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TECHNICAL PAPER

INFLUENCE OF FATIGUE ON BENDING OF *Pinus caribaea* WOOD

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KEYWORDS

fatigue, *Pinus caribaea*, static bending, analysis of variance, regression models.

ABSTRACT

This research aimed to evaluate the effect of the number of fatigue cycles (NC, 0 – reference, 450, 4500, 45000, and 90000) for frequencies (Fr) of oscillation equal to 0.5 and 1.0 Hz on the modulus of elasticity (E_m) and operating stress (σ_m) in the static bending of *Pinus caribaea* wood. E_m and σ_m were determined taking into account three specimens (SPEC) manufactured for reference condition and another three for each of the four NC levels and each Fr level, resulting in 27 SPEC. Sixty experimental determinations were obtained, being the approximate total time of sample exposure to fatigue of 350 hours. The same specimens used to determine E_m and σ_m for the reference condition were also used (via non-destructive tests) to obtain these properties for all fatigue cycles. The frequency and number of cycles significantly influenced both investigated properties. Reductions in E_m and σ_m values were observed after 45000 cycles. The progressive increase in the number of fatigue cycles caused more marked reductions in mechanical properties when compared to the increase in the frequency of oscillation.

INTRODUCTION

Wood is a material widely used in the manufacture of building components, such as partition panels, doors, frames, wainscoting, ceilings, and floors. Such employment has been growing despite some well-known prejudices inherent to wood, especially related to the insufficient dissemination of technological information already available about its properties under different operating conditions, and also due to the almost systematic lack of specific projects developed by qualified professionals (Nogueira et al., 2018).

Eucalyptus and Pinus are the species most commonly used in construction because, in addition to their mechanical characteristics, there is an incentive to plant in reforestation areas (Almeida et al., 2018).

The physical and mechanical properties of woods should be known to be used in construction. In Brazil, the project of wooden structures, as well as the methods and premises for obtaining physical and mechanical properties, are regulated by the Brazilian standard ABNT NBR 7190 (1997), named as "Project of Wooden Structures."

For dynamic and/or cyclical stresses, such as structures of bridges, silos, and others, in which the effect of mechanical fatigue is appreciable, the Brazilian standard does not present information regarding the variation of strength and stiffness properties of the wood due to fatigue cycles, which motivates the development of research on this subject.

In Brazil, the only study found that deals with fatigue in solid wood, which is also the objective of this research, is that of Guimarães et al. (2012), who evaluated the effect of the cyclic loading on mechanical properties obtained from the static bending test (strength and stiffness) of 4 forest wood species: *Dipteryx odorata*, *Pouteria guianensis*, *Cedrelinga catenaeformis*, and *Tectona grandis*. The specimens were subjected to 40,000 and 100,000 fatigue cycles, an oscillation frequency of 0.4 Hz, and strength equal to 40% of the rupture strength in the static bending test.

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According to Guimarães et al. (2012), the mean values of the modulus of resistance and modulus of elasticity in static bending were statistically equivalent between cycles, except for *C. catenaeformis*, which showed a significant reduction in these mechanical properties due to an increase in the number of cycles, thus showing variation of mechanical performance according to the evaluated wood species.

In other countries, much of the research involving fatigue is related to the analysis of glued laminated wood structures (with and without structural reinforcement), engineered products based on wood and joints (wood and mixed structures), as the studies by Hacker & Ansell (2001), Thompson et al. (2002), Dai & Hahn (2004), Myslicki et al., (2015), and Tannert et al. (2017).

To collaborate with useful information for the project of wooden structures in Brazil, which can be incorporated together with the results of correlated national surveys in new versions of the Brazilian standard ABNT NBR 7190, this study aimed to evaluate the effect of the number of fatigue cycles (0 – reference, 450, 4500, 45000, and 90000) for frequencies of oscillation equal to 0.5 and 1.0 Hz on the mechanical properties modulus of elasticity and operating stress in the static bending of *Pinus caribaea* wood.

MATERIAL AND METHODS

Woods of *Pinus caribaea* were properly stored at the facilities of the Laboratory of Woods and Wood Structures (LaMEM) of the São Carlos Engineering School (EESC) of the University of São Paulo (USP), with a moisture content close to 12%, which consists of the equilibrium moisture established by the Brazilian standard ABNT NBR 7190 (1997).

Twenty-seven specimens (SPEC) were made with a cross-section of 20 × 20mm and a length of 300 mm to perform static bending and fatigue tests, aiming at obtaining the values of the modulus of elasticity (E_m) and operating stress (σ_m) in the static bending. The small sample size is due to the limitation in the arrangement of the fatigue machine supports (Figure 1b).

The modulus of elasticity (E_m) (Equation 1) and operating stress (σ_m) in the bending (Equation 2) were determined according to the premises of the Brazilian standard ABNT NBR 7190 (1997). However, the tests were adapted to the non-destructive condition (Christoforo et al., 2017) because the limitation of the maximum displacement in the middle of the span of the bending test (Figure 1a) respect the L/200 ratio, in which L is the distance between supports, giving physical and geometric linearity. The maximum displacements in the fatigue test were limited to the L/300 ratio, and the linkages of samples at the ends restrict translation and turning movements (support of the 3rd genus).

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

$$\sigma_m = \frac{3}{2} \cdot \frac{F \cdot L}{b \cdot h^2} \quad (2)$$

From eqs (1) and (2), F is the value of strength obtained from the bending test with the displacement level L/200, δ is the displacement (L/200), L is the useful length of the sample (distance between supports), and b and h are the base and height of the cross-section, respectively. As these are small displacements, as in the case of verifying the limit state of use in projects of wooden structures, the bending stress calculated here is not the last one (flexural strength, f_m), but the operating (σ_m).

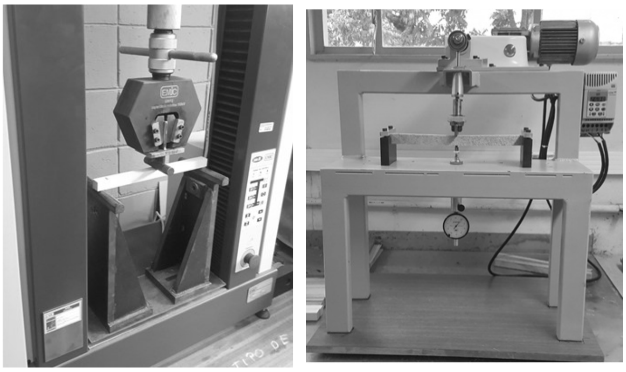

(a) (b)

FIGURE 1. Static bending (a) and fatigue test (b).

Frequencies of oscillation defined in the fatigue machine were 0.5 and 1.0 Hz, both higher than the frequency of 0.4 Hz used by Guimarães et al. (2012). The number of fatigue cycles was 0 (reference), 450, 4500, 45000, and 90000. These values are lower than the maximum number of cycles (100000) of the study developed by Guimarães et al. (2012). However, the highest frequency of oscillation in the present study is at least twice as high as the frequency used by Guimarães et al. (2012), which supported the use of a low number of cycles.

Samples were extracted in pairs and triplicates for each frequency and number of cycles, thus eliminating the intrinsic variability of the wood that could affect the statistical analysis of results.

The specimens were evaluated in the static bending and fatigue tests with faces in the same positions, thus avoiding the effects of wood anisotropy that could interfere with the analysis of results (Icimoto et al., 2013; Icimoto et al., 2015).

The 27 specimens were initially tested for the static bending (reference) in order to determine the modulus of elasticity and operating stress in the static bending in non-fatigued *Pinus caribaea* woods. Subsequently, for each combination (treatment) of frequency and number of cycles (Table 1), three specimens were tested in fatigue (Figure 1b). After the respective fatigue cycle, these three specimens were conducted to the testing machine (Figure 1a) to determine the modulus of elasticity and the operating stress in the bending. The approximate total time of exposure of *Pinus caribaea* woods to fatigue was 350 hours.

TABLE 1. Idealized experimental treatments.

Treatment	Frequency (Fr)	Number of cycles (Nc)
Ref	0	0
1	0.5 Hz	450
2	0.5 Hz	4500
3	0.5 Hz	45000
4	05 Hz	90000
5	1.0 Hz	450
6	1.0 Hz	4500
7	1.0 Hz	45000
8	1.0 Hz	90000

The analysis of variance (ANOVA) was carried out using the software Minitab® version 18 and used to investigate the influence of the number of cycles on mechanical properties. ANOVA was considered at the 5% significance level (α), and the null hypothesis (H_0) was the equivalence of means of treatments, and the alternative hypothesis (H_1) was the non-equivalence (of at least one). According to the ANOVA formulation, a P-value (probability P) lower than the significance level (0.05) implies rejecting H_0 (at least one mean differs from the others), accepting it otherwise (equivalent means).

The Anderson-Darling and Bartlett normality tests for homogeneity of variances (at the 5% significance level) were used to validate ANOVA. Considering the formulation of tests, P-values higher than or equal to the significance level imply accepting the normality and homogeneity of variances, which validates ANOVA models.

The Tukey multiple comparison test (contrast of means) was used to group levels of the factor (number of cycles for each frequency value) was used when the ANOVA test was considered significant. In the Tukey test, A denotes the level of the factor with the highest mean value of the studied property, B is the second-highest mean value, and so on, and the same letters imply treatments with statistically similar means.

After understanding the influence of fatigue cycles for each frequency evaluated by the Tukey test, two-parameter regression models (Table 2) were evaluated to establish a relationship between variables [E_m = f(Nc), σ_m = f (Nc)], allowing estimating the mechanical properties for fatigue cycles intermediate to those stipulated in this research.

TABLE 2. Regression models used to estimate mechanical properties.

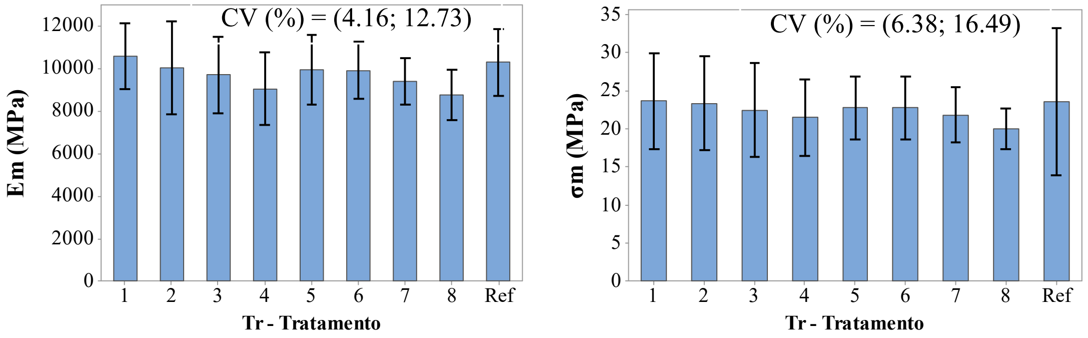
Adjustment type	Model
Linear polynomial (Lin)	$Y = a + b \cdot Nc$
Exponential (Exp)	$Y = a \cdot e^{b \cdot Nc}$
Logarithmic [Log]	$Y = a + b \cdot Ln(Nc)$
Geometric [Geo]	$Y = a \cdot Nc^{b}$

According to Table 2, Nc (number of cycles) is the independent variable, Y is the dependent variable (E_m or σ_m), and a and b are constants (parameters) of functions adjusted by the least-squares method. In the ANOVA of the regression models, also evaluated at the 5% significance level, the stipulated null hypothesis consisted of the non-representativeness of the tested models (H_0: β=0) and the representativeness as an alternative hypothesis (H_1: β≠0). P-value higher than or equal to the considered significance level implies accepting H_0 (the tested model is non-representative; variations of Nc are unable to explain variations in Y), refuting it otherwise (the tested model is representative).

In addition to the use of ANOVA, which allows accepting or not the representativeness of the tested models, the values of the adjusted coefficient of determination ($R^2_{adj.}$) were obtained as a way of choosing, among the models considered significant, the best fit by relationship.

RESULTS AND DISCUSSION

Figure 2 shows the mean values, confidence intervals of the mean (at the 5% significance level), and outliers of the coefficient of variation (CV) of each stipulated experimental treatment.



(a) (b)

Tr	Fr	Nc	Tr	Fr	Nc
Ref	0	0	5	1.0 Hz	450
1	0.5 Hz	450	6	1.0 Hz	4500
2	0.5 Hz	4500	7	1.0 Hz	45000
3	0.5 Hz	45000	8	1.0 Hz	90000
4	0.5 Hz	90000			

FIGURE 2. Results of the mechanical properties evaluated according to the stipulated experimental treatments.

Figure 2 shows a reduction in E_m and σ_m values with a progressive increase in the number of fatigue cycles.

The mean values of the modulus of elasticity in the static bending obtained for *Pinus caribaea* wood by Moura et al., (2012) (9623 MPa), Amorim et al., (2013) (10084.54 MPa), and Morales et al. (2014) (10000 MPa) are within the confidence interval of the reference condition (Figure 2a) of the present study, showing a similarity in the results.

The coefficients of variation obtained for the operating stress in the bending are in accordance with the coefficient of variation (18% for normal stresses and 28% for tangential stresses) established by the Brazilian standard ABNT NBR 7190 (1997) for resistance properties.

The ANOVA P-values for the analysis of the influence of the number of cycles (Nc) and frequency (Fr) on the evaluated mechanical properties (E_m and σ_m) varied from 0.000 to 0.013, showing a significant difference between the means of properties for both investigated factors (P-value<0.05). Table 3 shows the results of the Tukey test.

TABLE 3. Results of the Tukey test (5% significance) – E_m (MPa) and σ_m (MPa).

Prop.	**Fr (Hz)**			**Nc**				
	0	**0.5**	**1.0**	**0**	**450**	**4500**	**45000**	**90000**
$\mathbf{E_m}$	(10291) A	(9844) A	(9511) B	(10291) A	(10258) A	(9983) A	(9558) AB	(8911) B
$\boldsymbol{\sigma_m}$	(23.58) A	(22.73) A	(21.81) B	(23.58) A	(23.20) A	(23.04) A	(22.13) A	(20.71) B

Means are shown in parentheses.

The P-values of normality and homogeneity tests of variances of the investigated properties were higher than 5% (0.096; 0.522), which validates the results of ANOVA models.

Table 3 shows that an increase in frequency from 0.5 to 1.0 Hz resulted in a reduction in both mechanical properties, with a value of 7.6% for modulus of elasticity and 7.5% for the operating stress in the static bending in relation to the reference condition.

Regarding the factor number of cycles, no significant difference was observed between means of E_m and σ_m for 0, 450, and 4500 fatigue cycles. However, the modulus of elasticity had reductions from 45,000 cycles, and 45,000 or 90,000 cycles resulted in statistically equivalent mean values. The reduction in the modulus of elasticity of 90,000 fatigue cycles for the reference condition was 13.4%.

Only 90,000 fatigue cycles provided significant reductions (12.2% in relation to the reference) in the operating stress in the bending, a behavior equivalent to that found by Guimarães et al. (2012) for *Cedrelinga catenaeformis* wood.

Table 4 shows the best adjustments of the regression models according to the number of cycles per frequency and for each evaluated mechanical property.

TABLE 4. Results of the regression models.

Fr	**Model**	$\mathbf{R^2_{adj}}$	**P-value**
0,5 Hz	$E_m(MPa) = 10332.29 - 0.0142 \cdot Nc$	89.61%	0.001
	$\sigma_m(MPa) = 23.56 - 0.000024 \cdot Nc$	91.34%	0.000
1,0 Hz	$E_m(MPa) = 10076.77 - 0.0146 \cdot Nc$	93.08%	0.005
	$\sigma_m(MPa) = 23.11 - 0.000037 \cdot Nc$	92.11%	0.003

Table 4 shows that both models were significant by ANOVA (P-value<0.05), evidencing the effective relationship between mechanical properties and the number of cycles. For all cases, the linear model provided the best results, being highlighted the good precision of adjustments obtained by the adjusted coefficient of determination, which was higher than or equal to 89.16%, implying an error of up to 11% in the estimation of the evaluated mechanical properties.

CONCLUSIONS

The results of this research made it possible to conclude that:

- both mechanical properties were significantly influenced by the number of fatigue cycles and the frequency of oscillation.

- both properties and frequencies of oscillation (0.5 and 1.0 Hz) showed a reduction in the mean values after 45000 cycles, with the highest reduction associated with 90,000 fatigue cycles.

- the factor number of cycles proved to be more impacting (minimum reduction of 12.2%) than frequency (minimum reduction of 7.5%) due to the reductions provided in the modulus of elasticity and operating stress in the static bending.

These results corroborate with the execution of a safer structural project. However, more comprehensive models require the use of different wood species, which should be the focus of future studies.

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