Methodology for the Characterization of Elastic Constants of Wood from Tree Branches

Raquel Gonçalves,[a,]* Gustavo Henrique Lopes Garcia,[b] Sergio Brazolin,[c] Cinthya Bertoldo,[d] and Monica Ruy [b]

In biomechanical analyses, computational models are essential tools for simulating the behavior of a tree subjected to a load. However, such models allow only approximation of the actual behavior of the tree if the elastic parameters of the wood in different tree parts (stem, branches, and roots) and at least orthotropic behavior are not considered. In addition, as the wood is green, the parameters of strength and stiffness must be adequate for this level of moisture. However, even for stem wood, knowledge of elastic properties is not available for most species used in urban tree planting, and this scarcity of information is even greater for wood branches. The objective of this research was to evaluate methodology, based on wave propagation, in characterizing the 12 elastic constants of wood from branches. Complementarily, compression tests were performed to characterize the strength. The obtained elastic parameters using ultrasound tests were comparable with the values expected based on theoretical aspects related to the behavior of the wood. The results of the compression test complemented the ultrasound characterization, but the application of this method for the complete characterization of the elastic parameters is not feasible for tree branches because of their small size.

Keywords: Biomechanics; Longitudinal modulus; Poisson ratio; Shear modulus; Strength; Ultrasound

*Contact information: a: Professor – School of Agricultural Engineering (FEAGRI), University of Campinas (UNICAMP) Av. Cândido Rondon, 501 - Cidade Universitária, Campinas - SP, 13083-875-Brazil; b: PhD student– FEAGRI/UNICAMP; c: Researcher – Institute for Technological Research (IPT) Av. Prof. Almeida Prado 532 Cid. Universitária - Butantã. 05508-901 São Paulo/SP.- Brazil; d: Assistant Professor – FEAGRI/UNICAMP; * Corresponding author: raquel@feagri.unicamp.br*

INTRODUCTION

Lack of knowledge about the mechanical properties of wood from species used in urban arborization and of green wood has been an important obstacle to the development of studies related to biomechanics (Cavalcanti *et al*. 2018). This lack of knowledge is related to the small or nonexistent commercial appeal of these species and of the green moisture condition because they are not important for the construction sector, which is the primary area of demand for mechanical properties. This lack of knowledge is even worse for wood branches (Casteren *et al*. 2013).

One aspect of great importance in biomechanical studies of trees is wood stiffness because this parameter is responsible for the response of wood to the strain and displacements of its limbs (trunk, branches, and roots) when subjected to actions such as self-weight, wind, or snow. Aspects related to stiffness are also important for the movement of animals, such as monkeys, in trees because branches with great flexibility hinder the movement of animals by requiring a greater energy expenditure (Casteren *et al.* 2013).

As in the case of stiffness, strength properties are important in biomechanical studies of trees because they are related to the rupture of branches, trunks, and roots. Casteren *et al*. (2013) note that this property is also greatly important for animals that use tree branches to build their nests and to move around.

Because of the current need for a better use of natural resources, research has been carried out to analyze the physical and mechanical properties of wood branches, including for structural utilization (Dadzie *et al.* 2016). This study was carried out with wood at equilibrium moisture content, consistent with most of structural applications. Nevertheless, information about the mechanical properties of branches under green conditions and from species used in urban arborization is scarce. In searching for literature on the stiffness of green branches, important contributions were found from studies of monkey behavior (Thorpe *et al*. 2007; Gilman *et al.* 2011). The flexibility of the branches has a great influence on the mobility of animals, but no literature data are available. Current studies related to biomechanics that aim to analyze a tree's behavior as a structural element have proposed the use of computational models that allow simulation of this behavior (Lang and Kaliske 2013; Martinez and Dias 2016). However, the use of more complex models that are able to more closely approximate the actual condition of the tree requires knowledge of the complete elastic properties (compliance matrix), not the properties in only longitudinal direction as is generally found. If one considers wood to be an orthotropic material, this means knowing 12 elastic constants.

The 12 elastic constants of wood (three longitudinal modulus, three shear modulus, and six Poisson’s ratio) can be obtained using static tests but the methodology is expensive and laborious because it is necessary to use 6 specimens for one test – 3 specimens obtained in axes and 3 specimens obtained out of axes and around 36 strain-gages (Sinclair and Farshad 1987). So, researchers around the world were trying to obtain other techniques and methodologies to obtain these wood constants. The theoretical basis to obtain these constants using wave propagation was proposed by Christoffel in the 1800s and, driven by technological advances in transducers, authors have resumed studies with the goal of proposing methodologies based on this theory to obtain the complete characterization of wood (Preziosa *et al.* 1981; Preziosa 1982; Bucur and Archer 1984, Bucur and Perrin 1988; François 1995; Bucur and Rasolofosaon 1998; Gonçalves et al 2011a; Ozyhar *et al.* 2013; Gonçalves *et al.* 2014; Vázquez *et al.* 2015).

Considering the mentioned aspects, the objective of this paper was to present a methodology, associating ultrasound and compression test, and preliminary results for the complete elastic characterization of wood from tree branches of species used in urban arborization. The experimental design consisted of 80 specimens (37 for ultrasound tests and 43 for compression tests) collected from 16 pieces of branches obtained from 2 or 3 fork levels on six species of urban trees.

EXPERIMENTAL

Materials

For the seven trees sampled, pieces of branches were removed from the 2 or 3 first fork levels (Fig. 1). The trees sampled were obtained in urban areas of Campinas, São Paulo, Brazil. Campinas' climate is tropical in altitude (type Cwa according to Köppen), with a decrease in winter rainfall and an average annual temperature of 20.7 ° C, with mild, dry winters and rainy summers with moderately high temperatures. The warmest month in

February has an average temperature of 23.4 ° C and the coldest month in July is 17.2 ° C. Fall and spring are transitional seasons. The average rainfall is approximately 1350 mm annually, concentrated between October and March, with January having the most precipitation (226 mm).

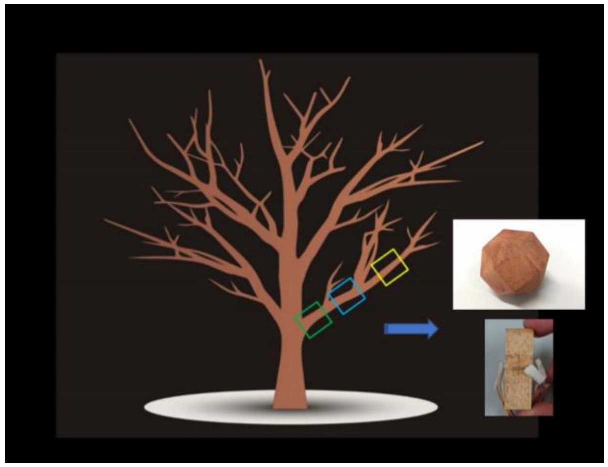


Fig. 1. Schematic of the locations of the pieces removed from branches at different fork levels and of the ultrasound (polyhedral) and static compression (prismatic) test specimens

The adoption of 2 or 3 fork levels depended on the diameter of the branch because it was necessary that the branch size was sufficient for the removal of the specimens. Polyhedral and prismatic specimens were obtained from each branch section for ultrasound and static compression tests, respectively (Fig. 1), according to the sampling indicated in Table 1.

Table 1. Number of Specimens Used in the Ultrasound and Static Compression Tests for Each Species and Fork Level

SPECIES	TREE	FORK 1	FORK 2	FORK 3	TOTAL SPECIMENS
ULTRASOUND					
Schinus terebinthifolia	1	2	2	2	6
Inga sessilis	1	2	2	0	4
Swietenia sp.	1	2	2	0	4
Gallesia integrifolia	1	2	2	2	6
Schinus molle	2	2 4	3 2	0 0	5 6
Acrocarpus fraxinifolius	1	3	3	0	6
TOTAL	**7**	**17**	**16**	**4**	**37**
STATIC COMPRESSION					
Schinus terebinthifolia	1	4	4	4	12
Inga sessilis	1	2	2	0	4
Swietenia sp	1	5	2	0	7
Gallesia integrifolia	1	2	2	2	6
Schinus molle	2	2 4	3 2	0 0	5 6
Acrocarpus fraxinifolius	1	2	2	0	4
TOTAL	**7**	**21**	**16**	**6**	**43**

The minimum dimension of the specimen for the ultrasound test (polyhedral) is limited by the diameter of the transducer, which needs to be circumscribed to the face and by the theoretical bases of the waves propagation infinite media; this depends on the relationship between the length of wave propagation by the wave length (Bucur 2006). For the compression tests (prismatic specimens) the dimension was established based on the Brazilian Standard (ABNT NBR 7190) that indicate length 3 times the dimension of the edges.

The polyhedral specimens were produced using firstly a lathe machine to make a cylinder, allowing have the axes (longitudinal, radial, and tangential) to be well targeted. A milling tool was used with the cylinder to cut the angles necessary to produce the 26 faces of the polyhedron.

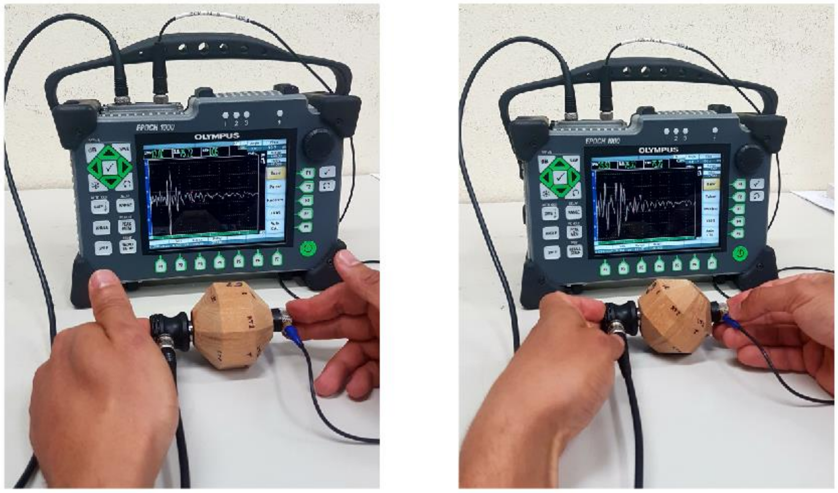
Methods

Ultrasound tests

Ultrasound tests were performed according to methodology used by this research group in the characterization of timber under equilibrium conditions (Gonçalves *et al*. 2014; Vazquez *et al.* 2015). This methodology can be regarded as adequate for the characterization of timber because by using just one polyhedral specimen (Fig. 1) it is possible to obtain the complete stiffness matrix, whose inverse allows the calculation of the compliance matrix. The compliance matrix allows calculation of the 12 elastic constants of the wood: modulus of elasticity in the longitudinal (E_L), radial (E_R), and tangential (E_T) directions; shear modulus in the radial-tangential (GRT), longitudinal-tangential (GLT) and radial-tangential (GRT) planes; and the 6 Poisson ratios (υ_{RL}, υ_{TL}, υ_{LR}, υ_{TR}, υ_{LT}, and υ_{RT}). For the wave propagation measurements, ultrasound equipment (Epoch 1000 series, Olympus, USA) and 1-MHz longitudinal and shear wave transducers were used.

The polyhedral specimen had nominal dimensions of 50 mm edges. These dimensions allow the transducer to completely bind to the face of the specimen, minimizing signal losses (Bucur 2006). Starch glucose was used as a coupling medium in all tests because it minimized signal losses, especially for shear waves (Gonçalves *et al*. 2011b).

For the test, the longitudinal transducers were positioned on the specimen faces parallel to the axis (Fig. 2a), allowing the propagation and polarization of the wave on the main axes: L (longitudinal), R (radial) or T (tangential). From these tests, the velocities V_{LL}, V_{RR}, and V_{TT} were obtained. Similarly, the shear transducers were positioned on the same faces of the specimen, allowing propagation on one of the main axes, L, R or T, and perpendicular polarization. With these measurements, the velocities V_{LR}, V_{LT}, V_{RL}, V_{RT}, V_{TR}, and V_{RT} were calculated. The first index corresponds to the propagation direction and the second the polarization direction. Considering the theoretical aspects related to the symmetries of stresses and strain accepted in orthotropic materials, the velocities V_{ij} should be equal to V_{ji}. In practice, there are small differences because the growth rings are not perfectly positioned nor totally free of curvature in the transverse section of the specimens. Thus, for the calculations, the average of the velocities obtained in V_{ij} and V_{ji} is adopted. To obtain the velocities outside the symmetry axes, the transducers were positioned on the inclined faces to each of the planes (Fig. 2b).



a b

Fig. 2. Example of the ultrasound tests on the main axes (a) and at 45° angle to the main axes (b). Source: Non-Destructive Testing Laboratory, FEAGRI/UNICAMP

Using the velocities obtained in the tests carried out along the symmetry axes (straight faces of the specimens), the stiffness coefficients of the diagonal of the matrix (Equation 1) were calculated,

$$C_{ii} = \rho . V_{ii}^2 \qquad (1)$$

where i = 1, 2, 3, 4, 5 and 6; ρ = density; and V = velocity of wave propagation.

In general, bulk density (ρ_{ap}) is used in Eq. 1. However, for green wood, large elastic constants will be obtained using ρ_{ap}, resulting in stiffness coefficients incompatible with theoretical basis from what it is expected uniform elastic constants above fiber saturation point (around 30% moisture content). Effective density can be used to obtain uniform elastic constants obtained by ultrasound for green wood (Sobue 1993; Mishiro 1996a,b; Wang *et al.* 2002; Gonçalves and Costa 2008), but its calculation requires ultrasound tests in different moisture content to obtain, by least squares method, the optimal k value that represents the free water mobility. So, to simplify the calculations and minimize the effect of moisture content on the stiffness coefficient, the basic moisture content was adopted in Eq. 1.

The three off-diagonal terms (C_{12}, C_{13}, and C_{23}) were obtained using the Christoffel equations (Eqs. 2, 3. and 4). For this, the velocities obtained in the inclined faces of the polyhedron, as previously described, were used.

$$(C_{12} + C_{66})\, n_1 n_2 = \pm \left[(C_{11} n_1^2 + C_{66} n_2^2 - \rho V_\alpha^{\,2})(C_{66} n_1^2 + C_{22} n_2^2 - \rho V_\alpha^{\,2})\right]^{1/2} \quad (2)$$

$$(C_{23} + C_{44})\, n_2 n_3 = \pm \left[(C_{22} n_2^2 + C_{44} n_3^2 - \rho V_\alpha^{\,2})(C_{44} n_2^2 + C_{33} n_3^2 - \rho V_\alpha^{\,2})\right]^{1/2} \quad (3)$$

$$(C_{13} + C_{55})\, n_1 n_3 = \pm \left[(C_{11} n_1^2 + C_{55} n_3^2 - \rho V_\alpha^{\,2})(C_{55} n_1^2 + C_{33} n_3^2 - \rho V_\alpha^{\,2})\right]^{1/2} \quad (4)$$

In Eqs. 2 through 4, α = wave propagation angle (out of symmetric axes); n_1 = cosine α, n_2 = sine α, and n_3 = 0 if α is taken with respect to axis 1 (Plane 12); n_1 = cosine

α, n_3 = sine α, and n_2 = 0 if α is taken with respect to axis 1 (Plane 13); and n_2 = cosine α, n_3 = sine α, and n_1 = 0 if α is taken with respect to axis 2 (Plane 23).

As using the generalize Hooke's Law, the stiffness matrix is equal to the inverse of the compliance matrix, the stiffness matrix was inverted to obtain the compliance matrix, and all the elastic parameters of the wood in the branches were calculated according to elasticity theory.

Compression tests

The static compression tests were performed to obtain the strength (f_c) because this parameter is not obtained from the ultrasound test. However, the specimens were analyzed with extensometers to measure the longitudinal strain, also enabling the determination of the modulus of elasticity in the longitudinal direction (E_L). The E_L value was later compared with those obtained by ultrasound. In cases where it was possible to obtain specimens with well-directed growth rings in the radial and tangential directions, the specimens were also analyzed in these two directions, allowing the calculation of the Poisson ratios υ_{LT} and υ_{LR}. Importantly, for the determination of the 12 elastic constants of the wood using the compression test, it was necessary to analyze 6 specimens for each replication: three specimens on the symmetry axes (L, R, and T) for the longitudinal elastic moduli and Poisson's ratio determination and another 3 specimens should be drawn at an angle with each of the symmetry planes (LR, LT, and RT) for the shear modulus determination. Considering the small size of the branches, the removal of these 6 specimens was unviable. For this reason, only the specimen whose loading direction coincided with the longitudinal direction was used for the compression test.

The compression tests were performed in a universal test machine (DL 30000, EMIC, Brazil). The strain was obtained using electric resistance strain gauges (KFG-5-120-C1-11, KYOWA, Japan) with a length of 5 mm, gage factor of 2.10 +/- 1.0% and gage resistance of 119.8 +/- 0.2 Ω. For each direction, strain gauges were attached to two parallel faces of the specimen (Fig. 3). Both the load cell and the terminals of the strain gauges were coupled to a data acquisition system (Spider8, HBM, Germany) that allowed automated readings of load and strain. The compression test was performed on 30 mm x 30 mm prismatic specimens with a length of 90 mm. The test methodology (speed and load cycles) was performed according to NBR 7190 (1997). The Young's moduli in the longitudinal direction (E_L) were determined from the slope of the stress/strain curve (σ_L/ε_L), and the data were fitted such that the curve was linear in a section between approximately 20% and 60% of the maximum stress with a determination coefficient (R^2) above 0.99 UNE 56535 (1977). The Poisson ratio was calculated from the relations between the radial and longitudinal strain (υ_{LR}) and between the tangential and longitudinal strain (υ_{LT}) within the same linear stretch.

Basic density determination

The same specimens used for the compression test were used for the determination of basic density. Therefore, the basic density of wood from branches of each species and at different fork levels was calculated using the relation between the green volume and oven-dried mass. The results are used in Eq. 1 to do the stiffness coefficient calculations.

Results analysis

The parameters obtained from the ultrasound and compression tests were initially analyzed considering, if available, values from the literature. Because of the scarcity of data on the wood parameters for tree branches of urban tree species, the results were also analyzed using relationships between parameters proposed considering the expected behavior of the wood. This procedure allows evaluation of the presence of distorted results or results that are far from the expected values, according to theoretical conditions of an orthotropic material.

To compare the results of the longitudinal elastic modulus (E_L) and the Poisson coefficients (υ_{LR} and υ_{LT}) determined from the ultrasound and static compression tests, the confidence interval (CI) of the difference between the means was used for each species. In this test, if the CI contains zero, there is no statistically significant difference between the means obtained in the two tests, with a confidence level of 95%. To verify the existence of groups of species with statistically equivalent longitudinal and shear moduli and Poisson ratios (υ_{LR} and υ_{LT}), an analysis of variance (ANOVA) was used. This statistical test decomposes the variance of the parameter under analysis into two components: within group (same species) and among groups (different species). If there was a significant difference, the multiple range test was applied to verify which species were significantly different. The same statistical analysis was used for each species to evaluate the variation in the density and longitudinal modulus of elasticity (ultrasound and compression) at different levels of branch forks.

RESULTS AND DISCUSSION

The individual results for the longitudinal elastic moduli (E_L) of the tree branches on different species obtained by ultrasound ranged from 1675 to 6522 MPa, while those obtained by static compression varied from 2100 to 6600 MPa. These results are comparable, in order of magnitude, with those obtained by Casteren *et al*. (2013), who studied 30 green branches from 10 species of tropical hardwood, of which the longitudinal elastic modulus obtained in static bending tests (EM) ranged from 900 to 4000 MPa.

In general, the variability of the elastic parameters obtained in the static compression test was higher than that obtained by ultrasound (Table 2), as also observed for wood from trunk (Gonçalves *et al*. 2011, 2014). But for our results (Table 2), both (static and ultrasound) were higher than those obtained for wood from the trunk (Gonçalves *et al.* 2011, 2014), especially for the Poisson coefficients. Caresten *et al.* (2013) also observed great variability in the longitudinal elastic modulus within the same species and even the same branch. These authors' results show the modulus of elasticity ranging from 1500 to 3000 MPa (average of approximately 2300 MPa) in bending tests using specimens taken at different axial positions of the branch. This great variability may be related to the branches' need to maintain an inclined equilibrium position along the annual increment of their own weight, promoting a negative gravitropic correction (Wilson 2000) that induces the production of differentiated tissues called reaction wood. Tsai *et al.* (2012), analyzed 15 branches from eight hardwood species and observed that, in contrast to the inclined trunks, the area of reaction wood is located in the inferior part of the branches and gelatinous fibers form in this zone.

Table 2. Average Results for the Modulus of Elasticity in the Longitudinal (E_L), Radial (E_R), and Tangential (E_T) Directions; Shear Modulus in the Tangential-radial (G_{TR}), Tangential-longitudinal (G_{TL}) and Longitudinal-radial (G_{LR}) planes; and Poisson ratios on the Tangential-radial (v_{TR} and v_{RT}), Tangential-longitudinal (v_{TL} and v_{LT}) and Longitudinal-radial (v_{RL} and v_{LR}) Planes Obtained from Ultrasound and Compression Tests

Test	E_L MPa	E_R MPa	E_T MPa	G_{TR} MPa	G_{TL} MPa	G_{LR} MPa	v_{RL}	v_{TL}	v_{LR}	v_{TR}	v_{LT}	v_{RT}
						Schinus terebinthifolia						
Ultrasound	2563 (14.9)	489 (50.3)	400 (43.5)	111 (32.0)	311 (12.9)	430 (60.0)	0.098 (81.2)	0.086 (12.0)	0.46 (30.5)	0.65 (16.9)	0.61 (37.7)	0.78 (11.8)
Compression	3760 (23.7)								0.31 (52.2)		0.50 (45.0)	
CI	+57.8 +2336								-0.12 +0.40		-0.26 +0.47	
						Inga sessilis						
Ultrasound	3983 (16.3)	442 (24.0)	290 (12.0)	115 (22.1)	270 (1.5)	374 (25.2)	0.056 (1.3)	0.048 (54.1)	0.51 (22.8)	0.49 (15.0)	0.65 (50.2)	0.75 (2.3)
Compression	3050 (44.0)								0.27 (25.5)		0.39 (53.1)	
CI	-5472 +3606								-0.64 -0.17		-1.44 +0.92	
						Swietenia sp						
Ultrasound	3369 (14.8)	332 (5.6)	231 (21.2)	82 (1.4)	269 (15.7)	381 (10.4)	0.056 (58.6)	0.044 (30.1)	0.54 (49.4)	0.54 (15.5)	0.65 (36.2)	0.78 (8.3)
Compression	4357 (38.7)								0.30 (59.9)		-	
CI	-1369 +3345								-0.62 +0.13			
						Gallesia integrifolia						
Ultrasound	3758 (8.8)	392 (9.2)	314 (5.2)	109 (20.6)	337 (16.9)	433 (11.3)	0.069 (50.4)	0.035 (67.0)	0.66 (50.3)	0.52 (12.6)	0.43 (68.7)	0.65 (13.5)
Compression	5100 (17.1)								0.49 (47.9)		0.48 (44.3)	
CI	+365 +2327								-0.63 +0.30		-0.43 +0.54	
						Schinus molle						
Ultrasound	3005 (20.7)	565 (33.1)	405 (33.3)	137 (28.0)	306 (16.9)	453 (21.3)	0.098 (58.3)	0.098 (28.3)	0.52 (48.5)	0.48 (20.4)	0.69 (23.9)	0.68 (23.2)
Compression	3600 (14.2)								0.24 (29.6)		0.53 (56.0)	
CI	+14.9 +1174								-0.53 -0.03		-0.42 +0.11	
						Acrocarpus fraxinifolius						
Ultrasound	5506 (18.3)	614 (21.6)	436 (15.0)	121 (13.9)	526 (8.1)	654 (11.2)	0.073 (26.7)	0.039 (52.3)	0.65 (21.4)	0.62 (10.1)	0.50 (59.2)	0.86 (4.2)
Compression	6350 (3.3)								-		0.48 (44.3)	
CI	-1006 +2695										-0.5 +0.5	

* Values in brackets are the coefficient of variation (%); CI = Confidence interval for the mean difference

The greater variability obtained in the compression tests (Table 2) may be related to the smaller dimensions of the specimen because in some cases, the specimen could have been composed entirely of compression wood and, in other cases, of wood outside that zone, while the polyhedral specimen, which was slightly larger, generally presented a mixture of these regions.

Comparison of the obtained results with data from the literature, even when using only the order of magnitude, was not feasible for most of the elastic constants because they are not available for wood from fresh tree branches (green condition). Thus, another way to validate the results is to verify the existence of discrepant results using ranges of expected values for relations between the terms of the compliance matrix. These expected relations are proposed considering the theoretical bases that govern the behavior of the wood. For the longitudinal and shear modulus of elasticity, it was verified that there was no discrepancy between the relationships obtained in this research and the relationships proposed in the literature (Table 3).

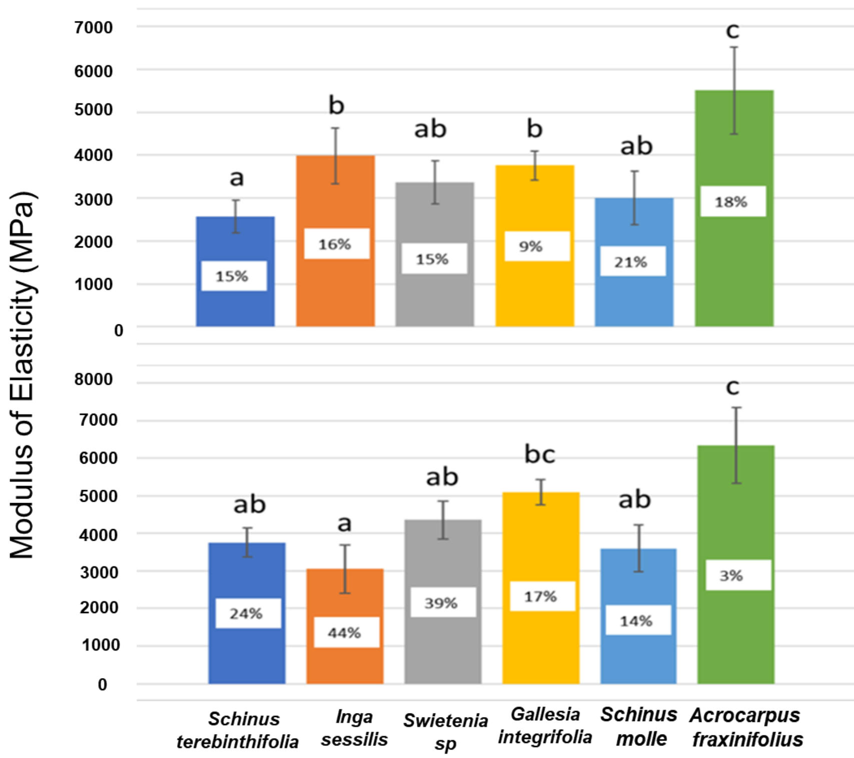
Table 3. Relationship Between the Terms of the Compliance Matrix (10^{-5}) Obtained in this Research Using Ultrasound Tests and the Range Obtained by Other Authors

Species/Literature source	E_L/E_T	E_R/E_T	G_{LR}/G_{RT}	G_{LT}/G_{RT}	E_L/G_{LR}
Schinus terebinthifolia	6.4	1.2	3.9	2.8	6.0
Inga sessilis	13.7	1.5	3.3	2.3	10.6
Swietenia sp	14.6	1.4	4.6	3.3	8.8
Gallesia integrifolia	12.0	1.2	4.0	3.1	8.7
Schinus molle	7.4	1.4	3.3	2.2	6.6
Acrocarpus fraxinifolius	12.6	1.4	5.4	4.3	8.4
Bucur (2006)*	4.5 to 33.1	1.0 to 2.1	2.9 to 16.9	2.4 to 13.1	4.9 to 7.6
Bodig and Jayne (1982)**	20	1.6	10	9.4	14
Preziosa *et al*. (1981)***	7.1 to 8.5	1.5 to 1.7	2.3 to 5.4	1.8 to4.4	6.8 to 9.8

*Tulip tree, Oak, Beech and Douglas fir
**Proposed values
***Oak and Douglas fir

Concerning the Poisson ratios, Bodig and Jayne (1982) indicate that lower values should be obtained for υ_{RL} and υ_{TL} (0.040 and 0.027 as references), while a larger value should be obtained for υ_{RT} (0.67 as a reference). For υ_{LR} and υ_{TR}, Bodig and Jayne (1982) proposed reference values for hardwood of $\upsilon_{LT} = 0.50$, $\upsilon_{LR} = 0.37$, and $\upsilon_{TR} = 0.33$. In any method, there is an inherent difficulty in obtaining reliable Poisson ratios for wood, especially in the case of υ_{RL} and υ_{TL} because they are very small (Bodig and Jayne 1982) and in all cases because they require that the growth rings are very well aligned with the axes and as straight as possible on the transverse section. Therefore, the values obtained in this research using ultrasound and compression tests (Table 2) may be considered adequate.

The longitudinal elastic moduli obtained from the ultrasound tests were statistically equivalent to those obtained from the compression tests for *Inga sessilis*, *Swietenia* sp., and *Acrocarpus fraxinifolius* (Table 2). For *Inga sessilis* and *Swietenia* sp., it is important to highlight the great variability of the results from the static compression test, which may have contributed to the statistical equivalence. The Poisson ratio υ_{LR} obtained by ultrasound and compression test was not statistically equivalent for the species *Inga sessilis* and *Schinus molle* (Table 2, zero is not included in the Confidence Interval of the mean difference), while υ_{LT} obtained by ultrasound and compression test was statistically equivalent for all species for which this value was obtained in both tests (Table 2, zero is included the CI of the mean difference). However, it is also important to highlight the high variability of these parameters. As in Casteren *et al*. (2013), groups of species that significantly differed in terms of the longitudinal elasticity modulus of their branches could be distinguished (Fig. 4). However, these groups were not equally detached based on the results of the ultrasound and compression tests (Fig. 3). Despite these differences, both tests show the importance of studies aiming to characterize tree branches because the stiffness differences will greatly influence the biomechanical behavior of trees and should be considered in tree simulations. On the other hand, being able to cluster species according to similar strength and stiffness properties is important in tree risk analysis because it allows us to extend the reach of the results.



* In each graph, the same letters indicate that the values of the moduli are statistically equivalent

Fig. 3. Mean longitudinal elasticity modulus, standard deviations and coefficients of variation (%) obtained from ultrasound (upper figure) and compression (lower figure) tests

The density variation in the branch pieces removed from different fork levels was not statistically significant (P-value = 0.44). Numerically, the tree density slightly increased from the first (458 kg.m^{-3}) to the second fork level (463 kg.m^{-3}) and decreased in the third level (428 kg.m^{-3}).

Density variations along the axes of branches are compatible with the results from analyses of anatomical variations in the axial direction of the branch (Bhat *et al*. 1989; Gartner 1995; He and Deane 2016), including those related to the location of the reaction wood and branch hydraulic functions.

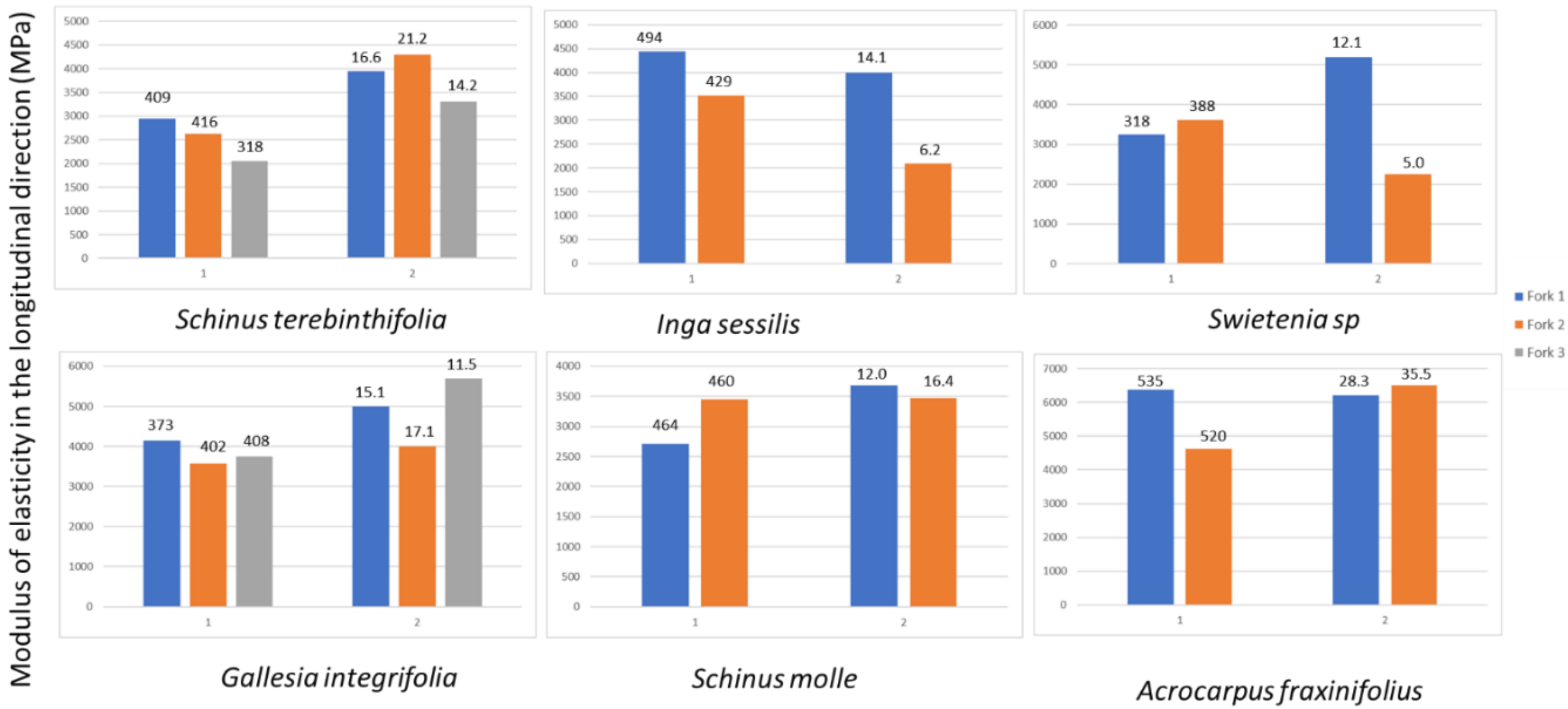
The phenomena that interfere with tests using ultrasound wave propagation and static compression are different. In the case of wave propagation, although density has a direct influence on the calculation of the stiffness coefficient (Eq. 1), velocity is the most influential parameter because its value is squared. The velocity can significantly vary due to variations in the anatomical structure (Bucur 2006) and thus overcome the influence of density (Bucur 2006).

Of the species evaluated in this research, half presented higher modulus of elasticity values for branches with higher densities (Fig. 4), while the moduli of the other half did not follow a pattern. Considering the differences between the tests (ultrasound and compression) and the anatomical structure and density variations along the axes of the branches (different fork levels), the behavior of the modulus of elasticity in the longitudinal direction (E_L) had no unique pattern, increasing or decreasing from the first to the other branching levels (Fig. 4).

The longitudinal elastic modulus (E_L) obtained in the compression test had a direct relationship with the compressive strength (f_c) for 4 of the 6-species studied (Fig. 4). Direct relationships between strength and modulus of elasticity are not found for forest species, as can be easily verified in tables of wood properties, in which species with higher strength than others present smaller stiffness (Nahuz *et al*. 2013).

No physical or mechanical property data are available, even for trunk wood, for most species used in this research, making a comparison of results difficult. Data from Lima *et al.* (2010) indicate a basic density of 430 kg.m^{-3} and a compressive strength (f_c) at an equilibrium moisture content of 18 MPa for wood from the trunk of *Gallesia integrifolia* species. In this study, the wood from branches of this species presented an average basic density of 394 kg.m^{-3} and an average compressive strength of 14.6 MPa under green conditions. If this value of compressive strength is corrected to the equilibrium moisture condition according to the equation proposed by ABNT NBR 7190 (1997), the inferred value is 18 MPa, which matches that obtained by Lima *et al*. (2010) for trunk wood. No stiffness data were found for this species, but considering its compressive strength and density, the modulus of elasticity should be below 9500 MPa, using the hardwood strength classes from ABNT (NBR 7190 1997) or from EN 338 (2010), making the result obtained in this research (Table 2) comparable to that in the literature for wood from trunk.

Due to the lack of data on the studied species, only a brief discussion is given here of the mechanical properties of trunk wood under green conditions using species with basic densities of the same order of magnitude as those studied in this research. The values obtained in this research were much lower than those in the literature, both for the modulus of elasticity and compressive strength. In data obtained from the Technological Research Institute (Nahuz *et al.* 2013) for green wood from species indicated for use in civil construction, the modulus of elasticity (in bending) varies from 7963 to 12258 MPa, and the compressive strength varies from 29.4 to 40.6 MPa for species with basic densities varying from 440 to 540 kg.m^{-3}. These differences in magnitude may be related to the characteristics of the species used in urban areas because the present results were very close to those obtained by Lima *et al*. (2010) for *Gallesia integrifolia*.



* The numbering above the bars of the ultrasound test results indicates the average density (kg.m^{-3}) in each section, and that above the bars of the compression test results indicates the mean compressive strength (MPa).

Fig. 4. Mean modulus of elasticity values obtained at the first, second, and third levels of branch forks in the ultrasound (1) and compression (2) tests for different species

Another explanation may be related to the differences between trunk and branch wood because the present results are of the same order of magnitude as those of Casteren *et al.* (2013), who also analyzed branch wood. Diaz and Martínez (2016) suggest that branch wood is less resistant than trunk wood, but they did not present results to support this statement. On the other hand, Dadzie *et al.* (2016) showed results for two hardwood species with 17% and 10% moisture and concluded that although the density of the branch wood was statistically superior to the density of trunk wood, the modulus of elasticity and strength in the bending and compressive strength tests were statistically equivalent.

Considering the practical aspects of applying the methodologies used to characterize branch wood, the ultrasound test is simpler and less expensive (do not need to use strain gages and universal test machine) than the static tests, but the preparation of the test specimen is more complex (polyhedron x prism). The use of strain gages requires a gage bonding step and cable soldering, which is laborious and requires extra time. In addition, when testing green wood, it is necessary to carry out the bonding and the test sequentially to avoid drying the wood because it is not possible to saturate the specimen with the gages. Additional care should be taken with the glue because the wood has a high moisture content. Finally, there were many problems with the operation of the gages, making it impossible to use automated spreadsheets to calculate the elastic modulus and Poisson ratios because a detailed and individualized analysis of the results is necessary to eliminate bad results. It is possible that, despite the careful analysis, the moisture content affected the glue in some cases.

CONCLUSIONS

An ultrasound methodology was applied to green wood branches to completely characterize the elastic properties of the wood. The obtained elastic parameters were comparable with the values expected based on theoretical aspects related to the behavior of the wood. The compression test allows determination of the strength, complementing the characterization obtained via ultrasound, but its application for the complete characterization of the elastic parameters is not feasible in wood branches because of their limited size.

ACKNOWLEDGMENTS

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES - Finance Code 001) for the scholarships and the Sao Paulo Research Foundation (FAPESP), São Paulo, Brazil (Proc. 2015/05692-3) for the research funding.

REFERENCES CITED

ABNT NBR 7190 (1997). "Projeto de estruturas de madeira," Associação Brasileira De Normas Técnicas, Rio de Janeiro, Brasil.

AENOR (1977). "Características físico-mecánicas de la madera. Determinación de la resistencia a la compresión," (Physical-Mechanical Properties of Wood. Determination of axial compression strength.), UNE 56535:1977, AENOR, Madrid.

Bhat, K. M., Bhat. K. V., and Dhamodaran, T. K. (1989). "Fibre length variation in steam and branches of eleven tropical hardwoods," *IAWA Journal* 10(1), 63-70.

Bodig, J., and Jayne, B. A. (1982). *Mechanics of Wood and Wood Composites*, Van Nostrand Reinhold, New York, p. 419.

Bucur, V. (2006). *Acoustics of Wood*, Springer Science & Business Media, Berlin, 2nd Edition.

Bucur, V., and Archer, R. R. (1984). "Elastic constants for wood by an ultrasonic method," *Wood Sci. Technol.* 18, 255-265.

Bucur, V., and Perrin, J. P. (1988). "Ultrasonic waves-wood structure interaction*," Proc. Inst. Acousti. Edinb.* 10(2), 199-206.

Bucur, V., and Rasolofosaon, P. (1998). "Dynamic elastic anisotropy and nonlinearity in wood and rock," *Ultrasonics* 36, 816-824.

Casteren, A. V., Sellers, W. I., Thorpe, S. K. S., Coward, S., Crompton, R. H., and Ennos, A. R. (2013). "Factors affecting the compliance and sway properties of tree branches used by the sumatran orangutan (*Pongo abelii*)," *PLoS ONE* 8(7), e67877. DOI: 10.1371/journal.pone.0067877.

Dadzie, P. K., Amoah, M., Frimpong-Mensah, K., and Oheneba-Kwarteng, F. (2016). "Some physical, mechanical and anatomical characteristics of stemwood and branchwood of two hardwood species used for structural applications," *Materials and Structures* 49(12), 4947-4958. DOI: 10.1617/s11527-016-0835-3.

Díaz, M. I., and Martínez, P. C. (2016). *Evaluación de Riesgo de Arbolado Peligroso: Principios, Indicadores y Métodos*, Asociación Española de Arboricultura, 2016, pp. 398.

François, M. (1995). *Identification des Symmetries Matérielles de Matériaux Anisotropies*, (*Identification of the Material Symmetries of Anisotropic Materials*), Ph.D. Dissertation, Université Paris 6, LMT, Cahan, pp. 137.

Gartner, B. L. (1995). "Patterns of xylem variation within a tree and their hydraulic and mechanical consequences," in: *Plant Stems: Physiology and Functional Morphology*, B. L. Gartner (ed.), Academic Press, San Diego, pp. 125-149.

Gilman, C. A., Bartlett, M. D., Gillis, G. B., and Irschick, D. J. (2011). "Total recoil: Perch compliance alters jumping performance and kinematics in green anole lizards (*Anolis carolinensis*)," *Journal of Experimental Biology* 215, 220-226.

Gonçalves, R., and Costa, O. L. (2008). "Influence of moisture content on longitudinal, radial and tangential ultrasonic velocity for two Brazilian wood species," *Wood and Fiber Science* 40(4), 580-586.

Gonçalves, R., Trinca, A. J., and Cerri, D. G. P. (2011a). "Comparison of elastic constants of wood determined by ultrasonic wave propagation and static compression testing," *Wood Fiber Sci.* 41(1), 64-75.

Gonçalves, R., Trinca, A. J., and dos Santos Ferreira, G. C. (2011b). "Effect of coupling media on velocity and attenuation of ultrasonic waves in Brazilian wood," *Journal of Wood Science* 57(4), 282-287.

Gonçalves, R., Trinca, A. J., and Pellis, B. P. (2014). "Elastic constants of wood determined by ultrasound using three geometries of specimens," *Wood Science and Technology* 48, 269-287. DOI: 10.1007/s00226-013-0598-8.

He, D., and Deane, D. C. (2016). "The relationship between trunk and twigwood density shifts with tree size and species stature," *Forest Ecology and Management* 372, 137-142.

Lang, R., and Kaliske, M. (2013). "Description of inhomogeneities in wooden structures: Modelling of branches," *Wood Science and Technology* 47, 1051-1070. DOI: 10.1007/s00226-013-0557-4.

Lima, I. L., Longui, E. L., Andrade, I. M., Garcia, J. N., Zanatto, A. C. S., and Morais, E. (2010). "Efeito da procedência em algumas propriedades da madeira de *Gallesia integrifolia* (Spreng.) Harms," *Revista do Instituto Florestal* 22(1), 61-69.

Mishiro, A. (1996a). "Ultrasonic velocity and average moisture content in wood. II. *Mokuzai Gakkaishi* 42(10). 612-617.

Mishiro, A. (1996b). "Ultrasonic velocity and average moisture content in wood. III. *Mokuzai Gakkaishi* 42(10), 930-936.

Nahuz, M. A. R., Miranda, M. J. A. C., Ielo, P. K. Y., Pigozzo, R. J. B., and Yojo, T. (2013). *Catálogo de Madeiras Brasileiras para a Construção Civil*, IPT – Instituto de Pesquisas Tecnológicas do Estado de São Paulo.

Ozyhar, T., Hering, S., Sanabria, S. J., and Niemz, P. (2013). "Determining moisture-dependent elastic characteristics of beech wood by means of ultrasonic waves," *Wood Sci. Technol.* 47, 329-341.

Preziosa, C. (1982). *Méthode de Détermination des Constantes Elastiques du Matériau Bois Par Utilisation des Ultrasons*, (*Method for Determining Elastic Constants of Wood by Use of Ultrasound*), PhD Dissertation, University of Orleans, France, pp. 90.

Preziosa, C., Mudry, M., Launay, J., and Gilletta, F. (1981). "Détermination des constantes élastiques du bois par une méthode acoustique goniométrique," ("Determination of elastic constants of wood by a goniometer acoustic method"). *CR Acad. Sci. Paris* 293(2), 91-94.

Sinclair, A. N, and Farshad, M. (1987). "Comparison of three methods for determining elastic constants of wood," *J. Test Eval.* 15(2), 77–86.

Sobue, N. (1993). "Simulation study on stress wave velocity in wood above fiber saturation point," *Mokuzai Gakkaishi* 39(3), 271-276.

Thorpe, S. K. S., Crompton, R. H., and Alexander, R. Mc. N. (2007). "Orangutans use compliant branches to lower the energetic cost of locomotion," *Biology Letters* 3, 253-256. DOI: 10.1098/rsbl.2007.0049.

Tsai, C. C., Hung, L. F., Chien, C. T., Chen, S. J., Huang, Y. S., and Huang, L. L. K. (2012). "Biomechanical features of eccentric cambial growth and reaction wood formation in broadleaf tree branches," *Trees* 26(5), 1585-1595. DOI: 10.1007/s00468-012-0733-4.

Vázquez, C., Gonçalves, R., Bertoldo, C., Baño, V., Veja, A., Crespo, J., and Guaita, M. (2015). "Determination of the mechanical properties of *Castanea sativa* Mill. using ultrasonic wave propagation and comparison with static compression and bending methods," *Wood Science and Technology* 49(3), 607-622. DOI: 10.1007/s00226-015-0719-7.

Wang, S., Chiu, C., and Lin, C. (2002). "Variations in ultrasonic wave velocity and dynamic Young's modulus with moisture content for Taiwania plantation lumber," *Wood Fiber Sci.* 34(3), 370-381.

Wilson, B. F. (2000). "Apical control of branch growth and angle in woody plants," *American Journal of Botany* 87, 601-607.

Article submitted: 17 April 2019; Peer review completed: July 20, 2019; Revised version received and accepted: August 30, 2019; Published: September 9, 2019.
DOI: 10.15376/biores.14.4.8439-8454