Determination of Young's Modulus in Three Orthotropic Directions for Calabrian Pine and Taurus Cedar Using Ultrasound and Digital Image Correlation (DIC)

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Abstract

Young's modulus in three orthotropic directions for Calabrian Pine (*Pinus brutia* Ten.) and Taurus cedar (*Cedrus libani*) has been investigated using ultrasound and digital image correlation technique (DIC). The materials used in the study consisted of 360 small clear specimens of nominal dimensions 20 x 20 x 60 mm. The influence of MC was studied over four batches of 15 specimens each, conditioned for 6-8 weeks before testing at a temperature of 20 ± 2ºC and at four different relative humidity levels (50%, 65%, 85%, and 95%). Time of flight value was measured with an ultrasonic commercial device Steinkamp BP-V. Measurements were made end to end directions (*L*, *R*, *T*) on each specimen, with a constant sensor coupling pressure. According to the time results of ultrasound devices, the sound velocities (length/time) and E_{dyn} were calculated. Samples were also tested in uniaxial compression in order to determine Young's modulus (*E*) and compression strength (*CS*) in three orthotropic directions using a Zwick Z 100 universal testing machine. The feed rate was defined in such a way that the failure of the specimen should be reached in 90 (±30) s. The strains were evaluated using the digital image correlation (DIC) technique. The R^2 values between E_{dyn} and *E* were 0.96 and 0.95, between *CS* and E_{dyn} were 0.90 and 0.94 for Calabrian pine and Taurus cedar, respectively. Moisture content seems to be an influencing factor on sound velocity and *E* and *CS* for all orthotropic directions.

Key words: Young's modulus, ultrasound, DIC, Calabrian pine, Taurus cedar

1. Introduction

Compression properties, particularly Young's modulus, in the three principal directions are important in design of wood members in structures. Young's modulus, also known as the elastic modulus, is a measure of the stiffness of an elastic material and is a quantity used to characterize materials. In general, there are many physical parameters that may affect Young's modulus such as moisture content (MC), specific gravity, temperature, creep, knots, number of annual growth rings and grain angle. Investigations regarding the influence of MC on Young's modulus have shown that if MC increases the Young' moduli decrease. While the influence of MC on the mechanical behavior of wood in the *L* direction is relatively well known [1], investigations on the behavior in the perpendicular directions (*R* and *T*) are limited. The interest on the moisture dependent orthotropic behavior is not new. So far, only few studies studied moisture dependent elastic properties of wood in the *R* and *T* directions [2,3,4,5,6]. Furthermore, moisture-dependent wood strength in the *R* and *T* directions, remain widely unrevealed for most wood species. The usable data are limited to a few references [5,6,7]. While selected moisture dependent elastic properties for some wood species can be found in Kretshmann and Green [7] and Ross [8].

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Young's modulus can be determined using both destructive and non-destructive methods. 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 [9,10]. Ultrasonic wave velocity has more advantages over other techniques in practical terms [11].

The ultrasonic technique has been utilized in many applications including tree quality evaluation in forests [12] and condition assessment of wood structures in service [13]. The ultrasonic modulus of elasticity determination in a solid depends on its elastic properties and its density. The velocity of sound in wood is influenced by many factors such as moisture content, grain orientation, density, decay, temperature and geometry [14, 15].

Information on the Young's modulus of wood in the orthotropic directions is not available for majority of Turkish species. Most of the studies deal with bending MOE, bending, tensile and compression strength at constant MC. Although data needed for three dimensional modeling of mechanical behavior depending on the MC change, no information is available for this purpose. In this study, Young's modulus in compression for Calabrian pine and Taurus cedar wood is determined by non-destructive and destructive testing at different moisture conditions.

2. Materials and Method

For the study, the sample trees for Calabrian pine (*Pinus brutia* Ten.) and Cedar (*Cedrus libani*) were selected from pine-cedar mixed stand in the Bucak Forest Region of the Southwest region of Turkey. The logs were sawn into lumber in a private mill. The specimens were cut from the radial and tangential planks considering sample matching.

The materials used in testing consisted of 360 small clear specimens of nominal dimensions 20 x 20 x 60 mm. The specimens were grouped into 4 batches of 15 specimens each and were tested in the ETH laboratories in Zurich, Switzerland. The influence of EMC was studied over four batches of nearly 15 specimens each, conditioned for 6-8 weeks before testing at a temperature of 20 ± 2ºC and at four different relative humidity conditions (50%, 65%, 85%, and 95%).

Time of flight value was measured with an ultrasonic commercial device Steinkamp BP-V using conical sensors of 22 kHz frequency. Measures were made end to end directions (*L*, *R*, *T*) on each specimen, with a constant sensor coupling pressure as shown in Figure 1. According to the time results of ultrasound devices, the sound velocities (SV, length/time) and E_{dyn} were calculated using the fallowing equation:

$$E_{dyn} = \rho \times V^2 \times 10^6$$

Where:
E_{dyn} is the dynamic modulus of elasticity, in N/mm^2;
ρ is the density, in kg/m^3;
V is the velocity of the ultrasound wave, in m/s.

Figure 1. Device used to measure time of flight

After the ultrasonic measurements, uniaxial compression tests were carried out using a Zwick 100 universal testing machine at standard climatic conditions (65 % RH and 20 °C). To minimize the influence of the MC change, specimens were tested immediately after removal from the climatic chamber. Wood MC was determined by the oven-drying method. The feed rate was defined in such a way that the failure of the specimen should be reached in 90 (±30) s. The strains were evaluated using the digital image correlation (DIC) technique. A high contrast random dot texture was sprayed on the surface of the specimen with air-brush to ensure the contrast needed for the evaluation of the displacements. Pictures were taken with a frequency of 4 Hz of the cross-sectional surface area of the specimen during testing (Figure 2). By means of the mapping software (VIC 2D, Correlated Solution), the surface strains were calculated from the displacements that occurred during deformation. A more detailed description of the strain computation by the DIC technique is given in Keunecke et al. [16]. Density of the samples was calculated according to TS 2472 [17]. The stress-strain curves obtained were used in order to evaluate Young's moduli and strength properties of the specimens. The Young's modulus was calculated from the ratio of the stress, σ, to the strain, ε, measured in the linear elastic range:

$$E_i = \frac{\Delta\sigma_i}{\Delta\varepsilon_i} = \frac{\sigma_{i,2} - \sigma_{i,1}}{\varepsilon_{i,2} - \varepsilon_{i,1}} \quad i \in R, L, T$$

Since the strength behavior of wood in *R* and *T* directions is obscure, maximum compression strength (*CS*) was calculated using 0.2% yield values using following formula.

$CS = P_{max}/A$,

Where; *CS* represents yield strength, P_{max} is the yield load and *A* is the cross-sectional area of the specimen.

Analysis of variance (ANOVA) general linear model procedure was run for data with SAS statistical analysis software to interpret the interrelationships among the properties measured of the clear wood samples.

Figure 2. Compression test set up.

3. Results

Average values for density, MC, sound velocities (SV), E_{dyn}, Young's modulus and compression strength (CS) values of the specimens tested are presented in Table 1 and 2. There was a good match among the density values in the different MC groups. In comparison to available literature references at similar MC, the measured density values were comparable. The correlation coefficients between density and MC; between MC and SV are presented in Table 3. The ratios of SV and Young's modulus in the principal direction are presented in Table 4. In Figure 3, the relationship between E_{dyn} and Young modulus; in Figure 4, the relationship between E_{dyn} and CS are presented.

4. Discussion

The SV are similar to those reported by Bucur [18]. Results indicate that there is negative weak correlation between density and SV for species tested. There is a contradiction in the literature on whether SV is positively correlated with wood density or not. Some authors [19,20,21] identified that there is no relationship between density and velocity while others [22,23] reported positive relationship of density and velocity. Some authors [20,24] claimed that velocity is related to the micro-fibrilar angle while Gerhards [25] and Beall [14] pointed out that grain angle has major impact on the SV.

Test results indicate clear differences between the SV along the principal directions ($SV_L > SV_R > SV_T$). The ratios found in this study are somewhat smaller than those reported by Bucur [18], Keunecke et al. [26] and Baradith and Niemz [23].

The wood of Calabrian pine and cedar significantly differ regarding their SV in the longitudinal direction at 20 °C and 65% RH. Their SV are identical in the perpendicular directions. Although cedar has higher average density than Calabrian pine its SV was lower for all principal directions. The higher SV of Calabrian pine can be due to longer fiber length. According to Beall [14] the SV in the radial direction range from 1000 to 2000 m/s and can be twice as the SV in the tangential direction.

Table 1. Sound velocity, E_{dyn}, Young's modulus and CS values for Calabrian pine

Direction	Density g/cm^3	MC (%)	Velocity (m/s) Mean	cov (%)	E_{dyn} (N/mm^2) Mean	cov (%)	Young's Modulus Mean	cov (%)	CS Mean	cov(%)
L	0.53	10.57	5302	3.66	14968	10.26	9131	19	38.42	6.67
R	0.53	10.76	2304	4.86	2860	12.08	1114	19	8.70	12.23
T	0.55	10.89	1680	4,02	1545	7.54	646	11	7.55	5.38
L	0.53	13.47	5045	3.26	13240	8.86	8650	14	33.14	578
R	0.53	12.76	2261	4.31	2713	10.57	917	16	8.25	10.69
T	0.54	13.42	1651	2.97	1480	5.58	624	14	6.71	7.23
L	0.52	19.85	5016	4.29	13222	9.32	7731	16	24.42	6.71
R	0.54	20.00	2120	6.36	2451	14.97	766	9	5.83	9.2
T	0.55	20.05	1570	1.84	1354	3.78	431	14	4.67	4.98
L	0.56	24.35	4821	3.45	13085	8.18	7380	13	21.16	5.15
R	0.57	24.64	2037	4.28	2360	8.07	676	15	5.21	5.49
T	0.56	24.37	1504	1.97	1265	3.60	402	23	3.85	8.26

Table 2. Sound velocity, E_{dyn}, Young's modulus and CS values for Cedar

Direction	Density g/cm3	MC (%)	Velocity (m/s) Mean	cov (%)	E_{dyn} (N/mm2) Mean	cov (%)	Young's modulus Mean	cov(%)	CS Mean	cov (%)
L	0.54	10.74	4458	5.41	10706	12.80	7857	18	45.82	6.41
R	0.58	10.88	2243	2.26	2933	7.96	1298	16	9.84	1.51
T	0.58	10,50	1902	5,01	2107	8,04	716	14	6.90	19.03
L	0.57	12,89	4388	7,55	10929	11,59	7496	11	41.33	5.98
R	0.57	12,87	2142	3,29	2605	11,74	974	21	9.21	13.03
T	0.53	14,80	1756	2,11	1641	7,94	663	21	6.17	13.87
L	0.62	20,59	4229	9,27	11115	13,66	6831	10	35.80	7.18
R	0.57	20,27	20,39	2,23	2360	9,41	850	11	7.86	11.63
T	0.54	20,72	1678	2,76	1532	8,49	490	19	5.20	10.42
L	0.59	26,05	4406	6,64	11428	9,03	6683	18	31.02	8.09
R	0.59	26,05	2001	2,87	2387	9,30	809	9	7.15	8.68
T	0.56	23,50	1612	2,40	1445	8,09	437	23	4.46	12.85

Table 3. Correlations coefficients between density, MC and sound velocity of species tested

			Sound velocity		
Species	parameter	direction	L	R	T
Calabrian Pine	density	L	-0.08194		
		R		-0.23347	
		T			-0.43119
	MC	L	-0.63150		
		R		-0.69188	
		T			-0.82657
Cedar	density	L	-0.60627		
		R		0.26398	
		T			0.25715
	MC	L	-0.06304		
		R		-0.78299	
		T			-0.84318

Table 4. Ratios of sound velocity and E_{dyn} for the main directions

Species	MC (%)	Ratio of sound velocities (*T:R:L*)	Ratio of Young's modulus (*T:R:L*)
Calabrian pine	10-11	1: 1.37 : 3.15	1: 1.72 : 14.13
	13-14	1: 1.36 : 3.05	1: 1.46 : 13.86
	16-17	1: 1.45 : 3.19	1: 1.77 : 17.93
	20-21	1: 1.35 : 3.20	1: 1.68 : 18.35
Cedar	11-12	1: 1.17 : 2.34	1: 1.72 : 10.97
	13-14	1: 1.21 : 2.49	1: 1.46 : 11.30
	18-20	1: 1.21 : 2.52	1: 1.73 : 13.94
	21-23	1: 1.24 : 2.73	1: 1.85 : 15.29

In general, there is a good negative correlation between MC and SV, and the correlations are higher in perpendicular directions. According to Gerhards [25], SV decreases by 1% when the MC increases by 1% within the hygroscopic range. The SV in all directions seem to decrease with increasing MC. The rate of change with changing humidity (%) ranged from 0.36 for Cedar in *L* direction to 1.38 for Cedar in *T* direction. SV in Calabrian pine showed the closest rate of decrease with increasing MC confirming Gerhards [25] statement. The effect of moisture content (MC) on velocity has been studied by number of researchers, who have shown that the velocity of acoustic waves decreases with moisture content up to the fiber saturation point [18,27,28].

The wood species tested clearly differ regarding their calculated Young's moduli. The values of Cedar are lower than those of Calabrian pine, although Cedar has slightly higher average density (0.56 g/cm^3) than Calabrian pine (0.54 g/cm^3).

The E_{dyn} calculated from sound propagation is much higher than the static Young's modulus because the measurements were not corrected with the Poisson's ratios. 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 [26].

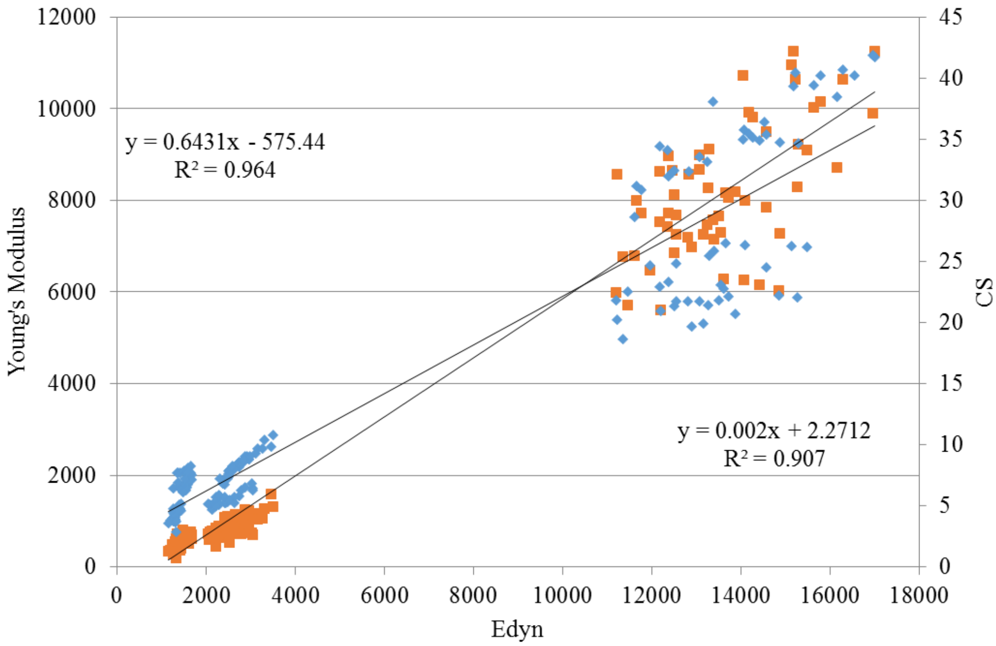

Figure 3. Estimation of Young's modulus and CS for Calabrian pine

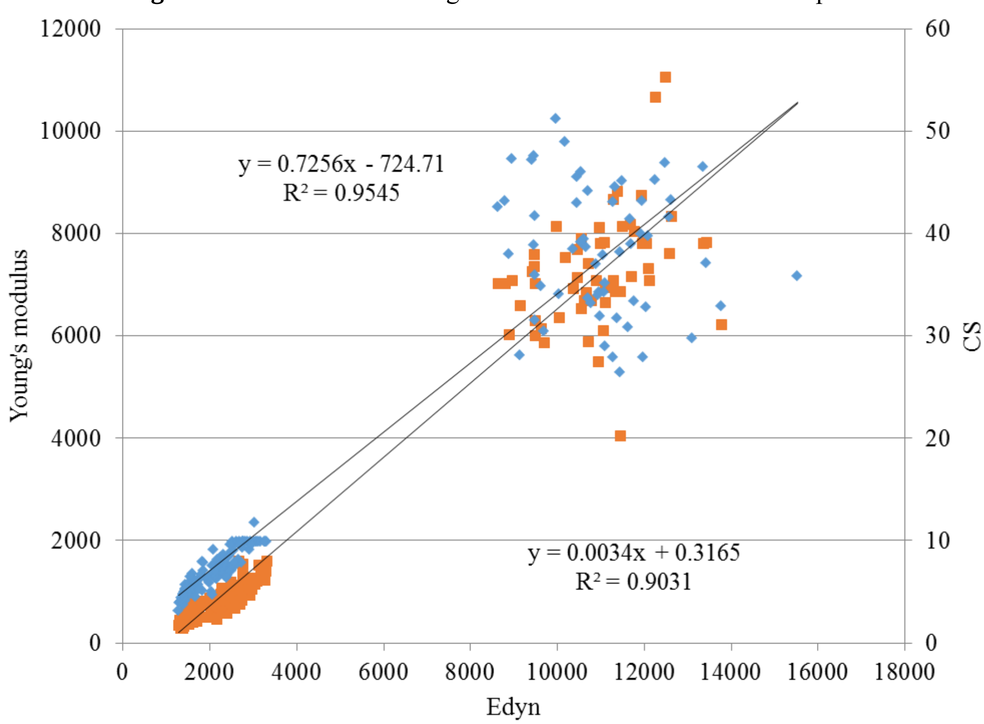

Figure 4. Estimation of Young's modulus and CS for Cedar

The ratio of Young's modulus in *L*, *R* and *T* directions was higher for increasing MC. It seems that anisotropy is higher for Calabrian pine than Cedar. It was reported by Baradit and Niemz [23] that anisotropy is higher in softwood than hardwoods in Europe while it is contrary for some Chilean wood species. Bodig and Jayne [29] stated that E_L:E_T ratio is nearly 24:1 in softwoods while Bucur [18] reported the largest E_L:E_T ratio which is nearly 28:1 for Scotch pine.

Young's modulus in all anatomical directions tended to increase at lower MC as expected. The three Young's moduli values are affected by moisture, but to a different degree. Young's modulus in the direction perpendicular to the grain (*R*, *T*) changes with MC at higher rates. Similar trend in mechanical properties due to the MC changes was reported by Gerhards [1], Ross [8], Hering et al. [3] and Ozyhar et al. [5]. Figure 3 and 4 clearly indicate that E_{dyn} and Young's modulus; E_{dyn} and CS are highly correlated.

Conclusions

Compression properties of Calabrian pine and Taurus cedar in all anatomical direction can be predicted using sound velocity. The coefficient of correlations between E_{dyn} and Young's modulus; E_{dyn} and CS are significantly high. The ratios of E_{dyn}, Young Modulus and CS in principal anatomic directions are similar to those reported in the literature. The effect of MC on SV is more pronounced than density of the samples.

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