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TRANSVERSAL STRESS WAVE VELOCITY IN THE TREE OF SERBIAN SPRUCE (Picea omorika (Pančić) Purkyně)

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Abstract: *In this paper, transversal stress wave velocity was measured in 30 trees of Serbian spruce (Picea omorika /Pančić/ Purk.) using a 2D sonic tomograph. Tomograms were analyzed and speed loss and average speed for Serbian spruce were calculated. Since there is no reference value for this species, in this research the reference value for stress wave velocity of Norway spruce (Picea abies /L./ H. Karst.) was used for comparison. The relative difference between referent and measured stress wave velocity indicates the amount of decay between the two sensors. The largest number of cross-sections had a speed loss of up to 10%, but there were also cross-sections with a speed loss of more than 50% in the transversal direction. This result shows that there are defects and damages in this direction that will reduce the strength of the wood. Summarizing data for trees with speed loss of less than 10%, the average stress wave velocity at the cross-sections is 1635 (1205-2170) m/s. Compared to Norway spruce, this velocity is higher, but not significantly.*

Key words: Serbian spruce, 2D tomography, stress wave velocity, tree health evaluation

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BRZINA TRANSVERZALNIH ZVUČNIH TALASA U STABLIMA PANČIĆEVE OMORIKE (*Picea omorika* (Pančić) Purkyně)

Izvod: *U ovom radu merena je brzina transverzalnih zvučnih talasa na 30 stabala Pančićeve omorike (Picea omorika /Pančić/ Purk.) korišćenjem 2D zvučnog tomografa. Analizirani su tomogrami i izračunati su gubici brzine i prosečna brzina zvučnih talasa za Pančićevu omoriku. S obzirom da za ovu vrstu ne postoji referentna vrednost, u ovom istraživanju je za poređenje korišćena referentna vrednost brzine talasa kod smrče (Picea abies /L./ H. Karst.). Relativna razlika između izmerene i referentne vrednosti brzine talasa ukazuje na količinu oštećenja između dva senzora. Najveći broj poprečnih preseka imao je gubitak brzine do 10%, ali je bilo i preseka sa gubitkom brzine više od 50% u poprečnom pravcu. Ovaj rezultat pokazuje da u ovom pravcu postoje devastacije i oštećenja koja će smanjiti čvrstoću drveta. Sumirajući podatke za stabla sa gubitkom brzine manjim od 10%, prosečna brzina talasa napona na poprečnim presecima je 1635 (1205-2170) m/s. U poređenju sa smrčom, ova brzina je veća, ali ne značajno.*

Ključne reči: Pančićeva omorika, 2D tomografija, brzina zvučnih talasa, procena zdravstvenog stanja drveta

1. INTRODUCTION

Today, wood is an irreplaceable raw material for many products, where the properties of wood significantly determine the application of final wood products, as well as their economic value. The development of new methods for non-destructive analysis of living trees has greatly helped to determine the future of the tree in relation to its quality and properties of wood as a material.

As a part of the project "Monitoring the habitat of the Serbian spruce (*Picea omorika* Pancic) in NP Tara", trees of Serbian spruce were inspected with a 2D sonic tree tomography. The speed of sound waves is used, as a non-destructive method, in the prediction of internal damage in wood. Many researchers have studied the relationship between wood mechanical properties and wave speed (Ishiguri *et al.*, 2013: Tannert *et al.*, 2014; Yue *et al.*, 2019). Damage in the wood often results in lower quality and speed of acoustic wave propagation, therefore sound wave propagation time provides usefuinforns on the physical-mechanical properties of wood (Goh *et al.*, 2018). Instruments for this purpose generally measure the speed of ultrasonic or sound waves in wood. The speed of sound propagation depends on the species and its characteristics, and it is necessary to establish reference speeds of sound wood to set criteria for each species. According to the results so far, the speed of sound is the highest in the axial direction, and the largest number of tests was done by monitoring the correlation between the longitudinal speed of sound and the properties of wood. In recent years, tomography techniques that were developed for engineering or medical applications have been evaluated for their applicability in standing trees. Investigations on trees showed great success in using tomography techniques to detect internal decay (Mahon *et al.*, 2007). Instruments for this purpose usually measure the speed of waves or sound traveling through the wood. Given that wood is a solid medium, the speed of the wave in it is much higher than in air and depends on the type of wave and the elasticity and density of the material. Damaged wood often results in a modified speed of propagation of the acoustic wave, so that the propagation time of the sound wave provides useful information about the mentioned properties of wood (Goh *et al.*, 2018). This means that wood quality can be assessed *in situ* and that the methods and devices in question can help us make the right decisions. Still, it must be pointed out that all the methods and devices used are only measuring and quantifying tools, and practical human experience cannot be replaced by any measuring tools (Živanović *et al.*, 2019). Arbotom is a device for pulse tomography that enables an internal examination of the condition of trees and tree trunks. Hidden rot, invisible cavities, and cracks, as well as their dimensions become visible with this device that uses sound signals. The software package of this tomograph will provide a graphic display of the measurement results (i.e., tomogram) showing differently colored cross-sectional zones depending on the degree of wood decay.

Serbian spruce is an endemic species with a fragmented natural distribution range, which is limited to the areas along the central part of the river Drina. In Bosnia and Herzegovina, it occurs in 13 localities (Petrović, 2018). In Serbia, there are several smaller populations and scattered groups of trees in the Tara Mts., and a single large population in the valley of the river Mileševka (Vidaković, 1991). Serbian spruce is a mountain species with an altitudinal range between 800 and 1550 m a.s.l. It requires a mountain climate with mean annual temperatures of 4 to 6 °C and annual precipitation of around 1000 mm. Even at high elevations, the occurrences are limited to steep north-facing slopes and deep ravines with abundant fogs and a high snow cover. Within its natural range, it grows mainly on scree fields and calcareous rocks with shallow soils. Natural populations of Serbian spruce have been under legal protection since 1964, and the species has been listed in the IUCN Red List of Threatened Plants as a vulnerable species in the restricted area since 1997. In many European countries, it is grown as a decorative plant or in commercial forest plantations (Ballian, 2006).

In this paper transversal stress wave velocity was measured in 30 trees of Serbian spruce using Arbotom, in order to evaluate the internal damage and health of Serbian spruce in Serbia and to determine an average stress wave velocity for this species.

2. MATERIALS AND METHODS

Thirty Serbian spruce trees in the protected zone, located in the Crvena Stena area, were examined. The stand resides on a slope with a greater incline, on very shallow soil with a high portion of stones. A high number of fallen trees was noticed. The standing trees were examined with a sound tomograph in one or two cross-sections at different heights from the ground (pictures 1 and 2). The internal wood decay was measured using a portable Sonic Tomograph (ARBOTOM® Rinntech Inc. Heidelberg, Germany).

Picture 1. *Arbotom measurements*

Picture 2. *Examined Serbian spruce trees*

The relative difference between the reference and the measured velocity indicates the amount of decay between the two sensors.

The relative decrease of stress wave velocity is determined in a percent:

$$\Delta Vrel = \frac{Vref - Vmes}{Vref} * 100$$

where $\Delta Vrel$ is the relative decrease of sound velocity, Vref is the reference velocity, and Vmes is the measured velocity (Dackermann, 2014).

3. RESULTS AND DISCUSSION

The measurement results for the cross-section devastation and sound velocity in 30 trees of Serbian spruce are shown in table 1. Based on these results, the values of the share of damaged wood were obtained, ranging from 50% for tree number V33, while as many as 14 trees were without any damage.

Table 1. *Cross-section devastation and sound velocity in 30 Serbian spruce trees*

No.	Tree mark	Dia-metar (cm)	Cross section devastation (%)			Stress wave velocity (m/s)			Mean reference value for stress wave velocity *	ΔVrel
			Sound wood	Partly damaged	Damaged	Vmin	Vavg	Vmax	(m/s)	(%)
1.	T40	17	80	20	--	310	1205	2100	931 – 1310	8.02
2.	V19T42	40	95	5	--	330	730	1130	931 – 1310	44.27
3.	T41	20	70	30	--	730	1395	2060	931 – 1310	0.00
4.	T11V15	35	75	5	20	320	1395	2470	931 – 1310	0.00
5.	T44	30	40	25	35	300	1495	2690	931 – 1310	0.00
6.	T45	40	10	--	--	150	580	1010	931 – 1310	55.73
7.	T43	40	100	--	--	690	940	1190	931 – 1310	28.24
8.	T12	65	35	30	35	120	565	1010	931 – 1310	56.87
9.	T9	60	95	5	--	150	580	1000	931 – 1310	55.73
10.	T10	60	95	5	--	150	580	1000	931 – 1310	55.73
11.	T7	50	100	--	--	50	580	1110	931 – 1310	55.73
12.	T5	45	100	--	--	630	950	1270	931 – 1310	27.48
13.	T8	20	100	--	--	700	1445	2190	931 – 1310	0.00
14.	T6	35	50	20	30	430	2170	3910	931 – 1310	0.00
15.	T4	50	100	--	--	260	690	1120	931 – 1310	47.33
16.	T33	15	70	30	--	140	1635	3130	931 – 1310	0.00
17.	T35	30	100	--	--	370	780	1190	931 – 1310	40.46
18.	T27	22	70	5	25	720	2025	3330	931 – 1310	0.00
19.	T24	20	100	--	--	130	1250	2310	931 – 1310	4.58
20.	T25	40	100	--	--	310	720	1130	931 – 1310	45.04
21.	T28	40	70	30	--	310	985	1660	931 – 1310	24.81
22.	T31V28	15	100	--	--	1300	1850	2400	931 – 1310	0.00
23.	T32	45	100	--	--	200	675	1070	931 – 1310	48.47
24.	V29	50	70	30	--	280	864	1550	931 – 1310	34.05
25.	V33	30	40	10	50	300	2115	3350	931 – 1310	0.00
26.	T29	45	100	--	--	870	1130	1390	931 – 1310	13.74
27.	T38	30	100	--	--	360	775	1190	931 – 1310	40.84
28.	T37	25	100	--	--	830	1120	1410	931 – 1310	14.50
29.	T36	35	100	--	--	830	1120	1410	931 – 1310	14.50
30.	T39	15	65	35	--	50	1020	1900	931 – 1310	22.14

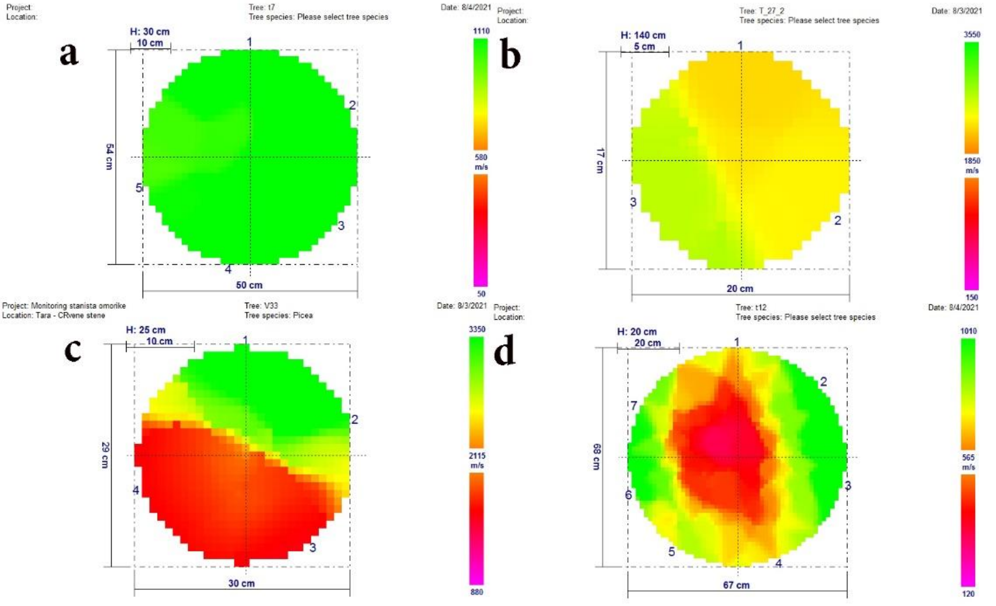
Since the speed of sound propagation greatly depends on the species and water content and density of the wood, the table gives average reference values for healthy trees of the genus *Picea*. By comparing these values with the measured values between individual sensors, the place of damage, rot, cavities, etc. were located. For sound wood, the stress wave velocities for longitudinal (parallel to the grain) and radial (perpendicular to the grain) orientations are listed for various wood species in table 2 by Dackermann (2014). These reference velocities can be used to evaluate the measured wave velocity and assess the internal condition of the timber specimen.

Table 2. *The stress wave velocities for longitudinal and transverse directions (Dackermann, 2014)*

Species	Species Stress wave velocity (m/s)	
	Longitudinal	Transverse
White ash	3,968–5,076	
Ash*		1,162–1,379
Beech*		1,670
Red beech*		1,206–1,412
Birch	4,695–5,747	1,140–1,479
Yellow birch	4,348–5,556	
Black cherry	4,831–5,435	1,451–1,613
Horse chestnut*		873–1,557
Sweet chestnut*		1,215–1,375
Fir*		910–1,166
Black fir*		1,480
Douglas-fir*		905–1,675
Japanese fir*		1,450
Silver fir*		1,360
Larch*		1,023–1,490
Lime*		940–1,183
Linden*		1,690
Black locust*		934–1,463
Maple*		1,006–1,690
Sugar maple	3,906–5,155	
Oak*		1,382–1,610
Live oak		627–1,631
White oak 1,258		1,258
Red oak	3,311–5,650	1,548–1,751
Pine*		1,066–1,146
Scotch pine*		1,470
Southern pine	5,000–5,882	
Plane*		950–1,033
Black poplar*		869–1,057
Pine poplar*		967–1,144
Silver poplar*		821–1,108
Yellow poplar	5,155–5,747	1,399–1,479
Spruce*		931–1,310
Sitka spruce	5,882	
Willow*		912–1,333

* Measured on a tree

For sound wood, the longitudinal stress wave velocities generally range between 3,500 and 5,000 m/s, while the velocity of transverse stress waves falls in the range of 1,000–1,500 m/s. Since there is no reference value for Serbian spruce, in this research value for the reference stress wave velocity of Norway spruce was used for comparison instead.



Picture 3. *Tomograms of different Serbian spruce trees cross-sections: a)sound wood, b) initial devastation, c and d) devastated wood*

Since longitudinal stress waves travel along the vertically oriented cells with only a few or no boundaries to pass, they have a higher velocity, while transverse waves encounter numerous interfaces and boundaries at the cell walls and travel at slower velocities. In picture 3, four different tomograms are shown. The first one (picture 3a) is for the wood with no damage. The second tomogram (picture 3b) is showing the sound speed loss and the beginning of devastation on the whole cross-section. The remaining two tomograms (pictures 3c and 3d) are for damaged and possibly rotten wood. Stress wave velocity was measured between all sensors on the cross-section. It was determined that the average stress wave velocity at the cross-sections is 1112 (565-2170) m/s.

Table 3. *Relationship between relative velocity decrease and decayed area (Fakopp Enterprise, 2011)*

Relative velocity decrease (%)	Decayed area ratio (%)
0–10	No decay
10–20	10
20-30	20
30-40	30
40-50	40
≥ 50	≥ 50

The relative difference indicates the amount of decay between the two sensors. The relationship between the relative velocity decrease and the decayed area is shown in table 3. The largest number of cross-sections had a speed loss of up to 10%, but there were also cross-sections with a speed loss of more than 50%

in the radial direction. This result shows that there are defects and damages in this direction that will reduce the strength of the wood.

Summarizing data for trees with less than 10% speed loss, the average stress wave velocity at the cross-sections is 1635 (1205-2170) m/s. Compared to Norway spruce, this velocity is higher, but not significantly. This value could be used as a reference value for Serbian spruce.

4. CONCLUSIONS

Stress wave velocity was measured between all sensors on the cross-section. It was determined that the average stress wave velocity at the cross-sections is 1112 (565-2170) m/s. Summarizing data for trees with less than 10% speed loss, the average stress wave velocity at the cross-sections is 1635 (1205-2170) m/s. Compared to Norway spruce, this velocity is only slightly higher. The relative difference between the reference and measured speed was used to assess the wood quality. The relative difference indicates the amount of decay between the two sensors. Based on the obtained results, the largest number of cross-sections had a speed loss of up to 10%, but there were also cross-sections with a speed loss of more than 50% in the radial direction. This result shows that there are defects and damages in this direction that will reduce the strength of the wood.

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Summary

Serbian spruce (*Picea omorika* /Pančić/ Purk.) is a endemic mountain species of the eastern part of Bosnia and Herzegovina and the western part of Serbia, which attracts the attention of researchers from all over the world. Natural populations of Serbian spruce have been under legal protection since 1964, and the species has been listed in the IUCN Red List of Threatened Plants as a vulnerable species in the restricted area since 1997.

As a part of the project "Monitoring the habitat of the Serbian spruce (*Picea omorika* Pancic) in NP Tara", 30 Serbian spruce trees were analyzed using sound tomography. Changes in the speed of sound waves and variations in wood density caused by rots were successfully detected. Based on the obtained results, the largest number of cross-sections had a speed loss of up to 10%, but there were also cross-sections with a speed loss of more than 50% in the radial direction. This result shows that there are defects and damages in this direction that will reduce the strength of the wood. The average speed of sound waves for Serbian spruce was also determined, which until now did not exist in the literature as a reference value and it is 1635 m/s.

The results presented in scientific papers show a good correlation between the speed of sound waves and the density of wood, as well as its other properties. Based on the measurement of the speed of sound flow through the wood, data on the health condition and properties of the wood is obtained. In this way, science and practice get significant data on the vitality and quality of wood, and the consumption of materials is minimized.

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Rezime

Pančićeva omorika (*Picea omorika* (Pančić) Purkyně) je endemska planinska vrsta istočnog dela Bosne i Hercegovine i zapadnog dela Srbije, koja privlači pažnju istraživača iz celog sveta. Prirodne populacije srpske omorike su pod zakonska zaštita od 1964. godine, a vrsta je od 1997. godine navedena na Crvenoj listi ugroženih biljaka IUCN-a kao ranjiva vrsta u ograničenom području.

U okviru projekta „Monitoring staništa pančićeve omorike (*Picea omorika* Pančić) u NP Tara", zvučnom tomografijom je analizirano 30 stabala omorike. Uspešno su otkrivene promene u brzini zvučnih talasa i varijacije u gustini drveta izazvane truljenjem. Na osnovu dobijenih rezultata najveći broj poprečnih preseka imao je gubitak brzine do 10%, ali je bilo i preseka sa gubitkom brzine više od 50% u radijalnom pravcu. Ovaj rezultat pokazuje da u ovom pravcu postoje nedostaci i oštećenja koja će smanjiti čvrstoću drveta. Utvrđena je i prosečna brzina zvučnih talasa za pančićevu omoriku, koja do sada nije postojala u literaturi kao referentna vrednost i iznosi 1635 m/s.

Rezultati prikazani u naučnim radovima pokazuju dobru korelaciju između brzine zvučnih talasa i gustine drveta, kao i njegovih drugih svojstava. Na osnovu merenja brzine proistiranja zvuka kroz drvo dobijaju se podaci o zdravstvenom stanju i svojstvima drveta. Na ovaj način nauka i praksa dobijaju značajne podatke o vitalnosti i kvalitetu drveta, a utrošak materijala je minimiziran.