Effect of fatigue on tropical wood species

Efeito da fadiga em espécies de madeira tropical

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Abstract

The aim of present study was to create a theoretical model that allowed, with security and reliability, to obtain values of strength and stiffness to which the structural element will be submitted throughout its useful life. The effect was studied for strength and stiffness properties, and the modulus of elasticity (E_M) and bending strength (f_M) on static bending test were evaluated according to the increasing number of cycles of the fatigue test for the five classes of hardwoods, recommended by NBR 7190 Standard Code. A reduction in strength and stiffness properties was observed with increasing loading N_{cycles} applied at two frequency levels. From the multivariate regression models and the respective determination coefficients, a generic model was obtained for the set involving the five wood species, emphasizing the insertion of the apparent density as an independent variable, which allowed a greater generalization of the use of the adjustments in the estimation of the E_M and f_M properties, presenting significant determination coefficients, ranging between 67.89% and 70.58%.

Keywords: Properties. Strength. Stiffness. Wood.

Resumo

O objetivo do presente estudo foi criar um modelo teórico que permitisse com segurança e confiabilidade obter, valores de resistência e rigidez aos quais o elemento estrutural será submetido ao longo de sua vida útil. O efeito foi estudado para as propriedades de resistência e rigidez, e o módulo de elasticidade (E_M) e a resistência à flexão (f_M) no teste de flexão estática foram avaliados de acordo com o número crescente de ciclos do teste de fadiga para as cinco classes de madeiras duras, recomendado por norma NBR 7190. Uma redução nas propriedades de resistência e rigidez foi observada com o aumento dos ciclos de carregamento N aplicados em todas as frequências. A partir dos modelos de regressão multivariada e dos respectivos coeficientes de determinação, obteve-se um modelo genérico para o conjunto envolvendo as cinco espécies de madeira, enfatizando a inserção da densidade aparente como variável independente, o que permitiu uma maior generalização do uso dos ajustes no estimativa das propriedades E_M e f_M, apresentando coeficientes de determinação significativos, variando entre 67,89% e 70, 58%.

***Palavras-chave**: Properties. Resistência. Rigidez. Madeira.*

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Introduction

When used in properly designed structures, associated with periodic preventive maintenance, wood presents itself as a structural material, which has qualities that compete directly with most other conventional materials used to solve engineering problems in different areas of construction civil, such as transport and buildings (CALIL JUNIOR; LAHR; DIAS, 2003; MOLINA *et al*., 2017; PALLUDO *et al*., 2017).

Due to the peculiar character of the actions that occur during the useful life of a bridge, the dynamic effect resulting from the passage of vehicles must be considered. In addition, it is important to point out that, in a bridge, use conditions with a minimum of maintenance must be guaranteed, seeking to avoid traffic interruption disorders and other undesirable aspects (CALIL JUNIOR; CHRISTOFORO, 2015; CHEUNG *et al*., 2017; SCALIANTE *et al*., 2016).

Faced with this broadly promising scenario, it is worth mentioning that there are still some aspects of specific behavior regarding wood that have not been the object of conclusive research (but that are vital for better structural use of wood) – this is the case of fatigue. Brazilian Standard NBR 7190 (ABNT, 1997) makes no mention of mechanical properties arising from the fatigue phenomenon, remembering that the effect of fatigue is of fundamental importance to be considered in a project whose structures are required by forces that vary over time.

The fatigue of a material can be understood as the change in its properties, resulting from the application of cyclic loads. According to Suresh (SURESH, 1991), the first researches on the deformation and fracture of materials caused by fatigue date from the 19th century. There has always been a great concern in being able to determine how long after the beginning of cracks or fractures, the material will still remain with sufficient bearing capacity to continue resisting the active demands.

Along with the development of "Material Sciences" and "Fracture Mechanics" in more recent decades, the "Fatigue of Materials" has emerged as an area of scientific research and application that covers the various areas of materials science (metals, ceramics, polymers and composites), involving several areas of engineering, including civil, mechanical and aeronautical (CALLISTER JUNIOR; RETHWISCH, 2018).

The objective of this work is to propose regression models for estimating wood properties in static bending (elasticity [E_M] and rupture [f_M]), based on the number of cycles and frequency in fatigue of tropical hardwood species from different strength classes recommended by NBR 7190 (ABNT, 1997). Regression models were also proposed to estimate E_M and f_M for the set of species, also considering the apparent density of the wood at a moisture content of 12%.

Materials and methods

Static bending tests

For the development of the present study, 5 tropical wood species from the hardwoods group were used according to the resistance classes recommended by NBR 7190 (ABNT, 1997), which are:

(a) Caixeta (*Simarouba amara* Aubl.), Strength Class C20;

(b) Cedroarana (*Cedrelinga catenaeformis*), C30;

(c) Cambará (*Erisma uncinatum Warm*), C40;

(d) Tatajuba (*Bagassa guianensis Aubl.*), C50 (attributed); and

(e) Roxinho (*Peltrogyne sp.*), C60.

The wood was purchased in commercial establishments in the Brazilian country and properly stored and processed for the production of specimens in the premises of the Wood and Timber Structure Laboratory (LaMEM), of the São Carlos School of Engineering, University of São Paulo. The classification of the lots in the strength classes was carried out according to Annex B of the NBR 7190 standard (ABNT, 1997). In addition, the apparent density at 12% moisture content ($\rho_{12\%}$) of the specimens was also estimated according to the NBR 7190 standard (ABNT, 1997). For each treatment and wood specie, 6 specimens were tested.

The curves of the elasticity modulus on static bending test (E_M) (Equation 1) and the conventional strength on static bending test (f_M) (Equation 2) were obtained for two stipulated displacement levels, being L/200 and L/100. It is worth mentioning that the measures L/200 and L/100 are established by the standard NBR 7190 (ABNT, 1997) in the verification of the limit state of use, according to the connection, with L/200 for simply supported beams and L/100 for cantilever beams. On the present research, only simply supported beams were evaluated.

$$E_M = \frac{F \cdot L^3}{4 \cdot \delta \cdot b \cdot h^3} \qquad \text{Eq. 1}$$

$$f_M = \frac{3}{2} \cdot \frac{F \cdot L}{b \cdot h^2} \qquad \text{Eq. 2}$$

From Equations 1 and 2, F denotes the value of the force obtained in the static bending test for the displacement levels L/200 and L/100, δ is the displacement (L/200 or L/100), L is length sample size (distance between supports), b and h are the base and height of the cross section, respectively. The tests to determine the properties of wood in static bending occurred in the universal testing machine EMIC, with a load capacity equal to 30 kN.

Fatigue tests

Fatigue tests on bending were performed on a specific machine developed at LaMEM, for this type of test (Figure 1). The displacements in the center of the span were limited to L/200 and L/100 and subjected to two different frequency values, 0,5 and 1,0 Hz and to different number of cycles, 450, 4500 and 45000.

The choice of the number of cycles and the frequencies used in the present study was based on the work developed by Guimarães *et al*. (2012). The authors of this research suggested that different cycles be used and also frequencies higher than 0,4 Hz, in which the objective of the study was to evaluate a non-destructive method for analyzing wood properties, in this case, ultrasound, not having as main objective the study of fatigue itself in the woods aiming at the use for structural purposes and by Macêdo (2018), who used frequencies of 1, 5 and 9 Hz in toothed splices glued from planted forest woods.

After the first of the six levels of the fatigue cycle for a given displacement value (L/200 or L/100), the specimen was taken to the universal testing machine for the static bending test in order to perform the determination of E_M and f_M, and then it was taken back to the fatigue machine for exposure to the next level of fatigue cycles.

It is worth mentioning that the specimens were tested on static bending before starting the fatigue cycles, which made it possible to monitor the evolution of properties depending on the number of cycles.

Statistical analysis

The factors investigated in determining the E_M and f_M values for each wood species were the Number of Cycles in Fatigue [Nci] (0, 450, 4500 and 45000) and the Excitation Frequency [Fr] (0.5 and 1 Hz). The combination of the levels of the two factors resulted in a planning with six different treatments (Table 1).

Figure 1 – **Fatigue test machine**

Table 1 – **Experimental Treatments**

Treatment	NCI	FR (Hz)
0 (Ref)	0	0
1	450	0,5
2	4500	0,5
3	45000	0,5
4	450	1,0
5	4500	1,0
6	45000	1,0

Three specimens were prepared (dimensions 20 mm × 20 mm × 300 mm) for fatigue tests and subsequent determination of E_M and f_M on static bending for each treatment and for wood species. Each six specimens for each treatment and each wood specie were taken from the same region of the piece of wood, and each was assigned to one of the six experimental treatments outlined, with the aim of reducing those of the natural variability of the wood in determining the mechanical properties (CHRISTOFORO *et al*., 2020). The total number of experimental determination is 210. The free span available for the test is 280 mm. It leads to a relation L/h (length/ height of cross section) resulting in 14. Such relation guarantees that the effect of shear on the specimen considering the displacement is not significant.

To investigate the influence of Nci and Fr factors on the values of E_M and f_M by wood species, the Tukey multiple comparisons test was used, at the 5% level of significance. In the Tukey test, the letter A denotes the group with the highest mean value, the letter B is the group with the second highest mean value, and so on, and equal letters for different groups implies statistically equivalent means.

To understand the effect of the two factors on the two properties evaluated for each wood species, multivariable regression models (Equation 3) with the aid of ANOVA (Analysis of Variance) were used to estimate such properties as a function of the free variables Nci and Fr. By test formulation, p-value greater than or equal to the significance level (0.05) implies assuming that the distribution of residuals is normal, which validates the ANOVA results.

$$Y = \alpha_0 + \alpha_1 \cdot Nci + \alpha_2 \cdot Fr + \alpha_3 \cdot Nci \cdot Fr + \alpha_4 \cdot Nci^2 + \alpha_5 \cdot Fr^2 + \varepsilon \qquad \text{Eq. 3}$$

On Equation 3, Y denotes the estimated property (E_M or f_M), α_i are the coefficients adjusted by the least squares method and ε consists of the random error obtained from the adjustment, with the quality of the models judged by means of the determination coefficient (R^2). After evaluating the models considering each wood species in isolation, in the sequence regression models were generated to estimate the values of E_M and f_M as a function of Nci, Fr and also the apparent density (Equation 4), allowing thus greater generalization of the results obtained.

$$Y = \alpha_0 + \alpha_1 \cdot Nci + \alpha_2 \cdot Fr + \alpha_3 \cdot \rho_{12\%} + \alpha_4 \cdot Nci \cdot Fr + \alpha_5 \cdot Nci \cdot \rho_{12\%} + \alpha_6 \cdot Fr \cdot \rho_{12\%} + \alpha_7 \cdot Nci \cdot Fr \cdot \rho_{12\%} + \alpha_8 \cdot Nci^2 + \alpha_2 \cdot Fr^2 + \alpha_3 \cdot {\rho_{12\%}}^2 + \varepsilon \qquad \text{Eq. 4}$$

Results and discussion

Caixeta wood specie

Figure 2 shows the variation of the mean values, intervals of the values of the coefficients of variation (CV) and the confidence intervals (at the 95% confidence level – estimate of the variation of the mean in the population) of the elasticity module (E_M) and of the rupture module (f_M) on static bending for the Caixeta as a function of the number of cycles and the frequency in fatigue.

Table 2 presents the results of the Tukey test of the mechanical properties as a function of the two factors evaluated (Nci and Fr) for Caixeta wood species. From Table 2, the results of the Tukey test show that 0 or 450 cycles and 0 or 0.5 Hz of frequency result in equivalent values of the elasticity modulus and the conventional strength on static bending, and that 45000 cycles or the frequency of 1.0 Hz promote significant reductions (8.92% in E_M and 7.21% in f_M) of both properties.

Figure 2 - **Variation of the mechanical properties of Caixeta wood specie: (a) as a function of the number of cycles [Nci] and (b) the frequency of excitation in fatigue [Fr]**

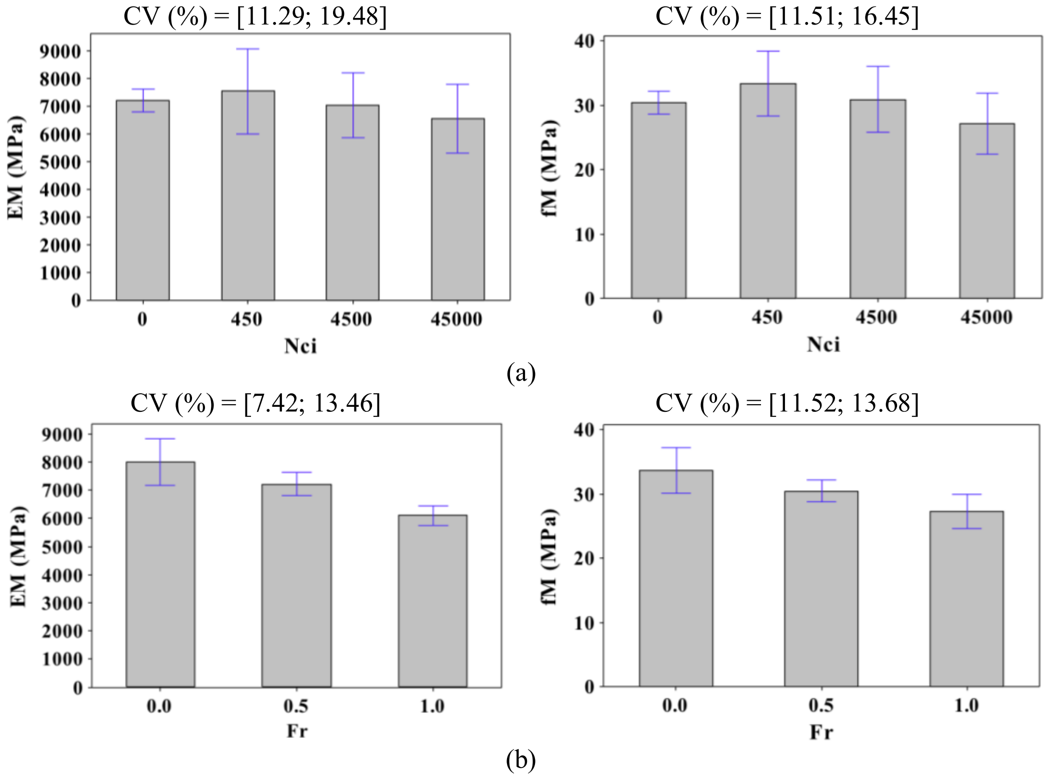


Table 2 - **Tukey test results of mechanical properties of Caixeta**

Properties	Nci				Fr (Hz)		
	0	450	4500	45000	0	0,5	1,0
E_M	A	A	A	B	A	A	B
f_M	A	A	B	B	A	A	B

The multivariable regression models and the respective determination coefficients for estimating the values of the elasticity and rupture module on static bending for Caixeta wood are expressed by Equations 5 and 6, respectively. The model was significant by the ANOVA, with p-value below 5%.

$$E_M = 7214 - 0.118 \cdot Nci - 4060 \cdot Fr - 0.0245 \cdot Nci \cdot Fr + 0.000003 \cdot Nci^2 + 5507 \cdot Fr^2 \qquad \text{Eq. 5}$$

$[R^2=70.34\%]$

$$f_M = 30{,}4 - 0.000553 \cdot Nci - 9.54 \cdot Fr - 0.000157 \cdot Nci \cdot Fr + 0.000000 \cdot Nci^2 + 16.6 \cdot Fr^2 \qquad \text{Eq. 6}$$

$[R^2=65.22\%]$

The values of the determination coefficients obtained in the estimation of the values of E_M and f_M indicate imprecision in the forecast of 29.66% and 34.78%, respectively, which estimates can be improved with the consideration of the set involving the five species of adopted in this research. From Equations 5 and 6 it is evident that increases in the values of the individual factors Nci and Fr provide reductions in the values of both mechanical properties, as verified by the Tukey test.

Cedroarana wood specie

Figure 3 shows the variation of the mean values, ranges of values of the coefficients of variation (CV) and the confidence intervals (at the 95% confidence level – estimate of the variation of the mean in the population) of the elasticity module (E_M) and of the rupture module (f_M) on static bending for Cedroarana as a function of the number of cycles and the frequency in fatigue.

Table 3 presents the results of the Tukey test of mechanical properties as a function of the two factors evaluated (Nci and Fr) for Cedroarana. From Table 3, the results of the Tukey test show that 0 or 450 cycles and 0 or 0.5 Hz of frequency result in equivalent values of the modulus of elasticity and of the rupture module in flexion, and that 45000 cycles or the frequency of 1.0 Hz promote significant reductions (9.56% in E_M and 8.19% in f_M) of both properties.

The multivariable regression models and the respective determination coefficients for estimating the values of the elastic modulus and rupture on static bending for Cedroarana wood are expressed by Equations 7 and 8, respectively. The model was significant by the ANOVA, with p-value below 5%.

$$E_M = 8578.89 - 0.118 \cdot Nci - 1271.14 \cdot Fr - 0.0480 \cdot Nci \cdot Fr + 2.3427 \cdot 10^{-6} \cdot Nci^2 + 3429.89 \cdot Fr^2 \quad \text{Eq. 7}$$

[R^2=61.26%]

$$f_M = 37.46 - 0.0007737 \cdot Nci - 7.197 \cdot Fr + 4.7968 \cdot 10^{-5} \cdot Nci \cdot Fr + 1.3965 \cdot 10^{-8} \cdot Nci^2 + 16.04 \cdot Fr^2 \quad \text{Eq. 8}$$

[R^2=53,89%]

The values of the determination coefficients obtained in the estimation of the values of EM and fM indicate imprecision in the forecast of 38.74% and 46.11%, respectively, which estimates can be improved with the consideration of the set involving the five species of adopted in this research. From Equations 5 and 6 it is evident that increases in the values of the individual factors Nci and Fr provide reductions in the values of both mechanical properties, as verified by the Tukey test.

Cambará wood specie

Figure 4 shows the variation of the mean values, intervals of the values of the coefficients of variation (CV) and the confidence intervals (at the 95% confidence level – estimate of the variation of the mean in the population) of the elasticity module (E_M) and of the rupture module (f_M) on static bending for the Cambará wood specie as a function of the number of cycles and the frequency in fatigue.

Figure 3 - **Variation of the mechanical properties of wood Cedroarana: (a) as a function of the number of cycles [Nci] and (b) the frequency of excitation in fatigue [Fr]**

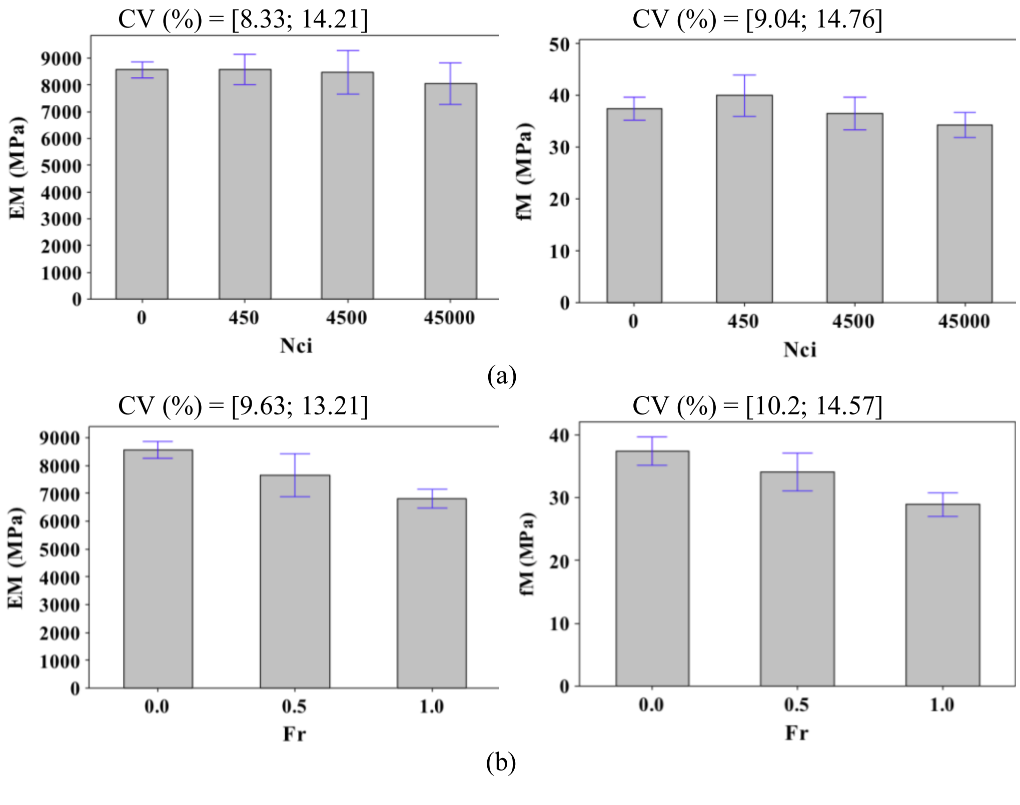


Table 3 - **Tukey test results of mechanical properties of Cedroarana**

Properties	Nci				Fr (Hz)		
	0	450	4500	45000	0	0,5	1,0
E_M	A	A	A	B	A	A	B
f_M	A	A	B	B	A	A	B

Figure 4 - **Variation of the mechanical properties of Cambará wood: (a) as a function of the number of cycles [Nci] and (b) the frequency of excitation in fatigue [Fr]**

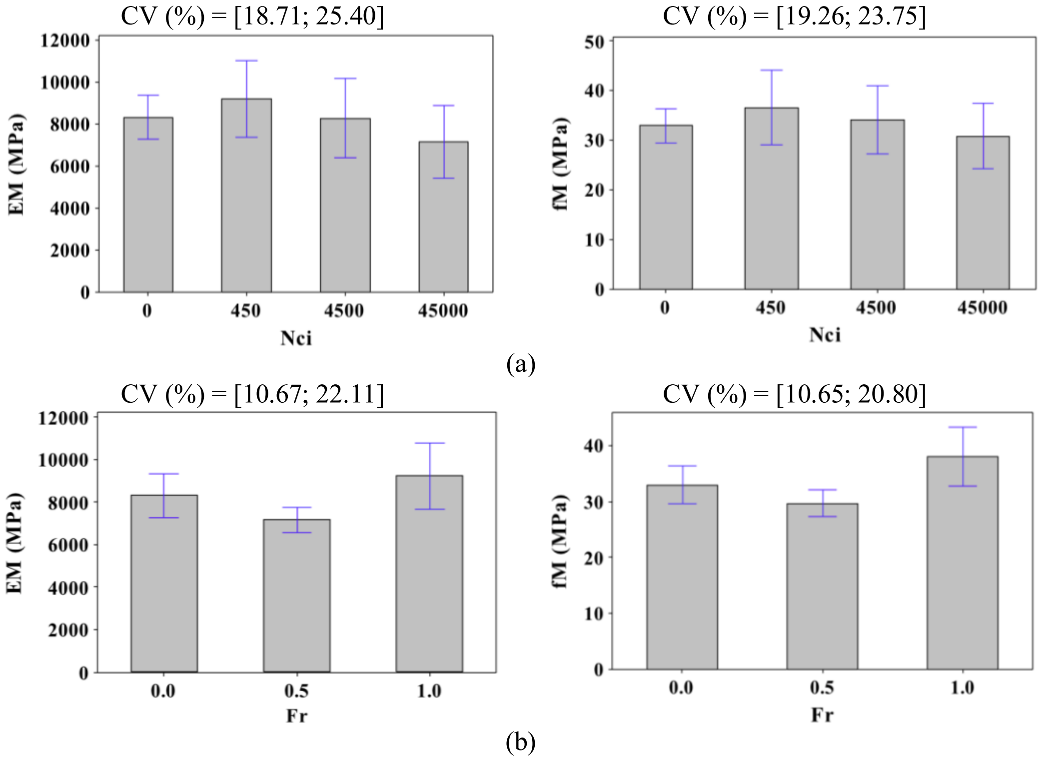


Table 4 presents the results of the Tukey test of mechanical properties as a function of the two factors evaluated (Nci and Fr) for Cambará. The multivariable regression models and the respective determination coefficients for the estimation of the values of the modulus of elasticity and of the rupture module in static bending for Cambará wood are expressed by Equations 9 and 10, respectively. The model was significant by the ANOVA, with p-value below 5%.

$$E_M = 8318.56 - 0.196716 \cdot Nci - 3599.96 \cdot Fr - 0.0671916 \cdot Nci \cdot Fr + 4.4293 \cdot 10^{-6} \cdot Nci^2 + 5899.28 \cdot Fr^2 \quad \text{Eq. 9}$$

[R^2=48.81%]

$$f_M = 33.0006 - 0.000443057 \cdot Nci - 14.8959 \cdot Fr - 0.000270559 \cdot Nci \cdot Fr + 1.13665 \cdot 10^{-8} \cdot Nci^2 + 24.0849 \cdot Fr^2 \quad \text{Eq. 10}$$

[R^2=41.25%]

The values of the determination coefficients obtained in the estimation of the values of EM and fM indicate imprecision in the forecast of 51.19% and 58.75%, respectively, which estimates can be improved with the consideration of the set involving the five species of adopted in this research.

Tatajuba wood specie

Figure 5 shows the variation of the mean values, intervals of the values of the coefficients of variation (CV) and the confidence intervals (at the 95% confidence level – estimate of the variation of the mean in the population) of the elasticity module (E_M) and of the rupture module (f_M) on static bending for the Tatajuba wood species as a function of the number of cycles and the frequency in fatigue.

Table 5 presents the results of the Tukey test of mechanical properties as a function of the two factors evaluated (Nci and Fr) for Tatajuba. The multivariable regression models and the respective determination coefficients for the estimation of the values of the modulus of elasticity and of the rupture module in static bending for Tatajuba wood species are expressed by Equations 11 and 12, respectively. The model was significant by the ANOVA, with p-value below 5%.

$$E_M = 12645.6 - 0.160522 \cdot Nci + 4310.8 \cdot Fr - 0.0134314 \cdot Nci \cdot Fr + 3.25535 \cdot 10^{-6} \cdot Nci^2 - 6727.85 \cdot Fr^2 \qquad \text{Eq. 11}$$

[R^2=58,21%]

$$f_M = 59.4144 - 0.000860275 \cdot Nci + 18.4491 \cdot Fr - 0.000132873 \cdot Nci \cdot Fr + 1.73446 \cdot 10^{-8} \cdot Nci^2 + 27.0325 \cdot Fr^2 \qquad \text{Eq. 12}$$

[R^2=51,09%]

The values of the determination coefficients obtained in the estimate of E_M and f_M indicate inaccuracy in the forecast of 41.79% and 48.91%, respectively, which estimates can be improved with the consideration of the set involving the five wood species adopted in this research.

Table 4 - **Tukey test results of mechanical properties of Cambará**

Properties	Nci				Fr (Hz)		
	0	450	4500	45000	0	0,5	1,0
E_M	A	A	A	B	A	B	A
f_M	A	A	B	B	B	B	A

Figure 5 - **Variation of the mechanical properties of Tatajuba wood: (a) as a function of the number of cycles [Nci] and (b) the frequency of excitation in fatigue [Fr]**

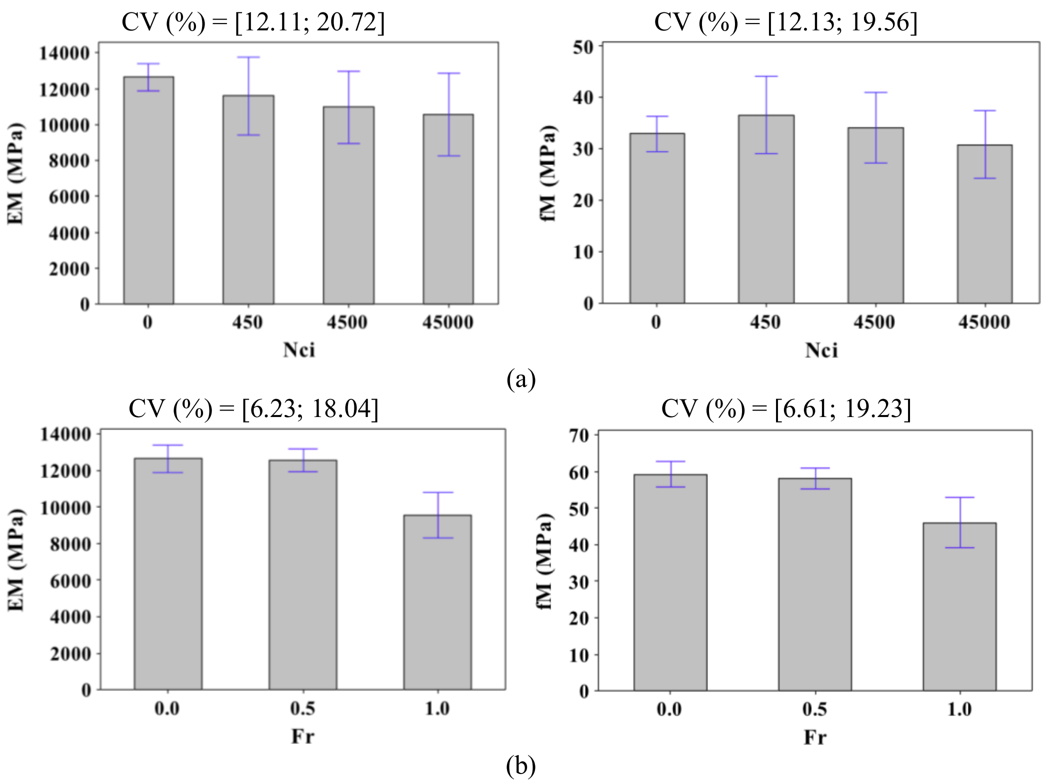


Table 5 - **Tukey test results of mechanical properties of Tatajuba**

Properties	Nci				Fr (Hz)		
	0	450	4500	45000	0	0.5	1.0
E_M	A	A	A	B	A	A	B
f_M	A	B	B	C	A	A	B

Roxinho wood species

Figure 6 shows the variation of the mean values, intervals of the values of the coefficients of variation (CV) and the confidence intervals (at the 95% confidence level – estimate of the variation of the mean in the population) of the elasticity module (E_M) and of the rupture module (f_M) on static bending for the Roxinho wood species as a function of the number of cycles and the frequency in fatigue.

Table 6 presents the results of the Tukey test of mechanical properties as a function of the two factors evaluated (Nci and Fr) for Roxinho. The multivariable regression models and the respective determination coefficients for the estimation of the values of the modulus of elasticity and of the rupture module on static bending for Roxinho wood species are expressed by Equations 13 and 14, respectively. The model was significant by the ANOVA, with p-value below 5%.

$$E_M = 15654.7 - 0.155182 \cdot Nci + 745.255 \cdot Fr + 0.0516713 \cdot Nci \cdot Fr + 2.34101 \cdot 10^{-6} \cdot Nci^2 - 3098.85 \cdot Fr^2 \quad \text{Eq. 13}$$

[R^2=50,94%]

$$f_M = 71.3756 - 0.00155421 \cdot Nci + 3.03048 \cdot Fr + 0.000611025 \cdot Nci \cdot Fr + 2.15213 \cdot 10^{-8} \cdot Nci^2 - 12.4466 \cdot Fr^2 \quad \text{Eq. 14}$$

[R^2=42,66%]

The values of the determination coefficients obtained in the estimate of E_M and f_M indicate inaccuracy in the forecast of 49,06% and 57,34%, respectively, which estimates can be improved with the consideration of the set involving the five wood species adopted in this research.

Set with all wood species

Figure 7 shows the variation of the mean values, ranges of values of the coefficients of variation (CV) and the confidence intervals (at the 95% confidence level) of the apparent density ($\rho_{12\%}$) of the five wood species studied.

Figure 6 - **Variation of the mechanical properties of Roxinho wood: (a) as a function of the number of cycles [Nci] and (b) the frequency of excitation in fatigue [Fr]**

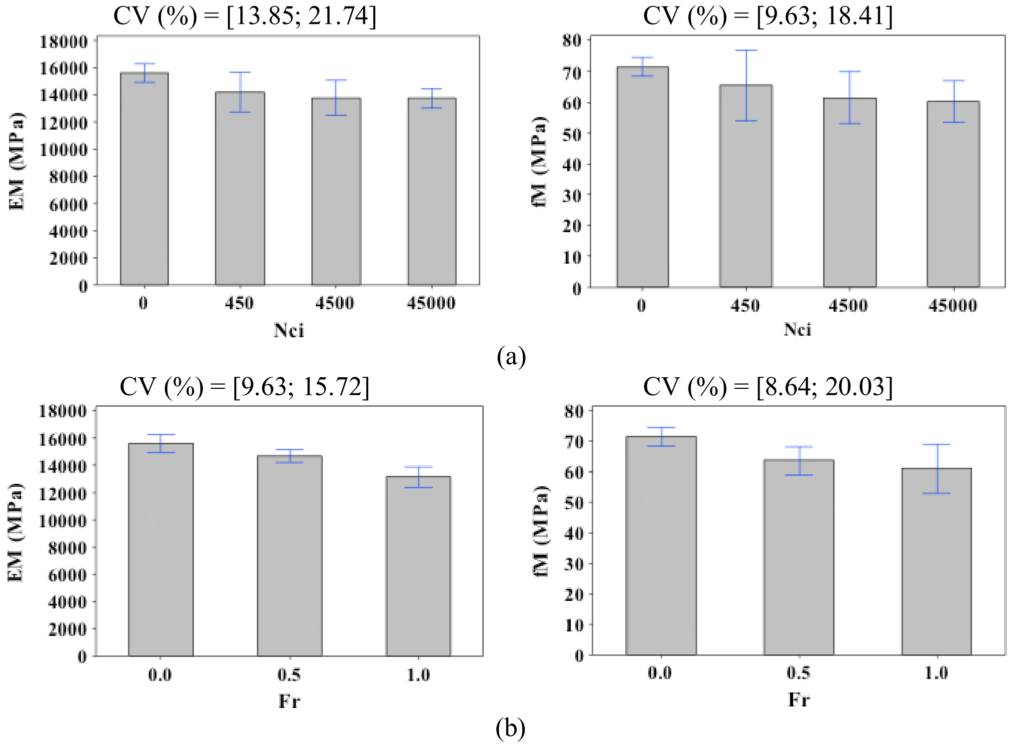
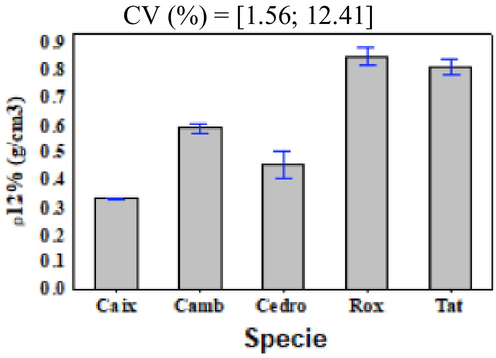


Table 6 - **Tukey test results of mechanical properties of Roxinho**

Properties	Nci				Fr (Hz)		
	0	450	4500	45000	0	0,5	1,0
E_M	A	B	B	B	A	A	B
f_M	A	A	B	B	A	B	B

Figure 7 - **Variation in the apparent density values of the wood species investigated**



Note:

Caix - Caixeta [C-20];
Camb - Cambará [C-40];
Cedro - Cedroarana [C-30];
Rox - Roxinho [C-60]; and
Tat - Tatajuba [C-50].

In order to obtain a single model for determining E_M and f_M, covering all species, regardless of the strength class to which they belong, an easy to obtain and broadly generic parameter was introduced at that moment for any wood species that if intended, the apparent density ($\rho_{12\%}$). The multivariable regression models and the respective determination coefficients for the estimation of the values of the elastic modulus and the stress on the static bending for the set involving the five wood species are expressed by Equations 15 and 16, respectively, emphasizing the apparent density was inserted as an independent variable in these models to allow greater generalization of the use of adjustments in the estimation of E_M and f_M properties. The models were significant by the ANOVA, with p-value below 5%, indicating the significance of the models.

$$E_M = 9707.66 - 0.0936647 \cdot Nci - 2117.43 \cdot Fr - 13666.8 \cdot \rho_{12\%} - 0.0567916 \cdot Nci \cdot Fr - 0.0453735 \cdot Nci \cdot \rho_{12\%} + 813.833 \cdot Fr \cdot \rho_{12\%} + 0.0676045 \cdot Nci \cdot Fr \cdot \rho_{12\%} + 2.32517 \cdot 10^{-6} \cdot Nci^2 + 2921.14 \cdot Fr^2 + 21913 \cdot {\rho_{12\%}}^2 \quad \text{Eq. 15}$$

[R^2=70,58%]

$$f_M = 46.4895 - 0.000189931 \cdot Nci - 5.39633 \cdot Fr - 84.4083 \cdot \rho_{12\%} - 0.000643106 \cdot Nci \cdot Fr - 0.000832534 \cdot Nci \cdot \rho_{12\%} + 3.47444 \cdot Fr \cdot \rho_{12\%} + 0.000100965 \cdot Nci \cdot Fr \cdot \rho_{12\%} + 1.23445 \cdot 10^{-8} \cdot Nci^2 + 9.67021 \cdot Fr^2 + 123.464 \cdot {\rho_{12\%}}^2 \quad \text{Eq. 16}$$

[R^2=67,89%]

The values of the determination coefficients obtained in the estimation of the E_M and f_M values for the set involving the five wood species indicate imprecision in the forecast of 29.42% and 32.11%, respectively, indicating a strong correlation, with good quality of adjustment (MONTGOMERY, 2012).

Conclusions

From the experimentation and the results obtained in this research, the following conclusions were reached:

(a) the fatigue effect was present and pronounced in all strength classes of wood studied;

(b) in all strength classes, there was a reduction in the properties of strength and stiffness with the increase in the number of loading cycles applied at all frequencies studied; and

(c) it was possible to obtain regression models for each species individually from the parameters number of cycles and frequency in fatigue to estimate E_M and f_M and, for the set of species covering all strength classes, also adopting the apparent density as a variable, the coefficient of determination was close to 70%, a good value for estimating wood properties, indicating a strong correlation. An exception was the Cambará wood, that presented an elevated CV value, indicating a great variation.

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