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PREDICTION OF BENDING PROPERTIES FOR SOME SOFTWOOD SPECIES GROWN IN TURKEY USING ULTRASOUND

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ABSTRACT

Ultrasound has been used in prediction of bending properties for some important wood species grown in Turkey including Calabrian pine, Anatolian black pine, Cedar and Oriental Spruce. Sound velocities of small clear wood specimens were determined using EPOCH 650 ultrasonic flaw detector with 2.25 MHz contact longitudinal transducers at constant moisture content. Following non-destructive measurements, specimens were subjected to three point bending tests. The measured average sound velocities for species tested in L directions were ranged from 4510 to 5254 $m \cdot s^{-1}$. Although spruce had the lowest density (425 $kg \cdot m^{-3}$), it had the highest sound velocity. The predicted average dynamic modulus of elasticity (E_{dyn}) values for the species tested varied from 10137 to 12856 $N \cdot mm^{-2}$. The correlation coefficients between E_{dyn} values and MOE values were higher than those between E_{dyn} and MOR. E_{dyn} values are higher than calculated MOE values. The correlation coefficient between predicted E_{dyn} and calculated MOE values ranged from 0.81 to 0.89. The correlation coefficient between E_{dyn} and MOR varied from 0.78 to 0.88 for the species tested. Results indicated that there was no certain relationship between the density and wave velocity except Calabrian pine which showed negative weak correlation. MOE is better indicator of MOR than E_{dyn} as expected.

KEYWORDS: Bending properties, softwoods, ultrasound.

INTRODUCTION

Bending properties are important in the design of wood members in structures. Most of wood members in use are subjected to compression and bending forces. While modulus of elasticity (MOE) is a measure of the stiffness of an elastic material and is a quantity used to characterize materials, modulus of rupture (MOR) is used to determine allowable stress limits. In general, there are many physical parameters that may affect bending properties such as moisture content (MC), specific gravity, temperature, creep, knots, number of annual growth rings and grain angle. Bending properties can be determined using both destructive and non-destructive methods. Conventional bending tests in order to determine MOE are costly, destructive, and difficult to carry out rapidly. Propagation velocity of ultrasound waves in materials, including wood, is an important parameter enabling to determine their quality characters in a non-destructive manner (Krauss and Kúdela 2011).

Use of non-destructive testing (NDT) and non-destructive evaluation (NDE) in the field of wood and wood based materials is advancing every day. There are wide spread NDT techniques, equipment and evaluation procedures available today which resulted from early NDT researches (Brashaw et al. 2009; Dündar and Divos 2014). Ultrasonic wave velocity has more advantages over other techniques in practical terms (Esteban et al. 2009).

Determination of the ultrasonic modulus of elasticity (E_{dyn}) in a solid depends on its elastic properties and its density (Oliveira et al. 2005). The velocity of sound in wood (SV) is influenced by factors such as MC, grain orientation, density, decay, temperature, and geometry (Oliveira and Sales 2006).

Oliveira et al. (2002) stated that nondestructive methods offer several advantages over conventional wood characterization methods, such as the possibility of evaluating the structural integrity of an element without extracting test specimens, faster analysis of large populations, and versatility to adapt to standardized production line routines. Mechanical properties have been mostly predicted from wood density, which was considered the most reliable and the simplest indicator of the wood strength (Tsoumis 1991). There is an approximately positive linear correlation between density and mechanical properties but density influence is often weakened by the natural growth features like knots, cross grains, etc., occurring in wood. Therefore, the usability of density for the prediction of mechanical properties is often limited only to clear straight-grained wood which does not correspond with the practice. Prediction of MOR using density is poor according to Baar et al. (2015), the best prediction is provided by MOE, since it is directly related to the velocity of wave propagation.

The purpose of this study was to evaluate the dynamic modulus of elasticity (E_{dyn}) of some softwood species grown in Turkey nondestructively through longitudinal ultrasound propagation and to determine the strength of the relationship between E_{dyn} predicted from ultrasonic based NDT technique and static bending properties (MOE and MOR).

This study was presented at the „International Multidisciplinary Congress of Eurasia", 11-13th July 2016, Odessa, Ukraine.

MATERIALS AND METHODS

Materials

Woods of Calabrian pine (*Pinus brutia*), Anatolian black pine (*Pinus nigra*), Cedar, (*Cedrus libani*) and Oriental spruce (*Picea orientalis*) were supplied commercially. Selected wood species covers largest area of the conifers grown in Turkey. They are important raw material for various fields of forest industry and construction.

Methods

100 specimens which were 20 x 20 x 400 mm in dimensions for each species were prepared for the study. 60 mm pieces were cut from end of each sample to measure sound velocities. The remaining part was subjected to 3-point bending tests. The specimens were stored in the

conditions of 65 % relative humidity and at 21°C until the MC of the samples stabilized. Apparent densities (ρ) of the samples were calculated according to TS 2472 (2005) using stereometric method which based on measurements of the sample volume and mass.

A direct pulse ultrasonic technique was used to obtain the wave velocities. The waves were generated using EPOCH 650 ultrasonic flaw detector. The longitudinal wave frequency was 2.25MHz. Two Olympus A133S-RMcontact transducers were used to carry out the measurements. To ensure coupling between the specimen and the transducers during measurements, a gel-like coupling medium (Ultragel II) was used. Constant coupling pressure during the measurements was provided by the use of a spring. Having obtained the wave velocities, E_{dyn} values of the samples were calculated using the following Eq. 1:

$$E_{dyn} = \rho V^2 10^{-6} \tag{1}$$

where: E_{dyn} - the dynamic modulus of elasticity ($N \cdot mm^{-2}$),
ρ - the density ($kg \cdot m^{-3}$),
V- the SV of the ultrasound wave ($m \cdot s^{-1}$).

After completing ultrasonic measurements, 3-point bending tests were carried out using universal testing machine at standard climatic conditions (65 % RH and 21°C). MOE of the samples were calculated according to following Eq. 2:

$$MOE = PL^3/4\Delta bh^2 \tag{2}$$

MOR of the samples were calculated using the following Eq.3:

$$MOR = 3P_{max}L/2bh^2 \tag{3}$$

where: MOE - bending stiffness,
MOR - bending strength,
P_{max} - maximum bending load obtained during testing,
P - P1-P2, load in the elastic limit,
Δ - d1 – d2, corresponding deformation in the elastic limit,
L - span of the supports,
b - width of the specimen,
h - height of the specimen.

Collected data were subjected to Normality test. Correlation analysis to interpret the interrelation ships among the properties measured were performed with SAS statistical analysis software of the clear wood samples. The regression analysis was also conducted to measure the strength of the relationship between MOE and MOR; E_{dyn} and MOR.

RESULTS AND DISCUSSION

Average values for density, MC, sound velocities (SV), E_{dyn}, MOE and MOR values of the specimens tested are presented in Tab. 1. In comparison to available literature references at similar MC, the measured density, MOE and MOR values were comparable.

Since the number of samples is less than 2000, Shapiro - Wilk test was used for normality. In the case of SV, E_{dyn}, MOE and MOR data with the Shapiro - Wilk test providing evidence that the data are normally distributed.

Tab. 1: Average values of the parameters determined.

Species		Density ($kg \cdot m^{-3}$)	MC (%)	Sound velocity ($m \cdot s^{-1}$)	E_{dyn} ($N \cdot mm^{-2}$)	MOE ($N \cdot mm^{-2}$)	MOR ($N \cdot mm^{-2}$)
Black pine	X	550	11.4	4834	12856	10988	106
	S. D.	67	1.2	488	2790	2371	15
	COV	12	10	10	21	22	14
Calabrian pine	X	528	12.5	4593	11127	10119	96
	S. D.	36	1.7	326	1516	1620	15
	COV	7	13	7	14	16	15
Cedar	X	498	12.2	4510	10137	9767	91
	S. D.	29	2.1	282	1179	946	9
	COV	6	17	6	12	10	10
Spruce	X	425	11.7	5254	11733	9500	81
	S. D.	54	1.5	338	2241	1736	16
	COV	13	13	6	19	18	20

The softwoods used in the study significantly differ regarding their SV in the longitudinal direction at 21°C and 65 % RH. SV values ranged from 4510 to 5254 $m.s^{-1}$ parallel to grain direction. Although Spruce had the lowest average density among the species tested, its SV was the highest. Calabrian pine and Cedar had similar SV values although their density values significantly differ.

The average SV values obtained in this study for spruce is similar to those reported for Sitka spruce and White spruce (Bucur 2006). The average SV values of Calabrian pine is lower than SV of known pine species (Halabe et al. 1997; Bucur 2006; Kraus and Kúdela, 2011; Hassan et al. 2013; Ribeiro et al. 2013). It is similar to those reported by Montero et al. (2015). Lower SV values of Calabrian pine can be attributed to high percentage of early wood. The wood of Cedar has also identical SV values of incense Cedar (Chiu et al. 2013) and higher SV than red cedar (3895 $m \cdot s^{-1}$). There is no information in the literature concerning SV values of Black pine. It seems that SV is related to homogeneity of annual rings.

Since the MOE is directly proportional to the density, the SV should be independent from the density (Kollmann and Cote 1968). The correlation analysis (Tab. 2) indicate that there is no correlation between density and SV for Black pine. SV is also not correlated with E_{dyn}, MOE and MOR for black pine. For Calabrian pine, there is negative weak correlation between SV and density. However, a strong positive correlation existed between E_{dyn} and MOE, E_{dyn} and MOR. For Spruce, there is also no correlation between SV and density values. SV is well correlated with E_{dyn} and MOE, but not MOR. For Cedar, SV is not correlated with density but highly correlated with E_{dyn}, MOE and MOR.

There is a contradiction in the literature on whether SV is correlated with wood density or not. Some authors (Oliveira et al. 2002; Ilic 2003; Teles et al. 2011) identified that there is no relationship between density and velocity while others (Oliveira and Sales 2006; Baradit and Niemz 2012) reported positive relationship of density and velocity. Some authors (Ilic 2003; Krauss and Kúdela 2011) claimed that velocity is related to the micro-fibrilar angle while

Tab. 2: Pearson correlation coefficients (r) between variables (Density, SV, E_{dyn}, MOE, MOR).

Black pine	**Density**	**SV**	**E_{dyn}**	**MOE**	**MOR**
Density	-	0.11n.s.	0.048	0.09	0.17
SV	0.11	-	0.22	0.17	0.11
E_{dyn}	0.048	0.22	-	0.86*	0.78*
MOE	0.09	0.17	0.86*	-	0.85*
MOR	0.17	0.11	0.78*	0.85*	-
Calabrian pine	**Density**	**SV**	**E_{dyn}**	**MOE**	**MOR**
Density	-	-0.43*	-0.06	-0.07	0.01
SV	-0.43*	-	0.79*	0.72*	0.87*
E_{dyn}	-0.06	0.79*	-	0.83*	0.88*
MOE	-0.07	0.72*	0.83*	-	0.78*
MOR	0.01	0.87*	0.88*	0.78*	-
Cedar	**Density**	**SV**	**E_{dyn}**	**MOE**	**MOR**
Density	-	0.20	0.48*	0.54*	0.43*
SV	0.20	-	0.62*	0.53*	0.78*
E_{dyn}	0.48*	0.62*	-	0.81*	0.84
MOE	0.54*	0.53*	0.81*	-	0.73
MOR	0.43*	0.78*	0.84*	0.73*	-
Spruce	**Density**	**SV**	**E_{dyn}**	**MOE**	**MOR**
Density	-	0.18	0.75*	0.78*	0.79*
SV	0.18	-	0.65*	0.46*	0.35
E_{dyn}	0.75*	0.65*	-	0.89*	0.79*

Gerhards (1982) and Beall (2002) pointed out that grain angle has major impact on the SV.

The average calculated MOE values ranged from 9500 to 10998 $N{\cdot}mm^{-2}$. The average MOR values varied between 81 and 106 $N{\cdot}mm^{-2}$. In comparison to available literature references at similar MC, the calculated MOE and MOR values are comparable. E_{dyn} values ranged from 10137 to 12856 $N{\cdot}mm^{-2}$. The values of E_{dyn} were higher than those obtained from static MOE. The results obtained by Oliveira et al. 2002 showed that the dynamic tests were 17 % higher than those of the static tests. Even higher differences were presented by Smulski (1991). Divos et al. (2007) reported that MOE determined by density and velocity is always higher than static MOE. The main reason for the difference is creep (Divos and Tanaka 2000). Halabe et al. (1997) explained the reason for the difference between E_{dyn} and the static MOE by considering wood as a highly damping and viscoelastic material. It is known that dynamically determined elastic properties are 10-20 % (or even more, depending on the frequency of ultrasonic waves) increased compared with statically calculated values (Keunecke et al. 2011).

In general, the MOE is accepted as the most important strength predictor parameter. Strong relationships were observed between E_{dyn}, MOE and other mechanical properties such as MOR. In non-destructive evaluation of wood, correlation coefficients are usually dependent on the methods, species used, moisture content, type of samples tested (Karlinasari et al. 2008; Teles et al. 2011). As stated by Ross and Pellerin (1994) that the correlation coefficient values can be as high as 0.98 and 0.88 for clear wood species and dimension lumber, respectively. Divos and Tanaka (2005) reported that correlation coefficients values between static and dynamic MOE values can be between 0.9 and 0.96. The correlation of coefficient using ultrasound can be somewhat lower than other non- destructive methods. The lower accuracy of the ultrasound method for the prediction of wood mechanical properties is probably caused by its measuring mechanism. Other methods such as stress wave and resonance involve determination of E_{dyn} which is based on much higher number of waves passing through the material and the entire section of the sample. However, the ultrasound method determines the velocity based on the passage of one wave in a limited area connecting two measuring sensors (Hansen 2006).

Using ultrasound, values of correlation coefficients between E_{dyn} and MOE in the range of 0.74 for the static modulus of elasticity and 0.60 for bending strength are cited (Horáček et al. 2012; Hassan et al., 2013 for softwoods. For hardwood species, values of correlation coefficients varies between 0.36 and 0.87 (Oliveira et al. 2002; Karlinasari et al. 2005; Baar et al. 2015).

Tab. 3: Regression equations of linear models to explain the relation of MOE vs. MOR and E_{dyn} vs. MOR.

Parameters (x vs. y)	Species	Linear regression model	R^2
MOE vs MOR	Black pine	y = 45.49 + 0.0054*x	0.72
	Calabrian pine	y = 18.64 + 0.0076*x	0.70
	Cedar	y = 18.2 + 0.0075*x	0.66
	Spruce	y = 3.80 + 0.0081*x	0.77
E_{dyn} vs MOR	Black pine	y = 47.77 + 0.0045*x	0.62
	Calabrian pine	y = 10.5 + 0.0076*x	0.62
	Cedar	y = 36.09 + 0.0054*x	0.54
	Spruce	y = 14.52 + 0.0056*x	0.62

Linear models relating the MOR and the MOE and the E_{dyn} were presented in Tab. 3. As can be observed, the static MOE can explain the variability of the MOR better than the E_{dyn}. The relationship between E_{dyn} and MOE, MOE and MOR, E_{dyn} and MOR are presented in Figs. 1-3.

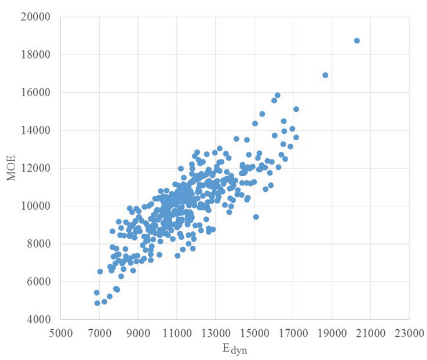

Fig. 1: The relationship between E_{dyn} and MOE of all species tested.

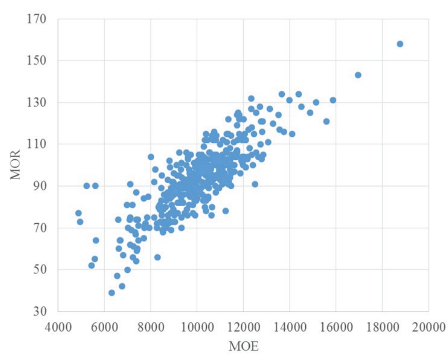

Fig. 2: The relationship between MOE and MOR of all species tested.

The individual coefficient of determinations between MOE and E_{dyn} ranged from 0.71 to 0.80 and the coefficient of determination between MOE and MOR varied between 0.66 and 0.77, and between E_{dyn} and MOR varied between 0.54 and 0.62. E_{dyn} reflects the properties in the measurement path of the sample only. That is one of the reasons why E_{dyn} is relatively poor predictor of the MOR. Stronger relationship between MOE and E_{dyn} is expected because SV

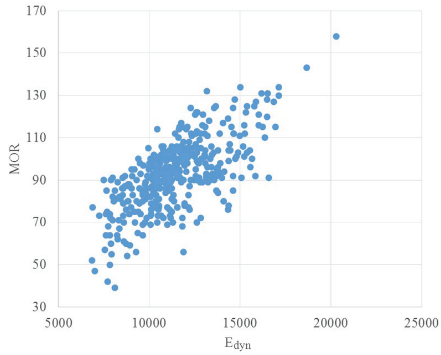

Fig. 3: The relationship between E_{dyn} and MOR of all species tested.

is directly related to elasticity (stiffness) not the failure point of the material (Daniels and Clark 2006).

CONCLUSIONS

E_{dyn} for important wood species grown in Turkey were measured using ultrasound and compared with static MOE and MOR. Results show that there are high correlations between predicted E_{dyn} and calculated MOE values for the species tested. Static MOE is better predictor of MOR than E_{dyn}. Comparing with other NDT methods such as stress wave and vibration used in the literature, correlation coefficients obtained using ultrasound seems to be lower. Ultrasonic wave technique may be considered as alternatives to destructive testing in characterizing bending properties of the species tested. The ultrasonic method is more rapid and offers an opportunity for much greater sampling.

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