to fail under high normal stresses, especially in applications where transverse loads are prevalent.

The distribution of normal stresses along the adhesive line was another focus of analysis. The results showed that these stresses are not uniformly distributed, being influenced by the geometry of the joint and the position of the applied load. It was observed that, in the elastic phase, normal stresses tend to concentrate at the ends of the adhesive line, as predicted by the theoretical models of [14]. In the plastic phase, the stress distribution became more uniform, indicating that the plasticization of the adhesive reduces stress concentration and potentially improves the strength of the joint to a certain point before failure. This behavior was observed in previous tests and confirmed by the analysis of the deformations recorded in the SGs. These results are consistent with the work of [29] on stress distribution in anisotropic materials, where they suggest that the geometry of the joint and the differential stiffness between the glued components can result in stress concentrations which, if not addressed, can lead to catastrophic failures. The application of these observations in engineering practice is critical for the development of stronger and more durable glued joints.

The experimental results of this study corroborate the theoretical predictions based on the classical theory of strength of materials and linear mechanical fracture theory. The correspondence between experimental data and theoretical models suggests that these approaches remain valuable tools for predicting the behavior of glued timber joints. However, the simplifications inherent in these models, such as the assumption of homogeneity and isotropy of materials, may not capture all the complexities of the interactions between wood and adhesive.

Previous studies, such as those by [11], established the foundations for stress analysis in solid materials, but recognized the limitations when applying these theories to anisotropic materials like wood. This study confirms the need to consider the specific characteristics of wood, such as its anisotropy and the influence of moisture, when applying these theories.

Moreover, the finite element technique, as suggested by [16], can offer a more detailed and accurate analysis of stress distributions in glued timber joints. Future studies could benefit from the use of three-dimensional simulations to improve the accuracy of predictions, especially in applications where normal and shear stresses interact in complex ways.

CONCLUSIONS

The main objective of this study was to investigate the influence of normal and shear stresses on the strength of glued timber joints, using test specimens of Eucalyptus grandis glued with resorcinol resin. The research focused on four main aspects: comparing the shear strength determined through the Push-out test with the direct shear test on the adhesive line; proving that the failure of joints occurs due to normal stresses, especially tension perpendicular to the fibers; evaluating the distribution of these stresses along the adhesive line; and comparing the experimental results with existing theories. The main conclusions reached are:

Regarding the difference in shear strength between the Push-out and direct shear tests, the study confirmed that there is a significant difference in shear strength when determined by the two testing methods. The Push-out test presented lower shear strength values compared to the direct shear test on the adhesive line. This is due to the concentration of stresses at the extremities of the adhesive line in the Push-out test, which may underestimate the joint strength. These results highlight the importance of considering the geometry of the test specimen and the stress distribution when interpreting the results of shear tests.

Regarding the influence of normal stresses on joint failure, the experimental results proved that the failure of glued joints, both in the Push-out test and in the direct shear test, occurs due to normal stresses, specifically tension perpendicular to the fibers. The low resistance of wood to perpendicular tension was identified as a critical factor contributing to the initiation of failures in the adhesive line, confirming the importance of normal stresses in determining the final strength of glued joints.

Regarding the distribution of normal stresses along the adhesive line, the analysis of deformations measured in the tests revealed that normal stresses are distributed nonuniformly along the adhesive line, with a concentration at the extremities during the elastic phase and a more uniform distribution in the plastic phase. These findings are consistent with theoretical predictions and highlight the importance of considering stress concentrations in the design of glued joints.

The experimental data obtained confirmed the validity of classical theories of strength of materials and linear mechanical fracture for predicting the behavior of glued timber joints. However, the simplifications of these models may not capture all the nuances of the interactions between wood and adhesive, especially in anisotropic materials such as wood. Comparison with previous studies reinforces the importance of continuing to develop and apply advanced techniques, such as finite element analysis, to improve the accuracy of predictions and the safety of timber structures.

This study contributed to a detailed understanding of the behavior of glued timber joints, offering experimental data that can be used to enhance engineering practices and the development of technical standards. The conclusions obtained emphasize the need for a careful approach in analyzing stresses in glued joints, considering both the material characteristics and the particularities of testing methods. The results provide a solid foundation for future research and applications in timber engineering, with the aim of ensuring the safety and durability of structures built with this sustainable material.

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