Comparison of Non-Destructive Methods Based on Natural Frequency for Determining the Modulus of Elasticity of *Cupressus lusitanica* and *Populus x canadensis*

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A non-destructive method for measurement of the modulus of elasticity (MOE) was compared with the static method on beams of *Cupressus lusitanica* and *Populus x canadensis*. The dynamic method is based on the principle of the resonance frequency, using longitudinal vibrations (Timber Grader MTG, accelerometer) and the static method for measurement of the flexural modulus of elasticity is according to EN 408 (2012). The differences between the ascertained dynamic and static MOE values were 1.1% to 2.4% for the *Populus x canadensis* sample and 12.7% to 15.5% for the *Cupressus lusitanica* sample. Furthermore, the correlation dependence of the applied methods was determined and the regression equations are shown. Experimental measurement showed the effect of the knot clusters, which appeared primarily in *Cupressus lusitanica* samples and considerably impacted the resultant values.

Keywords: Non-destructive testing; Dynamic MOE; Cupressus lusitanica; Populus x canadensis

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INTRODUCTION

The non-destructive testing of wood and investigation of its properties is a dynamically developing field that is being applied primarily in structures, where it is not possible to disrupt the investigated element by destructive testing, or in many cases even to remove them from the existing structures. For better effectiveness, various methods for non-destructive testing have been developed. The advantages consist in measuring without damaging the component and also in measuring components incorporated in structures (Kasal and Anthony 2004). For construction purposes, coniferous species are primarily used (80% to 90%) (www.fao.org). Coniferous softwoods are more commonly used in construction applications because coniferous forests cover most of the woodland areas in North America and Europe and are easier to process in comparison with harder, broadleaved wood.

The mechanical properties of wood, such as bending strength and modulus of elasticity in bending, depend on the wood species and their growing characteristics and defects. For the purposes of this study, the wood species *Cupressus lusitanica* and *Populus x canadensis* were selected. The former is a species introduced to Portugal from

Central America in the 17th century. Since then, it has spread in Portugal and become one of the most commonly found species in the inland intensively mountainous areas. *C. lusitanica* trees rise up to 35 m and have a straight stem. They are thus potentially suitable for sawn timber processing. These trees may also grow in unfavourable conditions and are widely used to re-forest degraded locations (Farjon 1993, 2005; Fernández-Pérez *et al.* 2013). For *C. lusitanica* Mill. (hereinafter CL), many studies have been conducted on its mechanical properties. Haslett (1986) describes the options for processing CL grown in New Zealand. In that research, it was established that this species is relatively easy to work with. Additionally, some other properties of CL include the interesting pattern of the wood, medium to low density, low shrinkage values, and significant natural durability of the wood. Shukla and Sangal (1986) tested samples to determine the mechanical properties of exotic species from Northern and North-Western India, which included CL. In their study, CL was evaluated as mechanically weak in comparison with teak wood (*Tectona grandis*) with a specific density of 430 kg/m^3, modulus of elasticity of 8.6 GPa, and bending strength of 74.8 MPa. Ng'ang'a (1992) evaluated the mechanical properties of CL green wood obtained in Kenya. The density was 390 kg/m^3, the modulus of elasticity was 6.3 GPa, and bending strength was 44.6 MPa. Kothiyal *et al.* (1998) ascertained the characteristics of 18-year-old CL wood from the Mahabaleshwar area (Western India). The wood had a large ratio of knots and a frequent presence of reaction wood. These samples had an average density of 440 kg/m^3, static bending modulus of elasticity of 4.3 GPa, and bending strength of 53.9 MPa. Moya and Muñoz (2010) tested the selected properties of CL and a further seven species from Central America (Costa Rica).

Apart from other physical and growth characteristics, researchers also measured the modulus of elasticity and bending strength at 12% moisture content. Eighteen test specimens were used, for which the following data were found: average modulus of elasticity of 7.6 GPa and bending strength 57.6 MPa for CL wood, with an average density of 430 kg/m^3. Elzaki and Khider (2013) recently presented a study of a 20-year-old sample of CL wood grown in Western Sudan. This sample had an average density of 446 kg/m^3. The measured average modulus of elasticity for a three-point bending test was 1.427 GPa, and the bending strength was 69.3 MPa. As is evident, the given studies substantially differ in terms of the values obtained during the mechanical tests, primarily because of the different origins of the samples.

The second wood species, *P. x canadensis*, initially originates from Central and Southern Europe, America, and some parts of Asia, but today it is broadly grown on almost all continents (Sheat 1948). The wood is widely used in the production of plywood, for carpentry, and also as packaging material (Kohli *et al.* 2009). Poplar wood has been used in structures for centuries, particularly in rural areas. In Italy from the 17th to the 19th centuries, poplar was the standard for use in structures in these rural areas because of an abundance of poplar in and around these areas, as well as its low density and dimensional stability (Castro 2007).

Studies have been conducted on the suitability of the use of poplar wood in structures, especially in the form of laminated veneer lumber (Castro and Paganini 2003; Castro and Zanuttini 2004; Castro and Fragnelli 2006) and oriented strand board (Zhou 1990), which have substantially broadened the use of poplar wood. Poplar wood also has the capability to bind a large volume of CO_2 (one hectare of poplar woodland binds up to 10 to 15 tons per year), and in combination with its wide availability on almost all continents, it is a species whose growth and processing is environmental friendly

(Basterra *et al*. 2012). *P. x canadensis* (PC) wood, according to literature, has a density of approximately 320 to 400 kg/m^3 and relatively good mechanical properties, particularly bending strength, approximately 40 to 70 MPa, and bending modulus of elasticity, approximately 7 to 10 GPa (Green *et al.* 1999).

When measuring the dynamic modulus of elasticity using frequency waves, several factors that impact the result come into play. One of them consists of the dimensions of the tested element. Casado *et al.* (2010) described the impact of the dimensions on the resonance properties of *Populus x euramericana*. According to the study's conclusions, size demonstrably has an impact on the resonance frequency: as the dimensions grow larger, the resonance frequency decreases. Seco and Barra (1996) monitored and described the dependence of the mechanical properties on the density and growth rate. Their observations were that the growth rate, as compared with the density, is a very weak predictor of mechanical properties. Researchers tested, among the others, *P. x euramericana*, and *Eucalyptus globulus*. The poplar sample was 12 years old and had an average density of approximately 383 kg/m^3, bending strength of 38 MPa, and bending modulus of elasticity of 7.8 GPa.

The method of measurement of the actual frequency is also known as the resonance method. It is a method used to ascertain the dynamic modulus of elasticity, which is a significant indicator of the mechanical properties of wood (Yang *et al* 2002; Ilic 2003). Measurement is done most often using a contact piezoelectric accelerometer or contactless microphone. The signal comprises mechanical excitation by hammer impact, subsequently picked up by a sensor and transformed into an electric signal. From the data of the excitation force and response of the material, a transmission function is set (the frequency response function – FRF; ASTM E1876 (2006)). It is used to create the resonance frequency, which is used together with the dimensions of the element, mass, and density to calculate the dynamic modulus.

For measurement of the longitudinal wave frequencies, the measuring and excitation devices are located at the end of the tested element. The similarity of the results of the static and dynamic modulus of elasticity (MOE) is the basis for successful use of these methods in practice. Some studies show a very close dependence (with the correlation coefficient of up to 0.96) of the static and dynamic MOE (Tanaka *et al.* 1991; Perstorper 1994; Ilic and Ozarska 1996; Kliger *et al.* 1998; Ilic 2001), although the values of the dynamic measurements themselves are often somewhat higher than in the case of static tests (Cho 2007; Hassan *et al.* 2013).

The objective of this study was non-destructive measurement of dynamic MOE in two samples, measurement of MOE and the modulus of rupture (MOR) using the static test in these samples, and subsequent comparison of the results. The major objective was comparison of dynamic MOE with static MOE to be able to determine the mechanical properties of PC and CL in practice using the non-destructive resonance method. Additionally, by mutual comparison of the results of the two devices used, it was desired to determine which one of them gives more precise results. Furthermore, the content of the knots was quantified and their impact on the measured values of MOE and MOR values was assessed. For comparison of the results, the correlation dependence of the data was monitored, and single factor analysis of the distribution and statistical linear regression were applied.

EXPERIMENTAL

Test Specimens

For measurement of the modulus of elasticity, PC and CL wood species were selected. Measurement was done on 60 test specimens of PC and 50 test specimens of CL, both with nominal dimensions of 80 x 80 mm (cross-section). The test specimens with the given dimensions were dried to an average moisture content of 12% and placed into an air-conditioned room with an air humidity of 65% ± 5% and temperature of 20 ± 2 °C. Both samples were taken from forest area in Portugal, namely from the Buçaco area in the case of CL and from the Soure Region for PC. Buçaco is a historically significant forest for experimental cultivation of forest species. The trees used to make the samples were solitarily planted. The following table shows the characteristics of the samples, including the knot content, which is quantified using the dimensions of the biggest knot, average size of the knot, and average number of knots per meter of the test specimen. Furthermore, the occurrence of knot clusters was also monitored. The knots clusters were detected in less than 10% of all PC specimens and in 100% of CL specimens.

Table 1. General Sample Information

Sample	N^0 of beams	Age (yr)	Diameter (cm)*	Biggest knot (average) (mm)	Knots in 1 m	Dimensions (mm)
CL	50	15 to 20	35 to 40	53 (29)	14	78 x 78 x 2917
PC	60			64 (29)	2.6	78 x 77 x 2494
*Diameter at breast height						

Method for Determination of MOE and MOR

The applied method determined the dynamic modulus of elasticity using the resonance frequency. The first measurement device was a piezoelectric accelerometer with a magnetic sensor (National Instruments Corporation, Austin, Texas-USA). A signal sensor was placed on the face of the test sample, and hammer impact on the opposite end was used as the source of the wave signal. Using Acquisition device hardware: NI-USB 4431 (National Instruments Corporation, Austin, Texas-USA) and the Signal Express program (National Instruments Corporation, Austin, Texas-USA), the signal was transferred to a computer and evaluated using the fast Fourier transform (FFT) principle, which is a method used on a standard basis to determine the frequency characteristics of materials (Cooley and Tukey 1965).

The second device used was the Timber Grader MTG (Brookhuis Applied Technologies WOOD, Enschede, Netherlands). It also operates by measurement of resonance frequency. Unlike the first method, only access to one end of the tested element is necessary. The Stress Wave Activator and Stress Wave Detector are integrated in the Timber Grader MTG. The device thus sends a stress wave, which reverberates from the opposite end and returns; the device detects it as a wave frequency, and using the defined dimensions, moisture content and mass, it calculates the MOE and sends the values to the computer *via* a Bluetooth interface. The test specimens were placed on rubber mats to ensure minimal attenuation of passing waves. Both methods work with the measured stress wave frequency, from which dynamic MOE is calculated using the formula,

$$E_D = 4\rho L^2 (\frac{f_{L,n}}{n})^2 \tag{1}$$

where ρ is the density of the element (kg/m^3); $f_{L,n}$ is the measured frequency of the longitudinal stress waves (Hz); L is the length (m), and n (= 1) is the coefficient for the longitudinal measurement method (Bucur 2006).

To compare the precision of measurement using dynamic methods, a bending test was done according to EN 408 (2012) and the static MOE was determined. During the test, the distances between the supports were 480 mm in the upper part and 1440 mm in the lower part of the test device. The bending strength was also determined including the rupture causes of the material. The knots were the most frequent cause of rupture. For the PC sample, rupture caused by knots occurred in 60% of the test samples; for CL, this percentage was up to 90%. Knots were analyzed according to EN 1310 and Portuguese NP 4305. The factor of knots was simplified to the biggest knot and the content of knots in one meter. Each knot was recorded as its visible area on the edge or face of the beam in square millimeters.

When processing the results, the statistical analysis of variance (ANOVA) was used, and regression analysis was done to describe the relationship between dynamic and static MOE. The significant differences between methods for MOE determination were assessed by Levene's and Tukey's tests. The STATISTICA 10 software was used.

RESULTS AND DISCUSSION

The results were subjected to statistical analysis. Normality was analyzed with the lowest p-value of Shapiro-Wilk test of 0.076 for CL-$\mathrm{MOE}_{\mathrm{ACC}}$ data. The Grubbs' test did not show any extreme values (the lowest p-value was 0.293 for PC-$\mathrm{MOE}_{\mathrm{STAT}}$ data). Table 2 shows the results of the descriptive statistics of the static and dynamic MOE measurements and the density for both samples.

Table 2. Modulus of Elasticity and Density

		Mean	Min.	Max.	COV (%)*
PC	$\mathrm{MOE}_{\mathrm{MTG}}$ (N/mm^2)	10366	7189	13571	14.2
	$\mathrm{MOE}_{\mathrm{AC}}$ (N/mm^2)	10002	6502	13713	17.8
	$\mathrm{MOE}_{\mathrm{STAT}}$ (N/mm^2)	10113	7339	14310	15.2
	Density (kg/m^3)	405.6	291.4	501.9	12.2
CL	$\mathrm{MOE}_{\mathrm{MTG}}$ (N/mm^2)	6180	3650	9130	22.0
	$\mathrm{MOE}_{\mathrm{AC}}$ (N/mm^2)	6331	3846	9276	21.7
	$\mathrm{MOE}_{\mathrm{STAT}}$ (N/mm^2)	7135	4268	11018	23.9
	Density (kg/m^3)	456.4	379.2	515.8	6.7

*COV – coefficient of variation
PC – *Populus x canadensis*
CL – *Cupressus lusitanica*
$\mathrm{MOE}_{\mathrm{MTG}}$ – dynamic MOE measured by MTG Timber grader (longitudinal vibration method)
$\mathrm{MOE}_{\mathrm{AC}}$ – dynamic MOE measured by accelerometer (longitudinal vibration method)
$\mathrm{MOE}_{\mathrm{STAT}}$ – static MOE measured according to EN 408

For the PC sample, the MTG measurement results showed higher MOE values than the static tests and the data from accelerometer showed lower values. Granted, these differences were very small. For the CL sample, the dynamic MOE values for both devices used were lower than those from the static test. The natural vibration frequency of the sample is highly related to its dimensions, namely to the length, so that longer beam has lower natural frequency (Bucur 1984). The lower frequency causes the decrease of dynamic MOE (Ouis 2002). Therefore, the measured data of dynamic MOE are mostly lower than static MOE. The longer sample (CL) shows lower results of dynamic MOE in relation to static MOE because of its lower natural frequency. The aim of MOE measurement study was to obtain the analogical correlation coefficients between the static and the dynamic methods for the sample of different effective length. In general, with the increasing specimen size the resonance frequency decreases and also the difference between dynamic and static MOE decreases (Casado *et al.* 2010). Some studies state the differences between the static and dynamic MOE measurements. Yang *et al.* (2002) report 36% to 39% higher dynamic MOE measured using the horizontal stress wave method and static MOE. Hassan *et al.* (2013) ascertained the same difference and the deviation was 22.3%. Cheng and Hu (2011) using various methods ascertained MOE for poplar wood, and the deviation from MOE as ascertained using longitudinal waves and static MOE was 10.4%.

The CL sample was substantially more knotty. Apart from the larger number of knots, the CL sample also had a presence of so-called knot clusters. These clusters of two or three knots do not influence the resonance frequency so much, but in bending tests they have a greater influence on the results (Riberholt and Madsen 1979; Hanhijärvi *et al.* 2005). The clusters cause substantial deviation of fibres in their vicinity, which had a negative influence on the results of mechanical properties (Dinwoodie 2002; Koman *et al.* 2013).

The monitored correlation of dependence between the individual methods for determination of the MOE between themselves and between each of these methods and bending strengths is recorded below for both samples and all measured variables. Table 3 shows the correlation coefficients for dependence between the individual methods of measurement. In the case of CL, the highest correlation dependence (0.993) was found between the results of the accelerometer and MTG. The smallest (0.633) was the correlation between MOE_{MTG} and bending strength. On average, lower correlations of dependence were found between MOE and static bending strength. For the CL samples, a low dependence was found between the MOE and bending strength. For the PC sample, a similar tendency was observed. The highest correlation of dependence was also found between MOE_{MTG} and MOE_{AC} (0.979).

Table 3. Table of Correlation Dependence of the Applied Methods

		MOE_{MTG}	MOE_{AC}	MOE_{STAT}
CL	MOE_{MTG}	1	0.993	0.931
	MOE_{AC}	0.993	1	0.937
	MOE_{STAT}	0.931	0.937	1
PC	MOE_{MTG}	1	0.979	0.898
	MOE_{AC}	0.979	1	0.906
	MOE_{STAT}	0.898	0.906	1

For comparison of the results of the three methods for determination of the MOE, a graph of the analysis of the distribution is given. The given graph in Fig. 1 shows the confidence intervals for MOE using all three methods for both species. The MOE values for PC, at approximately 10 GPa, comply with the previous studies investigating MOE in poplar wood (Green *et al.* 1999; Koman *et al.* 2013). Furthermore, significant differences between the measured data were found according to the individual methods and separately for CL and PC. The Levene's test of equality of variances demonstrated insignificant differences between the methods of measurement for CL ($p = 0.186$) and the same also applied to the PC sample ($p = 0.22$). The subsequent Tukey's test of variance of mean values demonstrated significant differences in the CL sample. The difference can be caused by a greater amount of knots and knot clusters and also by greater length comparing to PC sample. As is also clear from Fig. 1, there were significant variances between the values of the modulus of elasticity measured by MTG and by static MOE ($p = 0.0039$) and between the values from the accelerometer and by static MOE ($p = 0.019$). The difference between the two dynamic methods was not significant. In the PC sample, no statistically significant differences in the mean values were registered between the individual measurement methods. The stated differences are statistically significant at the confidence level of 0.05.

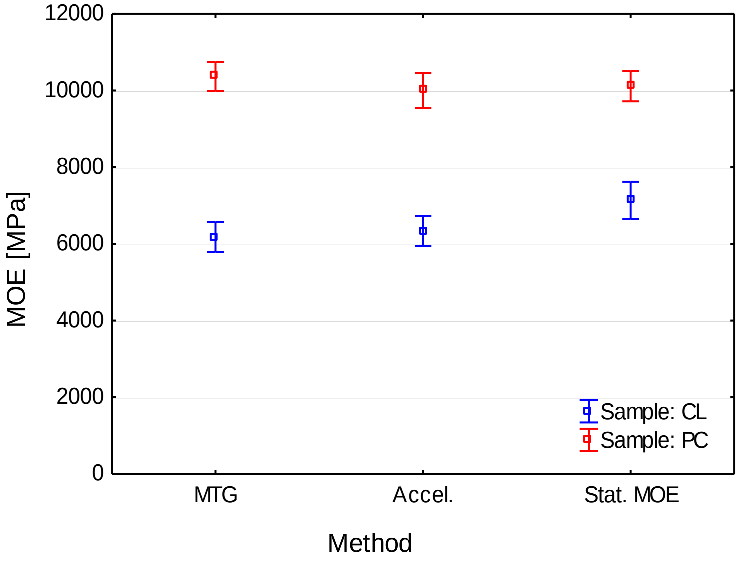

Fig. 1. The output of the analysis of the distribution of the modulus of elasticity values according to the applied methods for *C. lusitanica* (CL) and *P. x canadensis* (PC)

On the basis of the above-stated correlations and results of the dynamic and static tests, a dependence analysis was done using the linear regression method, the results of which are presented in the following graph and given regression equations. Table 4 contains the regression equations for CL and PC. The coefficient of determination (R^2) shows the degree of description given by the dependence or degree of reliability of MOE calculated according to the given equation. Dynamic MOE generally shows a lower correlation of dependence with bending strength than applies to the dependence of dynamic MOE and static MOE (Bodig and Jayne 1982; Larsson *et al.* 1998; Guntekin *et al.* 2013; Baar *et al.* 2015). For samples with a lower defect content (especially knots), these dependencies increase and the prediction of mechanical properties by dynamic testing is more accurate (Ayarkwa *et al.* 2000).

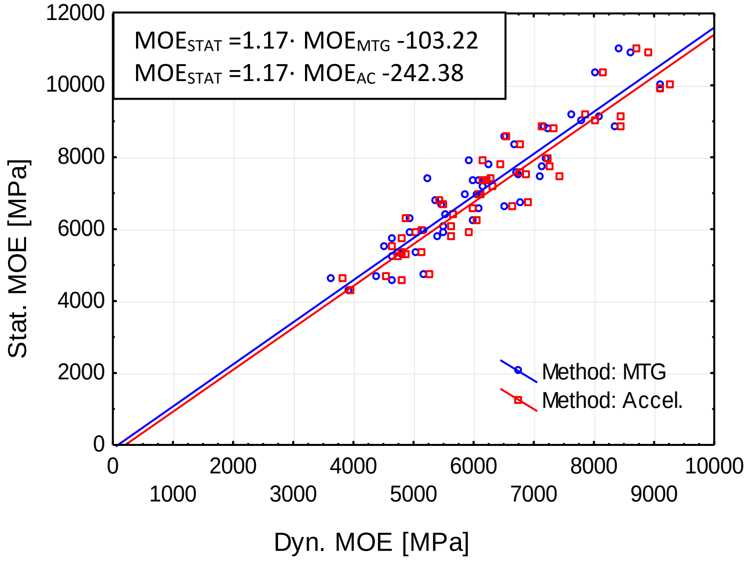

Fig. 2. Linear regression of the dynamic and static modulus of elasticity for the CL sample

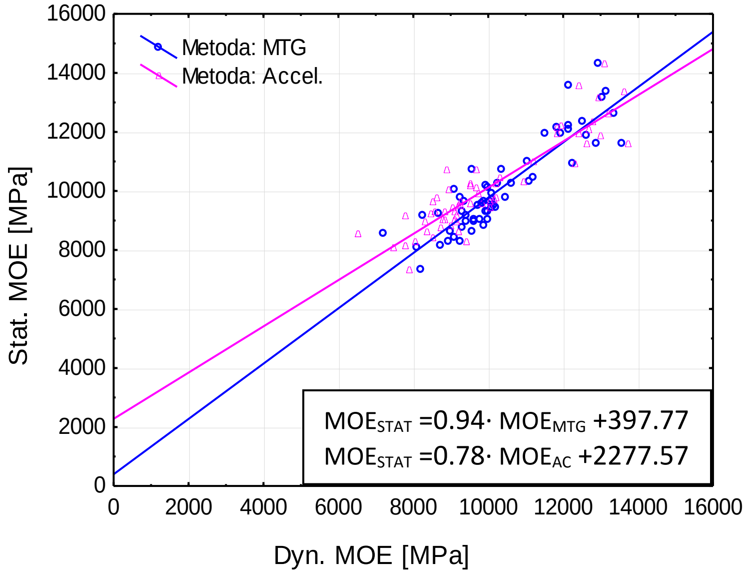

Fig. 3. Linear regression of the dynamic and static modulus of elasticity for the PC sample

Table 4. Regression Equation and Coefficient of Determination for the Applied Method

Method (x *vs*. y)		Regression equation	Coefficient of determination
CL	MTG. *vs*. MOE_{STAT}	$MOE_{STAT} = 1.17 \cdot MOE_{MTG} - 103.22$	0.87
	Acc. *vs*. MOE_{STAT}	$MOE_{STAT} = 1.17 \cdot MOE_{AC} - 242.38$	0.88
PC	MTG. *vs*. MOE_{STAT}	$MOE_{STAT} = 0.94 \cdot MOE_{MTG} + 397.77$	0.81
	Acc. *vs*. MOE_{STAT}	$MOE_{STAT} = 0.78 \cdot MOE_{AC} + 2277.57$	0.82

Nevertheless, some coefficients of determination between dynamic MOE measured by longitudinal vibration method and static MOE are published. Baar *el al.* (2015) tested three tropical species and achieved coefficients of 0.74, 0.72 and 0.23. Casado *et al.* (2010) tested *Populus x euramericana* with the same coefficient varying from 0.28 to 0.59. Comparing these data, the poplar dynamic and static methods presented are more accurate. *Cupressus lusitanica* is not as well-known regarding dynamic mechanical properties but linear regression analyses showed an even better relation between dynamic and static values of MOE than the PC sample (Table 4). It provides a prerequisite for possible construction use of this species.

For the purposes of measurement, samples with a content of knots were used as described above to allow for assessment of the real possibilities of MOE measurement in practice and to validate the possibility to use the dynamic methods for derivation of static MOE. For the PC sample, it was demonstrated that both measuring devices used (MTG and accelerometer) returned similar results, and these results may be used for credible determination of the static MOE. In the case of CL, on the contrary, a significant statistical deviation was registered between static MOE and both dynamic methods (15.5% for MTG and 12.7% for accelerometer). The difference between the results of the dynamic and static tests of solid wood may be caused by the viscoelastic properties of wood, which play a role in the static bending test; additionally, the duration of the load on the tested element, which causes creeping and distorts real MOE, is important (Bodig and Jayne 1982; Larsson *et al.* 1998). If the creeping effect were eliminated, the deviations between the static and dynamic values would decrease (Teranishi *et al.* 2008).

CONCLUSIONS

1. Dynamic MOE was measured by longitudinal vibration test method on *P. x canadensis* (PC) and *C. lusitanica* (CL) samples. When comparing the results with static 4-point bending test data, the deviations were 2.4% and 1.1% for PC and for CL sample 15.5% and 12.7%. Greater deviation between static and dynamic MOE of CL sample was caused by the higher content of knots and greater sample length.
2. Linear regression analysis gave high coefficients of determination for PC comparing to the literature (R^2 0.82) and even higher for CL sample (R^2 0.88).
3. *Cupressus lusitanica* may have a good prerequisites for the estimation of its mechanical properties by nondestructive methods based on longitudinal vibrations and by reducing some growth defects, especially the knots, even better correlation can be obtained.

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