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Evaluation of representativeness of elasticity modulus and apparent density of D20 strength class of Brazilian standard in timber structures design

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ABSTRACT. The Brazilian code ABNT NBR 7190-1 (2022) presents different strength classes for hardwood and displays representative values for apparent density, compressive strength parallel to the grain and modulus of elasticity in parallel direction of fibers to help designers for an appropriate timber structure design. This research evaluated to check if the representative value of modulus of elasticity in parallel direction of fibers and apparent density of D20 strength class (native wood species) still represent a secure value for designers. Also, it was checked the possibility to estimate compressive strength parallel to the grain and modulus of elasticity in parallel direction of fibers as function of apparent density using regression models, aided by the analysis of variance. The results showed that the representative value of modulus of elasticity in parallel direction of fibers and apparent density for D20 is close to the obtained in the present research. The analysis of variance indicated the impossibility to estimate strength and stiffness properties as function of apparent density.

Keywords: wood; hardwood; strength classes; stiffness; apparent density.

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Introduction

Wood is a material used since ancient times for several purposes, such shelters, food storage and agricultural equipment. In present times, wood has a great presence on civil construction, paper and pulp, sports equipment and furniture. In order to use a natural material, it is important to know wood properties (physical, chemical, anatomical and mechanical) (Aquino, Panzera, Magalhães, Christoforo, & Lahr, 2018; Bravo et al., 2020; Cheung, Scaliante, Lindquist, Christoforo, Calil Junior, 2017; Christoforo, Couto, Almeida, Aquino, & Lahr, 2020; Komariah, Hadi, Massijaya, & Suryana, 2015; Machado et al., 2014; Rescalvo, Valverde-Palacios, Suarez, & Gallego, 2018).

Brazil is the country with largest tree flora in the world, with 8715 wood species, with 4333 wood species being endemic to the country (Beech, Rivers, Oldfield, & Smith, 2017). Also, Brazil has large vegetal cover, being 58% of its territory (493,5 million hectares). It demonstrates the importance and the possibility to use wood on civil construction and the demand for characterization of new wood species for a properly utilization of natural material (Beech et al., 2017; Christoforo et al., 2017; Dewey et al., 2018; Dias & Lahr, 2004; Nadir, Nagarajan, Ameen, & Arif, 2016; Steege et al., 2020).

In order to considerate inherent variability of a natural material, wood characterization is performed taking into account the action performed on wood (tension, compression and shear), direction in relation to the grain (parallel or perpendicular) and moisture content (Adamopoulos & Passialis, 2010; Araújo, 2007; Komariah et al., 2015; Machado et al., 2014; Ruiz-Aquino, González-Peña, Valdez-Hernández, Romero-Manzanares, & Fuentes-Salinas, 2018).

In Brazil, the design of wood structures and the prescriptions for wood characterization is disposed on Brazilian Standard ABNT NBR 7190-1 (Associação Brasileira de Nortmas Técnicas [ABNT], 2022a), which also prescribes the strength classes for native wood species, which is based on characteristic value of compressive strength parallel to the grain ($f_{c0,k}$). There are five strength classes: D20 ($20 < f_{c0,k} \leq 30$ MPa), D30 ($30 < f_{c0,k} \leq 40$ MPa), D40 ($40 < f_{c0,k} \leq 50$ MPa), D50 ($50 < f_{c0,k} \leq 60$ MPa), and D60 ($f_{c0,k} > 60$ MPa). The standard also establishes mean values for modulus of elasticity on parallel direction of grain ($E_{c0,m}$) and apparent density for each strength class, as disposed on Table 1.

Table 1. Strength classes for hardwoods.

Classes	$f_{c0,k}$ (MPa)	$E_{c0,m}$ (MPa)	$\rho_{12\%}$ (kg m^{-3})
D20	20	10000	500
D30	30	12000	625
D40	40	14500	750
D50	50	16500	850
D60	60	19500	1000

Aiming to contribute to further standard review, use of reliable data on timber design and present values of modulus of elasticity on parallel direction of grain for eleven hardwood species for strength class D20, the present research investigated if the reference value of 10000 MPa proposed by the normative text is representative for the D20 strength class, considering the mean confidence interval (CI) (at 5% significance level) and the resampling technique bootstrap for simulation of mean confidence interval (100 to 1000000 simulations). For apparent density, the same technique was used, with same mean confidence interval and mean confidence interval. It was checked the possibility to estimate compressive strength parallel to the grain (f_{c0}) and modulus of elasticity in parallel direction of grain (E_{c0}) in function of apparent density using regression models.

Material and methods

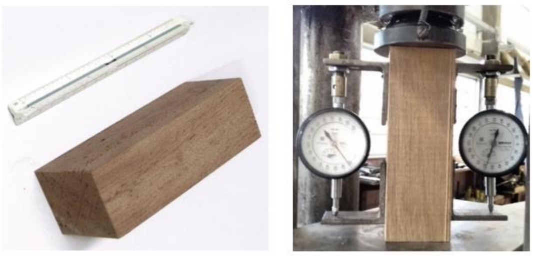
The eleven hardwood species from native forests listed in Table 2 were used to verify the representativeness of the reference value of 10000 MPa for the modulus of elasticity (E_{c0}) in the parallel compression to fibers for class D20 wood proposed by the Brazilian standard ABNT NBR 7190-1 (ABNT, 2022a).

Table 2. Names of tropical native hardwoods evaluated.

Popular Name	Scientific Name
Amescla	*Trattinnickia burserifolia*
Caixeta	*Simarouba amara*
Cajueiro	*Anacardium occidentale*
Cambará	*Erisma sp.*
Cambará Rosa	*Erisma uncinatum*
Cedro Doce	*Cedrella sp.*
Cedro	*Cedrella odorata*
Cedroarana	*Cedrelinga catenaeformis*
Marupá	*Simarouba sp.*
Tamanqueira	*Simarouba sp.*
Quarubarana	*Erisma uncinatum*

The wood from homogeneous batches was properly stored, resulting in a moisture content close to 12%, as recommended by the Brazilian standard ABNT NBR 7190-1 (ABNT, 2022a) and ABNT NBR 7190-3 (Associação Brasileira de Nortmas Técnicas [ABNT], 2022b). The assumptions and test methods of the Brazilian standard were followed to obtain the values of strength (fc0) and stiffness (Ec0) to compression in the direction parallel to the fibers as well as the values of apparent density (ρ12%).

Also as recommended by the Brazilian standard (ABNT, 2022b) (minimum characterization), twelve specimens per species were manufactured and tested in parallel compression (Figure 1) as well as twelve others for determining apparent density values, resulting in 756 experimental determinations in all.



(a) (b)

Figure 1. Standardized specimen illustration (5 × 5 × 15 cm) (ABNT, 2022b) (a) and the apparatus used to perform the compression tests in the direction parallel to the fibers (b).

When the specimens were broken in the universal testing machine (AMSLER - load capacity of 25 tons), their moisture content (U) at the time of the tests was obtained using the Marrari M5 contact humidity meter ($10.76 \leq U \leq 12.96\%$). With the moisture content in the specimens, the values of strength (f_{c0}) and elasticity modulus (E_{c0}) to compression in the direction parallel to the fibers were corrected to the moisture content of 12% ($f_{c0,12}$; $E_{c0,12}$) with the aid of Equations 1 and 2 (ABNT, 2022a), respectively, in which f_{c0}, U and E_{c0}, U consist of the specimens strength and stiffness associated with the moisture content U.

$$E_{c0,12} = E_{c0,U} \cdot \left[1 + \frac{2 \cdot (U - 12)}{100}\right] \tag{1}$$

$$f_{c0,12} = f_{c0,U} \cdot \left[1 + \frac{2 \cdot (U - 12)}{100}\right] \tag{2}$$

Based on the corrected values of compressive strength in the direction parallel to the fibers ($f_{c0,12}$), Equation 3 (ABNT, 2022b) was used to determine the characteristic value ($f_{c0,k}$) for the wood categorization (Tab. 1), where f_1, f_2 to f_n denote the compressive strength values ($f_{c\,0.12}$) in ascending order of the n test specimens tested (n = 12 per species of wood evaluated).

$$f_{c0,k} = Max \begin{cases} f_1 \\ 0.7 \cdot \frac{\sum_{i=1}^{n} f_i}{n} \\ 1.1 \cdot \left[2 \cdot \left(f_1 + f_2 + f_3 + \cdots + +f_{(n/2)-1}\right)\right] \end{cases} \tag{3}$$

The mean confidence interval (variation inference in the population mean value based on the sample), at the 95% reliability level, was used to calculate the mean value as well as the lower (2.5%) and upper (97.5%), and the Shapiro-Wilk test (5% significance) was used to assess the normal distribution of E_{c0} values considering the set of 21 wood species. For the assumptions assumed in the normality test, p-value (probability p) equal to or greater than the level of significance implies normality in the E_{c0} distribution, which validates the results obtained from the confidence interval.

In order to increase the results reliability, the Bootstrap resampling technique was used to simulate the average confidence intervals (95% reliability), with 100 to 1000000 simulations being considered.

Regression models (Equations 4-7) based on analysis of variance (ANOVA) were used to estimate the strength and stiffness properties as a function of the apparent density of the wood and the stiffness as a function of strength, with Y being the estimated property (variable dependent), X the independent variable and b and the parameters adjusted by the Least squares method:

$$Y = a + b \cdot X \text{ [Lin - linear]} \tag{4}$$

$$Y = a \cdot e^b \text{ [Exp - exponential]} \tag{5}$$

$$Y = a + b \cdot Ln(X) \text{ [Log - logarithmic]} \tag{6}$$

$$Y = a \cdot X^b \text{ [Geo - geometric]} \tag{7}$$

By the ANOVA of the regression models, it is considered at the level of 5% of significance (α), the null hypothesis formulated consisted of the non-representativeness of the tested models (H_0: $\beta = 0$) and in the representativeness as an alternative hypothesis. P-value higher than the significance level implies the acceptance of H_0 (the model is not representative - the variations of the independent variable are not able to explain the variations in the estimated properties), refuting it otherwise (the tested model is representative). The determination coefficient (R^2) was used to assess the quality of the adjustments obtained, making it possible to choose the best precision for each evaluated relationship.

Results and discussion

Table 3 shows the average values of apparent density ($\rho_{12\%}$), strength (f_{c0}) and stiffness (E_{c0}) to compression in the direction parallel to the fibers, as well as the characteristic value ($f_{c0,k}$ - Equation 3) of the referred strength property.

Table 3. Physical and mechanical properties results.

Wood Specie	$\rho_{12\%}$ (kg m^{-3})	f_{c0} (MPa)	$f_{c0,k}$ (MPa)	E_{c0} (MPa)
Amescla	425	25	21	10427
Caixeta	334	37	28	8270
Cajueiro	551	40	28	11178
Cambará	545	39	27	7956
Cambará Rosa	580	34	27	11967
Cedro Doce	505	31	27	9354
Cedro	479	37	29	9632
Cedroarana	571	40	28	10394
Marupá	402	35	27	9247
Tamanqueira	394	34	25	8968
Quarubarana	538	38	27	9067

The values of coefficient of variation (CV) for apparent density ($\rho_{12\%}$), compressive strength parallel to the fibers (f_{c0}) and modulus of elasticity on parallel direction of grain (E_{c0}) ranged between 3.25 and 7.40%, 13.38 and 17.34%, 15.36 and 20.12%, respectively. It is important highlight that CV values for f_{c0} were lower than the preconized by Brazilian Standard ABNT NBR 7190-3 (ABNT, 2022b), that establishes a maximum CV value of 18% on normal efforts for wood characterization to be considered adequate, i.e., to have statistical significance without further analysis.

Observing the results disposed on Table 3, the values of $\rho_{12\%}$, f_{c0} and E_{c0} were similar to the reached on other researches on the literature (ABNT, 1997; Aquino et al., 2018; Dias & Lahr, 2004; Lahr et al., 2016). It is important observe the maximum value of E_{c0} is 11178 MPa, 18% higher than predicted on Brazilian Standard (ABNT, 2022a) and the lowest value is 7956 MPa, 16% below the representative value of D20 strength class disposed on normative code.

The Shapiro-Wilk normality test was performed and the p-value reached was 0.3340, above the significance level (0.05), illustrating the normality on density values. On Table 4 is presented the mean confidence intervals (95% reliability) obtained considering the 11 species (t test) as well as the confidence intervals extrapolated by the Bootstrap technique.

Observing the information on Table 4, it is possible to check a convergence on lateral values and mean value above 10000 simulations with Bootstrap technique and the value 484 kg m^{-3} is the representative value of D20 strength class for Brazilian Standard ABNT NBR 7190-1 (ABNT, 2022a), 3% lower than the value disposed on the referred normative code (500 kg m^{-3}), indicating a representative values of strength classes on standard.

Considering the demand for review on representative values, it is possible that the modulus of elasticity on parallel direction of fibers (E_{c0}) may be overestimated. The Shapiro-Wilk normality test was performed on E_{c0} values and it was checked the normality on the values set, with p-value of 0.7579, above the significance value (0.05).

For the values disposed on Table 5, it is possible to observe the convergence on lateral values and mean value from 50000 simulation to 1000000 simulations on Bootstrap technique, with a mean value of 9678 MPa, with this value being the representative value of E_{c0}, 3% below the value disposed on the Brazilian code ABNT NBR 7190-1 (ABNT, 2022a). Then, it shows that the Brazilian Standard displays a close value for E_{c0}, with its value between mean value and superior limit.

Table 4. Confidence intervals results of the mean (CI) for the apparent density (kg m^{-3}).

Methods	CI (95% reliability)		
	Inferior Limit	Mean	Superior Limit
T test	428	484	540
Bootstrap - 100 simulations	434	483	524
Bootstrap - 500 simulations	435	482	521
Bootstrap - 1000 simulations	432	482	521
Bootstrap - 5000 simulations	438	484	522
Bootstrap - 10000 simulations	435	483	521
Bootstrap - 50000 simulations	435	483	522
Bootstrap - 100000 simulations	435	484	522
Bootstrap - 500000 simulations	435	484	522
Bootstrap – 1000000 simulations	436	484	522

Table 5. Confidence intervals results of the mean (CI) for the modulus of elasticity in parallel direction of grain (E_{c0}) (MPa).

Methods	CI (95% reliability)		
	Inferior Limit	Mean	Superior Limit
T test	8864	9678	10492
Bootstrap - 100 simulations	9052	9682	10269
Bootstrap - 500 simulations	9011	9686	10292
Bootstrap - 1000 simulations	9010	9668	10283
Bootstrap - 5000 simulations	9013	9686	10258
Bootstrap - 10000 simulations	9017	9672	10264
Bootstrap - 50000 simulations	9017	9676	10267
Bootstrap - 100000 simulations	9018	9679	10268
Bootstrap - 500000 simulations	9021	9678	10264
Bootstrap - 1000000 de simulations	9020	9678	10263

Table 6 presents the best adjustments obtained using regression models for the apparent density in the estimation of f_{c0} and E_{c0}, underlining the models considered significant by ANOVA (5% significance).

Table 6. Regression models based on apparent density as an estimator of compressive strength parallel to the grain and modulus of elasticity in parallel direction of fibers.

Property	Regression model (ANOVA)	P-value	a	b	R^2 (%)
f_{c0}	Linear	0.2649	28.90	0.02	13.57
E_{c0}	Linear	0.1170	6151	7.28	25.03

Observing the values of coefficient of determination (R^2), it is possible to infer that apparent density is not a good estimator of compressive strength parallel to the grain and modulus of elasticity in parallel direction of fibers, with values below 70%, indicating a bad quality on the adjustment. Also, the p-values were above 0.05, and by the analysis of variance (ANOVA), the models were not significant (5% significance level) (Montgomery, 2012).

Conclusion

With the information obtained in the present study, it is possible to conclude:

The representative value of modulus of elasticity in parallel direction of fibers displayed on the Brazilian Standard for D20 strength class is close to the obtained in this research;

Considering the ANOVA and coefficient of determination, the apparent density is not a good estimator of compressive strength parallel to the grain and modulus of elasticity in parallel direction of fibers, being unable to perform such estimations;

The representative value of apparent density for D20 strength class demand review on the Brazilian Standard, being close to the value obtained in this research (3% difference), indicating good accuracy between standardized value and this research value;

The values obtained on this research enhances timber structural design and helps designer to develop safer structures and guarantee a good performance of such structures along their lifespan.

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