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Characterization of Engineering Elastic Parameters of Oriented Strand Board (OSB) Manufactured from Poplar (*Populus deltoides*) Strands Using Ultrasonic Contact Pulse Transmission

Karakterizacija parametara elastičnosti ploče s orijentiranim makroiverjem (OSB) proizvedene od iverja drva topole *(Populus deltoides)* uz pomoć ultrazvučnoga kontaktnog prijenosa impulsa

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ABSTRACT • *When using wood and wood-based composites, it is necessary to determine the elastic constants of these engineered materials. Oriented strand board (OSB), as structural wood based panel, plays a significant role in the building sector, but the accessibility of such elastic constants of OSB is mostly limited. For this purpose, this study aimed at determining the elastic wave velocity, stiffness and all elastic constants of OSB made from Poplar (Populus deltoides) strands using ultrasonic through–transmission technique. Laboratory OSBs with the mean density of 760 kg/m³ were made with the average strand sizes of 0.6 mm in thickness, 120 mm in length and 30 mm in width. 8 % phenol-formaldehyde (PF) resin was used with the pressing conditions of 3.43 N/mm², 190 °C and 600 s as pressure, temperature and time of pressing, respectively. The OSBs were assumed as an orthotropic model. Three modulus of elasticity (E_1, E_2, and E_3), three shear modulus (G_{12}, G_{13} and G_{23}), and six Poisson's ratios (ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23}, ν_{32}) were calculated by longitudinal, transversal and quasi-transversal waves velocities. Ultrasonically determined stiffness coefficients of OSB were investigated by representative volume elements*

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(RVE). Therefore, the separation of scales requirement is satisfied, and the measured velocities can be applied to determine the engineering elastic parameters of the examined OSB. The results indicate that modulus of elasticity and shear modulus are in the same order of magnitude in comparison with other references, and the values of Poisson's ratios are valid in ultrasonic range measurement. In conclusion, the ultrasonic contact pulse transmission shows great potential to determine the characterization of elastic wave velocity, stiffness and engineering elastic parameters.

Keywords: *poplar (Populus deltoides); oriented strand bord; engineering parameters; ultrasonic waves*

SAŽETAK • *Za primjenu drva i kompozita na bazi drva iznimno je važno odrediti konstante elastičnosti tih konstrukcijskih materijala. Ploča s orijentiranim makroiverjem (OSB ploča), kao strukturna ploča na bazi drva, ima široku primjenu u građevnom sektoru, a pristup takvim konstantama elastičnosti OSB ploča uglavnom je ograničen. Stoga je cilj ove studije bio odrediti brzinu elastičnog vala, krutost i sve konstante elastičnosti OSB ploča proizvedenih od makroiverja topole (Populus deltoides) primjenom ultrazvučne tehnike. Od iverja prosječne debljine 0,6 mm, duljine 120 mm i širine 30 mm laboratorijski su izrađene OSB ploče srednje gustoće 760 kg/m^3. Upotrijebljena je 8 %-tna fenol-formaldehidna (PF) smola u ovim uvjetima prešanja: tlak je bio 3,43 N/mm^2, temperatura 190 °C, a proces prešanja trajao je 600 s. Pretpostavljeno je da su OSB ploče ortotropni modeli. Na temelju srednjih vrijednosti uzdužne, poprečne i kvazipoprečne brzine valova izračunana su tri modula elastičnosti (E_1, E_2 i E_3), tri modula smicanja (G_{12}, G_{13} i G_{23}) i šest Poissonovih omjera (ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23}, ν_{32}). Ultrazvučno utvrđene krutosti OSB ploča ispitivane su reprezentativnim volumnim elementima (RVE). Dakle, ispunjen je zahtjev za odvajanje skala, a izmjerene se brzine mogu primijeniti za određivanje inženjerskih parametara elastičnosti ispitivanih OSB ploča. Rezultati pokazuju da su moduli elastičnosti i moduli smicanja istog reda veličine u usporedbi s drugim referencama, a vrijednosti Poissonovih omjera vrijede u mjerenjima ultrazvučnog raspona. Zaključno, ultrazvučni kontaktni prijenos impulsa pokazuje velik potencijal za određivanje brzine elastičnih valova, krutosti i konstrukcijskih parametara elastičnosti materijala.*

Ključne riječi: *topola (Populus deltoides); ploča s orijentiranim makroiverjem; konstrukcijski parametri; ultrazvučni valovi*

1 INTRODUCTION
1. UVOD

OSB, as an engineered wood material, has got considerable attention in structural applications in recent years so that today OSB plays a remarkable role in both commercial and residential sectors. OSB is commonly used for wall and roof sheathing, flooring and I-joists. It is also used in different applications such as furniture, reels, pallets and boxes, trailer liners and recreational vehicle flooring (Smulski, 1997; Hiziroglu, 2006). Hence, with increasing applications of OSB, the determination of its mechanical properties is critical for ensuring reliable performance.

Elastic constants of OSB are of substantial importance to both science and technology as they not only describe the mechanical behavior of materials but are also significant for purposes of engineering design. Furthermore, engineering constants are required as input parameters for modern numerical simulation methods such as finite element method (FEM), which is often used in mechanics of engineered materials and civil engineering (Goncalves *et al.*, 2014). As a result, determination of the full set of elastic engineering parameters, including three modulus of elasticity (E_1, E_2 and E_3), three shear modulus (G_{12}, G_{13} and G_{23}), and six Poisson's ratios (ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23}, ν_{32}), is essential for a better understanding of the particular elastic behavior of OSB (Bodig and Jayne, 1993; Ozyhar *et al.*, 2013).

The availability of engineering parameters for engineered wood composites such as OSB is often limited and no adequate information can be found in the literatures because some properties such as shear modulus and six Poisson's ratios have never been properly addressed. For this reason, some researchers including Morris *et al*. (1995) used Poisson's ratio of other wood-based panels such as particleboard for simulating the behavior of OSB employing FEM (Morris *et al*., 1995). Besides, the conventional static test is the most common experimental technique to determine elastic properties of materials. Determination of the elastic constants by conventional static tests requires complex and expensive equipment, long test time and several specimens with special shape and dimensions (Kazemi Najafi *et al*., 2005). Measurements of shear modulus and Poisson's ratios are very sophisticated to perform and require very elaborate testing equipment, because it is complex to measure shear stresses and respective strains in the test specimens (Keunecke *et al*., 2007). To overcome these limitations, some researchers such as Bucur (1992, 2006), Bucur and Archer (1984), Kazemi Najafi *et al.* (2005), Keunecke *et al.* (2007), Kohlhauser and Hellmich (2012), Ozyhar *et al.* (2013), Goncalves *et al.* (2014) and Bader *et al.* (2016) proposed ultrasonic waves method as a nondestructive, cheap, fast, simple and flexible technique to determine the elastic constants of wood and wood-based composites. Ultrasonic waves can freely propagate in solids and liquids and are reflected at boundaries of internal flaws or change of medium. Accordingly, they are related to properties of the propagation medium. Therefore, the measurement of acoustical quantities, such as propagation velocities and attenuation, provides information about the elastic properties of the material.

Thus, with taking into account the limitations in availability of elastic constants of OSB, the aim of this study was to characterize elastic wave velocity, stiffness and anisotropic behavior, and also to provide all elastic constants of OSB made from Poplar (*Populus deltoides*) strands by means of ultrasonic waves.

2 THEORETICAL BACKGROUND
2. TEORIJSKE OSNOVE

In an orthotropic material, by the generalized Hook's law, stresses σ_{ij} and strains ε_{ij} are linked by six linear relations $\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl,}$ which define the stiffness matrix C_{ijkl} with nine independent constants: six diagonal terms and three off-diagonal terms:

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ 0 & C_{22} & C_{23} & 0 & 0 & 0\\ 0 & 0 & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix} \begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{bmatrix} \quad (1)$$

Where *σ, C* and *ε* are stress, stiffness and strain tensors, respectively

The relations between the terms of the stiffness matrix and the ultrasonic wave velocity are well known by the Christoffel's equation (Ozyhar *et al.*, 2013; Bucur, 1992):

$$[\Gamma_{ik} - \rho V^2 \delta_{ik}] = 0, \quad (2)$$

Where Γ_{ik} is Christoffel's tensor, δ_{ik} is the Kronecker delta symbol, *V* is the wave velocity and *ρ* is the density of the solid. The eigenvalues and eigenvectors of Christoffel's tensor, and stiffness tensor components can be calculated from the mass density of the material, and from the ultrasonic wave velocities, according to the theory of wave propagation in elastic media (Ozyhar *et al.,* 2013; Bucur, 1992):

$$C_{ij} = V_{ij}^2 \rho \quad (3)$$

Where the first index *i* of the velocities $V_{i,j}$ designates the wave propagation direction, and the second index *j* designates the direction of the particle motion induced by the wave, i.e. the polarization direction ($i = j$ for a longitudinal wave; $i \neq j$ for a transversal wave).

Accordingly, the normal stiffness tensor components C_{11}, C_{22}, and C_{33} are related to longitudinal wave velocities V_{11}, V_{22}, and V_{33} (Eq. 4); while the shear stiffness components C_{44}, C_{55}, and C_{66}, which are equal to the shear moduli G_{12}, G_{13}, and G_{23}, respectively, are related to transversal wave velocities V_{12}/V_{21}, V_{13}/V_{31} and V_{23}/V_{32} (Eq. 5). For the determination of off-diagonal terms C_{iijj}, the propagation of ultrasonic waves along non-principal directions in symmetry planes is necessary. For propagation directions in symmetry planes inclined by 45° to the principal directions of materials, the off-diagonal terms are related to wave velocity of the quasi-shear wave with propagation direction in direction $\mathrm{n} = \left(\frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}}\right)^T$ (*T* superscript denotes quasi-transverse mode) and particle motion in the $i - j$ plane. The off-diagonal elasticity components C_{iijj} can be determined by equations 6 (Ozyhar *et al.,* 2013).

$$C_{11} = V_{11}^{\ 2}\rho \qquad C_{22} = V_{22}^{\ 2}\rho \qquad C_{33} = V_{33}^{\ 2}\rho \quad (4)$$

$$C_{44} = (V_{32}^{\ 2}\rho + V_{23}^{\ 2}\rho)\,/2$$

$$C_{55} = (V_{13}^{\ 2}\rho + V_{31}^{\ 2}\rho)\,/2 \quad (5)$$

$$C_{66} = (V_{12}^{\ 2}\rho + V_{21}^{\ 2}\rho)\,/2$$

$$C_{12} = \sqrt{C_{11} + C_{66} - 2V^2_{12/12}\rho)(C_{22} + C_{66} - 2V^2_{12/12}\rho)} - C_{66}$$

$$C_{13} = \sqrt{C_{11} + C_{55} - 2V^2_{13/13}\rho)(C_{33} + C_{55} - 2V^2_{13/13}\rho)} - C_{55} \quad (6)$$

$$C_{23} = \sqrt{C_{22} + C_{44} - 2V^2_{23/23}\rho)(C_{33} + C_{44} - 2V^2_{23/23}\rho)} - C_{44}$$

The compliance tensor *S* of the orthotropic material is the inverse of the stiffness tensor *C*, i.e. $C^{-1}=S$. The compliance matrix is directly related to the elastic engineering parameters (Bucur and Archer, 1984):

$$Sij = \begin{bmatrix} S_{11}=1/E_1 & S_{12}=-\nu_{12}/E_2 & S_{13}=-\nu_{13}/E_3 & 0 & 0 & 0\\ S_{21}=-\nu_{21}/E_1 & S_{22}=1/E_2 & S_{23}=-\nu_{23}/E_3 & 0 & 0 & 0\\ S_{31}=-\nu_{31}/E_2 & S_{32}=-\nu_{32}/E_2 & S_{33}=1/E_3 & 0 & 0 & 0\\ 0 & 0 & 0 & S_{44}=1/G_{23} & 0 & 0\\ 0 & 0 & 0 & 0 & S_{55}=1/G_{13} & 0\\ 0 & 0 & 0 & 0 & 0 & S_{66}=1/G_{12}\end{bmatrix} \quad (7)$$

Three Young's moduli *of* E_1, E_2, E_3 refer to the principal directions of materials, three shear moduli G_{12}, G_{13}, G_{23} refer to principal planes of materials (symmetry), and out of six Poisson's ratios n_{12}, n_{21}, n_{13}, n_{31}, n_{23}, n_{32}, the first index of Poisson's ratio refers to the (passive) strain and the second index refers to the active strain. Bucur and Archer (1984) have described in detail the conversion between the components of the compliance matrix and the components of the stiffness matrix.

3 MATERIALS AND METHODS
3. MATERIJALI I METODE

3.1 Materials
3.1. Materijali

Poplar (*Populus deltoides*) trees, as a fast-growing species and widely planted in Iran, with an average DHB of 20-25 cm, were harvested from Chamestan Educational Forest, Noor, Iran. Logs were cut into 120 cm length and debarked by hand (Figure 1). The average wood density was 0.39 g/cm^3. The morphological characteristics and chemical composition of Poplar wood are listed in Table 1.

3.2. Panel manufacturing
3.2. Proizvodnja ploča

The veneers with thickness of 0.6 mm were prepared from poplar wood and then cut into strands with 30 mm width and 120 mm length by circular saw. The strands were dried at (105±5) °C in an oven to reach moisture content of 2.5-3 %. Phenol-formaldehyde

Figure 1 Harvesting and debarking Poplar tree
Slika 1. Sječa, izrada i otkoravanje drva topole

Table 1 Morphological characteristics and chemical composition of Poplar wood (Ramazani *et al.,* 2013)
Tablica 1. Morfološka svojstva i kemijski sastav drva topole (Ramazani *et al.,* 2013.)

Properties / *Svojstva*	**Poplar** *Topola*
Anatomical / *Anatomska*	
Fiber length / *duljina vlakna*, mm	0.76 (0.087)*
Fiber lumen diameter / *promjer lumena vlakna*, μm	15.67 (1.81)
Fiber overall diameter / *promjer vlakna,* μm	23.00 (2.5)
Fiber wall thickness / *debljina stijenke vlakna*, μm	3.6 (0.59)
Chemical / *Kemijska*	
Cellulose / *celuloza,* %	51
Lignin / *lignin,* %	22.3
Extractives / *ekstraktivne tvari*, %	5.1
Ash / *pepeo*, %	0.7

[a] Dissolved in alcohol-acetone. / *Otopljeno u alkohol-acetonu.*
* Values in parenthesis are the standard deviation. / *Vrijednosti u zagradama standardne su devijacije.*

(PF) resin was used at a level of 8 % based on oven-dry weight of wood strands to produce the panels. No wax or other additives were used. The characteristics of the PF resin are given in Table 2.

Table 2 Properties of PF resin
Tablica 2. Svojstva fenol-formaldehidne (PF) smole

Properties / *Svojstva*	**PF**
Color / *boja*	Dark / *tamna*
Solid content / *sadržaj čvrste tvari*, 105 °C, 3 H, %	62.00
Density / *gustoća*, g/cm^3	1.13
PH 25 °C	7.25
Viscosity / *viskoznost*, 20 °C, cPas	320
Gel time / *vrijeme geliranja*, 100 °C, s	300

OSB panels were manufactured using a standardized procedure that simulated industrial production at the laboratory. For the preparation of the panels, strands (120 mm × 30 mm × 0.6 mm) were mixed in a rotary blender equipped with resin spraying. The strands were oriented manually into a forming box and then the strands mats were hot-pressed at pressure of 3.43 N/mm^2 and temperature of 190 °C for 10 minutes. The dimensions of the panels were 460 mm × 460 mm × 16 mm. Target board density was set at 760 kg/m^3. The manufactured panels were conditioned at relative humidity of (65±5) % and temperature of (20±3) °C. The OSB panels are assumed as an elastic, anisotropic wood composite material with orthotropic symmetry, where the symmetry planes are defined in terms of parallel direction of strand alignment (direction 1), perpendicular direction of strand alignment (direction 2) and thickness of the panel (direction 3) (Figure 2).

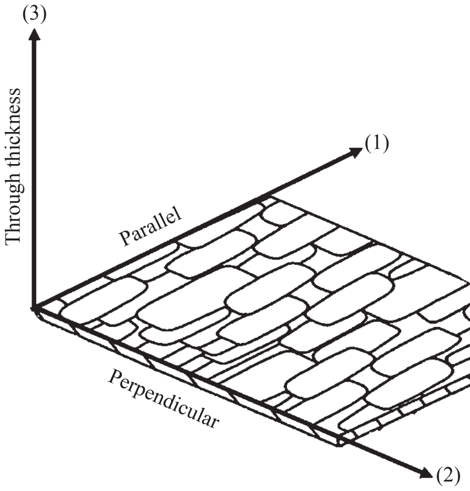

Figure 2 Schematic of principal axes of OSB
Slika 2. Shematski prikaz glavnih osi OSB ploče

3.3. Ultrasonic tests
3.3. Ultrazvučni testovi

Four types of samples with different orientations to the major axis of anisotropy for ultrasonic testing were of cubical shape with 16 mm edge length (Figure 3). For each sample, 6 replications and a total of twenty-four samples were provided. Density of all samples was kept at 0.76 g/cm^3. Prior to testing, all the specimens were conditioned at a temperature of (20±3) °C and a relative humidity (RH) of (65±5) % to ensure uniform moisture content.

In the present study, orthotropic symmetry was assumed for elastic properties of the OSBs. According to Bucur (2006), three longitudinal and three shear wave velocities propagating along the principal axes of anisotropy, and also three quasi-longitudinal or quasi-shear wave velocities, measured at the angle θ of the wave orientation vector, are needed in order to determine all independent components of the stiffness matrix. In this research, three longitudinal waves (*Vii*), six shear waves

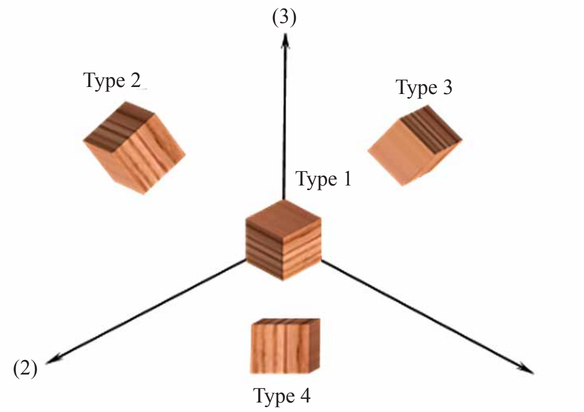

Figure 3 Types of specimens used for ultrasound velocity measurements in different orientations
Slika 3. Vrste uzoraka rabljenih za ultrazvučna mjerenja brzina različitih smjerova

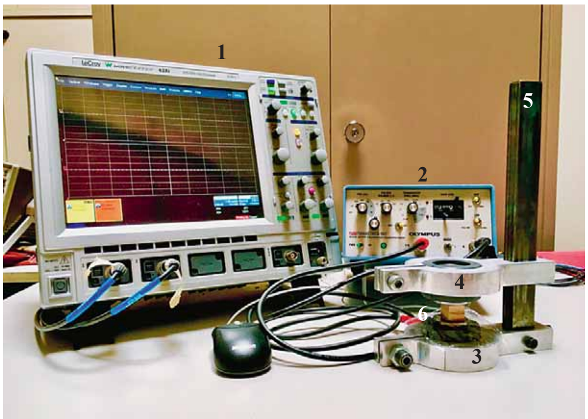

Figure 4 Ultrasonic equipment: 1. oscilloscope, 2. pulser-receiver, 3. transducer sender, 4. transducer receiver, 5. auxiliary testing device, 6. sample
Slika 4. Oprema za ultrazvučna mjerenja: 1. osciloskop, 2. prijamnik impulsa, 3. pretvornik-predajnik, 4. pretvornik-prijamnik, 5. pomoćni uređaj za ispitivanje, 6. uzorak

(*Vij*) and three quasi-shear waves at 45° (*Vij/ij*) were measured. The equipment used for performing ultrasonic measurements consists of a digital oscilloscope (WaveRunner 62Xi, Lecroy Corporation, Chestnut Ridge, NY, USA), a pulser-receiver (5077 PR, Panametrics Inc., Waltham, MA, USA), two pairs of transducers with frequencies of 100 kHz and 250 kHz for longitudinal and transversal waves, respectively, as well as an auxiliary testing device (Figure 4). For better contact between the transducers and the specimens, a thin layer of honey was used. A cellophane film was applied in order to prevent the infiltration of honey into the wood microstructure, and hence influencing its stiffness properties. In this study, through-transmission technique was used to determine the ultrasonic wave velocities. In this technique, two transducers are used, one sending a signal into the specimen and one receiving the sent signal on the opposite side of the specimen (Figure 4).

As reported by continuum (micro) mechanics (Salençon, 2001; Zaoui, 2002), ultrasound-derived elastic properties of micro-heterogeneous materials are defined by a representative volume element (RVE). Thus, the characteristic length of the RVE (L_{RVE}) must be considerably larger than the length of inhomogeneities d inside the RVE ($L_{RVE} \gg d$), and the characteristic length of the RVE (L_{RVE}) need to be smaller than the wavelength λ of the propagation waves ($L_{RVE} \ll \lambda$). Mathematically, this is expressed by means of the separation-of-scales requirement (Kohlhauser and Hellmich, 2013),

$$d \gg L_{RVE} \ll \lambda \tag{8}$$

The wavelength λ is readily accessible from the measured wave speed V and from the chosen signal frequency f as $\lambda = V/f$. The wave speed is equal to the travel distance s of the wave divided by the travel time t of the signal $V = S/t$.

4 RESULTS AND DISCUSSION
4. REZULTATI I RASPRAVA

Homogenized material properties of micro-heterogeneous materials are defined on representative volume elements (RVEs). The inhomogenities within an RVE of OSB result from the strands made from Poplar wood with an average fiber lumen diameter of 15.67 μm (Table 1). Thus, the minimum longitudinal and shear wavelength amounted to 9.3 and 3 mm, respectively, and the length of RVE≈0.76 mm (Table 4). In this study, it is implied that the characteristic length of RVE (L_{RVE}) is considerably larger than the lumen diameter of Poplar strands (*d)* inside the RVE, and L_{RVE} is smaller than both longitudinal and shear wavelength values. Consequently, the separation of scales requirement is fulfilled, and the measured velocities can be used to determine the elastic properties of the OSB.

The mean values and standard deviations of density and ultrasonic wave velocities are given in Table 3, and the corresponding wavelengths are given in Table 4. The maximum and minimum longitudinal wave velocities amounted to V_{11}= 4.2 and V_{33} = 0.93 km/s, respectively ($V_{11}>V_{22} \gg V_{33}$). This means that strands were predominantly oriented in the principal axis of the boards and they behaved as orthotropic materials. The velocities are related to the material elasticity, because the propagation of the wave generates mechanical oscillations (Keunecke *et al.*, 2007). As reported in literature (Bucur, 2006; Bucur and Archer, 1984; Gerhards, 1982), the velocities in thickness direction (V_{33}) are significantly lower than in parallel and perpendicular to manufacturing direction, respectively. In thickness direction (V_{33}), there is no continuous medium to make it possible to conduct the wave, so velocity is always lower in this direction.

The values of shear wave velocities with directions of propagation and polarization in the same symmetry plane are unequal. The different values for each shear wave velocities proved the anisotropy of OSBs. Generally, longitudinal wave velocities are higher than shear wave velocities, because the particle oscillations are parallel to the direction of longitudinal wave propagation, while they are perpendicular to each other in shear waves (Wang, 20013; Wang *et al.*, 2007; Zhang *et al.*, 2011). Wood-based panel anisotropy could be

Table 3 Mean values of density and ultrasonic wave velocities in OSB
Tablica 3. Srednje vrijednosti gustoće i brzina ultrazvučnih valova u OSB ploči

Density *Gustoća* g/cm^3	**Longitudinal wave, km/s** *Uzdužni val,* km/s			**Shear wave, km/s** *Poprečni val,* km/s						**Quasi-shear wave, km/s** *Kvazipoprečni val,* km/s		
Mean value *Srednja vrijednost*	V_{11}	V_{22}	V_{33}	V_{12}	V_{21}	V_{13}	V_{31}	V_{23}	V_{32}	$V_{12/12}$	$V_{21/21}$	$V_{13/13}$
0.76 (±0.08)[a]	4.2 (±0.16)	3.39 (±0.11)	0.93 (±0.05)	1.8 (±0.55)	1.67 (±0.36)	1.03 (±0.08)	1.72 (±1.09)	0.75 (±0.21)	0.83 (±0.17)	1.58 (±0.13)	1.00 (±0.08)	0.97 (±0.03)

[a] Values in parenthesis are the standard deviation. / *Vrijednosti u zagradama standardne su devijacije.*

Table 4 Mean values of wavelengths in OSB
Tablica 4. Srednje vrijednosti valnih duljina u OSB ploči

Wavelength / *Valna duljina*, mm											
λ_{11}	λ_{22}	λ_{33}	λ_{12}	λ_{21}	λ_{13}	λ_{31}	λ_{23}	λ_{32}	$\lambda_{12/12}$	$\lambda_{13/13}$	$\lambda_{23/23}$
42	33.9	9.3	7.2	6.68	4.12	6.88	3.00	3.32	6.32	4	3.9

Table 5 Anisotropy of OSB expressed by velocity ratios in principle anisotropic directions and planes
Tablica 5. Anizotropija OSB ploče izražena odnosima brzina u glavnim anizotropnim smjerovima i ravninama

Anisotropy in principal directions *Anizotropija u glavnim smjerovima*		**Anisotropy in symmetry planes** *Anizotropija u simetričnim ravninama*		**Birefringence in the same plane** *Dvostruka refrakcija u istoj ravnini*	
Longitudinal waves velocities *Brzine uzdužnih valova*	Ratios *Omjeri*	Shear waves velocities *Brzine poprečnih valova*	Ratios *Omjeri*	Shear waves velocities *Brzine poprečnih valova*	Ratios *Omjeri*
V_{11}/V_{22}	1.23	V_{12}/V_{13}	1.74	V_{12}/V_{21}	1.07
V_{11}/V_{33}	4.5	V_{13}/V_{23}	2.4	V_{13}/V_{31}	1.7
V_{22}/V_{33}	3.64	V_{13}/V_{23}	1.37	V_{23}/V_{32}	0.9

calculated by the ratios between velocities of longitudinal and shear waves in the three main symmetry directions (Bucur, 2006). The anisotropy of OSB can be deduced from the values noted in Table 5. V_{12}/V_{21}= 1.07 shows a low anisotropy in 1-2 plane. The highest anisotropy expressed by birefringence is in 1-3 plane. Bucur *et al.* (1998) argued that the anisotropy is much higher in planes containing the axis 3, and that it is related to the type and size of the particles.

Calculated stiffness properties are summarized in Table 6. The stiffness tensor components are arranged as follows:

$$C_{11}>C_{22}\gg C_{33},\ C_{66}>C_{55}>C_{44},\ \text{and}\ C_{12}\gg C_{13}>C_{23} \tag{9}$$

The order of the stiffness coefficients is related to the theoretical acoustic behavior and mechanical properties of wood and its composites (Goncalves *et al.*, 2011). The shear stiffness in the plane of the board C_{66} (2.31 GPa) is greater than the shear stiffnesses in the out-of-plane directions, where C_{44} (0.47 GPa) is smaller than C_{55} (1.44 GPa). The stiffness tensor components derived from ultrasonic tests are in the same order of magnitude as the values reported by Bucur *et al.* (1998), who worked on elastic constants of OSB, MDF and chipboard using ultrasonic velocity method (Table 6). Kazemi Najafi *et al.* (2005) also determined elastic constants of two types of commercial particleboards by means of ultrasonic technique, and they obtained a similar trend for stiffness coefficients. The values of stiffness components in this study are greater (13-44 %) than the stiffness values obtained by Bucur *et al.* (1998) (Table 6).

The values of engineering elastic constants of OSB are given in Table 7. The modulus of elasticity in parallel direction (refer to Figure 2) (E_1) is 7.14 GPa, which is 29 % greater than the modulus of elasticity in perpendicular direction (E_2) (5 GPa). Bucur *et al.* (1998) reported that the E_1 in OSB is 20 % higher than E_2, and Kazemi Najafi *et al.* (2005) also obtained the E_1 17 % higher than E_2 in particleboard. The minimum modulus of elasticity amounted to 0.5 GPa in thickness direction (E_3).

The literature, there are few references about modulus of elasticity in the perpendicular and thickness directions, shear modulus and Poisson's ratio. Mostly, the modulus of elasticity in the direction of strand alignment was measured in static tests on OSBs. Furthermore, the comparability between the measurement results obtained in this study with other results is generally complicated and unreliable since different manufacturing processes, glues, densities, specimen dimensions, frequencies and measurement techniques are used in the majority of cases.

In this study, shear modulus obtained from ultrasonic results, in parallel, perpendicular and thickness

Table 6 Mean values and standard deviation of stiffness tensor components derived from ultrasonic testing according to Equations 4, 5 and 6
Tablica 6. Srednje vrijednosti i stadardne devijacije krutosti komponente tenzora derivirane iz ultrazvučnih ispitivanja prema jednadžbama 4, 5 i 6

Diagonal stiffness tensor components *Komponente tenzora dijagonalne krutosti*	**Mean value, GPa** *Srednja vrijednost,* GPa	**Mean value#, GPa** *Srednja vrijednost#,* GPa	**Off-diagonal stiffness tensor components** *Komponente tenzora izvandijagonalne krutosti*	**Mean value#, GPa** *Srednja vrijednost#,* GPa
C_{11}	13.4 (±0.86)[a]	9.6	C_{12}	7.02 (±0.34)
C_{22}	8.8 (±0.41)	6.5	C_{13}	1.34 (±0.14)
C_{33}	0.66 (±0.08)	0.33	C_{23}	1.06 (±0.11)
C_{44}	0.47 (±0.07)	0.31		
C_{55}	1.44 (±0.09)	0.8		
C_{66}	2.31 (±0.12)	2.00		

[a] Values in parenthesis are the standard deviation. / *Vrijednosti u zagradama standardne su devijacije.*
Bucur and Archer (1984)

Table 7 Elastic engineering parameters determined from ultrasonic measurements
Tablica 7. Parametri elastičnosti određeni iz ultrazvučnih mjerenja

Young's modulus, GPa *Youngov modul,* GPa				**Shear modulus, GPa** *Modul smicanja,* GPa				**Poisson's ratios** *Poissonovi omjeri*					
E_1	E_2	E_3		G_{12}	G_{13}	G_{23}		ν_{12}	ν_{21}	ν_{13}	ν_{31}	ν_{23}	ν_{32}
7.14	5	0.5		2.32	1.43	0.47		0.66	0.46	0.93	0.06	0.7	0.07

direction, are about *E1*/3, *E1*/5 and *E1*/15, respectively. The values of Poisson's ratios were obtained from the literature, i.e. 0.23 in bending test in 1-3 plane (Ting and Chen, 2005), and Bucur (1992) measured the value of Poisson's ratio from 0.068 to 1.52 in flakboard. For validation of the obtained Poisson's ratios in this study, Poisson's ratio can be estimated as (Kazemi Najafi *et al.*, 2005; Bucur, 1992):

$$(1-\nu_{12}\cdot\nu_{21}) > 0$$
$$(1-\nu_{13}\cdot\nu_{31}) > 0 \qquad (10)$$
$$(1-\nu_{23}\cdot\nu_{32}) > 0$$

And the

$$(1-\nu_{12}\cdot\nu_{21}-\nu_{13}\cdot\nu_{31}-\nu_{23}\cdot\nu_{32}-2\cdot\nu_{21}\cdot\nu_{32}\cdot\nu_{31}) > 0 \qquad (11)$$

As a result, these conditions are satisfied and it can be deduced that the coefficients are valid in ultrasonic range of measurement. Theoretically, Poisson's ratios for anisotropic materials with orthotropic symmetry can have no bounds (Ting and Chen, 2005). In the present study, there are no values exceeding 1.00 for Poisson's ratios, while Ozyhar *et al.* (2013) and Bucur (1992) obtained Poisson's ratios with values exceeding 1.00. They stated that Poisson's ratios with values higher than one are assumed to be unusual for wood and wood composites, and they have not been reported in static tests. Kohlhauser and Hellmich (2012) and Bader *et al.* (2016) argued that the ultrasonic characterization of off-diagonal stiffness components is very sensitive to inaccuracies regarding the wave velocity measurements and, to solve this problem, they proposed a combined ultrasonic-mechanical method to obtain the Poisson's ratios.

5 CONCLUSION
5. ZAKLJUČAK

Engineering elastic parameters of OSB made from Poplar were studied using ultrasonic contact pulse transmission. The ultrasonic contact pulse transmission shows great potential to determine the characterization of elastic wave velocity, stiffness and engineering elastic parameters and also study the anisotropic behavior of OSB, as an easy, fast, reliable and economic method, since few information can be found in the literature about elastic constants (stiffness, shear modulus and Poisson's ratios) of OSB. Based on the findings of this study, the measured velocity V_{11} was 19 and 78 percent higher than V_{22} and V_{33}, respectively. Generally, the highest velocity was measured in the direction of strands alignment, and on the other hand, the lowest velocity was that of shear waves, observed in the transverse plane. The normal stiffness in thickness direction, C_{33}, was considerably lower than the normal stiffness in the plane of the board. The obtained order of stiffness tensor components was $C_{11}>C_{22}\gg C_{33}$, $C_{66}>C_{55}>C_{44}$. The ratio of longitudinal and shear velocities showed the highest anisotropy in 1-3 plane. The highest values of Young's modulus and shear modulus were calculated for E_1 and G_{12}. The value of Poisson's ratio ranged between 0.06 and 0.93.

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