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Determination of elastic constants for scots pine wood using ultrasound

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Abstract: Elastic constants of Scots pine (*Pinus sylvestris* L.) wood grown in Turkey were investigated using non-destructive ultrasound tests. Elastic modulus in longitudinal and perpendicular directions (E_L, E_R, E_T), shear modulus in principal planes (G_{LR}, G_{LT}, G_{RT}) and Poisson ratios (υ_{LR}, υ_{RL} υ_{LT}, υ_{LT}, υ_{RT}, υ_{TR}) were calculated using cubic samples (20 mm) which were conditioned at 65 % relative humidity and 21 °C. Longitudinal and transverse ultrasonic sound velocities in fiber (*L*), radial (*R*) and tangential (*T*) directions were measured using 2.25 MHz and 1 MHz sensors, respectively. Transverse sound wave velocities at an angle of 45° to the *L*, *R* and *T* directions were also measured with a 1 MHz sensor in order to calculate the Poisson ratios. The predicted elastic modulus based on ultrasound in *L*, *R*, *T* directions were 10600, 1300 and 470 N/mm^2, respectively. The predicted shear modulus based on ultrasound in *LR*, *LT*, *RT* planes were 1180, 1050 and 350 N/mm^2, respectively. Poisson ratios varied between 0.04 to 0.95. Comparing the data available in the literature, elastic constants of scots pine determined using ultrasonic method were within the acceptable values.
Keywords: Elastic constants, Prediction, Scots pine, Ultrasound

Sarıçam odununun elastik sabitlerinin ultrasonik yöntemle belirlenmesi

Özet: Türkiye'de yetişen sarıçamın (*Pinus sylvestris* L.) elastik sabitleri tahribatsız ultrasonik testler kullanılarak incelenmiştir. Boyuna ve liflere dik yönlerde elastikiyet modülleri (E_L, E_R, E_T), ana düzlemlerde kesme modülleri (G_{LR}, G_{LT}, G_{RT}) ve Poisson oranları (υ_{LR}, υ_{RL} υ_{LT}, υ_{LT}, υ_{RT}, υ_{TR}) % 65 bağıl nem ve 21 °C sıcaklıkta şartlandırılan 20 mm kenar ölçüsüne sahip kübik numuneler kullanılarak hesaplanmıştır. Lif (*L*), radyal (*R*) ve teğet (*T*) yönlerdeki boyuna ve enine ultrasonik ses hızları sırasıyla 2.25 MHz ve 1 MHz sensörler kullanılarak ölçülmüştür. Poisson oranlarını hesaplamak amacıyla *L, R ve T* yönlerine 45° açıyla enine ses dalgası hızları da 1 MHz sensörle ölçülmüştür. *L, R, T* yönlerinde ultrasona dayalı tahmin edilen elastik modül sırasıyla 10600, 1300 ve 470 N/mm^2 bulunmuştur. *LR, LT, RT* düzlemlerinde ultrasona dayalı tahmin edilen kesme modülü sırasıyla 1180, 1050 ve 350 N/mm^2 olarak hesaplanmıştır. Poisson oranları 0.04 ile 0.95 arasında değişmektedir. Literatürdeki veriler ile karşılaştırıldığında sarıçam odununun ultrasonik yöntemle belirlenen elastik sabitlerin kabul edilebilir değerler içerisinde olduğu görülmüştür.
Anahtar kelimeler: Elastik sabitler, Tahmin, Sarıçam, Ultrasonik yöntem

1. Introduction

Wood is considered as orthotropic material with different elastic constants in principal directions (Kretschmann, 2010). Orthotropic material properties are represented with three Young's modulus, three shear modulus and six Poisson's ratios (Bodig and Jayne, 1993). The elastic constants of well-known wood species can be found in Dinwoodie, 2000; Kretschmann, 2010; Ozyhar et al., 2013; Aira et al., 2014; Davies et al., 2016. In general, the two most influencing physical parameters that may affect the elastic properties are specific gravity and moisture content. Elastic properties also vary between and within species (Kretschmann, 2010). Use of three-dimensional models in advanced finite elements methods requires nine elastic constants to be used in order to achieve detailed analyses (Dahl, 2009).

In the recent decades, it has been proven that sound velocity is good predictor of elastic constants for wood and wood-based materials besides static testing which is time consuming and costly. Use of ultrasound velocity in determinations of Young's modulus and shear modulus found to be acceptable (Bucur and Archer, 1984; Ozyhar et al., 2013), but prediction of Poisson ratios has some drawbacks when the velocity measurements are made on different samples. According to Gonçalvez et al. (2011, 2014) and Vazquez et al. (2015) this disadvantage can be overcome when the measurements taken from the same sample or polyhedral samples are used.

Usable information regarding elastic constants of wood species grown in Turkey is limited. Moisture dependent elastic constants determined from compression tests for scots pine is reported by Güntekin and Akar (2019). Some elastic constants for beech wood and sessile oak also reported by Güntekin et al. (2016a) and Güntekin et al. (2016b), respectively. A recent study by Güntekin (2022) reported elastic constants for cedar wood. Scots pine (*Pinus sylvestris*) is one of the most widely distributed pine species in the world and can be found all the way across Eurasia. It is also important wood specie for Turkish forestry covering approximately 6.8 % of total forestland (Büyüksarı et al., 2017). In this study, elastic constants for Scots pine wood were determined using the ultrasonic method.

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2. Materials and methods

2.1. Materials

Clear wood specimens were prepared from Scots pine (*Pinus sylvestris*) wood which grown in Bolu - Aladaglar Forest District of Turkey. For ultrasonic tests, roughly 20 mm cubic samples for *L*, *R*, *T* and 45° angle in planes *LR*, *LT*, *TR* were prepared (Figure 1). The samples, 1a, 1b and 1c were used to measure the longitudinal and transverse sound velocities in the fiber (*L*), radial (*R*) and tangential (*T*) directions, respectively, and to calculate the E_i and G_{ij} values. The samples, 1d, 1e and 1f were prepared at a 45° angle to the *L*, *R* and *T* directions, respectively, and were used to calculate Poisson ratios. The number of replications was 10 for the ultrasonic measurements.

2. 2. Methods

All samples were conditioned at 21 °C and relative humidity of 65 %. Stereo-metric method was applied for determination of density. Olympus® EPOCH 650 ultrasonic flaw detector was used for measuring sound velocities. Longitudinal and shear wave velocities were measured using 2.25 and 1 MHz contact transducers, respectively. A gel medium and a small pressure was provided for coupling between the specimen and the sensors during measurements (Figure 2).

Hooke's three-dimensional law of elasticity for the representation of the orthotropic elastic behavior of wood was presented by Bodig and Jayne (1993). It is expressed by compliance matrix (S_{ij}). The compliance matrix consists of three modulus elasticity or Young's modulus (E_L, E_R, E_T), three modulus of rigidity (G_{LR}, G_{LT}, G_{RT}) and six Poisson's ratios (three of them are independent; υ_{LR}, υ_{LT}, υ_{RT}). Stiffness matrix, *C*, as shown in equation 1 can be expressed as sound velocities by using the Christoffel tensor as presented by Ozyhar et al. (2013):

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (1)$$

The terms of the main diagonal were defined in equations 2-10.

$$C_{11} = C_{LL} = \rho\, V_{LL}^2 \quad (2)$$
$$C_{22} = C_{RR} = \rho\, V_{RR}^2 \quad (3)$$
$$C_{33} = C_{TT} = \rho\, V_{TT}^{\,2} \quad (4)$$
$$C_{44} = C_{RT} = (\rho\, V^2_{RT} + \rho\, V^2_{TR}) / 2 \quad (5)$$
$$C_{55} = C_{LT} = (\rho\, V^2_{LT} + \rho\, V^2_{TL}) / 2 \quad (6)$$
$$C_{66} = C_{RL} = (\rho\, V^2_{RL} + \rho\, V^2_{LR}) / 2 \quad (7)$$
$$C_{12}+C_{66} = \sqrt{(C_{11} + C_{66} - 2\rho\, V^2_{LR/LR}) + (C_{66} + C_{22} - 2\rho\, V^2_{LR/LR})} \quad (8)$$
$$C_{13}+C_{55} = \sqrt{(C_{11} + C_{55} - 2\rho\, V^2_{LT//LT}) + (C_{33} + C_{55} - 2\rho\, V^2_{LT/LT})} \quad (9)$$
$$C_{23}+C_{44} = \sqrt{(C_{22} + C_{44} - 2\rho\, V^2_{RT//RT}) + (C_{33} + C_{44} - 2\rho\, V^2_{RT/RT})} \quad (10)$$

Where, C_{ij} is stiffness, ρ is density, and V_{ij} is velocity. C_{ij} of the *C* are related to the elastic constants of *S* as shown in equation 11:

$$[S] = \begin{bmatrix} \frac{1}{E_L} & -\frac{\upsilon_{21}}{E_R} & -\frac{\upsilon_{31}}{E_T} & 0 & 0 & 0 \\ -\frac{\upsilon_{12}}{E_L} & \frac{1}{E_R} & -\frac{\upsilon_{32}}{E_T} & 0 & 0 & 0 \\ -\frac{\upsilon_{13}}{E_L} & -\frac{\upsilon_{23}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} \end{bmatrix} \quad (11)$$

Where; E_i are the elastic modulus, G_{ij} are the shear modulus and υ_{ij} are the Poisson's ratios (Bodig and Jayne, 1993).

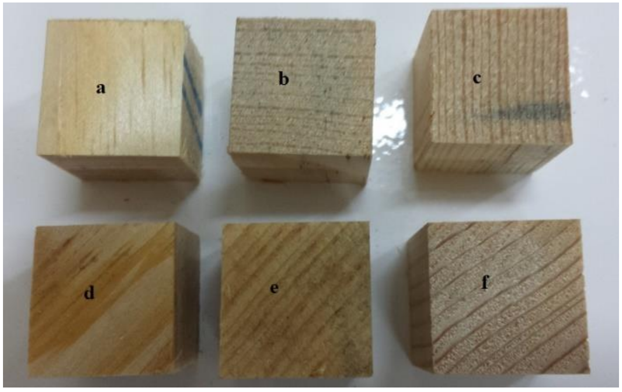

Figure 1. Examples used in measuring ultrasonic sound velocities and determining elasticity constants (a- C_{11}, C_{44}, b- C_{22}, C_{55}, c- C_{33}, C_{66}, d- C_{12}, e-C_{13}, f-C_{23})

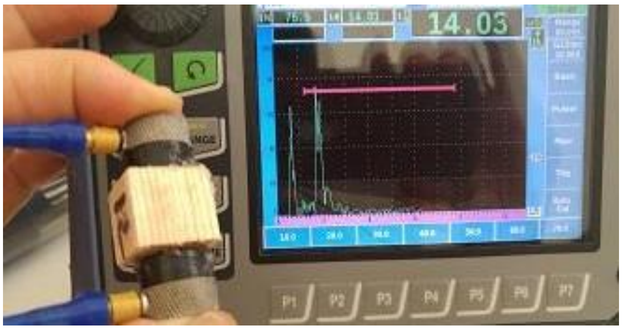

Figure 2. Measurement of sound velocity.

3. Results and discussion

Average values of parameters determined from the cubic samples are presented in Tables 1, 2 and 3, respectively. Average density and moisture content of the cubic samples tested was 520 kg/m^3 and 12.1 %, respectively.

Results show the well-known order among the sound velocities exist; ($V_{11} > V_{22} > V_{66} > V_{55} > V_{33} > V_{44}$). The average longitudinal sound velocity of Scots pine is lower than average sound velocities reported for softwood species. The average sound velocities in perpendicular directions are quite similar (Table 1). Lower sound velocities for softwood species were also reported in the literature (Oliveira et al., 2002; Baradit and Niemz, 2012; Llana et al., 2016). Bucur (2006) presented that the sound velocities are the highest in the longitudinal direction and range from 5000 to 6000 m/s for the air-dried clear small wood specimens. The sound velocities in *L* direction triples the sound velocities in *R*-direction. The sound velocity in *T*-direction is approximately half of the radial velocity (Beall, 2002). The ratio of sound velocities in principal direction for Scots pine was approximately 4.3:1.5:1. The coefficient of variations for the sound velocities calculated in this study was less than 5%.

Investigations conducted revealed that Scots pine wood has high variability regarding modulus of elasticity. Çetin and Gündüz (2017) reported that modulus of elasticity for Scots pine wood varies between 10475 and 12000 N/mm^2. Kaygın et al. (2016) indicated that modulus of elasticity for Scots pine wood is altitude dependent and ranges from 8515 to 17383 N/mm^2. Similar values were also presented by Yıldırım et al. 2015 and Keskin et al. 2003. Lowest modulus of elasticity (8444 N/mm^2) for Scots pine wood is reported by Ulker et al. 2012. According to Bodig and Jayne (1993) E_L is usually 10 to 20 times higher than E_R, and E_T is half of the E_R. Comparing with the values available in the literature, predicted elastic modulus values in principal directions for Scots pine wood using ultrasound are acceptable.

G_{LR} and G_{LT} values based on sound velocities are similar to values available in the literature. G_{RT} calculated from sound velocity is extremely high (Table 3 and 4). G_{LR}: G_{LT}: G_{RT} ratio according to Bodig and Jayne (1993) is 10:9.4:1 and results calculated from sound velocities do not comply to this ratio because of high G_{RT}.

Table 5 presents elastic ratios of some softwood species as well as Scots pine studied in the literature. Investigations have shown that the ratio of E_L:G_{LR} varies between 8 and 65 (Divos et al., 1998; Harrison, 2006). The differences or similarities in elastic constants reflects fiber orientation of wood structure which is highly variable.

In the case of the Poisson's ratios, some differences are observed between values obtained based on sound velocities and values available in the literature. Poisson's ratios υ_{LR} and υ_{LT} based on the ultrasonic sound velocity calculated in this study were higher than average Poisson's ratios presented for Scots pine wood. Poisson's ratios υ_{TL}, υ_{RL}, υ_{RT} and υ_{TR} were close or within in the range of published values. According to Kretschmann (2010) MC and specific gravity are the most influencing factors of Poisson's ratios. The difference between the predicted and published values can be explained by high variation. As pointed out by Dinwoodie (2000), variation would occur in every direction within a tree. According to Aira et al. (2014), differences even exist between cubic and prismatic samples of Scots pine wood tested in the same study.

Higher values of Poisson's ratios were also presented in the studies of Bucur and Archer (1984), Gonçalves et al. (2011), Ozyhar et al. (2013), and Aira et al. (2014) There is no logical explanation for the extreme Poisson's ratios. However, it should be noted that wood may not show perfectly elastic orthotropic symmetry. Sample source may also contribute to the contradictory results. Choosing different sample geometry may help to achieve reasonable results (Gonçalvez et al., 2014; Vazquez et al., 2015). According to Bucur (2006) the curvature of growth rings or fiber inclination may explain high Poisson's ratios.

4. Conclusions

Elastic constants of Scots pine wood can be estimated using ultrasonic sound velocities. Ultrasonic sound velocities measured for Scots pine wood are similar to those published for softwood species except in the longitudinal direction. Considering wood having high variability and use of different samples for ultrasonic and static testing, the results of the study are acceptable. The elastic ratios determined in this study are mostly similar to those for softwoods published in the literature. Ultrasound offers simpler method to determine elastic constants. The results of the study can be used in numerical modeling of structures constructed with Scots pine wood.

Table 1. Sound velocities measured for Scots pine wood (m/s)

MC (%)	V_{11}	V_{22}	V_{33}	V_{44}	V_{55}	V_{66}	V_{12}	V_{13}	V_{23}
11.8	4795	1713	1117	830	1420	1510	1434	1164	682
Softwoods*	5000-6000	1580-2330	1146-1990	298-600	1030-1660	1050-1630			

*Bucur (2006)

Table 2. Stiffness matrix values calculated from sound velocities

C_{11}	C_{22}	C_{33}	C_{66}	C_{55}	C_{44}	C_{12}	C_{12}	C_{23}
11956	1526	649	1186	1049	358	1325	780	498

Table 3. Elastic constants of Scots pine wood determined using ultrasound

E_L (GPa)	E_R (GPa)	E_T (GPa)	G_{RT} (GPa)	G_{LT} (Gpa)	G_{LR} (GPa)	υ_{LR}	υ_{LT}	υ_{RT}	υ_{TR}	υ_{RL}	υ_{TL}
10.6	1.3	0.47	0.35	1.05	1.18	0.72	0.8	0.95	0.4	0.09	0.04

Table 4. Elastic constants of Scots pine wood available in the literature.

E_L (GPa)	E_R (GPa)	E_T (GPa)	G_{RT} (GPa)	G_{LT} (Gpa)	G_{LR} (GPa)	υ_{LR}	υ_{LT}	υ_{RT}	υ_{TR}	υ_{RL}	υ_{TL}
14.9*	0.76	0.53	0.1	0.9	1.07	0.6	0.74	0.69	0.68	0.075	0.063
10.2**	1.9	0.9	0.7	1.2	1.33	0.39	0.62	1.13	0.79	0.1	0.068
16.3**	1.1	0.7	0.066	6.8	1.16	0.42	0.51	0.68	0.31	0.03	0.015

*Güntekin and Akar (2019), **Aira et al. (2014), ***Dinwoodie (2000).

Table 5. Elastic ratios of some softwood species from the literature

Species	ρ (g/cm^3)	E_L	E_L/E_R	E_L/E_T	E_L / G_{LR}	E_L / G_{LT}	E_L / G_{RT}
Douglas fir *	0.5	12600	15	20	16	13	143
Western Larch*	0.52	12900	13	15	16	14	143
Loblolly pine*	0.51	12300	9	13	12	12	77
Scots pine**	0.504	10283	5	10	8	8	14
Scots pine***	0.55	16300	15	29	14	24	247
Douglas fir***	0.59	16400	13	18	14	18	208

*Kretschmann (2010), **Aira et al. (2014), ***Dinwoodie (2000).

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