Shear moduli prediction of Calabria pine (*Pinus brutia* Ten.) using Ultrasonic Wave Propagation

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ABSTRACT

Shear moduli of Calabria pine (*Pinus brutia* Ten.) predicted using non-destructive test method in this study. Calabria pine logs harvested from Beşkonak, Burdur and sawn in to Radial and Tangential planks. 26 surface polyhedral NDT samples prepared in 65x65x65mm dimensions. All samples acclimatized at 20±1°C temperature and 65% RH conditions. Ultrasonic shear wave velocities of Calabria pine wood calculated using time of flight values. Time of flight values obtained using Olympus EPOCH 650 flaw detector and Panametrics NDT V153 shear wave transducers. Shear moduli predicted using calculated velocities. Average density and moisture content of the non-destructive test samples determined as 0.558g/cm^3 and 12.66%, respectively. Shear wave velocities and shear moduli of LR, LT, and RT planes were determined as 1408, 1306 and 666m/s and 1108, 952 and 248N/mm^2, respectively.

Keywords: *Ultrasonic, Shear wave velocity, Shear modulus, Calabria pine*

Kızılçam (*Pinus brutia* Ten.) Odunu Kesme Modüllerinin Ultrasonik Dalga Yayılımı ile Tahmini

ÖZET

Bu çalışmada Kızılçam (*Pinus brutia* Ten.) odunu kesme modülleri tahribatsız test yöntemi ile tahmin edilmiştir. Kızılçam tomruklar Beşkonak, Burdur yöresinden temin edilmiştir ve radyal ve teğet yönlerde kesilerek 65x65x65mm ölçülerinde 26 yüzeyli tahribatsız test örnekleri hazırlanmıştır. Test örnekleri 20±1°C sıcaklık ve %65RH'de iklimlendirilmiştir. Kızılçam odunu ultrasonik ses dalgası hızları sinyal uçuş süresi ile hesaplanmıştır. Bu süreler Olympus EPOCH 650 ultrasonik hata dedektörü ve Panametrics NDT V153 kesme dalgası transdüserleri kullanılarak elde edilmiştir. Elde edilen kesme hızları ile kesme modülleri belirlenmiştir. tahribatsız test örneklerinin ortalama yoğunluğu ve rutubet içeriği 0,558g/cm3 ve %12,66 olarak belirlenmiştir. LR, LT ve RT düzlemlerindeki kesme hızları ve modülleri sırasıyla 1408, 1306 ve 666m/sn ve 1108, 952 ve 248N/mm^2 olarak belirlenmiştir.

Anahtar Kelimeler: *Ultrasonik, Kesme dalgası hızı, Kesme Modülü, Kızılçam*

I. Introduction

Wood, a natural composite, has orthotropic nature and different mechanic properties through all principal axes. Mechanic properties can be divided into two; elastic properties and strength properties. Elastic properties that consist of three Young's modulus (E_L, E_R, and E_T), three shear modulus (G_{LR}, G_{LT}, and G_{RT}) and six Poisson ratios (μ_{LR}, μ_{RL}, μ_{RT}, μ_{TR}, μ_{LT}, μ_{TL}) define the elastic behavior of the material. Elastic behavior seen in elastic region and Yield point is the limit or end of this region. In this region deformation of the material is recoverable but from this point on, plastic deformation occurs on material and it's irreversible. Deformations are especially important for the materials that used for structural purposes. Therefore, elastic properties must be known to design safe structures and ensure their lifelong functionability. Drow and Mcburney [1] can be assumed as one of the first ones who figured out moisture content (MC) related elastic properties (except shear modulus) of wood and Mcburney et al. [2] determined elastic properties of wood at 11%MC.

Elastic, plastic and physical properties of wood can be determined or predicted by destructive and non-destructive methods. And, prediction of structural properties and defects using ultrasonic methods provided modest amount of achievements [3]. Ultrasonic wave propagation is one of the dynamic or non-destructive tests that used to characterize the elastic properties of wood and Hearmon [4], Zimmer and Cost [5], Bucur [6], Preziosa et al. [7] and Preziosa [8] were some of the initial studies. Dundar and Divos [9] reviewed the studies that performed in Europe to draw attention of Non Destructive Testing (NDT) and Non Destructive Evaluation (NDE) of wood. Dzbenski and Wiktorski [10] evaluated the mechanical properties of standing trees and sawn timber using ultrasonic measurements. Tallavo et al [11; 12] studied characterization of wood poles by ultrasonic measurements. Karlinasari et al. [13] determined the acoustical properties of some Indonesian's hardwood species using ultrasonic wave method. Hermoso et al. [14] evaluated scots pine boards using combined visual and ultrasonic grading method. Guntekin and Yilmaz Aydin [15] predicted bending properties of Turkish red pine, Anatolian black pine, Cedar, and Oriental spruce using ultrasound.

Ultrasonic measurements base on time of flight (ToF) value of propagated wave trough the medium. Wave propagation speed calculated using ToF values and distance of wave path or propagation length or sample size. And, following studies concerned with this issue. Dundar et al. [16] evaluated the ability of ultrasonic velocity to determine the dimensional stability of oak and chestnut woods. Metwally et al. [17] calculated ultrasonic wave velocities and mass densities of Tatajuba and Iroko woods. Karlinasari et al. [18] reported that ultrasonic wave velocities are 29.5% higher than sonic wave velocities that propagated along the standing agarwood trees. There are some factors affect the wave velocity that propagates through the wood. And following studies concerned with these issue. Puccini et al. [19] evaluated the ultrasonic wave velocity variation in defective wood. Calegari et al. [20] stated that ultrasonic pulse velocity decreases with the increase of the base-height ratio of the specimens. Wang and Wang [21] evaluated effect of hole size and amounts on ultrasonic wave velocity of Korean pine specimens and stated that there is negative correlation between them. Secco et al. [22] stated that holes in wood decrease the ultrasonic wave velocity due to changes in wave path. Karlinasari et al. [23] evaluated effect of MC on sound wave velocity in agarwood trees. And, according to Calegari et al. [20] MC is the major factor that decreases and specific gravity is the second factor that increases the ultrasonic pulse velocity, respectively. Yang et al. [24] stated that velocity decreases with the increase of MC. Dundar et al. [16] reported that ultrasonic velocities decreased with increase of MC. Van Dyk and Rice [25] reported that there is a strong inverse relation between ultrasonic wave velocity and MC.

Longitudinal wave propagation velocities in air and water (20°C) are 343 and 1497m/s, respectively [26]. And, it can be said that air inside the holes in wood inundates with water when MC of wood increases. From this point of view, an increase on wave velocity can be expected but lots of studies such as aforementioned ones proved the opposing results. In addition, because of shear waves do not propagate through the water, shear wave velocity decreases when MC of the wood increase.

Shear modulus is one of the several indicants that present the mechanical properties of wood [27] and this important elastic property of wood can be determined by static and dynamic tests. And, following studies concerned with determination of shear properties of wood. Gonçalves et al. [28] and Vázquez et al. [29] performed ultrasonic measurements to predict elastic properties of wood. Gonçalves et al. [30] and Vázquez et al. [31] predicted elastic properties of 26 surface polyhedrons using ultrasonic longitudinal and shear waves. Senalik et al. [32] expressed the details of shear wave as "*Shear waves have particle motion parallel to the wave front and normal to the direction of wave propagation*". Baradit and Niemz [33] determined three shear moduli of some Chilean wood species using ultrasonic measurements. Shear modulus can be modestly predicted using ultrasonic measurements. But in general ultrasonic measurements overestimates the results. And, according to Dackerman et al. [34] there is around 20% overestimation of shear modulus when ultrasonic measurements performed.

Kollmann et al. [35] stated the importance of shear modulus as "*Mechanical properties needed for structural design are primarily shear modulus and shear strength*". Shear strength of lots of species was determined while shear modulus not. And, this study aimed to predict shear moduli of Calabria pine using ultrasound.

II. EXPERIMENT

A. MATERIAL

In this study, Calabria pine (*Pinus brutia* Ten.) wood that harvested from Beşkonak, Burdur used to perform ultrasonic measurements. Logs were sawn into radial and tangential planks and then air-dried up to equilibrium moisture content (EMC). After this phase, defects free NDT samples prepared according to TS2470 [36] standard.

B. METHOD

NDT samples have complex (26 surface polyhedral) geometry and it's difficult to determine the density from this geometry. Therefore, 65x65x65mm cubic samples prepared and acclimatized in a chamber which operates at 65% relative humidity and 20±1 C° temperature till their weight becomes constant. Densities of the samples were determined according to TS2472 [37] standard and Eq. (1) used to calculate densities.

$$\delta_r = m_r/V_r \, (gr/cm^3) \tag{1}$$

where δr is density (g/cm^3), m_r is weigh (g), and V_r is volume (cm^3).

Then, defect free 26 surface polyhedral samples (as seen in

Fig. *1*) prepared from cubic samples to perform ultrasonic measurements. Figure 1 just showing the process of the sample preparation instead of tested one and samples were prepared from the sapwood of the timber by taking into consideration of the slope of grain, growth ring angle and etc.

Fig. 1. *Imaginative details of NDT sample preparation*

Shear wave velocities (V_{LR}, V_{LT}, V_{RL}, V_{RT}, V_{TL} and V_{TR}) calculated using ToF values of shear wave that propagated through the LR, LT, and RT planes and distance between the transducers. ToF values obtained using Olympus EPOCH 650 flaw detector (pursuant to EN12668-1 [38]) and Panametrics NDT V153 1MHz direct contact shear wave transducers as seen in

Fig. *2*.

Fig. 2. *Time of flight measurements of ultrasonic shear wave.*

And then, dynamic shear modulus of RT, LT, and LR planes calculated with velocity and density values using Eq. 2, 3, and 4 respectively;

$$C_{44} = C_{RT} = \rho \,((V_{RT} + V_{TR}) / 2)^2 \, 10^6 \tag{2}$$
$$C_{55} = C_{LT} = \rho \,((V_{LT} + V_{TL}) / 2)^2 \, 10^6 \tag{3}$$

$$C_{66} = C_{RL} = \rho \, ((V_{RL} + V_{LR}) / 2)^2 \, 10^6 \tag{4}$$

where G_{ij} or C_{ij} are terms of the main diagonal in the matrix or Shear moduli (N/mm^2), ρ is the density of the wood (kg/m^3), and V_{ij} are the wave velocities in IJ or JI direction (m/s).

Moisture content of the samples determined according to TS2471 [39] standard. At the end of ultrasonic measurements samples dried in the oven that operates at 103±2°C temperature. And weight of samples measured. Then Eq. (5) used to calculate MC values.

$$DRM = [(M_r - M_0) / M_0] * 100 \, (\%) \tag{5}$$

where DRM (%) is the EMC, M_r (gr) stabilized weigh at the end of acclimatization, and M_0 (gr) is the oven dry weight.

Coefficient of variation (V[%]) and mean values of ultrasonic test results presented using tables.

III. RESULTS AND DISCUSSION

As can be seen in Table 1, average density and moisture content of NDT samples determined as 0.558g/cm^3 and 12.66%, respectively. Coefficient of variation values calculated as 1.33 and 3.21 and these results show the homogeneity of the measured or calculated density and MC values of the samples.

Table 1. *Density and moisture content of samples.*

φ [%]	N [-]		d_n [g/cm^3]	ω [%]
65	20	X	0.558	12.66
		V[%]	1.33	3.21

V[%]coefficient of variation, ω[%]:Moisture content, φ [%]: Relative humidity, N:Sample size, X: Average, d:Density

Formula (2), (3) and (4) express that any changes on density affect the shear modulus. But, there are opposing studies reported that wave velocity was effected negatively [40] or positively [41-44; 33]. Also, neither positive nor negative influence of density reported [45-48]. According to Baar et al. [42] positive effects of density on wave velocity mostly abolished by some factors such as rigidity, macro-structure and micro-structure, chemical content of wood and others. Besides, age of tree assumed as another factor that affects the wave velocity [49].

Table 2 shows the calculated shear wave velocity through LR, LT, and RT planes. As can be seen from this table, shear wave propagates at higher velocity through LR plane than LT and RT planes. Halabe et al. [3] reported that velocity along the T and R directions is around 30 to 40% of the L direction. And, it's occurred due to orthotropic nature of wood which is a natural composite. According to Dackermann et al. [34] wave velocities decrease due to barrier function of annual rings. And, form and organizations of the hollow tubular cells of wood cause variation on both mechanical properties and anisotropy [50]. Mason et al. [51] stated that ultrasonic wave velocity is significantly correlated with microfibril angle (MFA) of wood. In this study, this issue was not taken into consideration.
Bucur [52] reported LR, LT and RT shear wave velocities as 1050-1630, 1030-1660, and 298-600m/s, respectively. As seen in Table 2, shear wave velocity through RT plane (V_{RT}) calculated 11% higher

than this reported range. According to Feeney et al. [53] inhomogeneity of wood along the R direction must be taken into consideration when performing acoustic wave velocity measurement.

Table 2. Shear wave velocities and statistical results.

φ [%]	N [-]		V_{LR} [m/s]	V_{LT} [m/s]	V_{RT} [m/s]
65	20	X	1407.76	1306.09	665.78
		V[%]	4.40	2.92	4.37

V[%]:coefficient of variation, φ [%]: Relative humidity, N:Sample size, X: Average, V_{ij}: Shear wave velocity in IJ or JI planes.

According to Hearmon and Barkas [54], Bodig and Goodman [55], and Neumann [56] RT shear stiffness of wood is about 1/3 or 1/4 of LR and LT values, respectively. According to Brabec et al. [57] G_{LR} is higher than G_{LT} due to reduction of longitudinal shear stiffness of wood by pith rays. But according to Gillis [58] sequence of shear modulus is $G_{LR} \approx G_{LT} > G_{RT}$. On the contrary, Hearmon [59] reported higher G_{LT} than G_{LR} of spruce as 7.7 and 7.5 10^8 N/m², respectively. As can be seen in Table 3, G_{LR} is a little bit higher than G_{LT} and 4.5 times higher than G_{RT} and the sequence of the shear modulus is as $G_{LR} > G_{LT} > G_{RT}$. Therefore, it can be said that results of this study are reasonable with the reported order.

Koponen et al. [50] modeled 6 different wood cell-wall and calculated elastic properties of these models. They reported G_{RT} value of wood2 model as 38N/mm² and also expressed literature G_{RT} values of softwood ranged from 23-85 N/mm². In this study G_{RT} of Calabria pine predicted as 248N/mm² and this is around 3 times higher than the maximum value that Koponen et al. reported. But Koponen et al. [50] did not mention the species of these softwoods and therefore it's not proper to compare with this study. Also, different values reported for softwood such as 70 to 230N/mm² by Ross [60] and 27 to 190N/mm² by Hearmon [59], Haines [61] and Ghelmeziu and Beldie [62]. Therefore, shear modulus values also determined experimentally to eliminate these high differences that put question marks in the minds. It's seen that experimental result obtained by off-axis compression test was around 12% lower than the ultrasonic result. And, as aforementioned, difference between ultrasonic and static test results is around 20% and therefore results of this study are reasonable.

Table 3. Shear modulus and statistical results

φ [%]	N [-]		G_{LR} [N/mm²]	G_{LT} [N/mm²]	G_{RT} [N/mm²]
65	20	X	1107.53	952.09	247.59
		V[%]	9.06	5.80	8.40

V[%]:coefficient of variation, φ [%]: Relative humidity, N:Sample size, X: Average, G_{ij}: Shear modulus in IJ or JI planes.

Guntekin et al. [63] determined the elastic properties of Turkish red pine using ultrasonic wave propagation through 20x20x20mm cubic samples. And, waves can only propagate through L, R, T directions when cubic samples used but waves can propagate not only through these directions but also 45° off all directions when polyhedral sample used. Therefore, this sample geometry allowed us to obtain quasi-shear waves velocities. Average density and MC of their samples were 0.53 g/cm³ and 12.5%, respectively. And, dynamic G_{LR}, $G_{LT,}$ and G_{RT} shear moduli values predicted as 1150, 850, and 235N/mm², respectively. Differences between G_{LR}, $G_{LT,}$ and G_{RT} of these two studies calculated as -

3.7%, 12%, and 5.53%, respectively and there may be lots of reasons that cause differences and these can be as followings; certified and correct contact gel usage or not, in-homogeneities in the wood structure, slope of grain, growth ring angle, transducer orientation and contact failures, fine tuning of flaw detector, surface properties of sample, growing conditions of tree, properties of cutting tools, size (due to attenuation of signal) and geometry (due to wave propagation path) of the sample and etc. But, results of this study show that sample size and geometry has little and negligible effects on shear modulus values when compared with the results reported by Guntekin et al. [63]. Near or far field, relation between propagation length and wave length (λ), effective frequency properties of propagated shear wave, used contact medium type, and polarization of transducers may play role on differentiation of obtained ToF values and therefore the results. Also, fingertips used to press transducers on sample surface by Guntekin et al. [63] but in this study a mold used to ensure transducer polarization as seen in

Fig. *2*. It's thought that differences between pressing value and polarization might have effects on the results. The fact remains that elastic, plastic or strength properties of wood alter notably even if belongs the same species [11].

IV. CONCLUSION

Shear moduli values are important elastic properties of structural materials and these properties must be known while designing structures. In this study, shear moduli of Calabria pine wood predicted using time of flight measurement of Ultrasonic wave propagation through all orthotropic planes of wood.

Consequently, shear wave propagates at higher velocity through LR plane than LT and RT planes for Calabria pine wood. Average wave velocity of samples was found as 1407.76 *m/s* (V_{LR}) LR plane, 1306.09 *m/s* (V_{LT}) LT plane and 665.78 *m/s* (V_{RT}) RT plane. As it can be seen in these results, wave velocity is differentiating according to plane direction. These results are thought to relate with wave velocities decrease due to barrier function of annual rings and other nature of wood.

Shear wave (except RT plane) and shear moduli values calculated in this study are in the reported range for softwoods. Calculated shear modulus for LR, LT and RT planes were found as 1107.53, 952.09 and 247.59 (N/mm^2), respectively. Differences between wave velocities and moduli values obtained in this study and literature may be occurred due to some factors such as slope of grain, MFA, annual rings, share of late and early wood, age of wood, growing conditions, and etc.

Obtained values can be used as input parameters with other necessary ones while performing non-linear analysis of Calabria pine wood via some engineering simulation programs like as ANSYS, CATIA, etc.

For further studies, it is proposed to perform comparative analysis of actual load behavior with load tests made by simulation programs using the obtained shear modules values.

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