Mechanical Properties Evaluation of *Eucalyptus grandis* Wood at Three Different Heights by Impulse Excitation Technique (IET)

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Wood is a natural material with great variability in its mechanical properties. This study analyzed the effectiveness of the impulse excitation technique (IET) to characterize the stiffness of 10-year-old *Eucalyptus grandis* wood at three different heights of 3 m, 6 m, and 9 m from the bottom (height A, B, and C, respectively). A nondestructive testing method—excitation impulse, using Sonelastic® PC-based technology—and a destructive static bending test were used. The mean value for the modulus of elasticity (MOE) in bending was 16.4 GPa and in IET the value was 16.6 GPa. The average values for MOE in static bending were 14.8 GPa at height A, 17.9 GPa at height B, and 17.0 GPa at height C, demonstrating that the greater the height in the trunk of the tree the greater its modulus of elasticity. The correlation equation between static MOE and dynamic MOE was $MOE_{STAT} = 0.743.MOE_{DYN} + 4.0983$, with the coefficient of determination of $R^2 = 0.85$.

Keywords: Wood; Rigidity; Static bending; Impulse excitation technique

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INTRODUCTION

Wood is a natural material that has been used for many purposes for centuries. It can be regarded as the embodiment of solar energy, stored in a stable form. It has a low environmental impact and high resistance to weight ratio. Thus, it is indispensable to know its properties to indicate its best possible use.

The genus *Eucalyptus* corresponds to the largest area of reforestation in the world. With its diversity of species, ecological plasticity, and excellent production, it is the raw material for a large number of forest industries. *Eucalyptus* regenerates after cutting, which is an attractive use for reforestation (Finger *et al.* 1993).

Technological knowledge about wood, including its physical and mechanical properties, promotes the introduction of species into the industrial market for specific purposes (Gonçalez *et al.* 2006). Wood's physical and mechanical properties must be evaluated to properly define its intended purpose. Together with other factors such as resistance to natural degradation, aesthetics, and market values, the properties allow the wood to be safely classified for appropriate uses, such as structural parts (Araújo 2007).

The methods used for the mechanical characterization of materials can be divided into destructive and nondestructive (NDT) categories. Stangerlin *et al*. (2010) reported that non-destructive methods were proposed internationally at the end of the 1950s by Bodig and Jayne (1982) and in Brazil at the end of the 1980s. A nondestructive test identifies the physical-mechanical properties of a material without changing those properties; thus, appropriate decisions regarding its applications can be made (Ross *et al.* 1998). To evaluate the mechanical properties and residual load capacity of existing wood members, non-destructive evaluation (NDE) is effective (Riggio *et al.* 2014). Almost all types of nondestructive testing can be used with wood and wood derivatives, and the choice for their use depends on the specific application (Bodig 2001).

Acoustic-based nondestructive methods can predict the bending modulus of elasticity (MOE), modulus of rupture, and compression parallel to grain strength (Yin *et al*. 2010; Cheng and Hu 2011). The analysis of sound propagation in isotropic materials is less complex than in wood (Hansen 2006). The acoustic response consists of the sound emitted by the specimen, which originates from the natural vibration frequencies of material. The frequencies depend on mass, dimensions, geometry, and stiffness (Moraes 2012).

According to Bucur (2006), the frequencies commonly used in acoustic methods for studies of wood are below 20 kHz. The state of equilibrium or momentary excitation (impact) can be used for dynamic vibration resonance tests when dynamic modulus of elasticity is determined, and an accurate measurement of engineering constants is important for engineering and product design.

Hodoušek *et al*. (2017) studied the MOE of *Cupressus lusitanica* (CL) and *Populus x canadensis* (PC) species, comparing the destructive and nondestructive methods. The Timber Grader MTG was used for the nondestructive testing method, which is based on the principle of frequency resonance using longitudinal vibrations to calculate the MOE. The difference between the values of dynamic and static modulus of elasticity for PC was between 1.1% and 2.4% and for CL between 12.7% and 15.5%. The coefficients of determination found by the authors for the regression analysis between the dynamic and static modulus of elasticity were $R^2 = 0.87$ for CL and $R^2 = 0.81$ for PC.

In a study by Ballarin and Palma (2009), *Eucalyptus grandis* wood was characterized using 24 trees at 21 years of age. Of these, 57 specimens with nominal dimensions of 2 cm × 2 cm × 46 cm were prepared. Beam identification by nondestructive grading (BING) equipment produced by CIRAD-Forest (CIRAD 2009) was used to measure the frequencies of transverse vibration. The mean values of dynamic and static MOE were 16990 MPa for and 15306 MPa, respectively. The correlation coefficient for the regression analysis between the dynamic and static elasticity modulus was $R^2 = 0.87$.

Segundinho *et al.* (2012) reported that nondestructive test methods for transverse vibration and longitudinal frequency are becoming increasingly relevant because they provide rapid responses and high linear correlations (R^2 equal to 0.8), and the cost of equipment has reduced over the years. They evaluated 24 beams of *Eucalyptus* sp. with nominal dimensions of 4 cm × 6 cm × 200 cm and 14 *Pinus oocarpa* beams with nominal dimensions 4.5 cm × 9 cm × 230 cm; both sets of beams were untreated. The wood was characterized by the impulse excitation technique using the Sonelastic® Stand Alone equipment and by the destructive method of static bending. Their values from the angular coefficients of the linear regression lines (R^2) indicate an average adjustment of 0.91.

This study evaluated the mechanical properties of *Eucalyptus grandis* wood species based on the nondestructive test method of impulse excitation technique for three heights of the tree. The relationships between dynamic and static modulus of elasticity as well as the frequencies (F) were also investigated.

EXPERIMENTAL

Materials

The raw materials used were collected at heights of 3 m, 6 m, and 9 m (heights A, B, and C) from the base of four 10-year-old *Eucalyptus grandis* trees, with diameter ranging from 30 to 40 cm, coming from Ribeirão Farm (Itapeva, Brazil) donated by Sudoeste Paulista (Itapeva, Brazil). Figure 1 demonstrates the heights in relation to the trunk of the tree.

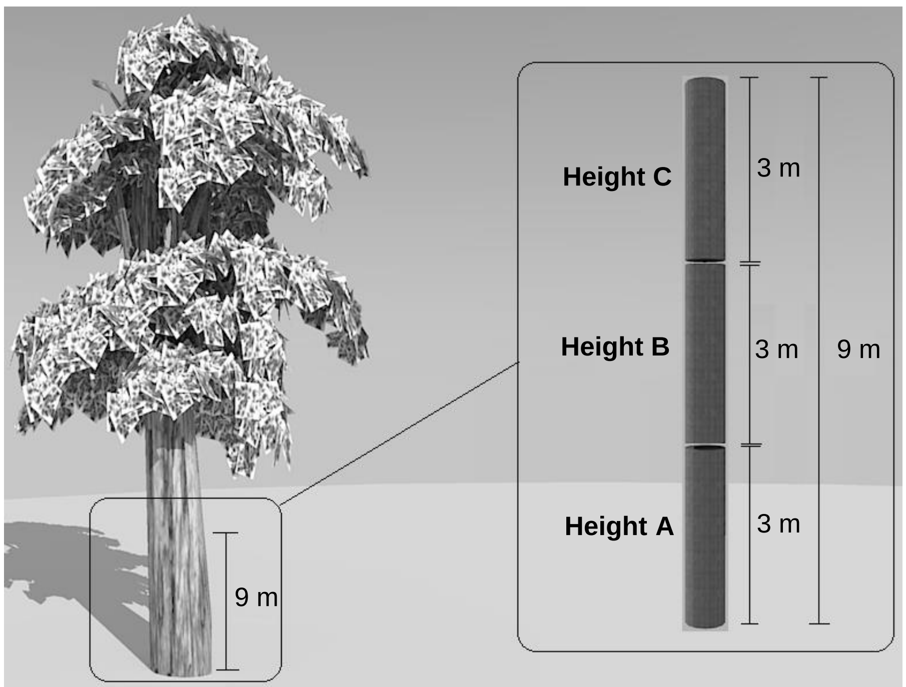

Fig. 1. Location of heights A, B, and C from the base of the tree

Fig. 2. PC-based technology Sonelastic® equipment. Source: Sonelastic® (2011).

The Sonelastic® PC-based technology (Sonelastic, Ribeirão Preto (SP), Brazil) was used to perform nondestructive impulse excitation tests. The components of the equipment were a notebook with Sonelastic® software, a microphone, and a hammer (Fig. 2).

Methods

Eucalyptus grandis specimens were submitted to the impulse excitation technique (IET) in accordance with the requirements of ASTM E-1876 (1976) for the determination of the vibration frequency and dynamic longitudinal modulus of wood species. The procedure was performed on a rubberized surface in an air-conditioned room. The samples were impacted by a hammer five times at the end of the static flexural test specimens, and the frequencies were recorded.

Static bending tests were conducted respecting the requirements of normative document ABNT: NBR 7190/1997. These tests were carried out through the Universal Testing Machine (EMIC, Instron Brasil, São José dos Pinhais, Brazil) at 30 tons with speed control at 10 MPa/min rate of loading, from the Material Properties Laboratory, at Campus of Itapeva of UNESP.

The wood specimens were used in nominal sizes of 5 cm × 5 cm × 115 cm for both destructive and nondestructive test methods. Each height (A, B, and C) included eight specimens, being two by tree.

The results were processed in relation to descriptive data and regression graphs, using statistical software R (R Foundation, Version 3.4.2, Vienna, Austria) and Microsoft Excel software (Version 2013, Redmond, WA, USA). For statistical analysis, the normality and homogeneity of the data were examined by the Shapiro-Wilk test. Regression analysis was used to determine if the studied variables were correlated and their correlation equations.

RESULTS AND DISCUSSION

The mean values of frequencies and the dynamic modulus of elasticity obtained from measurements by longitudinal vibration tests are shown in Table 1. The standard deviations (GPa) and coefficients of variation (%) related to these data are also shown.

Table 1. Dynamic Modulus of Elasticity and Frequency Values

	Height A		Height B		Height C	
	F (Hz)	Dyn MOE (GPa)	F (Hz)	Dyn MOE (GPa)	F (Hz)	Dyn MOE (GPa)
Mean	1776	14.8	2309	17.9	2270	17.0
SD	647	1.8	95.8	2.5	67.5	2.1
CV (%)	36	12	4.2	14	3.0	12.4

F, frequency; Dyn MOE, dynamic modulus of elasticity; SD, standard deviation; CV, Coefficient of variation

A regression analysis was performed to determine whether the dynamic MOE resulted as a function of heights A, B, and C. A P-value equal to 0.01764 was obtained, showing that dynamic MOE depends on the tree height.

Figure 3 shows the correlation between dynamic MOE and height. A higher tree height resulted statically in a greater dynamic longitudinal MOE. Iwakiri *et al.* (2013) found a similar result for *Tectona grandis* species with a nondestructive acoustic wave method. In the Figures 3 and 4, four lines represented the respective intervals of: superior confidence (green), inferior confidence (red), superior prediction (blue), and interior prediction (purple).

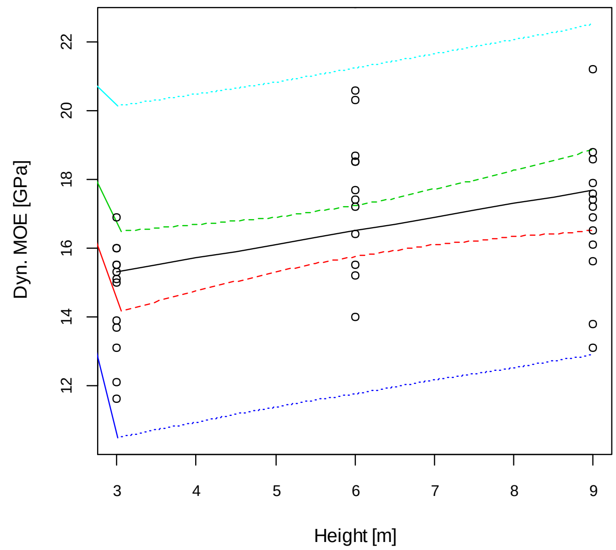

Fig. 3. Regression analysis of the dynamic MOE values according to height

Regression analysis was also performed to determine whether the frequency can be given as a function of heights A, B, and C. A P-value equal to 0.002873 was obtained, rejecting the hypothesis that the two are not dependent. Thus, the frequency depends on and can be given as a function of height. Figure 4 shows the graph of the correlation between the variables.

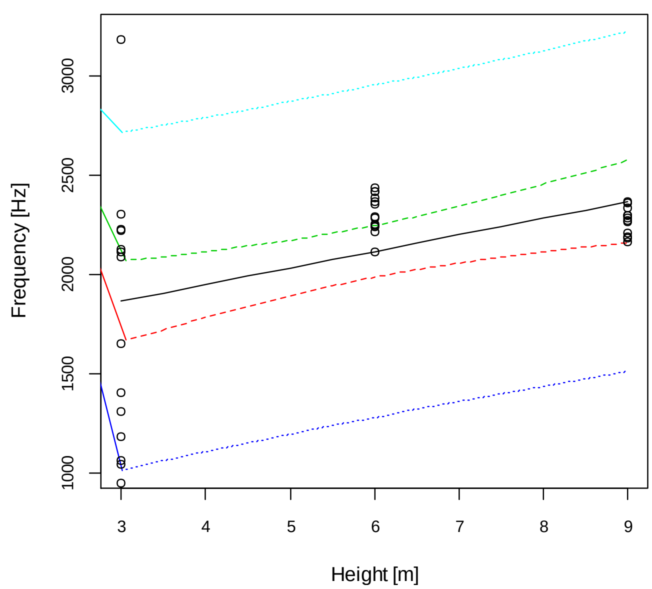

Fig. 4. Regression analysis of the frequency values according to height

Table 2 presents the mean values of static MOE obtained in the bending test as well as the standard deviations and coefficients of variation related to these data. The regression analysis was performed, with a significance level of 5%, to determine whether the static modulus of elasticity could be given as a function of the dynamic modulus of elasticity, for each of the heights. In the regression, an analysis P-value of 2.2×10^{-16} was generated, leading to the conclusion that statically the static modulus of elasticity depends on and can be given as a function of the dynamic modulus of elasticity (Fig. 5).

Table 2. Static Modulus of Elasticity Values

Parameter	Static MOE (GPa)		
	Height A	Height B	Height C
Mean	15.5	16.9	16.8
SD	1.27	1.41	1.50
CV (%)	8.2	8.3	8.9

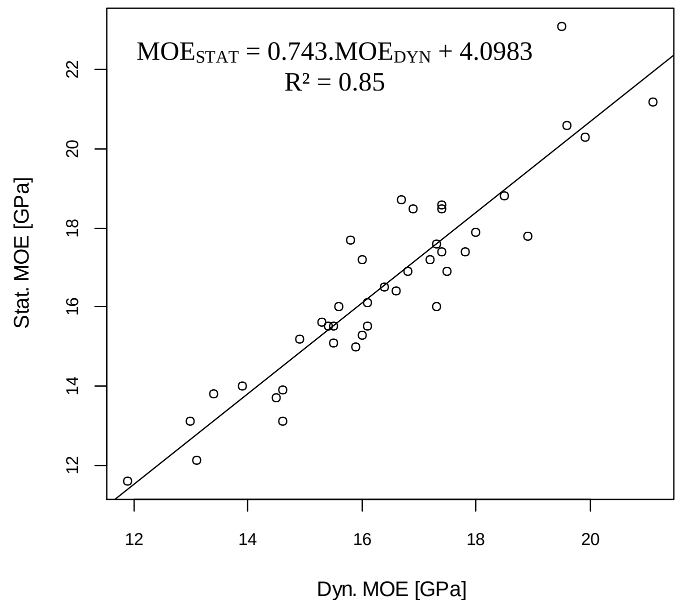

Fig. 5. Linear regression of the dynamic and static modulus of elasticity

The correlation equation $MOE_{STAT} = 0.743.MOE_{DYN} + 4.0983$ was obtained between the dynamic and static moduli values for all heights, with 0.85 R^2. This value is close to those found by other authors, indicating consistency of the correlation between the variables. Table 3 shows the coefficient of determination reported by other authors.

Table 3. Coefficient of Determination Found by Other Authors

Reference	Species	Coefficient of determination
Ballarin and Palma (2009)	*Eucalyptus grandis*	0.87
Cossolino *et al*. (2009)	*Pinus oocarpa*	0.89
Hodoušek *et al*. (2017)	*Cupressus lusitanica*	0.87
Hodoušek *et al*. (2017)	*Populus x canadensis*	0.81
Segundinho *et al*. (2012)	*Eucalyptus sp.*	0.89
Casado *et al*. (2010)	*Populus x euramericana*	0.59

Despite these authors, Baar *et al*. (2015) tested three tropical species and achieved coefficients of 0.74, 0.72, and 0.23. Comparing these data, the coefficient of determination obtained through the linear regression for 10-year-old *Eucalyptus grandis* was close to that of Ballarin and Palma (2009) for 21-year-old *Eucalyptus grandis*.

CONCLUSIONS

1. The average value of 16.4 GPa found for the modulus of elasticity in static bending was close to those cited in literature for wood of this species older than 10 years, indicating that they have potential for use in structures.
2. The mean values found for dynamic modulus of elasticity were 14.8 GPa at height A, 17.9 GPa at height B, and 17.0 GPa at height C (3 m, 6 m, and 9 m). These values followed the same statistical correlation as those mentioned in the literature analyzing the destructive test of static bending.
3. The correlation equation between static MOE and dynamic MOE was $MOE_{STAT} = 0.743.MOE_{DYN} + 4.0983$, with a coefficient of determination of $R^2 = 0.85$. These values are close to those cited in the literature.
4. The Impulse excitation technique is effective for characterizing the stiffness of 10-year-old *Eucalyptus grandis* wood, demonstrating good cost/benefit and speed for classification in relation to universal test machines, and an increase in the value added to lumber for construction.

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