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Evaluation of maximum strength and modulus of elasticity of Douglas-fir lumber in axial to grain tension by two nondestructive techniques

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ABSTRACT Modulus of elasticity (MOE) of Douglas-fir (*Pseudotsuga menziesii)* lumber loaded in parallel to grain tension was evaluated by nondestructive techniques (transverse vibration and longitudinal stress wave) and the results were correlated to the actual properties. Nondestructive parameters of specific gravity, wave frequency and attenuation and wave speed were measured. Destructive tests were performed with the use of static tension and bending techniques. Regression analyses were performed to correlate all nondestructive and destructive techniques. Results showed the MOE in static bending can be predicted with good efficiency. The correlation coefficients (R) for this test ranged from 0.818 to 0.941. The maximum tensile strength presented a poor correlation to the nondestructive parameters with the highest R=0.582.
Keywords: NDT, tensile MOE, *Pseudotsuga menziesii,* nondestructive techniques, transverse vibration, longitudinal stress wave.

Introduction

In 1959, B.A. Jayne (1959) proposed the principle of properties of energy storage and energy dissipation of wood materials and their use in nondestructive testing (NDT) of such materials. Jayne's proposal uses energy storage, measured by the speed by which a wave travels a certain length through wood, and energy dissipation, that is, the rate of the wave attenuation along the same material. These properties are controlled by the same mechanisms that determine the mechanical behavior of a material, such as fiber (strength), cross grain, anatomic composition, specific gravity, moisture content, presence of knots and other defects (source of weakness), viscoelasticity (JAYNE, 1959).

The concept of machine stress rating-MSR for mechanical grading of structural lumber evolved from NDT research. NDT parameters are used to correlate dynamic versus static testing on mechanical properties of lumber (ROSS; PELLERIN, 1994).

Many techniques are currently used for nondestructive evaluation of wood and wood-based products as well as for in-place assessment of wood structures and even standing trees (WANG et al., 2014; GUNTEKIN et al., 2014; CARREIRA et al., 2012; RAJESHWAR et al., 1997; VIKRAM et al., 2011; HASSAN et al., 2013). Measurement of MOE of oriented bonded panels and laminated veneer lumber can be easily performed with NDT (DEVALLANCE, 2009). Evaluation of internal bond, bonded joints and correlation to MOE and modulus of rupture (MOR) are other properties assessed by NDT techniques (WANG et al., 2014; BIECHELLE et al., 2011). The correlation between NDT parameter and the lumber properties is measured in terms of correlation coefficient (R).

Evaluation of wood and wood-based products by NDT is more common in assessing MOE and MOR in static bending. The assessment of wood in tension using NDT techniques is not fully explored in the literature.

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The transverse vibration technique takes advantage of the transverse oscillation that provides two important properties of the material, namely energy storage and energy dissipation. Such properties are obtained upon free vibration of the elastic system. It occurs when the body is displaced from its equilibrium position and released to vibrate freely. The vibration analysis of the board consists on measuring its natural frequency and attenuation to measure MOE. The computer then stores the resonant frequency (f_r), the wave attenuation (Att), damping ratio (measure of vibration energy absorption), and the weight (W). The sample specific gravity (SG) along with its computed MOE (ROSS; PELLERIN, 1994; CARREIRA et al., 2012; HASSAN et al., 2013) are displayed. These measurements can also be used to compute the calculated MOE taking the beam span (L), moment of inertia (I), acceleration due to gravity (g), and a constant that depends on the way it is supported:

$$E_d CTV = \frac{f_r^2 \,.\, W \,.\, L^3}{K \,.\, I \,.\, g} \qquad \text{Equation 1}$$

The longitudinal stress wave technique uses the speed at which an induced wave travels from the impact to the receiving point along the material. A wave is generated upon an impact at one end of the material and the speed of sound is recorded as it travels and reaches the other side. Particles are excited and transmit energy to the adjacent ones till they reach the other extremity of the piece. Consequently, they are reflected back and this movement occurs till it comes to complete rest due to wave attenuation. It happens as energy is being dissipated with time. The propagation speed of wave (C) is measured by the time it spends through the length span (L) on the lumber (ROSS; PELLERIN, 1994; WANG et al., 2014; GUNTEKIN et al., 2014; CARREIRA et al., 2012). The MOE of the wood is measured using also its density ρ and Equation 2:

$$E_d LSW = C^2 . \rho \qquad \text{Equation 2}$$

Each year a great amount of wood and wood-based products are destructively tested to evaluate strength and to control their quality prior to entering the market. Once tested, the material cannot be shipped to customers; instead, it can sometimes be recycled or converted to other products, which represents a cost for the companies producing wood-based products. Another drawback is that the properties of a production shift can only be possibly known after its shipping to the market. Therefore, any production error, if detected, can be corrected only afterwards. The use of a nondestructive testing technique can overcome these problems providing information that can be instantly reported to the production management in controlling the quality of that particular product. Besides, it has shown to be an accurate method of evaluating wood properties.

This study aimed to evaluate the modulus of elasticity (MOE) by two nondestructive techniques. Resonant frequency and stress wave speed and attenuation characteristics were determined and used as parameters to predict the MOE of Douglas-fir wood.

Material and Methods

A total of 21 pieces of lumber of Douglas-fir (*Pseudotsuga menziesii*) wood were used to correlate nondestructive MOE obtained from two NDT techniques and MOE from static bending test with maximum tensile strength (MTS) and static tensile MOE tests. Correlation coefficients were obtained by linear regression analyses using maximum tensile strength and static tensile MOE as dependent variable. The nondestructive techniques used were: transverse vibration (TV) and longitudinal stress wave (LSW).

The dimensions of the samples were 144.5x3.48x1.48 inches (3670x88.4x37.6 mm) and the average moisture content was 8%. The boards were conditioned at 23°C and 65% moisture content to perform the nondestructive tests.

The MOE from dynamic transverse vibration was determined by the computer program (E_dTV) or calculated (E_dCTV) using Equation 1. Each board was supported at the extremities (span L=142 inches - 3607 mm) and set to vibrate by a careful impact (finger tap) at the midspan. Dynamic transverse vibration was performed in an E-computer model 340 equipment (Metriguard) (Figure 1). Upon vibration, a varying force is transmitted to a load cell attached to one of the supports. An analog to digital (a/d) converter and microcontroller in the interface unit samples and converts the varying force signal into digital forms for the computer. The data received is processed and digitized force signals determine the vibration frequency, weight and damping ratio of the samples. These values, coupled with the sample dimensions and span, which were set into the computer by the operator, are combined to compute MOE and specific gravity.

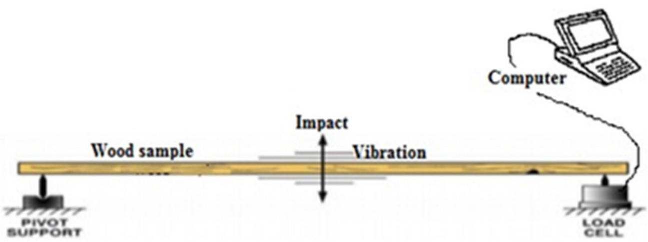

Figura 1. Vibração transversal no equipamento E-computer.
Figure 1. Transverse vibration test in E-computer device.

Regarding the LSW technique, data of wave speed, length span (140.6 inches - 3571 mm), and SG of each sample were used to calculate the dynamic longitudinal stress wave MOE (E_dLSW) using Equation 2. This test was performed in a Stress Wave Timer 239A equipment (Metriguard) (Figure 2). The samples were fixed at their extremes using clamps supported on a small metal frame, each one containing an accelerometer. A pendulum containing a steel ball fixed in one of the clamps was used to impact in the samples. Pulse energy was introduced to the specimen and the particle velocity in response to the induced longitudinal wave was recorded as the time spent (in microseconds) between the accelerometers.

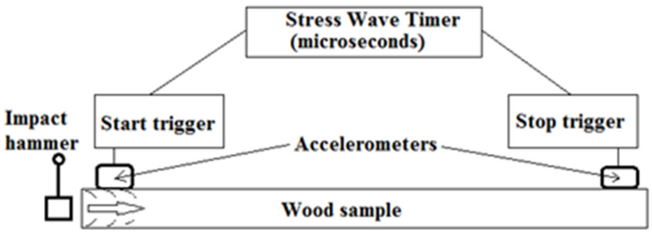

Figura 2. Esquema de teste do Equipamento *Stress Wave Timer* (Ross and Pellerin, 1994)
Figure 2. Schematic of the Stress Wave Timer device (Ross and Pellerin, 1994).

The MOE from static bending (E_SBE) tests was determined loading 10-pound (4.53 kg) weight load (P') at midspan (L=142 inches - 3607 mm) of each board supported flatwise at their extremities. The deflection (d) of the samples was measured and the E_SBE was calculated through Equation 3.

$$E_sBE = \frac{P'.\ L^3}{48\ .\ I\ .\ d} \qquad \text{Equation 3}$$

Finally, the boards were loaded flatwise and destructively tested in tension parallel to grain according to the American Society for Testing and Materials-ASTM D198-14 standard (ASTM, 2014). The test was performed in a tension machine of Washington State University using a span of 9' (2743 mm). A linear variable differential transformer-LVDT acting on a gauge length of 100 inches (2540 mm) was used to measure axial deformation of each sample.

Results and Discussion

The average wood density after conditioning was 526 kg/m^3 and the coefficient of variation was 7%. The means values of dynamic and static tests of the Douglas fir wood are presented in Table 1.

Tabela 1. Médias de ensaios estáticos e dinâmicos de madeira de Douglas fir para tração e flexão.
Table 1. Average values of static and dynamic tests of Douglas fir wood in tension and bending.

	Property [a]					
	E_dTV (GPa)	E_dCTV (GPa)	E_dLSW (GPa)	E_SBE (GPa)	E_STE (GPa)	MTS (MPa)
Mean	13.5	14.3	16.5	15.0	14.8	30.6
C.V. (%) [b]	14.8	14.5	13.9	18.3	16.6	38.0

[a] dynamic transverse vibration MOE (E_dTV); calculated dynamic transverse vibration MOE (E_dCTV); dynamic longitudinal stress wave MOE (E_dLSW); static bending MOE (E_SBE); static tensile MOE (E_STE); maximum tensile strength (MTS). [b] Coefficient of variation.

Instead of using an equation to calculate MOE as for E_dCTV and E_dLSW techniques, this nondestructive property was predicted by running a multivariable regression model. Results obtained after running different linear regression analyses are summarized in Table 2. The MTS showed low correlation coefficients. The best predictor for MTS was the E_dCTV with R=0.510. The result is similar to the correlation of 0.61 obtained by Ross et al. (2005) when studying nominal 2- by 4-in. (40- by 90-mm) Douglas fir peeler cores cut into wood samples using E_dLSW. Rajeshwar et al. (1997) tested different grades of Southern Pine wood and obtained MTS maximum of 88.04 MPa and correlation of 0.777 with MOE from transverse and stress wave tests. This result is expected, since maximum tension as well as modulus of rupture of wood at static bending is, in general, less predictable than rigidity (modulus of elasticity). All correlations between MTS and nondestructive parameters presented a poor distribution. A good correlation was observed among all dynamic and static properties, except for the MTS.

The property of tensile MOE (E_STE) was strongly correlated to the nondestructive parameters, mainly with the transverse vibration technique (either by computer or calculated), which resulted in a high correlation coefficient (R=0.941) (Figure 3).

Tabela 2. Resultados da regressão linear correlacionando o MOE na tração longitudinal e a tensão máxima aos parâmetros não destrutivos. Os coeficientes K e x são usados no modelo geral: Propriedade = K + x . preditor.
Table 2. Results of the linear regression correlating MOE in longitudinal tension, maximum tensile strength and nondestructive parameters. Coefficients K and x are used in the general model: Property = K + x . predictor.

Predictors [b]	Tensile MOE (E_STE)			Maximum Tensile Strength (MTS)		
	K	x	R [a]	K	x	R
E_dTV	- .122	1.157	.941	-1157	2855	0.491
E_dCTV	- .168	1.119	.941	-1492	2868	0.510
E_dLSW	- .093	0.944	.820	-1133	2349	0.431
E_SBE	.545	.734	.818	1599	1300	0.307
MTS	1.709	9.86E-05	.466	-	-	-

[a] Correlation coefficient; [b] dynamic transverse vibration MOE (E_dTV); calculated dynamic transverse vibration MOE (E_dCTV); dynamic longitudinal stress wave MOE (E_dLSW); static bending MOE (E_SBE).

This suggests that the correlation accounts for 88.5% of the variation. Transverse vibration measurement of wood in tension can separate high and low quality materials with good approximation. As previously discussed, the property of modulus of elasticity generally provides a higher correlation coefficient for wood than modulus of rupture, as reported by Baar et al. (2015). The tensile MOE also correlated very closely to E_SBE and E_dLSW (R's= 0.818 and 0.820, respectively). The correlation of E_STE versus E_dLSW (R=0.820) is similar to that found by Ross et al. (2005) for Douglas fir peeler cores (R=0.84). However, the mean value of static tensile MOE in this study (14.8 GPa) was higher than that reported by these authors (11.6 GPa). When E_STE was correlated against MTS, a correlation of 0.466 was observed.

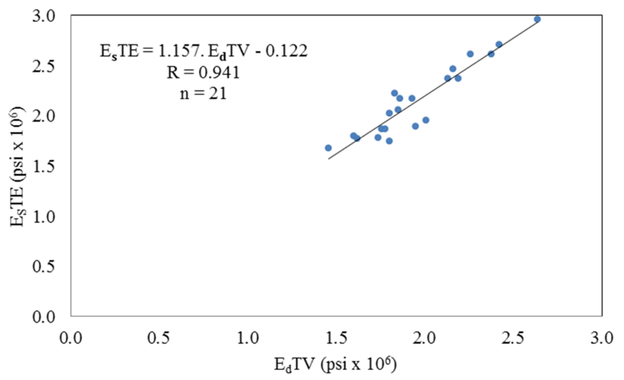

Figura 3. Linha de ajuste para MOE na tração estática versus vibração transversal dinâmica.
Figure 3. - Line fit plot for static tensile MOE versus dynamic transverse vibration.

The E_SBE follows the same trend of E_STE with good correlation to the E_dTV, either by computer or calculated, with R=0.822 (Figure 4), followed by the E_dLSW (R=0.688). This result is consistent with results reported by Ross et al. (2005) for correlating E_SBE and E_dLSW of wood from Douglas fir peeler cores with R=0.68, and Vikram et al. (2011) that obtained a correlation of R=0.91 for correlating E_SBE and E_dTV. However, both studies reported lower values of E_SBE (8.69 GPa and 10.9 GPa, respectively) as compared to this study (15.0 GPa). Carreira et al. (2012) also reported a correlation of 0.80 for transverse vibration technique, with values of E_SBE of 16.52 and 10.99 GPa in testing 24 wood samples of Guajará (*Micropholis venulosa*) and Teca (*Tectona grandis*), respectively. Good correlation was also obtained between E_SBE and E_STE with R=0.818. It is to have in mind that the wood used was not clear wood samples and the presence of defects such as knots may interfere in the accuracy of the predicting model. Wood density was not a good predictor of MOE in static bending.

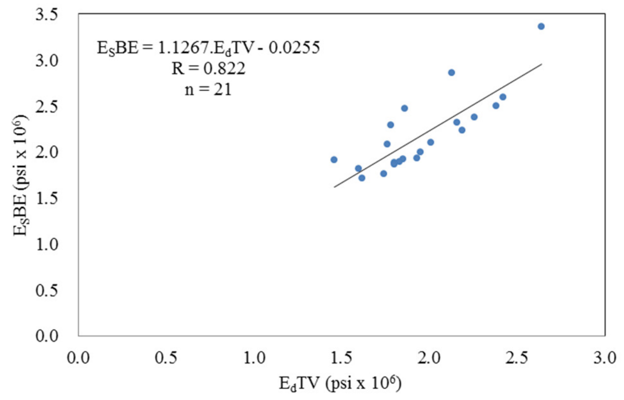

Figura 4. Linha de ajuste do MOE na flexão estática versus vibração transversal dinâmica.
Figure 4. - Line fit plot for static bending MOE versus dynamic transverse vibration.

Conclusions

Transverse vibration, specific gravity, and stress wave velocity are not good parameters to predict the MTS of Douglas-fir wood. MTS is also a poor predictor of tensile MOE as observed from the regression analysis performed. Wood samples presented sensitivity to weakness location and, during the test, rupture occurred most in the presence of knots or cracks. Therefore, new studies need to be performed to find a good predictor of tension properties.

Nondestructive parameters of stress wave velocity, frequency, attenuation, specific gravity, deflection and static MOE were very useful in the prediction of MOE from static tension (E_STE) tests. In this study, the best predictor for the actual E_STE was the transverse vibration technique with a high correlation coefficient of 0.941.

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