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ORIGINAL ARTICLE

Acoustic and bending properties in *Pinus elliottii* beams obtained from trees of different ages

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Abstract In contrast to wood from native forests, the lumber harvested from planted forests is primarily composed of boards from younger trees. Given the possibility of using wave propagation methods to classify wood for structural purposes, it is important to evaluate if the ultrasonic parameters tend to vary with the age of the tree in a similar manner as static bending parameters. Experiments were conducted using structural beams taken from *Pinus elliottii* trees that were 8, 9, 13, 15, 22 and 23 years old. The beams were tested by ultrasound in the longitudinal direction and by static bending. The results showed that age of the tree influences the wave propagation velocity, stiffness constant and modulus of elasticity. The results were sorted into two groups based on the variation of these parameters: wood pieces from trees up to 15 years old and wood pieces from trees older than 15 years of age. Statistically, the flexural strength did not change with age due to the significant influence of knots on this parameter, which overcomes the influence of age. The data obtained by ultrasound follow the same trends with age as the elastic modulus in static bending.

Keywords Wave propagation velocity · Ultrasound · Stiffness coefficient · Longitudinal modulus of elasticity · Flexural strength

Introduction

In Brazil, there is a standard for the classification of hardwood by means of ultrasound [1], and there is currently a similar rule being studied for application to softwoods. This mechanical classification by ultrasound, coupled with visual classification, will be used for the calculation of the modification coefficient ($k_{mod,3}$) in the standard of design of timber structures [2], which is in the final stages of revision in Brazil.

In the standard of structural timbers grading by ultrasound, the elastic modulus in bending (E_M) is the main property associated with the propagation velocity of ultrasound waves (V_{LL}) or the coefficient of the stiffness matrix (C_{LL}). The other properties (characteristic resistance in compression, $f_{c0,k}$, and elastic modulus in compression, E_{c0}) were statistically matched with each grading range. These properties ($f_{c0,k}$ and E_{c0}) were adopted so that they could be associated with the Brazilian Standard for the Design of Wood Structures [2], as the standard is based on those parameters.

The standard [1] was developed using wood from native tropical species with an average age of 40 years as reference material. In Brazil, however, the wood of planted forests has been marketed at much younger ages. Thus, it is important to assess whether ultrasound parameters (V_{LL}

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and C_{LL}) tend to vary with the age of the tree in a similar manner as those obtained in static bending tests (E_M and f_m—flexural strength).

There are many articles that present research aimed at assessing the influence of age on wood properties using a variety of methodological approaches. One approach, used by is to use structural parts or specimens taken from trees of different ages [3–5]. Another methodology involves using trees of the same age and obtaining the variation by the radial removal of the specimens [6–9]. In this approach, the most common method is the removal of small specimens, and the analyzed sample must be entirely within the growth rings that are considered to correlate with age. Studies evaluating the varying properties of juvenile and mature wood are also related to age assessment, although indirectly [10–14].

The main objective of the present study was to evaluate the variation of the parameters obtained from the ultrasound test (V_{LL} and C_{LL}) and those obtained in static bending tests (E_M and f_m) as a function of age. The results will support work being conducted in Brazil toward the development of an ultrasound-based classification standard for conifers.

Materials and methods

Pinus elliottii trees that were 8, 9, 13, 15, 22 and 23 years old were harvested from forests. Two trees were taken for each age, resulting in a total of 12 trees. The trees were randomly selected from forests located in Santa Catarina that belong to the company Rotta Timbers. Trees from the edge of the forest or with obvious growth or health problems were excluded. Table 1 contains the georeferencing data of the forests, the average diameter of the trees at breast height (DBH, 1.3 m above ground) and the number of beams obtained from the trees of each age (repetitions for each age).

One to three 3.5-m-long logs were removed consecutively from the trees. The number of logs obtained from each tree depended on the diameter of the tree, and the minimum diameter was that which was sufficient for the removal of boards with a minimum cross section of 0.05 m × 0.10 m. This cross section was adopted according to the Brazilian Standard for the Design of Wood Structures [2], which indicates that major structural components must have a minimum area of 0.005 m^2 and a minimum cross-sectional size of 0.05 m.

Considering the nature of tree growth, various ages are represented in the diameter and length. However, the objective of the present study was not to separate ages within a tree but to associate the average results with the age of the forest from which the beams were removed. Moreover, as it was necessary to use boards with structural dimensions for the purpose of this research, there was no way to remove them to ensure that they only contained growth rings for a specific age range, even in trees with a larger diameter. Thus, the results comprise average values obtained for age, irrespective of the radial or longitudinal position on the trunk. A similar consideration was used by other authors [3–5].

Immediately after cutting the trees, the logs were split into 90 beams that were 0.05 m wide (w), 0.10 m high (h) and 2.5 m long. The splitting was performed at the sawmill of the company (Rotta Timbers), and due to the specific process, it was impossible to map the position of the beams relative to the diameter of the log. The pith was not discarded during the splitting process.

The beams were tested by ultrasound in green condition. After these tests, the beams remained in a temperature- and humidity-controlled drying chamber until they reached the equilibrium moisture content that in Brazil is about 12 %. At this moisture level, the beams were once again measured using ultrasound. This procedure was performed because the standard [1] provides the classification of the beams using the velocity in green condition (V_{LLsat}) or the coefficient of the stiffness matrix (C_{LL}) obtained with the velocity in wood in equilibrium moisture content (V_{LL}). The Brazilian standard [1], which was designed for hardwood species, was utilized only with regard to the ultrasound test methods.

The time measurements of wave propagation were performed, for tests in both moisture content conditions, using ultrasound equipment (USLab, AGRICEF, Brazil) and flat-faced 45 kHz transducers. For these measurements, the transducers were positioned at the ends (direct longitudinal propagation) on three points of the cross section in accordance with Brazilian standard [1]. Medicinal

Table 1 Georeferencing data, average diameter and number of beams for each age

Age	Coordinates	Altitude (m)	DBH (mm)	Number of beams
8	S 26°41′16.1″/W 51°3′2.0″	1,027	223.5	6
9	S 26°41′35.2″/W 51°3′15.5″	1,080	222.5	4
13	S 26°41′35.2″/W 51°3′15.5″	1,080	240.5	8
15	S 26°41′52.8″/W 51°4′21.9″	1,001	261.0	15
22	S 26°41′52.8″/W 51°4′21.9″	1,001	278.5	20
23	S 26°41′35.2″/W 51°3′15.5″	1,080	364.5	37

DBH diameter of the tree at breast height gel was used as coupling media. Figure 1 illustrates the test and shows the equipment utilized for the measurements.

The average velocities were calculated using the wave propagation time (t), path length (in this case, the length of the beam, L_v) and longitudinal velocities (V_{LLsat} and V_{LL}) obtained in three positions using the following equation:

$$V_{LL} = \frac{L_v}{t} \times 10^6 \qquad (1)$$

With the average ultrasound wave propagation velocity (V_{LL}) and the apparent density (ρ), both of which obtained with the beam in the equilibrium moisture content condition, the coefficient of the stiffness matrix (C_{LL}) was calculated using following equation:

$$C_{LL} = \rho V_{LL}^2 \qquad (2)$$

The length of the beams (L_v) in the static bending test was adopted such that the span (L) was >21 times the height (h) of the beam, thereby minimizing the effects of shear in this experiment.

Given that the Brazilian standard [2] presents only normative tests for small-sized, clear specimens, static bending tests on beams were performed using American standard [15].

Although the flexural strength (f_m) is not covered by the Brazilian standard [1], this parameter was evaluated in the present study because it is accepted worldwide as an important parameter for wood grading.

The longitudinal elastic modulus (E_M) and flexural strength (f_m) were obtained from the static bending test using Eqs. (3) and (4), respectively. To determine the elastic modulus, vertical displacement measurements (Δ) were taken from the central point by means of an electronic linear position transducer with a resolution of 0.001 mm coupled to a data acquisition system (Quantun, HBM, Germany), which allows automated load and deformation readings. The adopted standard [15] indicates that the linear region chosen for the calculation of the elastic modulus is the responsibility of the user; however, ranges from 10 to 30 % or from 20 to 40 % of the maximum load (P_{max}) are typically used. The range adopted for the calculation of the elastic modulus in the present study was from 20 to 40 % of the maximum load (P_{max})

$$f_m = \frac{3P_{max}L}{2bh^2} \qquad (3)$$

$$E_M = \frac{(P_{40\%} - P_{20\%})L^3}{4bh^3(\Delta_{40\%} - \Delta_{20\%})} \qquad (4)$$

The variation of the parameters of the ultrasound test (V_{LL} and C_{LL}) and static bending test (E_M and f_m) on the beams as a function of age was evaluated statistically.

Results and discussion

The average results for V_{LLsat}, V_{LL}, E_M and f_m in the equilibrium moisture content condition (approximately 12 %) are shown in Table 2.

The average values of V_{LLsat} increased by 53 % from 8 to 15 years of age and fluctuated by approximately 3 % from 15 to 23 years of age. V_{LL} increased by 33 % from 8 to 15 years of age, remained nearly constant between 15 and 22 years of age and decreased by approximately 4 % after 23 years of age. C_{LL}, E_M and f_m, the latter two of which were obtained during the static bending test, increased by 58, 72 and 26 %, respectively, from 8 to 15 years of age. C_{LL} and E_M decreased by 2.2 and 1.8 %, respectively, from 15 to 23 years of age, while f_m increased by 16 % for the same age range.

The behavior of the wave propagation velocity was obtained in *Pinus radiata* trees from Greymouth, New Zealand, that were 8, 16 and 26 years old and concluded that the age of a tree had a large influence on the acoustic

Fig. 1 Transducer position on transversal section of the beam for the direct longitudinal time flight measurement (**a**) and ultrasound equipment used for the tests (**b**)

Table 2 Average values by tree age

Age (years)	Saturated condition	Equilibrium condition (moisture content of 12 %)				
	V_{LLsat} (m s^{-1})	ρ (kg m^{-3})	V_{LL} (m s^{-1})	C_{LL} (MPa)	E_{M} (MPa)	f_{m} (MPa)
8	2,153 (12.6)	419.5 (9.1)	3,758 (11.8)	6,681 (15.6)	4,001 (16.7)	34.0 (19.3)
9	2,355 (24.5)	442.6 (7.7)	3,991 (9.3)	6,377 (30.3)	3,893 (52.6)	30.8 (34.9)
13	3,094 (13.8)	448.4 (5.3)	4,568 (10.8)	9,387 (18.9)	6,064 (16.3)	44.0 (15.5)
15	3,287 (12.5)	419.4 (6.2)	4,984 (10.5)	10,581 (23.4)	6,899 (20.7)	42.8 (26.0)
22	3,388 (15.3)	458.7 (10)	4,961 (12.1)	11,587 (30.8)	7,715 (23.8)	48.6 (29.7)
23	3,187 (25.1)	453.9 (13)	4,759 (15.1)	10,814 (39.3)	6,779 (37.5)	49.6 (41.5)

Values in brackets represent the coefficient of variation (%)

V_{LLsat} longitudinal velocity in green condition, ρ apparent density at equilibrium moisture content, V_{LL} longitudinal velocity at equilibrium moisture content, C_{LL} stiffness coefficient at equilibrium moisture content, E_{M} modulus of elasticity at equilibrium moisture content, f_{m} flexural strength at equilibrium moisture content

properties of its wood [6]. In absolute numerical terms, the velocities obtained by those authors [6] are well below those obtained in the present study, especially at 16 (2,360 m s^{-1}) and 26 years of age (2,870 m s^{-1}). However, it is important to remember that in addition to dealing with another species of pine, the values in Table 2 refer to velocities obtained for beams, while those of those authors [6] were for standing trees. The variation of speed with age increased continuously and was 42 % in the range from 8 (2,020 m s^{-1}) to 26 years of age (2,870 m s^{-1}) [6]. The C_{LL} was obtained using the speed and density in the green condition [6]. From 8 to 16 years of age, C_{LL} increased by 28 % (6.58–8.44 GPa), and from 16 to 26 years of age, it increased by 36 % (8.44–11.52 GPa) [6].

The behavior of the variations in V_{LL} and C_{LL} that has been reported [6] was different from that obtained in the present study as these parameters increased more sharply from 16 to 26 years of age in their study, while the parameters in the present study increased until 15 years of age and then became relatively constant. However, it is worth noting that the C_{LL} calculated was in the saturated condition [6], and in the present study, the equilibrium moisture condition was used. Moreover, the experiments [6] were conducted on trees, while the present study used beams, making comparison difficult due to other parameters that may have influenced the results. Comparisons are especially important in analyzing the overall behavior of the speed according to the age of the tree and verifying the accuracy of the values obtained in terms of magnitude.

The strength and stiffness properties were obtained from the static bending tests of the wood of *Eucalyptus obliqua* trees from Tasmania that were 36, 54, 69 and 102 years old, and showed no significant differences between the stiffness properties (E_{M} and f_{m}) or density of the trees with age [3]. Given that this author [3] only used trees that were already considered to be mature, this result appears compatible with those obtained in the present study, which showed that the properties remain relatively constant above a certain age.

Tests with boards and specimens of *Pinus taeda* trees harvested from six trees that were 34 years old and evaluated the change in velocity with age in parts removed from different annual growth rings, concluding that the velocities of wave propagation in specimens of mature wood were always higher than those obtained from regions of juvenile wood [8]. For *Pinus taeda*, a research [13] concluded that juvenile wood would be present until the 14th growth ring. This result [13] is in agreement with those obtained in the present study because the properties for timber from a mature tree are considered to be constant.

Certain mechanical properties of wood from a hybrid clone of *Eucalyptus grandis* × *Eucalyptus urophylla* were studied at two ages (6 and 14 years) [4]. The flexural strength (f_{m}) increased by 24 % with age, and the elastic modulus (E_{M}) increased by 28 %. Given a range with approximately the same ages as those with the authors [4], 8–13 years old, the variation in f_{m} was close to those obtained in the present study (29 %); however, the variation in E_{M} was much lower (52 %).

The normality of the velocity data (dry and saturated), apparent density, modulus of elasticity and flexural strength obtained in bending were verified using the statistical parameters of asymmetry and kurtosis and the normal probability plot. The normality assumption could be accepted for all parameters, thus ensuring the validity of the statistical analyses that follow.

Table 3 summarizes the results of the statistical analyses for the comparison of means between the groups represented by different ages. This analysis was made using the complete sample. This table shows that V_{LLsat}, V_{LL}, C_{LL} and E_{M} behave similarly and describe two regions with a transition point between 13 and 15 years of age. Density and f_{m} did not differ significantly with age. For f_{m}, this result may be related to the large influence of defects (e.g.,

Table 3 Average variation with tree age

	8 years old	9 years old	13 years old	15 years old	22 years old	23 years old
V_{LLsat} (m s^{-1})*	2,153a	2,354a	3,094ab	3,287b	3,888b	3,187b
V_{LL} (m s^{-1})*	3,758a	3,991a	4,568ab	4,984b	4,961b	4,759b
ρ (kg m^{-3})	419.4a	442.6a	448.4b	419.4a	458.7a	453.9a
C_{LL} (MPa)*	6,681a	6,377a	9,387ab	10,581b	11,587b	10,814b
E_M (MPa)*	4,001a	3,893a	6,064ab	6,899b	7,714b	6,779b
f_m (MPa)	34.4a	30.8a	44.0a	42.8a	48.6a	49.5a

Multiple range test: numbers followed by the same letters indicates that there is no significant difference among groups of different ages at 95 % confidence level

V_{LLsat} longitudinal velocity in green condition, V_{LL} longitudinal velocity at equilibrium moisture content, ρ apparent density at equilibrium moisture content, C_{LL} stiffness coefficient at equilibrium moisture content, E_M modulus of elasticity at equilibrium moisture content, f_m flexural strength at equilibrium moisture content

* There is a significant difference of the evaluated parameters with age

knots, slope of the tracheids), which can overcome the influence of age. While the differences in average values appear large, especially between 8 and 9 years of age, the variability of values within the same age group exceeds the variability between ages, generating statistical equality.

For *Sitka spruce*, the longitudinal velocity increased continuously until 14 years of age and that above this age, the velocity stabilized [12]. This author [12] states that this behavior was observed for logs removed from the area at breast height (1.30 m above ground), central logs and logs obtained from the top of the tree trunk, i.e., the behavior was the same regardless of the longitudinal position of the withdrawal of the logs.

Results obtained for pine trees show a strong increase in the longitudinal velocity (V_{LL}) with tree age until 9 years of age and small changes in velocity (both upwards and downwards) above that age [12]. This behavior is consistent with those observed in the present study.

The variation in wood properties with age of *Pinus taeda* from the region of Sengés in Parana, Brazil was evaluated [5]. For this purpose, timber from trees that were 9, 13 and 20 years old was used. The results obtained by the authors [5] showed that neither the apparent density nor the flexural strength (f_m) is statistically affected by age, as confirmed in the present study. Nevertheless, numerically (using averages) the authors [5] did observe significant trends in the density and f_m according to tree age. The density increased by 14 % from 9 to 13 years of age and by 14 % from 13 to 20 years of age, while f_m increased by 27 % from 9 to 13 years of age and by 19 % from 13 to 20 years of age.

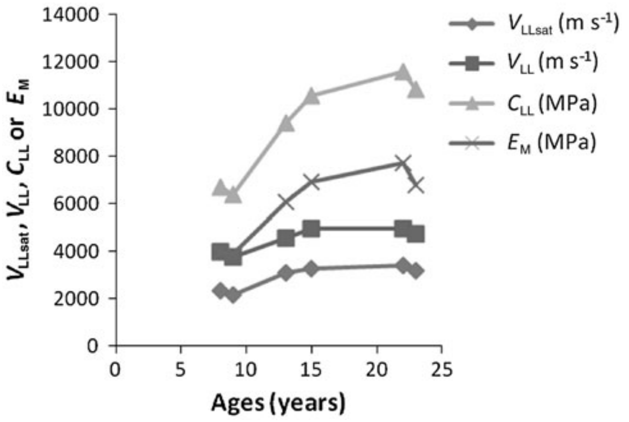

Fig. 2 Behavior of the average velocity values in the green condition (V_{LLsat}) and equilibrium condition (V_{LL}), the coefficient of stiffness (C_{LL}) and the elastic modulus (E_M) according to the age of the tree from which the beams were removed

The graphs in Fig. 2 represent the behavior of the acoustic and mechanical parameters that showed statistically significant variation with age. This figure shows that the destructive and non-destructive parameters have the most significant growth up to 15 years of age and then continue to grow more slowly or remain relatively constant. In addition, the behaviors of the results obtained in non-destructive and destructive tests have the same trends of change with age, indicating the sensitivity of the non-destructive tests for detecting variations in mechanical properties with age. Due to the changes in the slope of the graph from 8 to 15 years of age and from 15 to 23 years of age, regression analyses were performed by separating these two data segments.

Table 4 summarizes the regression results for each parameter as a function of age with the two ranges of variation highlighted by statistical analysis. When the P value of the ANOVA table is ≤0.05, there is a statistical correlation between the parameters evaluated within a 95 % confidence level. The correlation coefficient is shown in these cases. The regressions were performed with all of the values, not only the averages as in Fig. 2. Using the average for each age, the regression models do not change significantly, but the correlation coefficients (R) increase significantly because the numbers of pairs in the range

Table 4 Regression models

Regression	R	P value*
Range considering samples from 8 to 15 years of age		
$V_{\mathrm{LLsat}} = 10{,}241 + 150 \times \mathrm{age}$	0.76	0.0000
$V_{\mathrm{LL}} = 2{,}556 + 160 \times \mathrm{age}$	0.70	0.0000
$C_{\mathrm{LL}} = 1{,}551 + 602 \times \mathrm{age}$	0.66	0.0000
$E_{\mathrm{M}} = 288 + 443 \times \mathrm{age}$	0.71	0.0000
Range considering samples above 15 years of age		
$V_{\mathrm{LLsat}} \times \mathrm{age}$	–	0.8261
$V_{\mathrm{LL}} \times \mathrm{age}$	–	0.3029
$C_{\mathrm{LL}} \times \mathrm{age}$	–	0.8064
$E_{\mathrm{M}} \times \mathrm{age}$	–	0.9367

V_{LLsat} longitudinal velocity in green condition, V_{LL} longitudinal velocity at equilibrium moisture content, C_{LL} stiffness coefficient at equilibrium moisture content, E_{M} modulus of elasticity at equilibrium moisture content

* Since the P value is <0.05, there is a statistically significant relationship between variables at 95 % confidence level

from 8 to 15 years of age and from 15 to 23 years of age were reduced to four and three instead of 33 and 72, respectively. However, the significance of the model is reduced using a few pairs of values.

Table 4 shows that in above 15 years of age, there is no statistical correlation between age and the destructive and non-destructive testing parameters (P value >0.05), indicating no influence of age, as shown in the graphs. For the range from 8 to 15 years of age, there is a statistically significant correlation for the destructive and non-destructive parameters. In the regression models, age appears to have the greatest influence on C_{LL} (higher slope coefficient), followed by E_{M} and the velocity (V_{LLsat} and V_{LL}).

Conclusion

The variation of the velocity of propagation of ultrasound waves in the direction parallel to the grain (V_{LLsat} and V_{LL}), the stiffness coefficient (C_{LL}) and the elastic modulus as a function of age showed the same pattern, increasing more rapidly until 15 years of age and then increasing at a slower rate or remaining constant. The C_{LL} was most affected by age, followed by E_{M} and V_{LL}. The flexural strength (f_{m}) showed no statistically significant variation with age.

Based on these results, it is possible to conclude that the classification of very young wood using V_{LLsat} classification ranges obtained from mature wood may result in E_{M} predictions above the actual range because the velocity in newer timber is 53 % lower than that in the stable zone (with little variation in acoustic and elastic properties), while E_{M} can vary by up to 72 %.

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