

# Analysis of Relations between the Moduli of Elasticity in Compression, Tension, and Static Bending of Hardwoods

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Accurate estimation of average modulus of elasticity in compression parallel to the grain ( $E_{c0}$ ) is of paramount importance for rational sizing of timber structures, given the use of this property in the estimation of stability of compressed parts (ultimate limit state, ULS) and in calculation of excessive strains (serviceability limit state, SLS). In Brazil, if values cannot be experimentally determined, ABNT NBR 7190 (1997) allows for estimation of  $E_{c0}$  through relations to average modulus of elasticity both in tension parallel to the grain ( $E_{t0}$ ) ( $E_{c0} = E_{t0}$ ) and in bending ( $E_M$ ) ( $E_{c0} = E_M/0.90$ ). This research aimed to access the efficiency of these relations by testing 30 tropical wood species. The analysis of variance results showed that  $E_{c0}$  and  $E_{t0}$  were statistically equal. However,  $E_{c0}$  and  $E_M/0.90$  were not statistically equal, and the method of least squares resulted in a coefficient of 0.98, which was 8.89% higher than the one suggested by ABNT NBR 7190 (1997) and close to 1, thus, validating the results of ANOVA, which pointed on the equivalence between  $E_{c0}$  and  $E_M$  ( $E_{c0} = E_M$ ). As an alternative to simplified equations of the standard, two-parameter regression models were used. The geometric model with  $R^2 = 91.67\%$  proved to be the model of best fit, which demonstrated that  $E_{c0}$  could be calculated as a function of  $E_M$ .

*Keywords:* Hardwood; Regression model; Mechanical properties; Timber structure

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## INTRODUCTION

Considered the material of the future (Kuzman and Sandberg 2017; Żmijewki and Wojtowicz-Jankowska 2017), timber is becoming increasingly popular and widely applied in civil construction (Wieruszewski and Mazela 2017). This is not only because wood is a natural, biodegradable, renewable, recyclable and, hence, environmentally friendly raw material (Wang *et al.* 2014; Araujo *et al.* 2016; Lima, Jr. *et al.* 2018; Souza *et al.* 2018), but also due to characteristics that make it an efficient building material compared to traditionally used steel and concrete (Ramage *et al.* 2017).

One such characteristic of wood is its excellent mechanical strength-to-density ratio (Pries and Mai 2013; Ramage *et al.* 2017; Huber *et al.* 2018; Lima, Jr. *et al.* 2018) that favors the use of wood in construction applications where weight of the structure itself

presents a considerable load (*e.g.*, roofs, bridges, and tall buildings) as well as in buildings subjected to seismic loading, given that heavier structures are subjected to higher seismic load (Ramage *et al.* 2017).

Given the effectiveness of wood as a structural element, timber constructions have become the most common, practical, and economical housing solution for most countries in the northern hemisphere (Araujo *et al.* 2016), leading to widespread use of timber in countries such as Austria, Japan, Scotland, and New Zealand, where 40%, 45%, 83%, and 85% of houses are made of wood, respectively (Mahapatra *et al.* 2012; Hurmekoski *et al.* 2015; Araujo *et al.* 2018).

Nevertheless, in Brazil, despite having the largest biodiversity of species on the planet (Beech *et al.* 2017), with evident reforestation potential, and a growing demand for housing, the use of timber for dwelling construction is still low (Araujo *et al.* 2018). This motivates the development of research that disseminates, mainly to the consumer market, information regarding benefits of timber constructions and physical-mechanical properties of wood that are necessary for rational elaboration of structural design.

Among these properties, average value of modulus of elasticity in compression parallel to the grain ( $E_{c0}$ ) is of paramount importance, given its use in checks of stability of compressed parts (buckling) in the ultimate limit state (ULS) and in calculation of excessive strains in compliance with the serviceability limit state (SLS).

In Brazil, Annex B of ABNT NBR 7190 (1997) “Design of wooden structures” provides experimental methods for the determination of physical-mechanical properties of wood. Given that there are 17 physical-mechanical properties that need to be estimated, a complete characterization of species requires an extensive number of tests. The execution of these tests is time-consuming, expensive, and implies expenditure with materials and labor.

Given the many catalogued tree species in the Amazonian region as a whole, and in the Brazilian Amazon specifically (12000 and 7696, respectively, according to Steege *et al.* (2016)), any procedure aimed at reducing the number of tests is greatly desirable.

To simplify the assessment of  $E_{c0}$ , ABNT NBR 7190 (1997) allows estimation of the  $E_{c0}$  value through relation with the average value of modulus of elasticity in tension parallel to the grain ( $E_{t0}$ ) and static three-point bending ( $E_M$ ), as shown in Eqs. 1 and 2, respectively:

$$E_{c0} = E_{t0} \quad (1)$$

$$E_{c0} = E_M / 0.90 \quad (2)$$

Several previous works have sought to determine correlations between wood properties, particularly, with bulk density ( $\rho_{ap}$  - an easily determinable physical property), which proves the academic interest in simplifying the characterization of wood.

Igartúa *et al.* (2015) studied the Argentinian species *Acacia melanoxylon* and found a strong correlation (with coefficient of determination ( $R^2$ ) above 70%) between  $\rho_{ap}$  and parallel and normal to the grain compressive strength, as well as between  $\rho_{ap}$  and modulus of elasticity and conventional bending strength.

Silva *et al.* (2018) used regression models to study whether physical-mechanical properties of *Goupia glabra* Aubl. (popularly called Cupiúba in Brazil) can be estimated as a function of  $\rho_{ap}$ . They obtained regression models with good precision ( $R^2 \approx 70\%$ ) for 15 studied relations. The most significant relation ( $R^2 = 87.96\%$ ) was between  $\rho_{ap}$  and hardness parallel to the grain.

Almeida *et al.* (2017) and Dias *et al.* (2019) studied wood shrinkage estimation as a function of  $\rho_{ap}$  with regression models based on experimental results from 15 and 43 tropical wood species, respectively. In both works, analysis of variance (ANOVA) results demonstrated weak correlation between investigated parameters, showing that  $\rho_{ap}$  is not a reliable estimator for dimensional stability of wood.

In recent years, research has assessed the accuracy of estimated properties obtained through relationships provided by ABNT NBR 7190 (1997) and determined coefficients that best fit the proposed relationships. Matos and Molina (2016) studied correlations between characteristic shear strength ( $f_{v0,k}$ ) and compressive strength parallel to the grain ( $f_{c0,k}$ ) of conifer ( $f_{v0,k} = 0.15 \cdot f_{c0,k}$ ) and dicot ( $f_{v0,k} = 0.12 \cdot f_{c0,k}$ ) woods. The authors evaluated *Pinus elliotti* and *Eucalyptus saligna* species and for conifer woods obtained a relation approximately 95% higher compared to that from ABNT NBR 7190 (1997).

Based on three- and four-point static bending tests, Lahr *et al.* (2017) determined a relation between longitudinal ( $E$ ) and tangential ( $G$ ) modulus of elasticity. From the results obtained of five different tropical wood species tested, the authors determined the relation  $E = 35 \cdot G$ , with the coefficient being 75% higher than the one given by ABNT NBR 7190 (1997) ( $E = 20 \cdot G$ ).

Recently, Christoforo *et al.* (2019) studied relations between characteristic compression strength ( $f_{c0,k}$ ), characteristic tensile strength parallel to the grain ( $f_{t0,k}$ ), and characteristic shear strength ( $f_{v0,k}$ ). The coefficients ( $\alpha$ ) they obtained after testing five tropical wood species were 0.96 and 0.23 for relations  $f_{c0,k} = \alpha \cdot f_{t0,k}$  and  $f_{v0,k} = \alpha \cdot f_{c0,k}$ , respectively, which were 25% and 92% higher than the coefficients specified by ABNT NBR 7190 (1997).

These studies demonstrate that some relations between properties of wood prescribed by ABNT NBR 7190 (1997) need to be revised to obtain reliable estimates for structural design. Thus, the aim of this work was to investigate statistical equivalence between modulus of elasticity obtained in bending, compression, and tension parallel to the grain (Eq. 1 and Eq. 2) and, in case equivalence is not confirmed, to define correlations between these properties that would give more accurate  $E_{c0}$  estimates.

## EXPERIMENTAL

### Materials

Thirty different wood species were used in this study (Table 1), and these were obtained, from local companies, in the same manner as timber used in Brazilian civil construction, in the form of boards sized approximately 6 cm  $\times$  11 cm  $\times$  200 cm. Therefore, it was not possible to identify origin and age for the trees.

The wood was properly stocked and tested in three different research labs in the country: the Laboratory of Wood and Timber Structure (LaMEM) of the University of São Paulo (USP); the laboratories of Federal University of Minas Gerais (UFMG), campus Belo Horizonte (State of Minas Gerais); and at the laboratories of São Paulo State University (UNESP), campus Itapeva (State of São Paulo).

### Methods

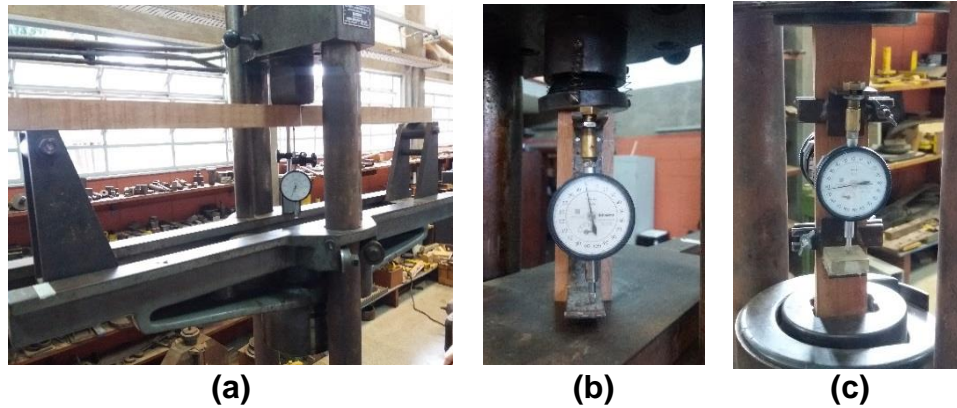
To determine  $E_{c0}$ ,  $E_{t0}$ , and  $E_M$ , the static three-point bending test (Fig. 1a), compression (Fig. 1b), and tensile test (Fig. 1c) parallel to the grain were performed, respectively.

**Table 1.** Brazilian Tropical Wood Species Used in the Study

ID	Brazilian Popular Name	Scientific Name *	ID	Brazilian Popular Name	Scientific Name *
1	Angelim amargoso	<i>Vatairea fusca</i> (Ducke) Ducke	16	Copaíba	<i>Copaifera multijuga</i> Hayne
2	Angelim araroba	<i>Vataireopsis araroba</i> (Aguiar) Ducke	17	Cutiúba	<i>Goupia paraensis</i> Huber
3	Angelim ferro	<i>Hymenobium</i> cf. <i>heterocarpum</i> Ducke	18	Goiabão	<i>Planchonella pachycarpa</i> Pires
4	Angelim pedra	<i>Hymenobium petraeum</i> Ducke	19	Guaiçara	<i>Luetzelburgia</i> cf. <i>guaissara</i> Toledo
5	Angelim vermelho	<i>Dinizia excelsa</i> Ducke	20	Guajará	<i>Micropholis venulosa</i> (Mart. & Eichler) Pierre
6	Angico preto	<i>Anadenanthera colubrina</i> var. <i>cebil</i> (Griseb.) Altschul	21	Guarucaia	<i>Peltophorum dubium</i> (Spreng.) Taub.
7	Branquilha	<i>Sebastiania commersoniana</i> (Baill.) L. B. Sm. & Downs	22	Itaúba	<i>Mezilaurus itauba</i> (Meisn.) Taub. ex Mez
8	Cafearana	<i>Andira antheimia</i> (Vell.) Benth	23	Jatobá	<i>Hymenaea courbaril</i> L.
9	Canafístula	<i>Cassia ferruginea</i> (Schrad.) Schrad. ex DC.	24	Louro preto	<i>Ocotea neesiana</i> (Mig.) Kosterm.
10	Casca grossa	<i>Pouteria</i> cf. <i>pachyphylla</i> T. D. Penn.	25	Louro verde	<i>Sextonia</i> cf. <i>rubra</i> (Mez) van der Werff
11	Castanheira	<i>Bertholletia excelsa</i> Bonpl.	26	Maçaranduba	<i>Manilkara</i> cf. <i>inundata</i> (Ducke) Ducke
12	Cedro amargo	<i>Cedrela odotara</i> L.	27	Parinari	<i>Parinari excelsa</i> Sabine
13	Cedro doce	<i>Cedrela</i> cf. <i>fissilis</i> Vell.	28	Piolho	<i>Tapirira</i> sp. Aubl.
14	Cedroarana	<i>Cedrelinga cataniformis</i> (Ducke) Ducke	29	Sucupira	<i>Diploptropis</i> sp. Benth.
15	Champanhe	<i>Dypterix odotora</i> (Aubl.) Willd.	30	Tachi	<i>Tachigali glauca</i> Tul.

\* According to Rio de Janeiro Botanical Garden (Jardim Botânico do Rio de Janeiro 2019)

For each species and mechanical property, 12 specimens were produced and tested, which gave a total of 1080 experimental results. All the tests were conducted on the universal testing machine AMSLER (250 kN loading capacity) (Shimadzu Corporation, Kyoto, Japan) following the procedure described in Annex B (Determination of wood properties for structural design) of ABNT NBR 7190 (1997).



**Fig. 1.** Static bending test (a), compression test parallel to the grain (b), and tensile test parallel to the grain (c)

The wooden boards were ambient-dried. After drying, the boards presented moisture level around 12%. According to the ABNT NBR 7190 (1997), 12% is a reference moisture level for presentation of the experimental results. Values of stiffness properties ( $E_{c0}$ ,  $E_{t0}$ , and  $E_M$ ) obtained with moisture levels (U%) different from 12% were adjusted for 12% moisture level using Eq. 3, as prescribed by the ABNT NBR 7190 (1997), where  $E_{12\%}$  and  $E_{U\%}$  are values corresponding to moisture levels of 12% and U%, respectively.

$$E_{12\%} = E_{U\%} \cdot \left[ 1 + \frac{2 \cdot (U\% - 12)}{100} \right] \quad (3)$$

The accuracy of relations proposed by ABNT NBR 7190 (1997) (Eqs. 1 and 2) was evaluated using ANOVA at the 5% significance level through BioEstat5.3<sup>®</sup> software (Mamirauá Institute, Belém, PA, Brazil). A null hypothesis ( $H_0$ ) was that the average of the groups ( $E_{c0}$  and  $E_{t0}$ ,  $E_{c0}$ , and  $0.90/E_M$ ) was equal, and the alternative hypothesis ( $H_1$ ) was non-equivalence. Hence, a p-value higher or equal than the selected significance level (p-value  $\geq 0.05$ ) implied accepting  $H_0$  (tested relation was accurate). Otherwise (p-value  $< 0.05$ ),  $H_1$  should be accepted.

Upon discovering non-equivalence (p-value  $< 0.05$ ), two-parameter ( $a$  e  $b$ ) regression models (Eq. 4 to Eq. 7) were used to estimate  $E_{c0}$  (dependent variable –  $y$ ) as a function of  $E_{t0}$  and  $E_M$  (independent variables –  $x$ ):

$$y = a + b \cdot x \quad (\text{Linear}) \quad (4)$$

$$y = a \cdot e^{b \cdot x} \quad (\text{Exponential}) \quad (5)$$

$$y = a + b \cdot \ln(x) \quad (\text{Logarithmic}) \quad (6)$$

$$y = a \cdot x^b \quad (\text{Geometric}) \quad (7)$$

Regression models based on ANOVA at a 5% significance level were used in considering the grouping of species and respective average values of properties. For ANOVA of regression models, a null hypothesis ( $H_0: \beta = 0$ ) was that the tested models were not representative and an alternative hypothesis ( $H_1: \beta \neq 0$ ) was that they were representative.

P-values higher than the selected significance level ( $p\text{-value} > 0.05$ ) implied accepting  $H_0$  (tested regression model was not representative - variations of  $x$  did not explain variations of  $y$ ). In the opposite case, this hypothesis would be rejected ( $p\text{-value} \leq 0.05$  - regression model was representative).

In addition to ANOVA, values of coefficient of determination ( $R^2$ ) were obtained, which allowed for evaluation of the quality of estimated fit and determination of the most accurate representative model ( $p\text{-value} \leq 0.05$ ), that is, the model that best described variations of dependent variable  $y$  as a function of independent variable  $x$ .

Along with regression models, the least squares method (Eq. 8 and Eq. 9 - used in studies by Christoforo *et al.* (2012), Icimoto *et al.* (2015), Ferro *et al.* (2015), Lahr *et al.* (2017), Almeida *et al.* (2018), and Christoforo *et al.* (2019)) using Newton's method with quadratic approximation was applied for determination of the optimal coefficient ( $\lambda$ ) for relations  $E_{c0} = \lambda \cdot E_{t0}$  and  $E_{c0} = E_M/\lambda$ :

$$f(\lambda) = \frac{1}{2} \cdot \sum_{i=1}^n (E_{c0i} - \lambda \cdot E_{t0i})^2 \quad (8)$$

$$f(\lambda) = \frac{1}{2} \cdot \sum_{i=1}^n (E_{M_i} - \lambda \cdot E_{c0i})^2 \quad (9)$$

## RESULTS AND DISCUSSION

Table 2 shows the experimentally obtained average values ( $X_m$ ) and coefficients of variation ( $C_v$ ) of stiffness properties ( $E_{c0}$ ,  $E_{t0}$ , and  $E_M$ ) for each tested species.

**Table 2.** Stiffness Properties of 30 Studied Wood Species

ID	$E_{c0}$		$E_{t0}$		$E_M$		ID	$E_{c0}$		$E_{t0}$		$E_M$	
	$X_m$ (MPa)	$C_v$ (%)	$X_m$ (MPa)	$C_v$ (%)	$X_m$ (MPa)	$C_v$ (%)		$X_m$ (MPa)	$C_v$ (%)	$X_m$ (MPa)	$C_v$ (%)	$X_m$ (MPa)	$C_v$ (%)
1	15242	16	16393	16	15562	13	16	12400	17	13604	13	11947	6
2	11467	12	11085	12	11132	20	17	18317	14	15093	14	16851	19
3	17054	13	18318	20	17196	9	18	19003	16	18345	22	19213	20
4	10529	8	10407	18	9793	17	19	15168	12	17016	12	14811	12
5	16744	11	17271	13	15314	10	20	20754	13	21885	17	20292	14
6	14731	23	16854	19	16625	11	21	17273	13	14507	15	16105	26
7	13706	15	14654	17	16573	22	22	17038	11	17691	9	16902	14
8	13766	28	12491	21	13673	16	23	22543	12	21350	3	21842	11
9	15149	18	14798	10	16026	13	24	15731	8	14232	13	15873	31
10	17564	9	18995	10	16993	9	25	15395	14	13619	14	16872	12
11	15441	14	13021	10	14044	14	26	22699	11	22078	6	20191	15
12	10094	6	9472	13	9136	6	27	21843	9	18781	6	18391	8
13	8499	17	9896	25	8814	16	28	13683	28	12889	19	12431	17
14	9828	11	9822	14	9527	9	29	20754	13	21885	17	20292	14
15	22732	11	21165	9	24653	10	30	19025	15	18746	27	20294	16

Both coefficients of variation and average stiffness values were consistent with experimental results from González and Gonçalves (2001), Grobério and Lahr (2002), Dias and Lahr (2004), Araújo (2007), Faria *et al.* (2012), Ferro *et al.* (2015), Jesus *et al.* (2015),

Moreira *et al.* (2017), Lahr *et al.* (2017), Aquino *et al.* (2018), and Almeida *et al.* (2018) that determined some of the stiffness properties of the species studied here.

The values of  $E_{c0}$  determined in this study and found in the literature were in agreement with values presented in Appendix E (Common average strength and stiffness values of some native and afforestation woods) of ABNT NBR 7190 (1997), which includes among its 50 hardwood species 18 wood species tested in this work (*Vataireopsis araroba* (Aguiar) Ducke, *Hymenolobium cf. heterocarpum* Ducke, *Hymenolobium petraeum* Ducke, *Dinizia excelsa* Ducke, *Sebastiania commersoniana* (Baill.) L.B. Sm. & Downs, *Andira anthelmia* (Vell.) Benth, *Cassia ferruginea* (Schrad.) Schrad. ex DC., *Pouteria cf. pachyphylla* T.D.Penn., *Cedrela odotara* L., *Cedrela cf. fissilis* Vell., *Dypterix odotora* (Aubl.) Willd., *Goupia paraensis* Huber, *Luetzelburgia cf. guaissara* Toledo, *Peltophorum dubium* (Spreng.) Taub., *Hymenaea courbaril* L., *Ocotea neesiana* (Mig.) Kosterm., and *Manilkara cf. inundata* (Ducke) Ducke). These comparisons supported the results shown in Table 2.

The ANOVA showed that group means of  $E_{c0}$  and  $E_{t0}$  were statistically equal because the p-value was higher than the significance level (p-value  $\geq 0.05$ ). Hence, the relation  $E_{c0} = E_{t0}$  was accurate and gave a good estimate of  $E_{c0}$ . For the relation between  $E_{c0}$  and  $E_M$ , the p-value was less than the significance level (p-value  $< 0.05$ ), which indicated that group means of  $E_{c0}$  and  $E_M/0.90$  were not statistically equivalent. Hence, the equation  $E_{c0} = E_M/0.90$  did not estimate  $E_{c0}$  value accurately.

The regression models (Eq. 4 to Eq. 7) and least squares method (Eq. 9) were used as an alternative to the equation  $E_{c0} = E_M/0.90$ , for formulation of equations that could accurately estimate  $E_{c0}$  values as a function of  $E_M$ . All models (linear, exponential, logarithmic, and geometric) were significant (p-value  $< 0.05$ ), and the geometric model described by Eq. 10 showed the best fit ( $R^2 = 91.67\%$ ):

$$E_{c0} = 1.82 \cdot (E_M)^{0.94} \quad (10)$$

The least squares method gave the optimal coefficient for the relation  $E_{c0} = E_M/\lambda$  for the entire group of species equal to 0.98 (Eq. 11) that was 8.89% higher than the coefficient (0.90) provided by ABNT NBR 7190 (1997):

$$E_{c0} = E_M / 0.98 \quad (11)$$

It should be mentioned that  $E_{c0} = E_M/0.90$  ratio was established by the Brazilian standard ABNT NBR 7190 (1997) without an adequate statistical analysis that would prove the reliability in the comparison of the groups of values ( $E_{c0}$  and  $E_M$ ). In the present work, ANOVA was applied in order to investigate the relationship between  $E_{c0}$  and  $E_M$  ( $E_{c0} = E_M$ ), which showed equivalence between the two groups. This result shows that the  $E_{c0} = E_M$  ratio is more precise than the  $E_{c0} = E_M/0.90$  equation, proposed by the Brazilian standard. This highlighting the need for revision of this item in future versions.

## CONCLUSIONS

1. The ANOVA at 5% significance level demonstrated an equivalence between group means of  $E_{c0}$  and  $E_{t0}$ , which indicated the accuracy of  $E_{c0}$  estimation for hardwood species through the equation  $E_{c0} = E_{t0}$  proposed by ABNT NBR 7190 (1997).

2. The ANOVA at 5% significance level demonstrated that group means of  $E_{c0}$  and  $E_M/0.90$  were not equal, which indicated that the coefficient of 0.90 did not give an accurate estimation of  $E_{c0}$  through the equation  $E_{c0} = E_M/0.90$ .
3. All regression models used for estimation of  $E_{c0}$  as a function of  $E_M$  were significant and with a good fit. The best fit was achieved by the geometric model, which showed that  $E_{c0}$  could be estimated by Eq. 10.
4. The optimal coefficient obtained by the least squares method (Eq. 11) for the relation between  $E_{c0}$  and  $E_M$  was higher than the one established by ABNT NBR 7190 (1997). The value of this coefficient was around 1, thus, validating the results of ANOVA that indicated equivalence between  $E_{c0}$  and  $E_M$  ( $E_{c0} = E_M$ ).
5. Given the significant number of species tested in this study,  $E_{c0} = E_M$  ratio appeared to be widely applicable model for estimation of  $E_{c0}$ .

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