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Variation in Mechanical Properties within Individual Annual Rings of the Resonance Spruce Wood [*Picea abies* (L.) Karst.]

Varijacije mehaničkih svojstava unutar pojedinih godova rezonantne smrekovine

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ABSTRACT • *This paper shows results of specific modulus of elasticity and specific tensile strength in the resonance spruce wood [Picea abies (L.) Karst.] in relation to its heterogeneity within individual annual rings. It also presents changes in the average values of microfibril angle in S2 layer measured in tangential walls of tracheids (MFA) within individual annual rings. On the grounds of the results, it can be concluded that specific modulus of elasticity and specific tensile strength of wood are strongly influenced by the position of the sample in annual rings. Generally, the values of these parameters increase along the width of annual rings. It is also noted that the specific modulus of elasticity and specific tensile strength depend on MFA. As MFA decreases, the values of these parameters increase.*

Key words: *resonance wood, spruce wood, specific modulus of elasticity, specific tensile strength, MFA*

SAŽETAK • *U radu se prikazuju rezultati istraživanja specifičnog modula elastičnosti i specifične vlačne čvrstoće rezonantnog drva smreke [Picea abies (L.) Karst.] s obzirom na njihovu heterogenost unutar pojedinih godova. Također su prikazane i promjene prosječnih vrijednosti kuta mikrofibrila u sloju S2 izmjerene u tangencijskim stijenkama traheida (MFA) unutar pojedinih godova. Na temelju dobivenih rezultata može se zaključiti da položaj uzorka u godovima ima velik utjecaj na specifični modul elastičnosti i na specifičnu vlačnu čvrstoću drva. Općenito, vrijednosti tih parametara povećavaju se uzduž širine godova. Također je zabilježeno da specifični modul elastičnosti i specifična vlačna čvrstoća ovise o MFA. Kako se MFA smanjuje, vrijednosti tih parametara se povećavaju.*

Ključne riječi: *rezonantno drvo, smrekovina, specifični modul elastičnosti, specifična vlačna čvrstoća, MFA*

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1 INTRODUCTION
1. UVOD

Wood quality is understood as a number of its attributes that are beneficial for its application. Therefore, the timber for different applications should be characterized by different specific properties. Resonance wood should meet specific demands for instruments production. High quality, defect-free spruce wood with thin growth rings (latewood should not exceed 30 %) is preferred to produce violin soundboards (Blossfeld *et al*., 1962). On the other hand, the definitions of the fundamental quantities characterizing the resonance properties of wood, such as sound velocity (*C*), acoustic impedance (*Z*), acoustic constant (*K*) and damping of sound radiation (*V*) that are shown below, imply that the high modulus of elasticity (*MOE*) at the lowest possible density (ρ) is the most important for instrument production (Wegst, 2006):

$$C = \sqrt{\frac{MOE}{\rho}}, \tag{1}$$

$$Z = \rho \cdot \sqrt{\frac{MOE}{\rho}}, \tag{2}$$

$$K = \sqrt{\frac{MOE}{\rho^3}}, \tag{3}$$

$$V = \frac{\sqrt{\frac{MOE}{\rho}}}{\rho}. \tag{4}$$

In other words, for this purpose wood should be characterized by a high ratio of *MOE* to density (*MOE*/ρ), known as the specific modulus of elasticity. This is why wood with poorly developed latewood (small contribution and low density of latewood) is the most suitable for the construction of musical instrument soundboards. According to Bucur (1995), a wide zone of latewood impedes the sound waves propagation. Some authors even believe that antique violins were made from trees grown during the Maunder Minimum (Topham and McCormick, 1998, 2000; Burckle and Grissino-Mayer, 2003). Moreover, good resonance wood should be characterized by small differences between early and latewood cells structure, which give low density gradient within individual annual rings (Buksnowitz, 2006; Spycher *et al*., 2008). Recently, a hypothesis has been put forward that the famous Stradivarius violins were made of the old and enzymatically degraded wood. This hypothesis seems to be confirmed by Schwarze *et al*. (2008), who studied the microstructure, density and *MOE* of partly enzymatically degraded wood of spruce and sycamore subjected to controlled enzymatic degradation. Consequently, wood density was reduced as a result of partial destruction of thick-walled anatomical elements. The resultant decrease in the modulus of elasticity (*MOE*) was small, which gave an increase in the *E*/ρ relative to that in the wood not subjected to degradation. Lower density and similar *MOE* give higher specific modulus of elasticity compared to non treated wood. It is generally believed that higher density gives higher *MOE* and vice versa, but *MOE* also depends on the microfibril angle in S2 layer (*MFA*). A good example illustrating the impact of cell wall ultrastructure on the *MOE* has been given by Easterling *et al*. (1982) regarding the balsa wood. Increased density of the wood from 78 to 218 kg/m^3 (2.8-fold) causes a 6.5-fold increase in *MOE* values. According to the authors, more than twice (2.3-fold) higher increase in *MOE* is attributed to changes in mechanical properties of cell walls. Cave (1968) and Cave and Walker (1994) have reported that the decrease in the average *MFA* value from 40 to 10° causes even a 5-fold increase in *MOE*. Many other authors (e.g. McMillin, 1973; Donaldson, 1992; Evans *et al*., 2000) have reported that *MFA* decreases with increasing height of the tree, increase in wood density and low rate of growth of trees. Therefore, in modeling the mechanical properties of wood, as well as its moisture deformation, not only the wood density and its microstructural parameters (shape and size of the cells) are taken into regard, but also the arrangement of microfibrils in the cell wall (Mark, 1967; Cowdrey and Preston, 1966; Cave, 1968, 1969; Astley *et al*., 1998; Xu and Liu, 2004; Mishnaevsky and Qing, 2008). All these factors are reflected in the acoustic properties of wood. They should be taken into account in the choice of wood for the production of musical instruments (Wegst, 2006), in using sound propagation speed to evaluate the wood quality (useful for construction) and for the production of pulp (Huang *et al*., 2003).

This paper presents results of a study on the resonance wood of spruce [*Picea abies* (L.) Karst.]. Of particular interest was the wood heterogeneity within individual annual rings manifested by differences in specific modulus of elasticity (*MOE*/ρ), essential for desirable acoustic properties of wood. In view of the fact that (*MOE*/ρ) depends not only on the density of wood, analysis of *MFA* was also made.

2 MATERIALS AND METHODS
2. MATERIJAL I METODE

The experimental material used in this study was a plank of spruce [*Picea abies* (L.) Karst.], previously classified as a resonant wood. The wood was obtained from the Chair of Wood Science at the University of Technology, Zvolen (Slovakia). The plank was 50 cm long, 95 mm wide along the radius and 35 mm thick in tangential direction. At the fronts of the board, a strip of about 5 mm in thickness was cut off. The front surface of the strip was sanded with fine sandpaper to visualize the annual rings. The width of individual annual rings and the width of the latewood zones were measured by a computer image analyzer. These measurements were made at wood moisture content of 7 %. The remaining part of the plank was adjusted to 9 mm thickness in the tangential direction using a planer. From this part of the plank, two adjacent wood samples were cut out from the region in which the borders of annual rings were straight lines parallel to the longer axis of the plank. Each sample was 80 mm in length. One of them was cut along the fibers into 3 pieces and each of them was placed in distilled water for two weeks.

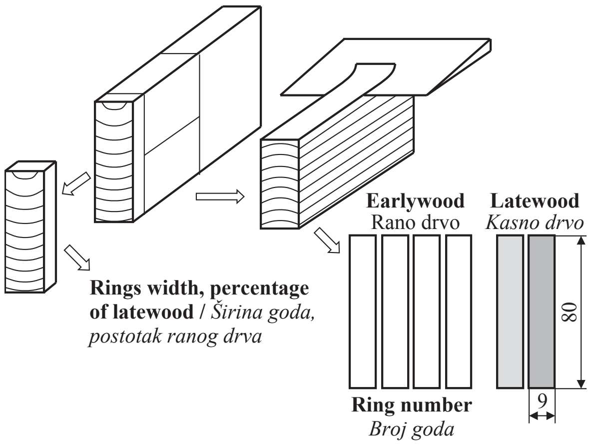

Figure 1 A scheme of sample preparation for determination of the density gradient, tensile strength along the grain and modulus of elasticity within individual annual rings
Slika 1. Shema pripreme uzoraka za određivanje gradijenta gustoće, vlačne čvrstoće uzduž vlakanaca i modula elastičnosti unutar pojedinih godova

As previously established, such a long wetting of wood allowed a correct slicing of wood samples without the need of pre-heating. Then, with the use of a microtome sledge, the tangentially oriented samples of about 200 μm in thickness were sliced. Each sample was marked to identify its position. A scheme of preparation of the microtome samples is shown in Figure 1.

The microtome samples were conditioned in laboratory to obtain equilibrium moisture content. Further measurements were made for the samples from 10 annual rings (No. 5, 10, 12, 17, 26, 30, 37, 54, 62 and 67 counted from the edge closest to the pith).

After stabilization of sample weight, the widths of the samples were measured in the middle of the length and at a distance of 2 cm from the centre, with a Brinell magnifying glass to the accuracy of 0.1 mm. At the same sites, the thickness of the sample was measured by a micrometer (with ratchet stop) screw gauge to the accuracy of 0.001 mm, and length – by a rule to the accuracy of 1 mm. Each sample was weighed on a laboratory balance to the accuracy of 0.0001 g, so as to be able to calculate the wood density.

After these measurements, the ends of samples were covered with hardboard of the size 20 x 20 mm and thickness of 3 mm with glue Pattex Compact. This procedure effectively protected the samples against damage in the jaws of the testing machine (Moliński and Krauss, 2008; Krauss, 2010; Krauss *et al*., 2011).

After laboratory conditioning that followed, the samples were subjected to tensile strength measurements on a testing machine ZWICK ZO50TH, equipped with an extensometer ZWICK 066550.02. The tensile test was applied at the rate of 0.6 mm/min, under the preliminary loading of 10 N and the extensometer base of 25 mm (Fig. 2).

The data were fed into a computer to calculate the mechanical strength and *MOE* along the grains. From each annual ring, the measurements were made for a few samples of earlywood and at least 1 sample of latewood. Only the results for the samples that broke up in the middle of the length were assumed reliable.

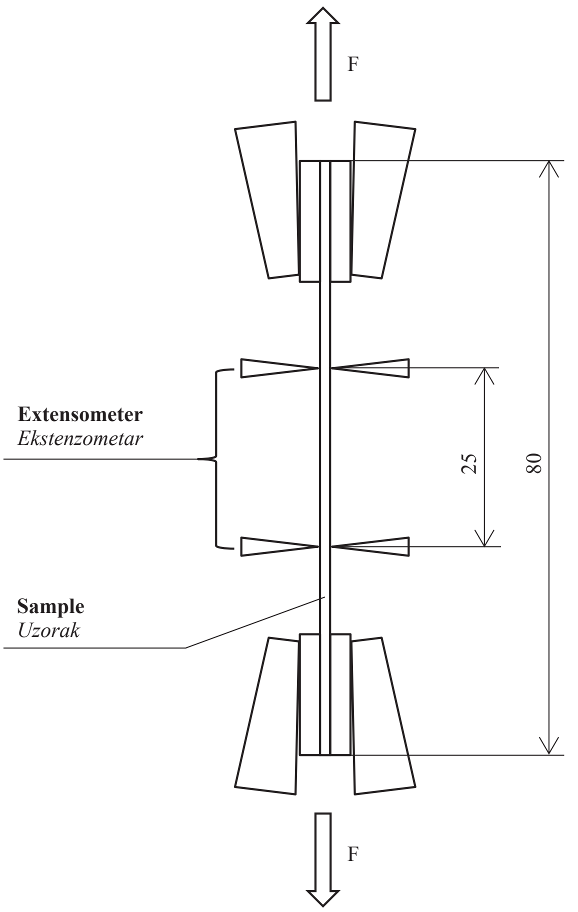

Figure 2 A scheme of sample mounting in the jaws of the testing machine and tensile strength measurement
Slika 2. Shema smještanja uzorka na uređaj za mjerenje vlačne čvrstoće

The next step was to determine the value of *MFA* in tangential tracheid walls. For this purpose, the samples in which macro-structural parameters were determined, were heated in a 20 % $Cu(NO_3)_2$ solution at 80 °C for 24 hours. After heating, samples were rinsed in distilled water. Then, the samples were boiled in distilled water at a temperature of 100 °C for 2 hours. This procedure allowed the visualization of *MFA* in the cell walls, also in other wood species (Wang *et al*., 2001; Fabisiak *et al*., 2006, 2009; Fabisiak and Moliński, 2007; Roszyk *et al*., 2010a, 2010b, 2012; Krauss *et al*. 2011). Then, tangential microscopic preparations, about 20 μm thick, were cut out of the front strip at the sites corresponding to the annual rings, from which the samples for tensile tests were taken. In those preparations, MFA was measured in tangential walls of tracheids by a computer image analyzer. From 10 to 15 angles were measured on each preparation. The results of these measurements allowed checking a correlation between the appropriate mechanical properties of wood and the average *MFA* for each timber sample.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Macrostructure of the tested wood is characterized by the data shown in Figure 3 and Table 1.

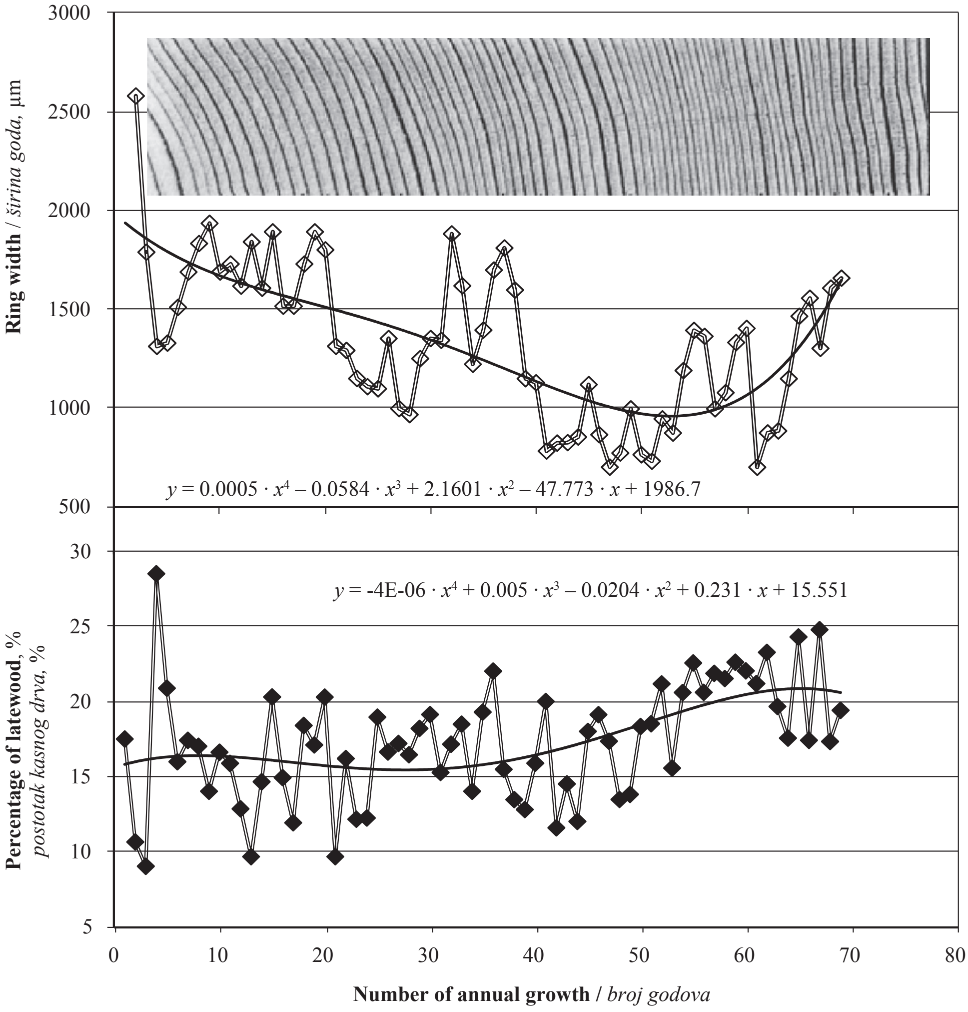

Figure 3 Changes in the width of annual rings and contribution of latewood in the rings (samples for measurements of wood density and mechanical parameters were sliced from the rings marked with points)
Slika 3. Promjene u širini godova i udio kasnog drva u godovima (uzorci za mjerenje gustoće drva i mehaničkih parametara izrađeni su od godova označenih točkama)

They show that the width of the annual rings (omitting the first ring and pith zone) ranged from 0.5 to 2 mm with average contribution of latewood of 17 %. In this respect, the wood meets the requirements of the industry standard (BN-85/9221-06). A certain disadvantage is the irregularity of the annual rings width; it undergoes a rapid decrease from ring 20 to 30 (counting from the edge of pith zone) relative to the width of preceding ones, and another decrease is noted for the rings 32 to 37, and a particularly pronounced decrease in width is observed for rings 40 to 52.

However, Spycher *et al*. (2008) claim that the quality of resonance spruce wood is more dependent on the latewood percentage contribution than on the ring width as in the narrow rings (less than 2.5 mm) no significant changes in the density of wood are noted. Nevertheless, these authors have observed a certain increase in the damping of sound propagation with increasing ring width. Analysis of the data in Figure 3 shows that the latewood percentage in rings from 20 to 30 is comparable to that in the preceding and subsequent rings. Taking into regard the claims of the above authors, it can be assumed that density of the wood with narrow and wide rings can be comparable as well. Nonetheless, the variation in macrostructural parameters of the wood studied is relatively high. Consequently, according to Spycher *et al*. (2008) and Buksnowitz (2006), this wood cannot be classified as a very good resonance material, even though it meets the requirements specified by standards.

Table 1 Macrostructural characteristics of the studied spruce wood
Tablica 1. Makrostrukturna obilježja istraživanog drva smrekovine

Examined property *Istraživano svojstvo*	**Basic statistical parameters** / *Osnovni statistički parametri*				
	min *min.*	average *sredina*	max *maks.*	Standard deviation *Standardna devijacija*	Coefficient of variation, % *Koeficijent varijacije, %*
Ring width, mm / *Širina goda, mm*	0.54	1.33	1.94	0.33	24.6
Percentage of latewood, % *Postotak kasnog drva*	8.9	17.3	27.8	3.9	22.5

Table 2 Density of earlywood and latewood of all examined rings
Tablica 2. Gustoća rana i kasnog drva istraživanih godova

Density, kg/m^3 *Gustoća*, kg/m^3	**Basic statistical parameters** / *Osnovni statistički parametri*		
	min – average – max *min. – srednje – maks.*	Standard deviation *Standardna devijacija*	Coefficient of variation, % *Koeficijent varijacije*, %
Earlywood / *Rano drvo*	175 - 240 - 342	46.9	19.5
Latewood / *Kasno drvo*	430 - 604 - 811	91.0	15.1

The macrostructural heterogeneity of the wood can be used only for initial qualification of its resonant properties. Definitely more important is the density of wood, which is a determinant of its elasticity. Thus, these two parameters are inextricably linked. Generally speaking, with the growth of wood density, its *MOE* increases as well (e.g. Kollmann and Côté, 1984; Gibson and Ashby, 1997). The wood density values obtained from measurements of 55 earlywood and 15 latewood samples, which were mostly broken in the middle of their length, are summarized in Table 2.

Border measurements of early and latewood are excluded. The table shows that the ratio of the average latewood density to average earlywood density is close to 2.5. The ratio of the maximum density of latewood to the minimum density of earlywood in the whole board exceeded 4.5 (811 kg/m^3 : 175 kg/m^3). Bearing in mind that wood density variation in resonance discs, even within a single annual growth, affects their vibration and determines the quality of the sound (Bucur, 1995; Yoshitaka *et al.*, 1997; Stoel and Borman, 2008; Spycher *et al.*, 2008; Schwarze *et al.*, 2008), the results confirm the above remark that the tested board cannot be classified as a suitable material for resonance purposes. It should be marked, however, that the masters of the violinmaking can reduce or even eliminate some faults in the material during the production process (Wegst, 2006). Buksnowitz *et al.* (2007) claim that luthiers can assess the resonance wood quality by its visible features, though such subjective prediction of acoustic quality is poor.

Density is not the only parameter that characterizes resonance wood quality. This parameter should be considered together with the modulus of elasticity (*MOE*/*ρ*). The higher the wood density is, the higher the *MOE* gets. However, as mentioned above, *MOE* is strongly related to the quality of the cell walls, so also to the arrangement of the formed microfibrils. The *MFA* variation within a single annual growth is relatively well known. *MFA* is claimed to be the largest in the elements produced in the early stages of tree growth (earlywood) and it decreases, sometimes quite significantly in the summer, when the latewood develops (Abe *et al*., 1992; Anagnost *et al*., 2002; Barnett and Bonham, 2004; Abe and Funada, 2005; Donaldson, 2008; Fabisiak *et al*., 2009). Their arrangement in the spruce wood (*Picea abies*) of Austrian origin differs from the general picture of the *MFA* variation in S2 layer of the cell wall. Reiterer *et al*. (1999) have shown that the *MFA* in the tangential walls of the early tracheids, between ring 17 and 37 (from the pith), is approximately 5 degrees, and in the walls of the late tracheids it is 20 degrees. In the rings up to 44, MFA were nearly the same in the early and latewood. Lichtenegger *et al*. (1999) presented similar research results. Analogous studies on the same species of wood, but of Swedish origin (Sahlberg *et al*., 1997), showed that the average *MFA* in the walls of the early and late tracheids is only about 1 degree higher. For comparable *MFA* in the tracheids from the walls of early and latewood, the specific modulus of elasticity (*MOE*/*ρ*), determined for samples cut from different places of annual growth, should be similar. From the perspective of homogeneity of wood tissue, such situation would be very beneficial. The changes in specific modulus of elasticity determined for annual rings across their width are illustrated in Figure 4.

This figure contains, for clarity, the data obtained from 8 rings only. The figures also show changes in the specific tensile strength along the grains. The data imply that both *MOE* and tensile strength along the grains are strongly influenced by the sample location in individual annual rings. In general, the parameters take the lowest values at the beginning of the earlywood zone. Then, they increase reaching a maximum in the latewood zone at a distance from the boundary with the next increment (ring 30, 37 and 62), or right at the boundary. The average values of these mechanical parameters, calculated separately for the early and latewood for all examined annual growth, are given in Table 3.

Table 3 Average values of specific tensile strength and specific modulus of elasticity along the grains in early and latewood
Tablica 3. Prosječne vrijednosti specifične vlačne čvrstoće i specifičnog modula elastičnosti uzduž vlakanaca ranoga i kasnog drva

Examined property *Istraživano svojstvo*	**Basic statistical parameters** / *Osnovni statistički parametri*		
	min – average – max *min. – srednje – maks.*	Standard deviation *Standardna devijacija*	Coefficient of variation, % *Koeficijent varijacije*, %
Specific tensile strength, kNm/kg *Specifična vlačna čvrstoća, kNm/kg*			
earlywood / *rano drvo*	41 - 150 - 285	52.8	35.2
latewood / *kasno drvo*	142 - 246 - 350	62.1	25.2
Specific modulus of elasticity, kNm/kg *Specifični modul elastičnosti, kNm/kg*			
earlywood / *rano drvo*	12 407 - 23 551 - 33 881	4 252	18.1
latewood / *kasno drvo*	18 547 - 32 516 - 42 947	5 898	18.1

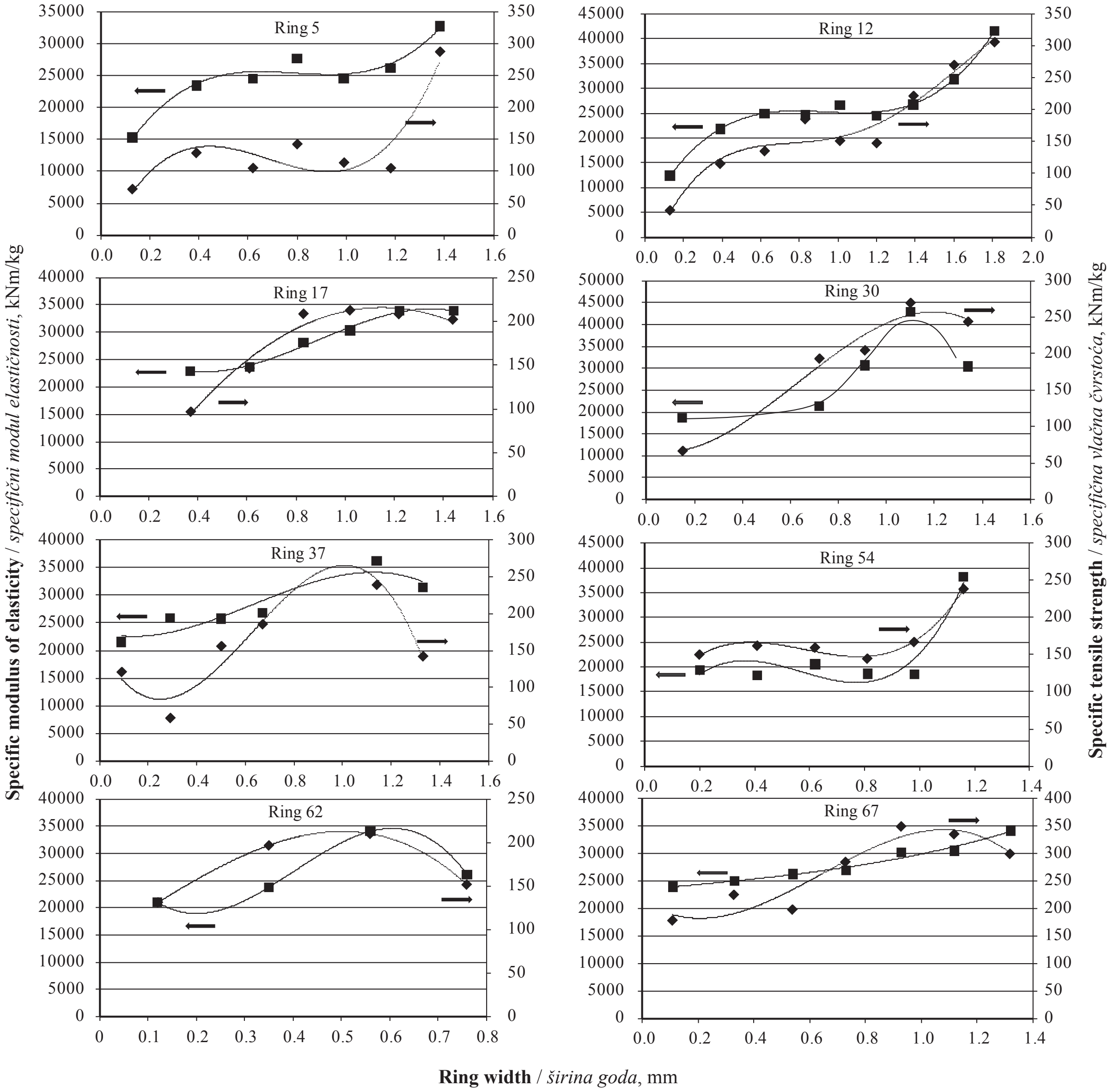

Figure 4 Specific modulus of elasticity and specific tensile strength along the grains in selected annual rings
Slika 4. Specifični modul elastičnosti i specifična vlačna čvrstoća uzduž vlakanaca u odabranim godovima

This table also gives the basic statistical parameters, similarly as that with the density of wood data. As fallows from the data, the average value of the relevant areas of modulus of elasticity for the earlywood zone (23-550 kNm/kg) is only 40 % lower than the corresponding figure for latewood (32-516 kNm/kg). This small variation is due to the fact that the earlywood zones included also the transition zone, as the classification of wood samples as early or latewood was made on the basis of their location in different rings and earlier measurements of the rings widths. Hence, such differences appear in the densities of these wood zones (Table 2). As to the specific tensile strength, the difference in its average values for early (150 kNm/kg) and latewood (246 kNm/kg) is much higher and exceeds 60 %. The difference in the parameters describing mechanical properties is related to the variation in *MFA* in the cell walls. Changes in the average *MFA* along the width of the selected annual rings are shown in Figure 5.

The average values of the *MFA* were very low (1.5 to 4.2°). However, the obtained *MFA* values correspond to the values reported by other authors (e.g. Lichtenegger *et al*., 1999; Gierlinger *et al*., 2010), who proved that the *MFA* in the spruce wood, especially in rings placed further from the pith, may be close to 0°. Bearing in mind that the correlations between *MFA* and modulus of elasticity and tensile strength are negative (Fig. 6), variations in these parameters within a single annual growth should be related to changes in *MFA* within the tracheids walls.

Based on the presented data, a relatively low coefficient of determination emerges probably due to the fact that the *MFA* measurements were made only in tangential cell walls. A similar conclusion was formulated by Roszyk *et al*. (2010a), who claimed that the trend in variation of the radial specific tensile strength and specific modulus of elasticity of a non-resonance spruce wood were a mirror image of the *MFA* changes in the coils walls of tracheids.

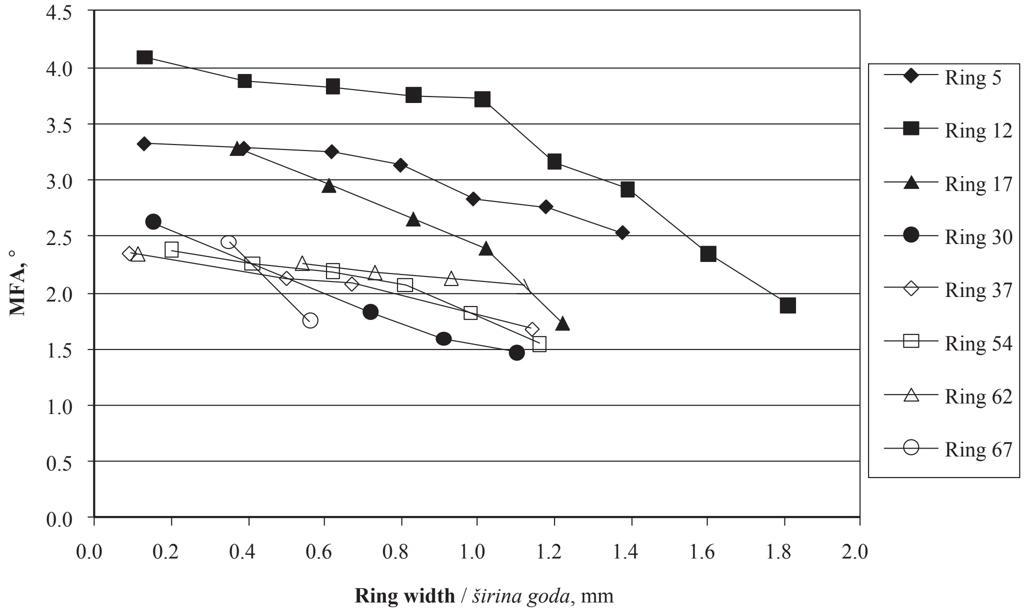

Figure 5 Changes in *MFA* values across the width of selected annual rings
Slika 5. Promjene vrijednosti *MFA* unutar širine goda u odabranim godovima

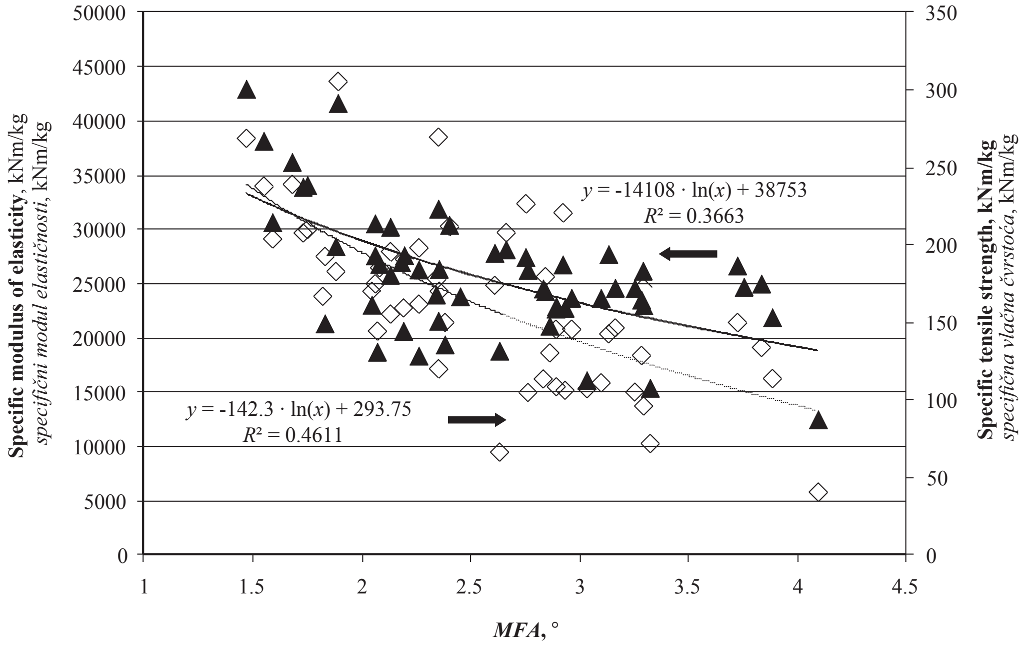

Figure 6 Correlation between *MFA* and specific modulus of elasticity and tensile strength along the grains
Slika 6. Korelacija između vrijednosti *MFA* i specifičnog modula elastičnosti te vrijednosti *MFA* i vlačne čvrstoće uzduž vlakanaca

4 CONCLUSIONS
4. ZAKLJUČCI

On the grounds of the variation in the specific modulus of elasticity and tensile strength in the resonance spruce wood [*Picea abies* (L.) Karst.] within a single annual growth, the following conclusions can be drawn.

Specific modulus of elasticity and specific tensile strength are strongly influenced by the sample position in the annual ring. Generally, the values of these parameters increase with the growth of annual rings.

The values of specific modulus of elasticity and specific tensile strength depend on the microfibril angle in S2 cell wall layer; these parameters increase with decreasing *MFA*.

Wood with similar characteristics as the plank tested cannot be classified as a high quality resonance wood because of its non-uniform character manifested as the variation in average *MFA* value of early and latewood.

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