Influence of Specimen Dimensions in the Determination of Strength and Modulus of Elasticity in Static Bending of Hardwoods

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In Brazil, standard ABNT NBR 7190 (1997) prescribes the determination of strength (f_M) and modulus of elasticity (E_M) in static bending from specimens measuring 5 cm × 5 cm × 115 cm. Thus, the relationship between the test span (L) and the specimen height (h) greater than or equal to 21 ($L/h \geq 21$) is respected, ensuring that the effect of shear in the calculation of displacements is negligible (Euler Bernoulli Theory). Considering the expressive number of tree species cataloged in the Brazilian Amazon Forest, any procedure that aims to facilitate the realization of experimental tests is highly desirable because it provides the knowledge of unusual species. These wood species may potentially replace woods that have been traditionally used and historically exploited. Using five hardwood species, this research aimed to verify, while maintaining constant $L/h \geq 21$ ratios, the influence of specimens dimensions in the determination of f_M and E_M. For all species studied, the statistical analysis found equivalence in the values of f_M and E_M determined as a function of the sample sizes. Therefore, respecting the ratio $L/h \geq 21$, the size of the specimens does not influence the determination of strength and stiffness in static bending.

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INTRODUCTION

Countries such as Japan, Scotland, and New Zealand have 45%, 83%, and 85% of the houses made of wood, respectively (Mahapatra *et al*. 2012; De Araujo *et al*. 2018). In Brazil, despite having an area of native forest cover of 60.7% of the national territory, the application of wood for residential use is still insignificant compared to the potential it represents (Vidal *et al*. 2015).

Among the factors contributing to this are historical-cultural issues, shortage of skilled labor, and lack of knowledge of the species and their properties. This issue motivates the development of research that disseminates, mainly, consumer market information regarding the benefits of wooden buildings, the material's physical-mechanical properties, and the methods for obtaining such properties.

In Brazil, the normative document ABNT NBR 7190 (1997) establishes the methods for dimensioning wood structures and the methods for determining the physical-mechanical properties of the material.

Among these properties, the determination of the strength (f_M) and the modulus of elasticity (E_M) in static bending are important for the rational design of wood structures projects, mainly due to the several structural elements subjected to bending such as beams and covering purlins. According to ABNT NBR 7190 (1997), to obtain f_M and E_M, the specimens must have dimensions of 5 cm × 5 cm × 115 cm, respecting the relationship between the bending test span (L) and the cross-section height (h) greater than or equal to 21. This relationship guarantees that the shear forces present in the static bending test can be neglected, validating the calculation model (Euler Bernoulli's beam theory) used by ABNT NBR 7190 (1997) and other normative documents in determining the properties of strength and stiffness in static bending. If the specimen is short, with a ratio L/h less than 21, the shear forces become significant in determining the displacements that lead to the calculation of E_M and G (transverse elasticity modulus).

Reducing the dimensions of the static bending test specimens prescribed by ABNT NBR 7190 (1997) implies a reduction in material consumption and the use of smaller equipment. It facilitates the performance of experimental tests that currently, in Brazil, are concentrated in a few laboratories with expensive equipment.

Thus, any procedure that aims to facilitate the performance of experimental tests is highly desirable, since there is a high number of tree species cataloged in the Brazilian Amazon Forest [7696 - according to Steege *et al*. (2016)]. The mechanical properties of many of these wood species are unknown and may have an equivalent or superior potential to wood for conventional use in civil construction.

In order to support future revisions of ABNT NBR 7190 (1997), this research aimed to determine, for hardwoods, whether there is statistical equivalence in the values of f_M and E_M determined from specimens of different dimensions but with the same L/h ratio.

EXPERIMENTAL

Materials

Batches of wood from Caixeta (*Simarouba amara* Aubl.), Cajueiro (*Anacardium* sp.), Garapa (*Apuleia leiocarpa*), and Maçaranduba (*Manilkara* sp.) were acquired in the local market in the form of planks, in a similar way as the woods are obtained for Brazilian civil construction. Thus, it was not possible to identify the origin and age of the trees. Such species are commonly used as single pieces (solid wood) in structural elements.

Methods

The values of apparent density at 12% moisture ($\rho_{ap,12\%}$) and the characteristic strength in compression parallel to grain ($f_{c0,k}$) of the studied woods were determined following the requirements of ABNT NBR 7190 (1997).

The values of conventional strength in the static bending test (f_M) and conventional modulus of elasticity in bending (E_M) were obtained following the recommendations of ABNT NBR 7190 (1997). For this purpose, specimens of square cross-section were made with dimensions: 2 cm × 2 cm × 46 cm, 3 cm × 3 cm × 69 cm, 4 cm × 4 cm × 92 cm and 5 cm × 5 cm × 115 cm [dimension recommended by ABNT NBR 7190 (1997)]. The ratio between the length and height of the specimen's cross-section was kept constant at 23, respecting the ratio $L/h \geq 21$, recommended by ABNT NBR 7190 (1997) for the static bending test. Three-point bending tests were performed with load applied at mid-span, this test configuration was maintained for all tested specimens.

Twelve specimens were adopted for each species studied to obtain $\rho_{ap,12\%}$ and $f_{c0,k}$. Equipment such as a band saw and a circular bench saw were used to make the specimens. Following the requirements of ABNT NBR 7190 (1997), the samples were free of defects (knots, cracks, warping, *etc*.). Likewise, for the determination of f_M, 12 specimens were used for each species and sample size. Considering all the tests, a total of 288 experimental determinations were obtained.

The influence of specimen measurements on f_M and E_M values was evaluated by Tukey's multiple comparisons test, evaluated at a 5% significance level and with the help of Minitab® software version 18 (State College, PA, USA).

To validate the results of the Tukey test, the normality (Anderson-Darling) and the equality of variances (multiple comparisons) of the residuals were tested; both tests were also evaluated at a 5% significance level. Based on the test formulation, a p-value (p probability) greater than or equal to the 5% significance level implies normality and homogeneity of variances, thus validating the results of Tukey's test.

From Tukey's test, the letter 'a' denotes the group or treatment related to the highest mean value, the letter 'b' related to the group associated with the second highest mean value, and so on, and equal letters imply in treatments with statistically equivalent means between them.

RESULTS AND DISCUSSION

Table 1 shows the mean values, and the respective coefficients of variation (C_v) of the apparent density ($\rho_{ap,12\%}$) and the compressive strength parallel to grain (f_{c0}), as well as the characteristic value of the compressive strength parallel to grain ($f_{c0,k}$), of the four wood species evaluated.

Table 1. Result of Apparent Density at 12% Moisture Content and Compressive Strength Parallel to grain

Species	$\rho_{ap,12\%}$ (g/cm^3)	C_v (%)	f_{c0} (MPa)	C_v (%)	$f_{c0,k}$ (MPa)
Caxeta	0.31	2.67	35.42	12.65	28.80
Cajueiro	0.51	5.89	37.48	10.69	33.32
Garapa	0.89	5.94	68.41	12.31	58.56
Maçaranduba	1.10	6.98	80.02	7.45	76.68

The woods of Caxeta, Cajueiro, Garapa and Maçaranduba were categorized, respectively, into the resistance classes C20 ($f_{c0,k}$ < 30 MPa), C30 (30 MPa $\leq f_{c0,k}$ < 40 MPa), C40 (40 MPa $\leq f_{c0,k}$ < 60 MPa), and C60 ($f_{c0,k} \geq$ 60 MPa). Thus, the adopted species included all resistance classes prescribed by ABNT NBR 7190 (1997) for the hardwood group, evidencing the coverage and relevance of this work.

It is worth noting that the average values of the properties ($\rho_{ap,12\%}$ and f_{c0}), as well as the resistance classes categorized here, are in accordance with those obtained previously by Jesus *et al*. (2015), Dias *et al*. (2019), Duarte *et al*. (2020), and Lahr *et al*. (2021).

Tables 2 and 3 show the mean values of f_M and E_M, the values of the coefficient of variation (*Cv*), as well as the results of the Tukey test (5% significance) of the values of strength and stiffness in static bending for the wood species as a function of the established dimensions of the specimens. Notably, the ratio $L/h \geq 21$ stipulated by ABNT NBR 7190 (1997) was maintained, which guarantees that the effect of shear in the calculation of displacements is negligible.

Table 2. Mean Values of the Strength in the Static Bending Test, Values of the Coefficient of Variation (*Cv*) and Results of the Tukey Test

Dimensions (cm)	Results	Species			
		Caxeta	Cajueiro	Garapa	Maçaranduba
2×2×46	f_M (MPa)	59.33	71.83	96.83	142.83
	Cv (%)	5.61	5.73	10.38	6.94
	Tukey test	a	a	a	a
3×3×69	f_M (MPa)	57.08	71.00	98.50	144.17
	Cv (%)	5.20	11.68	11.64	8.62
	Tukey test	a	a	a	a
4×4×92	f_M (MPa)	59.67	70.50	97.17	142.23
	Cv (%)	4.33	10.76	14.27	8.78
	Tukey test	a	a	a	a
5×5×115	f_M (MPa)	59.12	69.83	96.67	141.67
	Cv (%)	5.87	6.98	9.13	7.74
	Tukey test	a	a	a	a

Table 3. Mean Values of the Modulus of Elasticity in the Static Bending Test, Values of the Coefficient of Variation (*Cv*) and Results of the Tukey Test

Dimensions (cm)	Results	Species			
		Caxeta	Cajueiro	Garapa	Maçaranduba
2×2×46	E_M (MPa)	9051	11272	15392	20693
	Cv (%)	7.42	4.19	3.07	7.18
	Tukey test	a	a	a	a
3×3×69	E_M (MPa)	9090	11136	15513	20633
	Cv (%)	7.84	7.24	5.09	6.70
	Tukey test	a	a	a	a
4×4×92	E_M (MPa)	9084	11081	15499	20774
	Cv (%)	6.63	5.63	3.28	7.45
	Tukey test	a	a	a	a
5×5×115	E_M (MPa)	9046	11185	15604	20659
	Cv (%)	7.81	4.57	4.46	7.12
	Tukey test	a	a	a	a

The p-values of the normality test (Anderson-Darling) and equality of variances (multiple comparisons) for the two properties (Tables 2 and 3) and the four wood species evaluated were both higher than the adopted significance levels (5%), which validates the results obtained from the Tukey test.

From Tables 2 and 3, the letter 'a' denotes that, by Tukey's test, the means of the confronted groups are equivalent to each other. Thus, for all species studied, there were no statistically significant differences in the mean values of f_M and E_M as a function of the dimensions of the specimens. This result shows that keeping the ratio $L/h \geq 21$, the size of the specimens does not influence the determination of such properties.

CONCLUSIONS

1. The Tukey test found statistical equivalence in the f_M and E_M values obtained from the used specimens for all wood species studied. As long as the $L/h \geq 21$ ratio prescribed by ABNT NBR 7190 (1997) is respected, the size of the samples does not influence the determination of such properties.
2. The results obtained are of great importance since the adoption of specimens with smaller dimensions allows the performance of experimental tests in smaller laboratories. It makes it possible to know the properties of ultimate strength and modulus of elasticity in static bending tests of species of non-traditional use by the Brazilian technical community, placing wood at even more competitive levels.

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