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Resonance of scantlings indicates the stiffness even of small specimens of *Eucalyptus* from plantations

Paulo Ricardo Gherardi Hein · José Tarcísio Lima ·
Joseph Gril · Antônio Marcos Rosado ·
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Abstract The aim of this study was to establish the relationship between the stiffness of scantlings, approaching structural size materials, and small specimens of 6-year-old *Eucalyptus urophylla* × *grandis* wood using a resonance technique. The correlation between the elastic modulus (E) of the scantlings in longitudinal vibration and small specimens in flexural vibration was $r = 75$ when comparing the scantling values with the averaged values of the specimens per scantling. However, when the E of each single specimen was compared with its respective scantling, the coefficient of correlation decreased to $r = 0.64$ in the longitudinal tests and $r = 0.61$ in the flexural tests. A roughly linear correlation ($r = 0.59$) between specific modulus and loss tangent was obtained for the small specimens of *Eucalyptus*. In short, the resonance technique rapidly provided a large, accurate data set of mechanical wood properties as required for high-throughput phenotyping in recent genetic studies.

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Introduction

The main objective of *Eucalyptus* breeding programs for the pulp and paper industry was to produce varieties of trees with high levels of cellulose with the least possible amount of lignin. However, trees with these characteristics can be a major problem in the field because of their fragility that makes them susceptible to breaking.

Natural vibration analysis is a simple and efficient way of characterizing the mechanical properties of many materials, including wood (Brancheriau and Baillères 2002). Using various species of wood, sample dimensions, and growth conditions, several studies have shown a strong linear correlation between dynamic and static modulus of elasticity (Ross et al. 1991; Wang et al. 2001; Green et al. 2004; Biblis and Carino 1999; Biblis et al. 2004). For instance, Ilic (2001) obtained strong correlations between static test and longitudinal ($r = 0.95$) or flexural ($r = 0.99$) elastic modulus using short specimens ($20 \times 20 \times 300$ mm) of *Eucalyptus delegatensis* R. Baker. Using larger pieces, Brancheriau and Baillères (2002) reported good correlation between Young's modulus in four-point bending and the flexural vibration modulus of elasticity on 76 beams ($60 \times 155 \times 3,500$ mm) of *Dicorynia guianensis* Amsy.

Dynamic tests based on the resonance frequency have been applied successfully in order to analyze, among other elastic properties, the dynamic modulus of elasticity of small, clean specimens (or clearwood) at laboratory scale (Haines et al. 1996; Ilic 2003; Brancheriau and Baillères 2003; Ohsaki et al. 2007), as well as of structural timber (Haines et al. 1996; Burdzik and Nkwera 2002; Liang and Fu 2007; Jiang et al. 2010) and logs (Ouis 1999; Wang et al. 2002; Grabianowski et al. 2006). To the authors' knowledge, few studies have been conducted in order to establish the relationship between the mechanical properties obtained on large pieces of wood and on small specimens sampled from them. For instance, Haines et al. (1996) compared mean values of transverse resonance (13.3 GPa) obtained for wood beams measuring $1 \times 5 \times 30$ mm with mean values from previous static tests (13.6 GPa) reporting differences of less than 3%. Ilic (2003) compared the dynamic elasticity of specimens measuring $20 \times 20 \times 300$ mm with that of small wood beams ($120 \times 20 \times 1.6$ mm) reporting high correlations ($R^2 = 0.96$ – 0.98) for groups of softwood and hardwood. Carter et al. (2006) reported good relationship ($R^2 = 0.86$) between dynamic modulus of elasticity in air-dried and green conditions using 42 boards of 24-year-old *Pinus*. They also showed strong correlation ($R^2 = 0.94$) between acoustic properties between logs and boards; however, this study uses a small number of samples (6 logs). In effect, the relationship between the mechanical properties of small clear specimens and larger-sized samples approaching structural size material is still not well established. Hence, the aim of this study was to establish the correlation between the stiffness of scantlings and small specimens of *Eucalyptus* wood. These findings would be useful in explaining the scale effect observed on the mechanical behaviors of wood of different dimensions.

Here, longitudinal and flexural dynamic tests were performed on scantlings and small specimens of clones of *Eucalyptus grandis* \times *urophylla* hybrids using the BING (Beam Identification by Non-destructive Grading) system developed by

CIRAD (<http://www.xylo-metry.org>). The procedure used for preparing the samples, the dimensions, and the relationships established in this study are factors that may help explain parts of the mechanical behavior of wood. The effect of these factors on over- or underestimating the wood quality on the basis of resonance frequency of large and small specimens was discussed. Complementarily, the effect of the radial position on the resonance frequency of these wood samples was investigated.

Materials and methods

Origin and preparation of wood samples

One hundred (100) logs of 6-year-old *Eucalyptus grandis* × *urophylla* hybrids coming from a clonal test established in Brazil (19°17'S, 42°23'W, alt. 230–500 m) were used in this study. The type of climate is Aw (tropical savanna climate), according to the classification by Köppen (Peel et al. 2007), with a mean annual rainfall of 1,205 mm. The mean annual temperature is around 25°C, and the average annual humidity is 67%. The trees were planted in a randomized design, and the density of the plantation was 1,667 trees/ha (3 × 2 m spacing).

A total of 160 pieces of wood with nominal sizes of 45 × 60 × 2,100 mm (hereafter referred to as “scantlings”) were taken from 100 central boards (Fig. 1). As the scantlings were removed systematically at each 45 mm of the boards (60 mm in thickness), naturally, some parts of the scantlings contained pith, knots, and other features inherent to wood. Subsequently, a pile of scantlings was set up for air drying under protected exterior conditions for 90 days. After air drying, the scantlings presented defects such as small cracks, checks, and splits at their ends and, therefore, they were trimmed to variable dimensions, depending on the extent

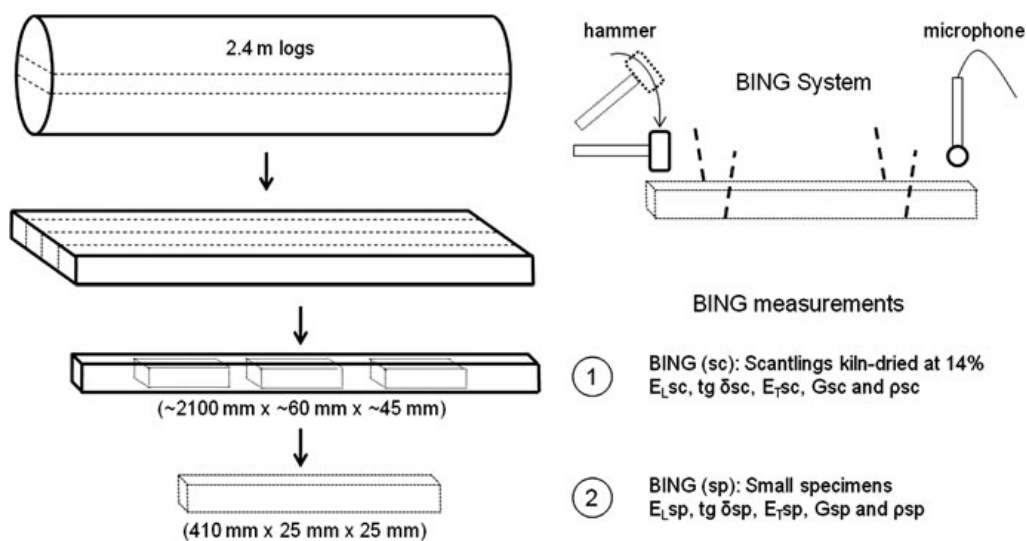


Fig. 1 Procedure of sample preparation and acoustic measurements

of their defects. The clean scantlings had, on average, a length of 1.82 m varying from 1.65 to 2.08 m (COV = 13.7%), and the averaged width and thickness were 60 and 43 mm, respectively, fluctuating slightly (COV = 5.7% for width and COV = 2.8% for thickness). Thus, all pieces were free of large fissures, biological affections, defects produced in the saw mill as severe reduction of width or thickness, but they presented knots and small cracks as well. Finally, the scantlings were kiln-dried at 14% (nominal) under soft conditions for 2 weeks. The wood samples here investigated contain only juvenile wood.

Dynamic tests on woods

The pieces of wood were submitted to flexural and longitudinal vibration tests. In flexural vibration, the first four modes of vibration were measured and used for estimating the dynamic transversal modulus of elasticity (E_F) of wood, which represents its stiffness under bending stress, the dynamic shear modulus (G), and the loss tangent ($\text{tg } \delta$), also called internal damping. In longitudinal vibrations, the first vibration mode was measured and used for estimating the dynamic longitudinal modulus of elasticity (E_L) of wood, which represents its stiffness under compressive stress, and the $\text{tg } \delta$. The theoretical models of motion and their solutions used to estimate such elastic properties are described in detail by Brancheriau and Baillères (2002). The mass and the dimensions of each wood sample were measured at the moment of the dynamic tests giving the density (ρ) of the wood samples.

This study is divided into two sections: First, the masses of the kiln-dried scantlings were measured providing the weight density of the scantlings (ρ_{sc}). The scantlings were submitted to dynamic tests providing the information labeled as E_{Lsc} , $\text{tg } \delta_{sc}$, E_{Fsc} , and G_{sc} . In the second section, 160 scantlings were selected from the best ones (i.e., annual rings well oriented and free of large cracks) and surfaced on the plane machine; beams were cut from them and trimmed to a nominal cross-section of 25×25 mm using a circular saw machine.

Then, small specimens measuring $25 \times 25 \times 410$ mm (knot and defect free) were cut from the beams according to the standard D 143-94 (ASTM 1997). The mass and dimension were measured, and the weight density (ρ_{sp}) of each specimen was calculated. The small specimens were submitted to vibration tests, which provided the data labeled as E_{Lsp} , $\text{tg } \delta_{sp}$, E_{Fsp} , and G_{sp} . Prior to the tests, the specimens were conditioned in a room at 20°C and 65% relative humidity to maintain the equilibrium moisture content of 14%. The error of measure was 0.1 g and 0.1 mm for mass and dimension, respectively, for the scantlings and 0.001 g and 0.001 mm for the small specimens. Figure 1 summarizes the procedure of sample preparation and acoustic measurements.

Procedure of dynamic tests

The scantlings were placed on elastic supports so as to generate free vibrations. An exciting impulse was produced by slightly striking the scantlings with an instrumented hammer at the opposite side of the output transducer (acoustic microphone). The flexural vibration was induced by an edgewise impact, and the

longitudinal vibration, by an impact along the end. The input and output signals were transmitted via a low-pass filter to an acquisition card on a computer and recorded as described in Brancheriau and Baillères (2003).

Equations of motion

The theoretical model used to describe the motion of a uniform prismatic beam that vibrates transversely freely was proposed by Timoshenko (1921) as follows:

$$E_X I_{Gz} \frac{\partial^4 v}{\partial x^4} - \rho I_{Gz} \left(1 + \frac{E_X}{K G_{XY}} \right) \frac{\partial^4 v}{\partial x^2 \partial t^2} + \frac{\rho^2 I_{Gz}}{K G_{XY}} \frac{\partial^4 v}{\partial t^4} + \rho A \frac{\partial^2 v}{\partial t^2} = 0 \quad (1)$$

where E_X is the Young's modulus; I_{Gz} is the moment of inertia; v is the transversal displacement; ρ is the density; G_{XY} is the shear modulus; K is a constant that depends on the geometry of the section (for rectangular section, $K = 5/6$); x is the distance along the axis of the beam; A is the cross-sectional area of the beam; t is the time. Using Bordonné's (1989) solution for this differential equation, the shear effect is taken into account, but the support effects are ignored. The elastic (E_X) and shear modulus (G_{XY}) were calculated according to the following equation, described in Brancheriau and Baillères (2002):

$$\frac{E_X}{\rho} - \frac{E_X}{K G_{XY}} \left[Q F_2(m) 4\pi^2 \frac{AL^4 f_n^2}{I_{Gz} P_n} \right] = 4\pi^2 \frac{AL^4 f_n^2}{I_{Gz} P_n} [1 + Q F_1(m)] \quad (2)$$

where f_i is the resonance frequency of the order i and P_n is the solution of Bernoulli (rank n). Parameters Q , F_1 , F_2 , m , and θ are calculated as follows:

$$Q = \frac{I_{Gz}}{AL^2} \quad (3)$$

$$F_1(m) = \theta^2(m) + 6\theta(m) \quad (4)$$

$$F_2(m) = \theta^2(m) - 2\theta(m) \quad (5)$$

$$\theta(m) = m \frac{\tan(m) \tanh(m)}{\tan(m) - \tanh(m)} \quad (6)$$

$$m = \sqrt[4]{P_n} = (2n + 1) \frac{\pi}{2}, \quad n \in N^* \quad (7)$$

Parameters m , P_n , $F_1(m)$, and $F_2(m)$ are calculated on the basis of index n and are used in practical applications to calculate the value of the modulus E_X and that of the shear modulus G_{XY} .

In longitudinal vibrations, the first vibration mode can be used in order to estimate its dynamic longitudinal modulus of elasticity (E_L), which represents its stiffness under compressive stress, by means of the formula:

$$E_X = 4L^2 \rho f_1^2 \quad (8)$$

A detailed discussion about different theoretical models of motion, their approximate solutions, and their respective hypotheses in longitudinal and flexural

vibrations and the effects of the elastic support required by the BING system were provided in the study by Brancheriau and Baillères (2002).

To extract the damping parameters from acoustic sounds, the concept of additive synthesis was applied (Brancheriau et al. 2006). Each temporal signal $s(t)$ was then considered as a sum of exponentially damped sinusoids as follows:

$$s(t) = \sum_{i=1}^{\infty} \beta_i \exp(-\alpha_i t) \sin(2\pi f_i t + \varphi_i) \quad (9)$$

where s is the radiated signal as a function of time t and φ_i is the phase shift. The parametric method of Steiglitz and McBride (1965) was used to simultaneously determine the first resonance frequency f_1 , the amplitude β_1 , and the temporal damping α_1 associated with f_1 . Only the first frequency was considered because of its high energy. The internal friction ($\text{tg } \delta$) associated with the complex modulus concept was calculated with respect to flexural or longitudinal vibrations (Aramaki et al. 2007) according to the equation given by Brancheriau et al. (2006):

$$\text{tg } \delta = \frac{\alpha_1}{\pi f_1} \quad (10)$$

Parameter of dynamic tests

The analysis of the spectral signal, the selection of the peaks of the natural frequency of vibration of the wood samples, and the estimates of the E_F , G , E_L , and $\text{tg } \delta$ were performed using the software BING® (CIRAD, Montpellier, France, version 9.1.3). The sampling frequencies of the signal were 78,125 and 39,062 Hz for longitudinal and flexural vibrations, respectively. The spectral acquisition was carried out by using 32,768 points for each test. An analogical to numeric conversion with 12-bit resolution was used.

Results

Dynamic properties and densities of the scantlings and specimens

Table 1 lists the descriptive statistics of the dynamic properties and densities of the 160 scantlings (sc) and the 334 small specimens (sp) of *Eucalyptus* wood. The loss tangent values of the scantlings were calculated from the longitudinal test, while the $\text{tg } \delta$ of the specimens was derived from flexural vibrations. As the software warns of imprecise estimations, only 143 values were used for $\text{tg } \delta_{Lsc}$ and 141 for $\text{tg } \delta_{Fsp}$.

The variation ranges of wood properties for this young *Eucalyptus* (Table 1) are higher than those reported by Ilic (2001), who evaluated mature *E. delegatensis* R. Baker ($E_L = 18$ GPa with $\text{COV} = 25.9\%$ and $G = 1.32$ GPa with $\text{COV} = 30.1\%$). A comparison of the variation range of these young wood samples (Table 1) with other young softwoods reveals the high stiffness of the *Eucalyptus* clones. For instance, the elastic modulus of *Pinus radiata* wood clones (4 years) ranged from 2.6 to 6 GPa (Lindström et al. 2004), while this property varied from 6.5 to

Table 1 Descriptive statistics of dynamic properties of scantlings and the small specimens of *Eucalyptus grandis* × *urophylla*, including weight density (ρ , kg m⁻³), resonant frequency (f , Hz), elastic modulus (E , MPa), specific modulus (E' , MPa m³ kg⁻¹), loss tangent ($\text{tg } \delta$, 10⁻³), and shear modulus (G , MPa) estimated by longitudinal (L) and flexural (F) vibration tests

Step 1	Scantlings kiln-dried at 14%								
	ρ_{sc}	f_{Lsc}	E_{Lsc}	E'_{Lsc}	$\text{tg } \delta_{Lsc}$	f_{Fsc}	E_{Fsc}	E'_{Fsc}	G_{Fsc}
Average	556	1,672	13,673	24.5	7.49	98.76	13,982	25.1	719.30
Sd	69.2	384	2,698	3.20	1.28	42.81	2,654	3.10	193.1
Min	384	1,032	7,944	18.2	4.45	43.1	8,195	14.8	123.0
Max	776	3,414	23,136	44.3	11.2	434.2	21,609	32.3	1,388
COV	12.5	23.0	19.7	13.1	17.1	43.3	19.1	12.7	26.85
N	160	160	160	160	143	160	160	160	154
Step 2	Small specimens sampled from scantlings (moisture content = 14%)								
	ρ_{sp}	f_{Lsp}	E_{Lsp}	E'_{Lsp}	$\text{tg } \delta_{Fsp}$	F_{Fsp}	E_{Fsp}	E'_{Fsp}	G_{Fsp}
Average	518	6,174	13,391	25.66	7.33	721.6	12,495	24.02	693.6
Sd	59.05	395	2,540	3.52	1.01	42.52	2,356	3.082	168.5
Min	362.4	4,918	6,522	16.27	5.71	567.4	5,930	14.05	344
Max	708.3	6,945	20,785	32.43	10.5	805.9	18,732	30.61	1,499
COV	11.4	6.41	18.97	12.53	13.8	5.89	18.80	12.81	24.3
N	334	334	334	334	141	334	334	334	334

20.7 GPa for the *Eucalyptus* clones. In comparison with mature wood of other important species, the mean mechanical properties of these young *Eucalyptus* samples (Table 1) are comparable to those reported by Green et al. (2004) for teak ($\rho = 550 \text{ kg m}^{-3}$ and $E_L = 10.7 \text{ GPa}$), by Ilic (2003) for poplar ($E_L = 13.3 \text{ GPa}$ and $\rho = 448 \text{ kg m}^{-3}$), and by Keunecke et al. (2007) for Norway spruce ($\rho = 400 \text{ kg m}^{-3}$, $E_L = 13.8 \text{ GPa}$, and $G = 617 \text{ MPa}$).

Figure 2 shows the correlation ($r = 0.64$) obtained between the modulus of elasticity in the longitudinal test of the scantlings (E_{Lsc}) and the modulus of elasticity in the flexural test of the small specimens (E_{Fsp}) cut from them. The small specimens presented lower stiffness than the scantlings: the cloud of points is below the dotted line. The $E_{Lsc} \times E_{Fsp}$ plot (Fig. 2) reveals that the stiffness of small specimens strongly varied among the same scantling. Depending on external factors such as the presence of knots and small cracks, the resonance frequency of wood can under- or overestimate its properties.

To facilitate the understanding, the scantlings cut from the external region (near the bark) were classified as “ext” and they are represented by open circles; scantlings cut from the internal region (near the pith) were labeled as “int” and are represented by full rhombs in Figs. 2, 3, and 4. Figure 2 shows that the scantlings cut from the external portions (open circles) of the logs were stiffer than those sampled from the internal portions (full rhomb).

The number of specimens cut from each scantling was not the same. For instance, the less stiff scantling (labeled as “A”) gave only one specimen, while the stiffer

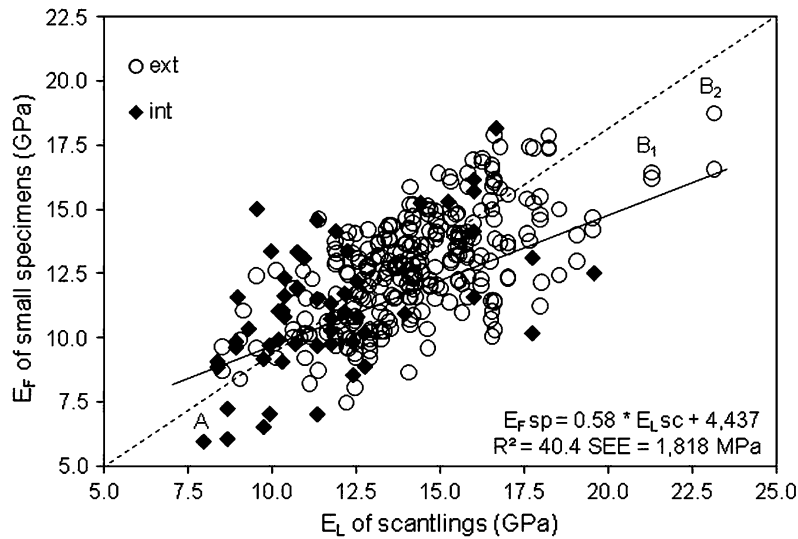


Fig. 2 Correlation between the modulus of elasticity in longitudinal test of scantlings (E_{Lsc}) and the modulus of elasticity in flexural test of small specimens (E_{Fsp}) of *Eucalyptus grandis* × *urophylla*. The scantlings sampled from external or internal regions of the logs are represented by *open circles* and *full rhomb*, respectively

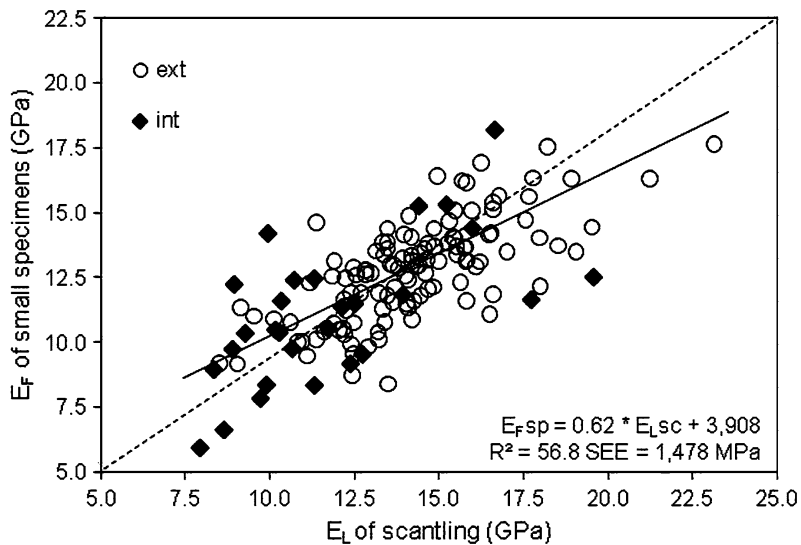


Fig. 3 Correlation between the modulus of elasticity in longitudinal test of scantlings (E_{Lsc}) and the averaged modulus of elasticity by beam in flexural test of small specimens (E_{Fsp}) of *Eucalyptus grandis* × *urophylla*. The scantlings sampled from external or internal regions of the logs are represented by *open circles* and *full rhomb*, respectively

scantlings (labeled as “B”) gave two specimens (Fig. 2). It is important to notice that specimens cut from the same scantling show variable properties, especially stiffness. When analyzing the stiffness of the scantling labeled as B₁ ($E_{Fsc} = 21.7$ GPa), its specimens presented lower, but closed values for modulus of elasticity (16.2 and 16.4 GPa), while for the scantling B₂ ($E_{Fsc} = 23.5$ GPa), its specimens presented lower and spread values of E_{Fsp} (16.6 and 18.7 GPa).

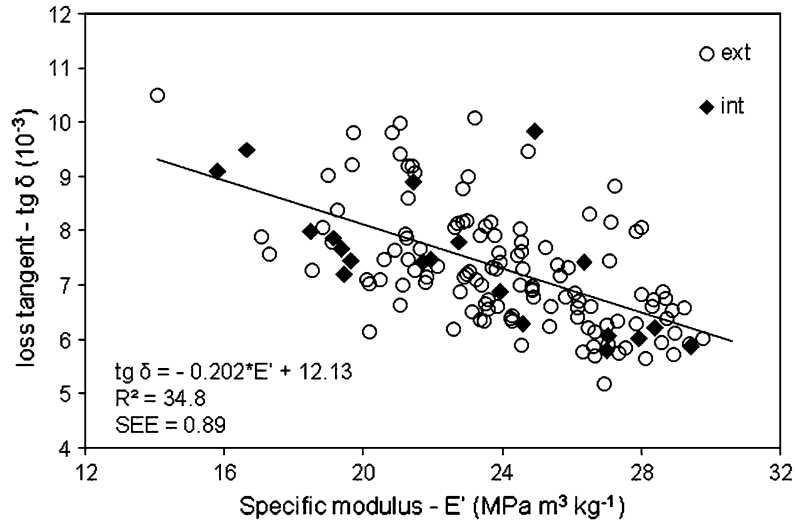


Fig. 4 Correlation between the loss tangent and the specific modulus of the small specimens of *Eucalyptus grandis* × *urophylla*. The specimens from external or internal regions of the boards are represented by *open circles* and *full rhomb*, respectively

Averaging mechanical properties of small specimens by scantling

In order to minimize the effect of the variability within scantlings, the averaged value of the small specimens was used to correlate them with their respective scantlings. Table 2 shows the coefficient of correlation between each single value of the small specimens with its correspondent scantling (below diagonal) and the correlations between the averaged value of small specimens per scantling with its correspondent scantling (above diagonal).

Figure 3 shows, in detail, the correlation between E_L of the scantlings and the averaged E_F of the small specimens cut from them. Again, due to the effect of the side of the scantlings where the specimens were removed (near the pith), the averaged stiffness of the specimens was lower than the stiffness of the scantlings that generated them. On average, the size scale effect can be indicated by the linear coefficient (3.9 GPa) of the regression. It was attempted to fit these data using a

Table 2 Correlations between physical and elastic properties of the scantlings and the small specimens

	ρ_{sc}	ρ_{sp}	E_{Lsc}	E_{Fsc}	E_{Lsp}	E_{Fsp}
ρ_{sc}		0.732	0.824	0.791	0.563	0.578
ρ_{sp}	0.720		0.598	0.534	0.845	0.822
E_{Lsc}	0.824	0.574		0.920	0.692	0.754
E_{Fsc}	0.791	0.518	0.920		0.685	0.733
E_{Lsp}	0.538	0.812	0.628	0.619		0.978
E_{Fsp}	0.552	0.795	0.636	0.615	0.972	

Below the diagonal are the correlations of each single small specimen with its correspondent scantling, while above the diagonal are the correlations taking into account the averaged values of small specimens by scantling. All correlations were statistically significant at $P < 0.001$

polynomial model but the coefficient of determination was statistically similar to the linear model.

Loss tangent \times specific modulus of specimens

Figure 4 shows the correlation between the loss tangent ($\text{tg } \delta$) and the specific modulus (E') of the specimens of *Eucalyptus*. This plot presents the loss tangent values and the specific modulus of the 141 specimens obtained from flexural test. The correlation between the specific modulus and loss tangent was roughly linear ($r = 0.59$). The radial position of the samples did not show any particular trend.

Discussion

Few studies have compared the dynamic properties obtained on wood samples and small specimens obtained from them (Ilic 2003; Haines et al. 1996). Moreover, the differences between sample dimensions were small and did not take into account the effect of defects (knots or small cracks). For example, Ilic (2003) compared specimens measuring $300 \times 20 \times 20$ mm with smaller specimens measuring $120 \times 20 \times 1.6$ mm. Here, the elastic properties of structural timbers measuring 63×43 mm of cross-section and 645–2,080 mm in length were compared with elastic properties of small specimens measuring $410 \times 25 \times 25$ mm in length.

Dynamic tests of wood

While flexural vibrations are influenced by the shear effect, the longitudinal vibrations can be affected by the Poisson effect when the length-to-thickness ratio of the beams is small (Rayleigh 1877). Early studies on the dynamic tests of wood (Hearmon 1961, Ilic 2001) showed important differences between E_L and E_F ; however, when Ilic (2001) applied the Timoshenko correction, the difference between E_L and E_F varied from 13% (for uncorrected E_F) to 1.1% (for corrected E_F). Table 1 shows that the average value of E_L was higher than that of E_F for the scantlings, although there was no statistically significant difference between the elastic modulus values. In this study, the differences between E_L and E_F did not come from shear effects on flexural vibration because the model used to estimate the E_F takes into account the shear effect. Here, the solution proposed by Bordonné (1989) was applied to the Timoshenko (1921) motion equation for the first four vibration modes of the wood beams. Moreover, the Poisson effect in longitudinal vibrations is negligible because the length-to-thickness ratio of the scantlings and small specimens was superior to 30 and 15, respectively. Additional factors affecting the flexural vibrations were reported by Murphy (2000).

The nominal dimension of each freshly cut scantling was $45 \times 60 \times 2,100$ mm, but after air and kiln drying, the pieces of wood were trimmed to variable dimensions. Thus, scantlings of different lengths were evaluated. At the outset, it was believed that this experimental condition would be a limitation of this study;

however, the tightness of the correlations shows that the system is suitable for characterizing wood of any dimensions, with good accuracy and repeatability.

Stiffness and density of wood

It is well known that the values of the modulus of elasticity increased with increasing wood density (Kollmann and Coté 1968), especially in small specimens. This is also valid for relationships between density and vibrationally deduced elastic constants since a number of studies have demonstrated the linear correlation between static and dynamic tests (Sinclair and Farshad 1987; Ilic 2001; Brancheriau and Baillères 2002). Thus, as expected, the density of the scantlings showed good correlation ($r = 0.79\text{--}0.84$) with their elastic properties (Table 2). E_L presented higher correlations with density than E_F , both for the scantling and for the small specimens. The main reason for this trend is the lower uncertainty of measurement for the longitudinal test. The higher correlations with density for E_L are in accordance with the findings by Ilic (2001), who tested small samples of *Eucalyptus delegatensis* R. Baker and found good correlations between air-dried density and longitudinal ($r = 0.83$) and flexural ($r = 0.81$) dynamic elastic modulus. Bektas et al. (2002) showed good relationships between compression strength and air-dry density, static bending strength, and oven-dry density, and impact bending strength and oven-dry density; the coefficients of correlation (r) were 0.71, 0.75, and 0.73 for these data, respectively.

Scale effect on mechanical properties of wood

Jiang et al. (2010) state that when compared with the small, clean specimen, a lower relationship between mechanical and/or physical properties could be obtained for the large pieces of wood due to their defects. However, here, it was shown that longitudinal elastic moduli of the scantlings (E_{Lsc}) were useful for estimating the flexural elastic modulus of the specimen (E_{Fsp}). The results of this study show that vibration analysis of large pieces of wood can be used to estimate the stiffness of small specimens.

The plots presented in Figs. 2 and 3 clearly show that the specimens present lower modulus of elasticity than the scantlings where they were sampled from. The reason for this trend is explained by the procedure to cut specimens from scantlings. The technician systematically surfaced the internal side (near the pith) of each scantling with the plane machine and then he cut the beams from them. Hence, the specimens represent the less stiff portion of the scantlings and the cloud of points remains always below the dotted line. Thus, the resonance frequencies of scantlings can over- or underestimate the stiffness of specimens depending on the sampling procedure.

The results of this study showed that the stiffness of wood varied strongly along the same scantling. This observation can be attributed to the existence of factors such as knots, grain slope, and shake that affects the mechanical properties of wood. If the purpose is to use these scantlings as structural timber, this variability can be a major problem.

Averaged elastic properties of specimens per scantling

The elastic properties of the small specimens were averaged to a single value per scantling (each scantling yielded 1, 2, 3, or 4 specimens). As expected, when the values of the properties of specimens were averaged to a single value of small specimens per scantling, the correlations between properties of small and large wood samples were higher (correlations above the diagonal in Table 2). For instance, the correlations between the E_L of the scantlings and the correspondent averaged E_F of the specimens ($R^2 = 56.8$; Fig. 3) were better than the relationships presented in Fig. 2 ($R^2 = 40.4$). Averaging the elastic properties of specimens, the variability within the beam, and the uncertainty of the measurement is minimized. From the last line of Table 2, some important considerations can be drawn. First, the average modulus of elasticity of the specimens presents weak correlation with the density of the scantlings ($r = 0.55$), while a moderate correlation ($r = 0.79$) was obtained for the density of the specimen. This means that the specimens with high density are stiffer; however, high-density scantlings will not necessarily provide stiffer wood. Second, longitudinal tests on scantlings gave a modulus of elasticity adequately correlated with the flexural test of small specimens (0.64). The flexural test on the scantlings also provides good correlations with E_F of specimens, but of lesser magnitude (0.61). Using the averaged values of elastic properties, E_F of the specimens was satisfactorily correlated with E of the scantlings (0.75) for both vibration modes. These results can be useful for initial classifications, screenings, or preliminary selections. As reported by Burdzik and Nkwera (2002), this method proved to be fast and highly repeatable and does not require heavy equipment, making it the ideal method for the on-site determination of wood stiffness at the sawmill.

One aspect not covered in this study was the effect of grain slope on transverse vibration modulus. It is well known that spiral grain reduces both strength and stiffness of wood (Skatter and Kucera 1997) and that the stiffness differs in each of the orthogonal directions of wood (Kollmann and Coté 1968). As the small samples are cut carefully with orthogonal faces, the effect of the grain slope on wood stiffness may play a major role on the scantlings.

Viscoelastic properties of wood

Internal friction (loss tangent— $\text{tg } \delta$ —or damping coefficient) is the term used to denote the mechanism that causes energy dissipation when wood is strained (Green et al. 1999). Previous studies involving the loss tangent have demonstrated that there is a relationship between internal friction and specific modulus (E/ρ). For instance, Ono and Norimoto (1984) used a non-linear model to establish the correlation between specific modulus and internal friction on 30 kinds of broad-leaved woods, taking into account the effect of wood porosity. Obataya et al. (2000) also found a non-linear relationship between E' and $\text{tg } \delta$ in *Picea sitchensis* Carr. Most of the studies regarding this issue were done for noble woods because of the use of wood for the manufacture of musical instruments. According to Ono and Norimoto (1983, 1984), wood having high specific modulus and low loss tangent is suitable for

soundboards, for instance. Previous studies have used this criterion for evaluating the potential of alternative wood species as substitute materials for violin bows, but some findings indicate that specific modulus and low loss tangent are not the main factors affecting the vibrational properties (Minato et al. 2010).

The correlation between loss tangent and specific modulus for *Eucalyptus* wood is poorly reported in literature. Moreover, loss tangent is a wood characteristic hard to accurately measure. In *Eucalyptus* from plantations, the basic visco-elastic properties of wood are of interest since they play a role when attempting to reduce the energy consumption of mechanical pulping in paper and pulp industry (Havimo 2009). In the present study, a roughly linear correlation ($r = 0.59$) between specific modulus (E/ρ) and loss tangent from flexural vibration for 141 small specimens was found (Fig. 4). This $E' \times \text{tg } \delta$ plot for *Eucalyptus grandis* \times *urophylla* was quite similar to the non-linear correlations reported by Ono and Norimoto (1983, 1984, 1985) and Obataya et al. (2000). Figure 4 shows no tendency according to the radial position where the specimens were sampled. In contrast, Yano (1994) reported higher $\text{tg } \delta$ values for heartwood than for sapwood specimens of *Thuja plicata*. The trends observed by Yano (1994) can be attributed to the extractive presence, which is less evident in juvenile wood such as the 6-year-old *Eucalyptus* samples in this study. Variations in moisture content also affect the damping properties (Green et al. 1999), although this factor is negligible in this study because the wood samples used here had the same moisture content.

According to Ono and Norimoto (1984, 1985), the values of elastic modulus and loss tangent of wood are determined in large parts by the microfibril angle in the S_2 layers of the wood cell. According to these authors, the specific modulus decreases and the loss tangent increases with increasing average microfibril angle within the cell walls.

Conclusion

The relationships between the mechanical properties obtained on large pieces of wood (scantlings measuring $\sim 45 \times \sim 60$ mm of cross-section and a length ranging from 645 to 2,080 mm) and small specimens (measuring $25 \times 25 \times 410$ mm) were investigated. Correlations were found from 0.68 to 0.75 between E of scantlings and small specimens of *Eucalyptus* wood when E of the scantling was compared with the averaged E of the specimens per scantling. When the E_F value of each single specimen was compared with its respective scantling, the coefficient of correlation decreased to 0.64 in the longitudinal tests and to 0.61 in the flexural tests. A roughly linear correlation ($r = 0.59$) between specific modulus and loss tangent was obtained for the small specimens of *Eucalyptus*.

The findings demonstrate that resonance technique can potentially characterize the mechanical properties of wood in a simple and rapid way and at low cost. The dynamic tests enabled to rapidly estimate key mechanical properties (such as the Young's, the shear modulus and the loss tangent) of the wood even in lumbers containing knots, small cracks, and also slightly damaged areas. In short, the

resonance technique rapidly provided a large accurate data set of mechanical wood properties as required for high-throughput phenotyping in recent genetic studies.

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