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Effect of Cyclic Loading on Bending Stiffness of Glued Laminated Pieces

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Glued laminated timber (Glulam) is important structural solution. Knowing its mechanical response under repeated forces, a gap in knowledge area, is fundamental to guarantee structures long-term performance. This study aims evaluating Glulam behavior under fatigue, considering excitation frequency (1 and 2Hz); cycles number (NC – six levels) and their interactions. Marupá and Pequiá, tropical species within density range of Brazilian Code NBR 7190-1, were adopted. Adhesive RS-216-M (CASCO ®, Hexion), usual in industry, was chosen. Modulus of elasticity in bending (E), obtained before cyclic forces application, was taken as reference and determined based usual equation. Results indicated slight stiffness decrease after repeated forces on Glulam pieces. E mean presented significant variation (by ANOVA, 95% significance) when NC ranges from 1,000 to 691,200, both frequencies. NC and frequency explained E variations for Marupá; for Pequiá, only NC. Glue lines were evaluated, in function of NC, without problems identified, enabling both species for Glulam manufacture.

Keywords: *Bending test, Cyclic forces, Phenol-resorcinol, Microscopy.*

1. Introduction

Glued laminated timber (Glulam) has the same typical properties of solid wood: lightweight, low weight-to-strength ratio, flexibility, diversity of shapes for structural elements, and easy processing[1,2]. In addition, it is characterized by ease of shaping into different sections compared to solid wood, and ensures high strength under static loads. Glulam is especially used for load-bearing structures such as roofs, bridges, and pedestrian bridges. Its lamellae are bonded with resorcinol-phenol-formaldehyde (RFF), melamine-urea-formaldehyde (MUF), or castor oil-based polyurethane (PUR) resin[3].

Currently, Glulam is an internationally recognized product and one of the most versatile and efficient for structural purposes. Glulam offers some advantages, such as allowing the use of reforested wood or even replacing native species with certified tropical species. Furthermore, member dimensions are not limited to trunk diameter, making timber structures increasingly competitive[4]. In addition to these sustainability aspects, Glulam also provides significant mechanical benefits. The manufacturing process reduces the presence of natural defects, enhancing both strength and stiffness properties[5]. Moreover, the lay-up configuration influences the anisotropic behavior of the material, allowing for better optimization of structural performance[6]. These factors contribute to the improved efficiency and reliability of Glulam in structural applications.

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Brazil, in particular, is a country with wood diversity and availability. Due to its tropical flora reserves (certified wood) or large-scale reforestation, structural use of wood is more than desirable. From certified areas in Tropical Forest of the country, there is a noticeable increasing availability of wood from species of low and medium density in the market, which represents significant potential for of Glulam production. Thus, well-known species with high natural durability for structural applications must gradually be replaced, as evidenced by Almeida et al.[7] and Araújo et al.[8].

Nonetheless, there are several knowledge gaps related to the mentioned Brazilian tropical species that must be filled, based on scientific approach, related:

(i) to their physical and mechanical properties;
(ii) to their long-term performance in usual structures;
(iii) to their long-term behavior in glulam structures, regarding adhesive efficiency under cycling loads[9,10].

Most engineering structures are subject to loads, usually variable over time, although they may initially be considered static actions. Others are directly subjected to cyclical forces over time, undergoing unpredictable amplitude variations, a situation that can significantly compromise performance during structure's lifespan[11].

It must be considered that the values of wood stiffness and strength required in different structural situations are influenced by variables, crucial for structural analysis, such as forces frequency, intensity and application duration. Some researchers point out that structural timber members - when subjected to cyclical forces, reach superior deformation related to those evaluated in statical conditions (fatigue phenomenon)[12].

NBR 7190-1[13] as well as other international codes, does not mention any changes in mechanical properties due to fatigue phenomenon, despite its potential influence on various aspects of structural design, such as components subject to bending and connections subjected to dynamic forces, whether constant (cyclical) or varying over time.

Knowledge of fatigue performance is necessary and fundamental in Glulam structural components, subjected to cyclical forces during their lifespan, such as vehicle traffic on bridges, product circulation in silos, and wind effects on roof structures. These examples represent some of the many references to Glulam applications in different fields of civil construction[14-17].

Dynamic forces play an important role in study of fatigue in structural elements. Here mentioned as example, according to Segundinho[18], Vašková et al.[19], Šurdilović et al.[20], a simple walk generates time-variable dynamic forces with components pointing in various directions, with multiple frequencies generated by body mass acceleration and deceleration. These frequencies can range from 0.7 to 2.44 Hz. Authors assert that footbridges are structural elements with high potential to experience excessive vibrations due to dynamic effect of pedestrian action. Besides causing discomfort to users (serviceability limit state), they are responsible for inducing fatigue in structural elements over time, resulting in changes in their mechanical properties to be considered in structural design.

The cited studies do not address the influence of interaction between frequency and number of cycles. While they provide valuable insights into wood stiffness under specific cyclic loading conditions, these studies do not explore how the combination of these two factors can jointly affect wood mechanical properties.

A comprehensive and timely contribution on the topic of fatigue in wood and wood-based products was published by Yang et al.[21]. The study discusses the relationship between the stress induced by cyclic loading and the number of applied cycles. However, the authors do not address the variation in stiffness of glued-laminated timber elements as a function of the number of load cycles.

So, future studies should consider this interaction to provide a more comprehensive and accurate assessment of wood performance characteristics of wood in such structural applications. In this context, assessment of Glulam components behavior under fatigue, considering variables frequency, cycle number and interaction between them (by statistical analysis), is the focus of this research, representing an original approach to a relevant topic aimed at enabling appropriate design procedures for these structural elements.

2. Materials and Methods

2.1. Materials

The studied species originated from the Community-Based Sustainable Forest Management Plan, developed in the Nossa Senhora do Perpétuo Socorro do Rio Arimum community, located in the Verde Para Sempre Extractive Reserve (RESEX). The specimens were extracted in the longitudinal direction and consisted of mature wood, cut with nominal dimensions 45 × 2 × 1 cm (length, width, and thickness, respectively).

2.1.1. Wood species

Wood species used in this study were Marupá (*Simarouba amara*) and Pequiá (*Caryocar villosum*). The choice of these species is due to Marupá present apparent density 458 kg.m^{-3} and Pequiá 730 kg.m^{-3}, within the upper (750 kg.m^{-3}) and lower (400 kg.m^{-3}) limits recommended by Code NBR 7190-1[13].

2.1.2. Adhesive and Assembly of Glulam

For lamellas bonding, Cascophen RS-216-M phenol-resorcinol adhesive (CASCO®, Hexion), commonly adopted in industry, was used. The adhesive is a two-component adhesive formulated from a resin based on resorcinol formaldehyde and prepared with FM60M hardener. To apply the adhesive, a ratio of 5:1 was used, with five parts of resin and one of hardener, as indicated by the manufacturer.

Lamellas were organized in pairs for gluing. To make each Glulam element, two lamellas with parallel fibers were joined. Sixteen Glulam elements were made, eight from Marupá and eight from Pequiá, for 1 Hz frequency; same quantities for 2Hz frequency.

Lamellas were glued with a weight of 300 g.m^{-2}, per double glue line, as indicated by manufacturers. A brush was used to adhesive distribution, on wood pieces surfaces. Then, lamellas were joined and pressed for 24 hours, under 1 MPa. Right away, the elements were removed from press and kept in laboratory until completing adhesive cure. Then, they were taken to the carpentry, planned to remove adhesive excess and adjusted to final dimensions: 2 × 2 × 45 cm (height × width × length).

2.2. Methods

2.2.1. Planning

In the static bending test, modulus of elasticity of the specimens were obtained at completion of each proposed cycles: 0; 1,000; 86,400; 172,800; 345,600; and 691,200 repetitions. From 86,400 cycles, the specimen residence time in the corresponding testing machine for each cycle was calculated. For 1 Hz, times for each cycle are: 1,000 corresponds to 17 minutes; 86,400 to 1 day; 172,800 to 2 days; 345,600 to 4 days; 691,200 to 8 days. For 2 Hz, the times for each cycle are: 1,000 corresponds to 8 and a half minutes; 86,400 to 12 hours; 172,800 to 1 day; 345,600 to 2 days; 691,200 to 4 days.

2.2.2. Static bending and cyclic forces tests

For static bending and cyclic loading tests, Amsler Universal Testing Machine, Figure 1a, and cyclic loading test equipment, Figure 1b, were respectively employed.

Static bending test was conducted according to guidelines set in NBR 7190-3[22], on the 32 test specimens, with 42 cm span. Modulus of elasticity was determined using Equation 1.

$$E_M = \frac{F \times L^3}{4 \times \delta \times b \times h^3} \quad (1)$$

where F represents the force in bending test that cause displacement (δ) equal to L/200, corresponding to the limit displacement (obtained by a deflectometer, Figure 1b) in timber beams, as indicated by NBR 7190; L is sample span (distance between supports); b (base) and h (height) are dimensions of the sample's cross-section.

Test span was based on Code NBR 7190-3[22], which establishes using span equal to 21 times the specimen height.

Values of modulus of elasticity in static bending (E), obtained before cyclic application of forces, were used as a reference to elaborate a graph relating modulus of elasticity and number of cycles [E × Nc].

Three-point static bending test was adapted for a non-destructive condition, assuming that displacements in fatigue machine was limited, following Brazilian Code NBR 7190[23]. The measure L/200 checks serviceability limit state and two different frequencies were used: 1 and 2 Hz. This displacement ensures material physical and geometric linearity, commonly used in E determination in non-destructive tests, as in researches carried out by Christoforo et al.[24], Icimoto et al.[25], Zangiácomo et al.[26], Segundinho et al.[27], and Lahr et al.[28].

For the displacement limit of L/200 (adopted in compliance with the serviceability limit state, NBR 7190-1), the bending stress acting on the sample is approximately 2 MPa for Marupá. According to Table 1 of NBR 7190-3, Marupá batches fall into class D20, with a characteristic value for parallel-to-grain compression of 20 MPa. Applying the safety parameters (γ_w and k_{mod}) indicated by NBR 7190-1, the design value ($f_{c0,d}$) is determined to be 10 MPa, which complies with the normative limits. Similarly, for Pequiá (class D60), the acting stress on the sample is 16 MPa, which is below the recommended normative limits.

Figure 1. Testing machines Amsler Universal (a) and cyclic loading (b).

Table 1. Results of the modulus of elasticity (E) in static bending of Marupá wood as a function of excitation frequencies of 1 Hz and 2 Hz.

Frequency	NC (k cycles)	E (GPa)	Tukey	CV (%)
1Hz	0.0	7.750	A	[1.40; 3.92]
	1.0	7.665	A	
	86.4	7.636	A	
	172.8	7.390	AB	
	345.0	7.212	BC	
	691.2	6.912	C	
2Hz	0.0	7.783	A	[1.13; 6.31]
	1.0	7.751	A	
	86.4	7.401	AB	
	172.8	7.181	B	
	345.0	7.082	B	
	691.2	6.498	C	

From the Tukey's mean comparison test (5% significance level), A denotes the treatment with the highest mean value of the evaluated property, B the second highest mean value, and so on successively, and equal letters imply different treatments associated with statistically equivalent means.

2.2.3. Sample preparation for microscopic analysis

Samples for microscopic analysis techniques were prepared from Glulam pieces, obtaining specimens with dimensions of approximately 1 cm^3 at most. This technique allows analyzing glue line's microstructure after cyclic force tests to determine if any damage occurred during tests.

Specimens taken from the Glulam presented final nominal dimensions 1cm × 1cm × 1cm, compatible with microtomy equipment. Analysis of the glue line, performed on an optical microscope. For the sample analysis, a SteREO Discovery Stereomicroscope equipment was used.

3. Results and Discussion

3.1. Marupá wood

3.1.1. Bending static and cyclic tests

In Table 1, the mean values, confidence intervals of the mean (95% confidence), extreme values of the coefficient of variation (CV), and the results of the Tukey's test for mean contrast regarding the modulus of elasticity (E) of Marupá wood are presented. These were determined based on two levels of investigated frequency (in addition to the reference condition) and the number of fatigue cycles (NC). It is worth noting that the p-values (0.152; 0.969) obtained from the Anderson-Darling normality test were higher than the adopted significance level (5%), validating the results of the analysis of variance (ANOVA) and the Tukey's test.

Regarding evolution of glulam pieces stiffness as function of the number of cycles, variation was observed between the initial and final stiffness (10.8 and 16.5%, for frequencies 1 and 2 Hz) variation, as exemplified in Table 1. This variation can mainly be justified by reorganization in anatomical wood structure (especially in polyose chains) and by eventual modest superficial variation in moisture content of pieces[29], during time in which experiments very conducted.

Macêdo[30], studying fatigue in solid wood elements and finger joints pieces, species of *Pinus caribaea hondurensis* and *Eucalyptus grandis*, observed reduction in tensile stiffness of approximately 5% for both conditions, in a range of 1,000 to 150,000 cycles, frequencies of 1, 5, and 9 Hz. Carvalho et al.[31], investigating fatigue in Caixeta (*Simarouba amara Aubl.*), Cedroarana (*Cedrelinga catenaeformis*), Cambará (*Erisma uncinatum Warm*), Tatajuba (*Bagassa guianensis Aubl.*), and Roxinho (*Peltogyne sp.*), reported 10% reduction in bending stiffness for these species, using frequencies 0.5 and 1 Hz, and cycle counts of 450, 4,500, and 45,000. Guimarães et al.[29] observed no reduction in conventional static bending strength under cyclic loading conditions with frequencies 0.4 Hz and 40,000 and 100,000 cycles, for species (*Dipteryx odorata*, *Pouteria guianensis*, *Cedrelinga catenaeformis* and *Tectona grandis*).

In Table 2, the results of the Pareto chart regarding the influence of individual factors (Fr; NC) as well as the interaction effects (Fr × NC) on the values of the modules of elasticity of Marupá wood are presented.

From Table 2, it can be observed that there is no influence of the interaction effect on the modulus of elasticity of Marupá wood. However, both individual factors were considered significant.

Table 2. Pareto chart regarding the influence of individual factors and the interaction effects (Fr × NC) on the modulus of elasticity in static bending for Marupá wood.

Term	Standardized Effect	Significance
NC	9.181	Significant
Fr	3.104	Significant
Fr × NC	1.482	Not Significant

Criterion: Factors are considered significant if they are positioned to the right of Pareto's line (reference value = 2.042).

Individual factors, both frequency (Fr) and number of cycles (NC), are positioned to the right of the Pareto line, meaning that they significantly influence the elastic modulus of Marupá wood. This indicates that changes in the loading frequency or the number of repeated cycles directly impact the wood stiffness (E). These results suggest that both factors play a critical role in the mechanical response of wood to cyclic forces.

The interaction effect (Fr × NC) between frequency and number of cycles (Fr × NC) does not appear to have a significant influence, as it is positioned to the left of the Pareto line. This means that although both factors independently affect the elastic modulus, their combined effect does not produce a measurable interaction that significantly alters the behavior of Marupá wood.

This finding helps to isolate the main drivers of mechanical changes in Marupá wood under cyclic loading and allows future studies or practical applications to focus more on adjusting either the frequency or the cycle count independently to modify wood stiffness, without having to consider their interaction effects.

The linear regression model for estimating the variation of the modulus of elasticity of Marupá wood as a function of the number of cycles is illustrated in Figure 2.

Due to the relatively small variation in E, a linear regression is sufficient to model and describe the relationship between the modulus of elasticity and the number of cycles.

The goodness of fit of the linear regression is confirmed by the high R^2 values (coefficients of determination), which indicate a good fit for the linear models in both cases. This means that the models can reliably estimate the elastic modulus over the entire range of fatigue cycles tested (1,000 to 691,200 cycles). The high R^2 values show that the models capture most of the variability in the data and that the linear approach is appropriate to describe the phenomenon.

Although not explicitly stated, the differences in regression slopes between the two frequencies (1 Hz and 2 Hz) can be examined to understand how frequency affects the rate of stiffness degradation. However, based on the linear nature of both regressions, the impact of frequency on the rate of E degradation appears consistent, further supporting the robustness of Marupá wood against fatigue at different frequencies.

The linear regression models in Figure 2 provide a clear and reliable method for estimating how the elastic modulus of Marupá wood changes with increasing fatigue cycles. The small variation in E, combined with the high-quality fit of

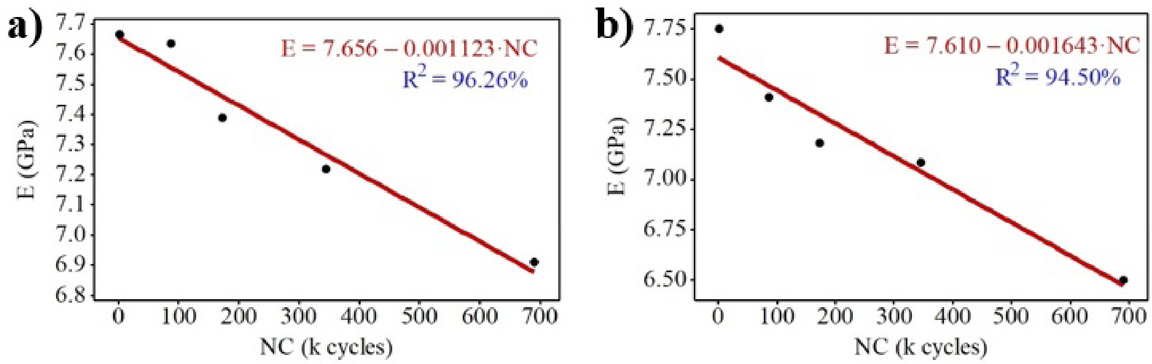

Figure 2. Linear regression model for estimating the modulus of elasticity of Marupá wood as a function of the number of fatigue cycles for excitation frequencies of 1 Hz (a) and 2 Hz (b).

Table 3. Results of the elastic moduli (E) in static bending of Pequiá wood as a function of excitation frequencies of 1 Hz and 2 Hz.

Frequency	NC (k cycles)	E (GPa)	Tukey	CV (%)
1Hz	0.0	11.944	A	[7.64; 10.16]
	1.0	11.745	A	
	86.4	12.301	A	
	172.8	12.177	A	
	345.0	11.349	A	
	691.2	10.663	A	
2Hz	0.0	12.225	A	[5.58; 9.62]
	1.0	11.386	A	
	86.4	11.537	A	
	172.8	11.218	AB	
	345.0	11.297	AB	
	691.2	10.221	B	

From Tukey's mean comparison test (5% significance level), A denotes the treatment with the highest mean value of the evaluated property, B the one with the second highest mean value, and so on successively. Equal letters imply different treatments associated with statistically equivalent means.

the regression models, suggests that Marupá wood exhibits a strong resistance to stiffness degradation under cyclic loading, making it suitable for applications where repeated loading is expected. The models allow direct predictions of E within the given range of cycles and can inform future structural and design applications involving Marupá wood.

3.2. Pequiá wood

3.2.1. Static bending and cyclic tests

In Table 3, the mean values, confidence intervals of the mean (95% confidence), extreme values of the coefficients of variation (CV), and the results of the Tukey's mean comparison test regarding the modulus of elasticity (E) of Pequiá wood are presented.

These values are determined based on the two investigated frequency levels (in addition to the reference condition) and the number of fatigue cycles (NC). It is worth noting that the p-values (0.152; 0.969) obtained from the Anderson-Darling normality test were higher than the adopted significance level (5%), validating the results of the analysis of variance and the Tukey's test.

As already mentioned, regarding evolution of glulam pieces stiffness as function of the number of cycles, significant variation was observed between the initial and final stiffness (10.7 and 16.4%, for frequencies 1 and 2 Hz), as exemplified in Table 3. This variation can mainly be justified by reorganization in anatomical wood structure (especially in polyose chains) and by eventual modest superficial variation in moisture content of pieces[29], during time in which experiments very conducted.

Table 4. Pareto chart regarding the influence of individual factors and the interaction effects (Fr × NC) on the modulus of elasticity in static bending for Pequiá wood.

Term	Standardized Effect	Significance
NC	2.325	Significant
Fr	1.781	Not Significant
Fr × NC	0.126	Not Significant

Criterion: Factors are considered significant if they are positioned to the right of Pareto's line (reference value = 2.042).

In Table 4, the results of the Pareto chart regarding the influence of individual factors (Fr; NC) as well as the interaction effects (Fr × NC) on the elastic modulus values of Pequiá wood are presented. In Table 4, the Pareto chart highlights the influence of individual factors — frequency (Fr) and number of cycles (NC) — along with their interaction

(Fr × NC) on the values of the modulus of elasticity of Pequiá wood. The factors and interactions positioned to the right of the red Pareto line (set at 2.042) are considered statistically significant.

In the chart, it is clear that the interaction between frequency and number of cycles (Fr × NC) does not significantly affect the modulus of elasticity of Pequiá wood, as it is positioned to the left of the line. Frequency (Fr) itself also has no significant effect. However, the number of cycles (NC) stands out as a significant factor, showing a strong influence on the modulus of elasticity, with its bar clearly extending beyond the critical value in the Pareto chart. This suggests that as the number of cycles increases, it significantly impacts the stiffness of Pequiá wood, while frequency and the interaction between frequency and cycles do not have a significant effect.

The linear regression model for estimating the variation of the elastic modulus of Pequiá wood as a function of the number of cycles is illustrated in Figure 3.

As E variation is slight in function of NC, linear regressions are sufficient to describe the phenomenon, even with the adjustment quality observed. Equations permit estimating E for NC between 1,000 and 691,200 cycles.

It is worth mentioning, solely for illustrative purposes, the study by Ferraz et al.[32], which investigated the effects of cyclic forces on structural plywood components. They concluded that there is a 21% reduction in stiffness when reaching one hundred thousand cycles of force causing vertical displacement at the midpoint of the tested samples (three-point bending).

However, any comparison with the results obtained here is not viable, as plywood studied by those authors used phenol-formaldehyde as adhesive, known to present inferior performance compared to the resin used in present study.

3.3. Microscopic analysis

In microscopic analysis, it can be observed that there was no damage in glue lines, even though specimens were taken from the position where the highest stresses occurred.

Figure 4 shows samples microscopic images (magnification of 12.5x), where the entire length of the specimen can be observed. The arrows indicate the glue line.

In Figure 4d, the fissures indicated with a circle were due to sample preparation.

For measurements of adhesive line thickness, images with a 40x magnification were considered. Adhesive penetration into wood is observed, as indicated by arrows. Figure 5 presents microscopic images of the species.

Table 5 presents mean values of adhesive line thickness, 10 measurements along the sample.

In Table 5, it can be observed that the adhesive line thickness in Marupá wood was significantly greater than in Pequiá wood. This phenomenon can be attributed to the higher permeability of Marupá, which allows for greater penetration and dispersion of the adhesive, forming a darker band visible in the wood. In contrast, the lower permeability of Pequiá resulted in a relatively thinner adhesive line, possibly due to greater adhesive expulsion from the sides during the pressing process.

Although it is possible to distinguish adhesive slight penetration in Pequiá (most likely due to the position of medullary rays in relation to faces in which adhesive was applied), no reduction in Glulam stiffness test specimens was observed. Thus, the high resistance capacity of the adhesive line is demonstrated within the scope of the number of cycles of applied forces.

For Marupá, adhesive penetration was visibly up to about 0.5 mm, showing species greater permeability, in addition to the favorable contribution of medullary rays' position in relation to the glued faces. In addition, no statistical variations in Glulam pieces stiffness were detected within the scope of the number of cycles of applied forces.

Table 5. Mean values of adhesive line thickness.

Frequency	Adhesive line thickness (μm)	
	Marupá	Pequiá
1 Hz	111.12	46.18
	(10.52%)	(11.61%)
2 Hz	135.84	59.11
	(17.26%)	(15.08%)

Values in parentheses refer to coefficients of variation.

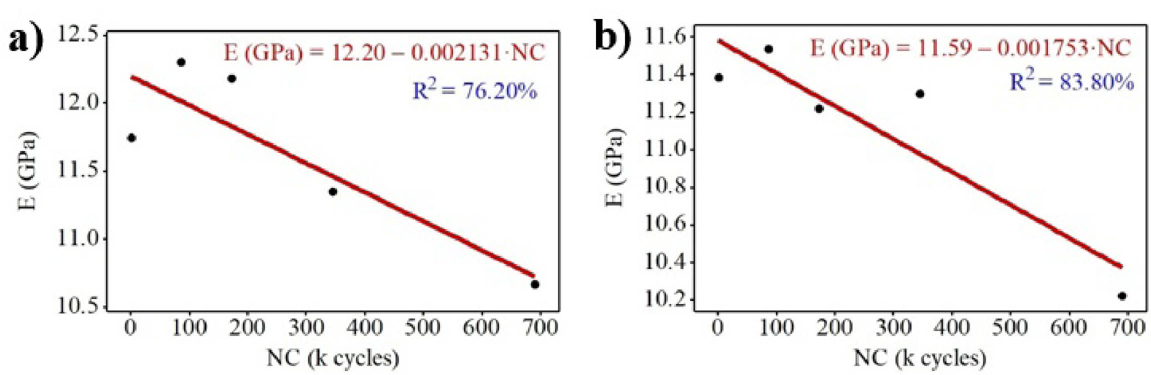

Figure 3. Linear regression model for estimating the elastic modulus of Pequiá wood as a function of the number of fatigue cycles for excitation frequencies of 1 Hz (a) and 2 Hz (b).

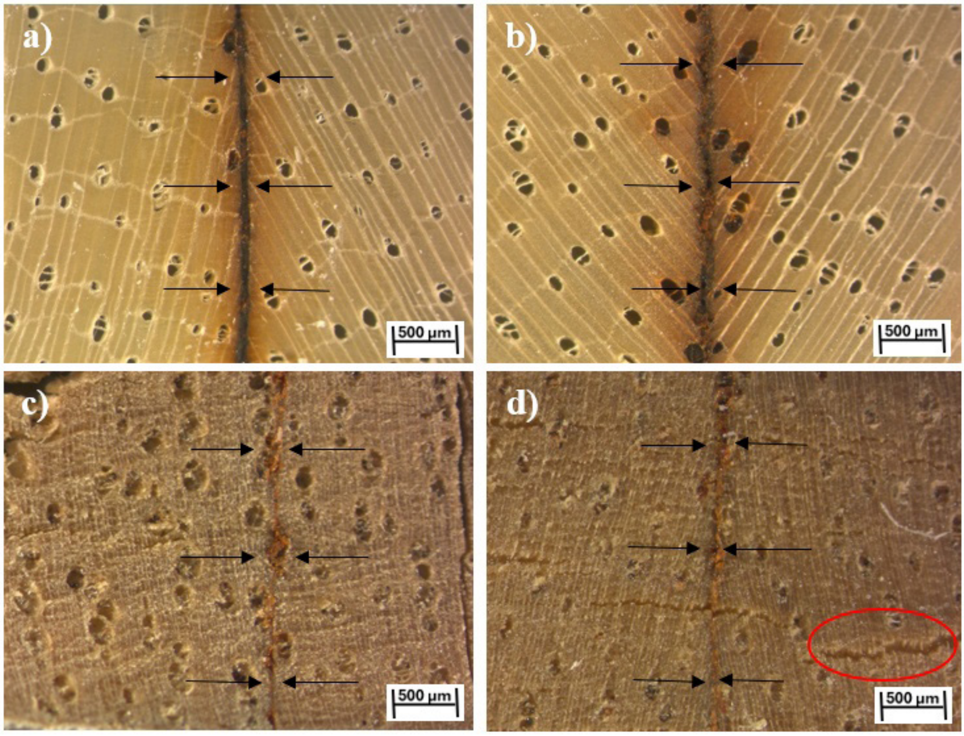

Figure 4. Microscopy 12,5x of species Marupá, frequency 1 Hz (a); Marupá, frequency 2 Hz (b); Pequiá, frequency 1 Hz (c) and Pequiá, frequency 2 Hz (d). Figure 5. Microscopy 40x of species Marupá, frequency 1 Hz (a); Marupá, frequency 2 Hz (b); Pequiá, frequency 1 Hz (c) and Pequiá, frequency 2 Hz (d).

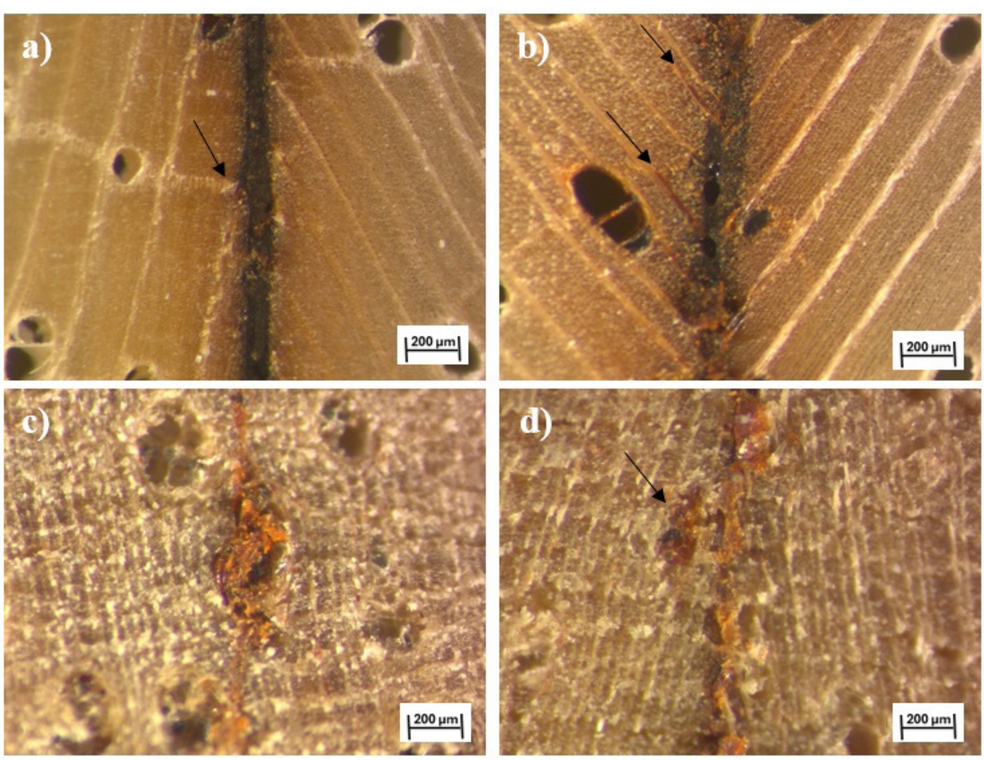

Figure 5. Microscopy 40x of species Marupá, frequency 1 Hz (a); Marupá, frequency 2 Hz (b); Pequiá, frequency 1 Hz (c) and Pequiá, frequency 2 Hz (d).

4. Conclusion

Modulus of elasticity mean values, for the two wood species studied, present (between 10.7 and 16.5%), significant variations when number of cycles ranges between 1,000 and 691,200 and frequencies between 1 and 2 Hz.

For Marupá, both cycle number and frequency were significant, while for Pequiá, only cycle number was significant to explain E variations, results that can be influenced by anatomical aspects. When possible, authors suggest carrying out new experiments, incrementing number of specimens for species an expanding cycle number to better reliability of obtained results.

Density range indicated by NBR7190-1 for species to be used in Glulam proved to be adequate (400 to 750 kg/m^3), as no damage to glue lines was identified with the adopted microscopy techniques. This aspect implies that species permeability, within the considered range, is compatible for their use in Glulam.

5. Acknowledgements

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Data Availability

The dataset supporting the results of this study is not publicly available (Does not apply to articles with datasets in SciELO Data).