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GRADIENT OF SELECTED MECHANICAL PROPERTIES WITHIN INDIVIDUAL ANNUAL RINGS IN THE RESONANCE SPRUCE WOOD (*PICEA ABIES* L.)

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ABSTRACT

Resonance spruce wood from Slovakia has been characterised as to the inhomogeneity of its macrostructure, density, mechanical strength and modulus of elasticity in selected annual rings. The widths of annual rings and widths of latewood in them were measured with the help of a computer image analyser. The density of wood at its moisture content 6-7 % was determined on microtome samples of the size 80x9x0.2 mm (LxTxR) subjected to tensile stress along the grains on a numerically controlled testing machine equipped with an extensometer. The profiles of wood density changes, its tensile strength and modulus of elasticity within individual annual rings depends on the annual ring width and the contribution of latewood in the ring. The increase in wood density in an individual annual ring from 200 (earlywood) do 800 (latewood) kg.m^{-3} corresponds to a 7-fold increase in the elasticity modulus and a 10-fold increase in the tensile strength.

KEYWORDS: Resonance wood, spruce wood, inhomogeneity indices.

INTRODUCTION

According to musicologists, variation in the density of wood in resonance boards, also within individual annual rings, influences the vibrations and determines the sound quality. These observations have been confirmed by the studies of Yoshitaka et al. (1997), showing that gradients in wood density following from changes in the width of annual rings and the contribution of latewood in the rings have a significant effect on the resonance properties of wood. Similar conclusions follow from the work of Spycher et al. (2008), who analysed correlations between the physical parameters of wood determining its usefulness for making musical instruments with its histological parameters. The paper by Schwarze et al. (2008) presents the parameters characterising resonance wood, including density, of spruce and sycamore wood subjected earlier to intended partial enzymatic destruction by the fungi (*Physiporinus vitrius* – spruce and *Xylaria longines* – sycamore). The partial enzymatic destruction resulted in decrease in the thickness of cell walls, especially of the thick-walled elements, which considerably reduced the wood density and slightly reduced the sound velocity. The controlled destruction of wood, without decomposition of the intercellular layer, endowed the wood, normally characterised with undesired damping of sound radiation, with features resembling those of the wood grown in the so-called Maunder Minimum (prolonged sunspot minimum). Because of low temperatures and shortened vegetation period, the wood that grew in these years was characterised by narrow annual rings and reduced gradient of density within individual annual rings, accompanied by high modulus of elasticity. These features are assumed to be responsible for the unique sound of the Stradivari violins, who used for their construction wood that grew in the Maunder Minimum period. This hypothesis is confirmed by the results of studies of Stoel and Borman (2008). These authors studied by computer tomography the violins built in the 18th century and in contemporary period and found that the average wood density of the resonance boards (top) and backs was similar but the variations in wood density in these elements was much greater in contemporary built than in the old instruments.

Tab. 1: Fundamental quantities characterising resonance properties of wood.

Quantity	Formula	Explanation
Sound propagation velocity, C	$C = \sqrt{\frac{MOE}{\rho}}$	MOE – modulus of elasticity ρ – density
Acoustic resistance, Z	$Z = C\rho = \rho\sqrt{\frac{MOE}{\rho}}$	
Damping of sound radiation, V	$V = \frac{C}{\rho} = \frac{\sqrt{\frac{MOE}{\rho}}}{\rho}$	
Acoustic constant (musical), K	$K = \sqrt{\frac{MOE}{\rho^3}}$	
Logarithmic decrement of damping, δ	$\delta = ln\frac{a_2}{a_1}$	a_1, a_2 – values of neighbouring amplitudes characterising internal damping of vibrations, determined by internal friction

Nagyvary et al. (2006) claim that this hypothesis is false. They studied fragments of violins from the 18th century and contemporary by infrared spectroscopy and discovered that the wood of which Stradivari built his violins contained the chemical compounds usually not found in wood.

They established an unusually high content of borax, fluorides, chromium and iron salts in the instruments from the 18th century, which was interpreted as introduced by the violin making masters with substances used to protect wood or to destroy the fungi or insects that may have been present in them. This modification might as well contribute to reduction of the wood density gradient and improvement of its mechanical properties.

The above literature data indicate that the gradient of wood density in resonance boards and within annual rings has a significant effect on the quality of musical instruments. Gradients of wood density are inextricably related to the gradients of its mechanical parameters, including the modulus of elasticity of wood. Wood density and modulus of elasticity determine all parameters characterising the suitability of wood for production of resonance boards. The fundamental quantities characterising the resonance properties of wood are given in Tab. 1.

The best resonance wood should be characterised by high modulus of elasticity and low density. Apparently these demands are mutually contradictory as the value modulus of elasticity of wood increases with its increasing density (Kollmann and Côté 1984). However, as follows from a number of literature reports, the wood density is not the only one determinant of its mechanical parameters. The mechanical parameters of wood have been found to depend on the quality of cell walls determined by the distribution of chemical compounds of structural importance, mainly cellulose in the form of microfibrils (Cave 1968, Bendtsen and Senft 1986, Walker and Woollons 1998, Moliński and Krauss 2008, Via et al. 2009, Krauss et al. 2011). Results concerning the radial variation in mechanical parameters of early wood from pine (Moliński and Krauss 2008) and spruce (Moliński et al. 2009) illustrate the above. These authors have established that the density of earlywood decreases with increasing cambial age of annual rings, while the mechanical parameters (mechanical strength and modulus of elasticity) increase. This, contrary to the commonly assumed, relation between the mechanical performance and density of wood is a result of the arrangement of microfibrils in the S_2 layer of secondary cell wall. With growing maturity of wood tissue, the inclination angle of microfibrils (MFA) towards the longitudinal axis of tracheids decreases. A negative correlation between the inclination angle of the cellulose helix and the mechanical parameters of wood (mechanical strength and modulus of elasticity) implies that this parameter has a dominant effect on the radial variation in mechanical parameters of earlywood.

Taking into regard the fact that inhomogeneity of wood has a significant effect on its acoustic parameters, this study was undertaken to characterise the resonance wood of spruce by determination of variation in its macrostructure, density, mechanical strength and modulus of elasticity within selected annual rings.

MATERIAL AND METHODS

The experimental material used in this study was a plank of spruce (*Picea abies* L.), wood cut out along the radius obtained from the Chair of Wood Science at the Technical University, in Zvolen (Slovakia). The plank was 50 cm long, 95 mm wide along the radius and 35 mm thick in tangent direction. It had linear fibres and annual rings of similar width. This material was classified as resonance wood and has been studied at the University in Slovakia, where the density of wood at 10 % moisture content was measured as 338 $kg.m^{-3}$ and the modulus of elasticity determined by the resonance method was 7.37 GPa. The acoustic constant calculated on the basis of these values (K) was 13.81 $m^4.kg^{-1}$.

The width of annual rings and the contribution of latewood in them and the variation in these parameters along the width of the rings determine the wood homogeneity and significantly determine its resonance properties. The width of individual annual rings and the width of the latewood zones in them were measured by a computer image analyser. The image of the wood sample was shown on a monitor by a camera and then with the help of MicroScan program the linear measurements of all annual rings were made to the accuracy of 0.001 mm. The measurements were made on a stripe of wood of about 5 mm in thickness cut off from the front of the plank. The moisture content was 7 %.

The other part of the plank was subjected to dressing to diminish its thickness in tangent direction to 9 mm. Then, from the region with linear course of annual rings two neighbouring sections were cut out, of 80 mm in length. From one of them a number of microtome samples were obtained, while the other was left as reserve. The part to be studied was cut along the fibres into 3 pieces and each of them was placed in distilled water for 2 weeks. As established in the preliminary attempts of its slicing, such a long wetting of wood allowed correct slicing of wood samples without the need of its preliminary heating. Then with the use of a microtome sledge, the tangentially oriented samples of about 200 μm in thickness were sliced. The sliced samples were placed on filtration tissue in the order of their slicing to permit the identification of their position in a given annual ring. A scheme of preparation of the microtome samples is shown in Fig. 1.

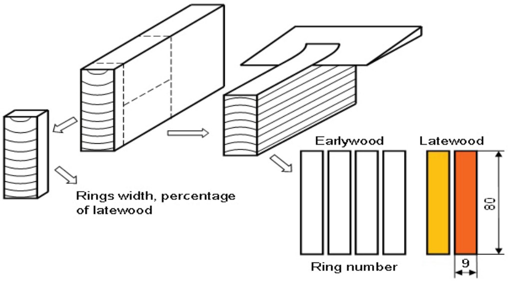

Fig. 1: Scheme of sample preparation for determination of the density gradient, tensile strength along the grain and modulus of elasticity within individual annual rings.

The microtome samples were conditioned in laboratory to ensure that they have equilibrium moisture content. Further measurements were made for the samples from 10 annual rings (2, 7, 9, 14, 23, 27, 34, 51, 59 and 64 counted from the edge closest to the pith). After mass stabilisation, at the middle of the length and at a distance of 2 cm from the middle of the length the widths of the sample were measured with a Brinell magnifying glass to the accuracy of 0.1 mm and the same sites the thickness of the sample was measured by a micrometer screw gauge to the accuracy of 0.001 mm, and length – by a rule to the accuracy of 1 mm. Each sample was weighted on a laboratory balance to the accuracy of 0.0001 g 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 the thickness of 3 mm with a 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 subsequent conditioning of the samples in laboratory they were subjected to tensile strength measurements on a testing machine ZWICK ZO50TH, equipped with an extensometer ZWICK 066550.02. The tensile stress was applied at the rate of 0.6 mm.min^{-1}, under the preliminary loading of 10 N and the extensometer base of 25 mm (Fig. 2).

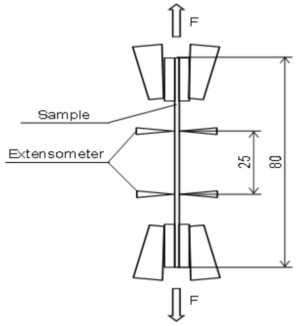

Fig. 2: Scheme of sample mounting in the jaws of the testing machine and tensile strength measurements.

After feeding the sample sizes to a computer, the software applied (Zwick testXpert Master) calculated their mechanical strength and static modulus of elasticity. The modulus was determined as a ratio of stress, in the range from initial value to the limit of proportionality, to the corresponding strain (Reiterer et al. 1999, Krauss et al. 2011). From each annual ring the measurements were made for a few samples of earlywood and 2 samples of latewood. As reliable results we assumed those for the samples that broke up in the middle of the length.

RESULTS AND DISCUSSION

The measured widths of annual rings and the contribution of latewood in them are presented in Fig. 3.

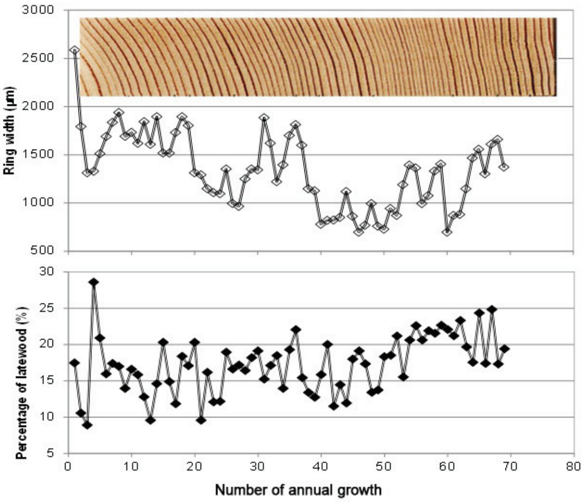

Fig. 3: Changes in the width of annual rings and contribution of latewood in the rings (samples for measurements of wood density and mechanical parameters were sliced from the rings marked with points).

The same figure also presents a scan of the front surface of the plank studied. The width of annual rings in the sample studied varied in a rather large range; from 2.6 mm in the first full ring to 0.55 mm in rings no. 46 and 60. The maximum difference in width was as much as 4.7 times. Apart from the first full annual ring measured, the greatest width of about 1.9 mm was measured for rings no. 8, 14, 18 and 31. Thus, the difference in width of the other widths was also high – 2.7 times. The mean value of ring with in the plank studied was 1.33 mm. The contribution of latewood in the annual rings slightly increased along the width of the plank studied, from 8.9 to 24.8 %, and the mean value for the whole plank was 17.3 %. The basic statistical data on the macrostructural parameters of the plank studied are given in Tab. 2, the data for the first annual ring were left out.

Comparison of these data with those reported by Spycher et al. (2008) obtained for the resonance spruce wood classified by violin-makers as good and very good, shows that the wood sample we studied can be evaluated at most as good resonance wood. The wood sample we studied was characterised by similar mean widths of annual ring and similar contributions of latewood, but the variation in these parameters was over twice greater than that in the work of Spycher et al. (2008).

Tab. 2: Macrostructural characterisation of the spruce wood sample studied.

Examined the property	**Basic statistical parameters**				
	Min.	**Average**	**Max.**	**Standard deviation**	**Coefficient of variation (%)**
Ring width (mm)	0.54	1.33	1.94	0.327	24.6
Percentage of latewood (%)	8.9	17.3	24.8	3.9	22.5

Exemplary profiles of changes in wood density, tensile strength and modulus of elasticity measured in individual annual rings are presented in Fig. 4.

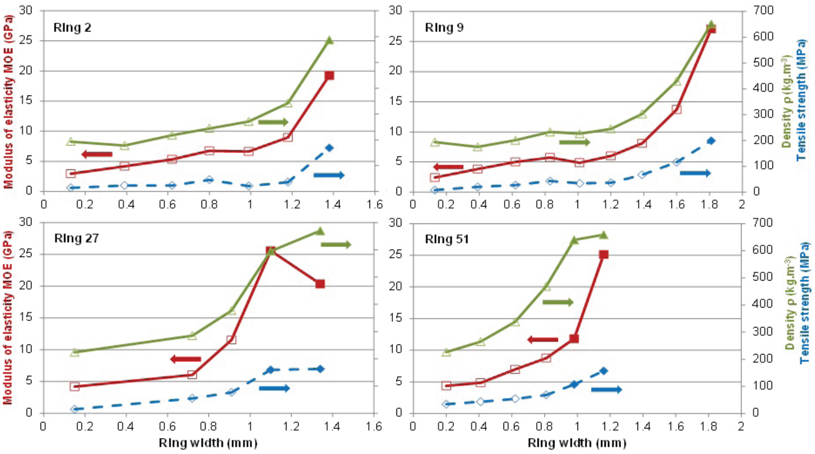

Fig. 4: Changes in the density, tensile strength and modulus of elasticity measured on a testing machine along the grains in selected annual rings.

Empty squares correspond to the data for earlywood, while filled ones – to latewood. As follows from the data presented in Fig. 4, the wood density and mechanical parameters measured increase with increasing distance of samples from the border of the previous ring. This effect is a result of changes in the size of the cells, mainly their lumens and cell walls (Zobel and van Buijtenen 1989). The profiles of changes in the parameters presented in Fig. 4 are closely related to the width of annual rings and the contribution of latewood in them. In wider rings and in those of a small percentage of latewood (rings no. 2 and 9) the changes in these parameters as a function of ring width are rather small in earlywood, increase in the transitional wood and reach the maximum values in the end of latewood.

The range of changes in these parameters determined for all 10 annual rings studied is illustrated by the data from Tab. 3.

Tab. 3: Variations in wood density, tensile strength along the grains and modulus of elasticity for early- and latewood in 10 selected annual rings studied.

Examined the property	**Basic statistical parameters**			
	Min.	**Average**	**Max.**	**Standard deviation (%)**
Density (kg.m^{-3})				
earlywood	175	240	342	46.9
latewood	430	604	811	91.0
Tensile strength (MPa)				
earlywood	12.0	36.7	77	16.8
latewood	53.0	128.2	211.0	45.5
Modulus of elasticity (GPa)				
earlywood	2.4	5.7	9.0	1.67
latewood	11.8	19.2	27.7	4.90

This table does not give the data obtained from measurements on samples from the border between the earlywood and latewood. The data from Tab. 3, concerning the earlywood, include also the results obtained for the samples from the so-called transition zone in the rings studied, but the results obtained for the samples from the border between the earlywood – transition zone and transition zone – latewood have been left out. In this paper the transition zone is not considered only to be able to assign directly the results of measurements to the macrostructural parameters of the wood taken into regard in evaluation of its suitability for production of resonance boards. The data given in Tab. 3 were collected from measurements of 55 samples of earlywood and 15 samples of latewood that upon the test broke up in the middle of their lengths. The mean density of earlywood was about 2.5 times smaller than that of latewood. The maximum density of earlywood was 4.5 times smaller than that of latewood (811/175). The mean tensile strength of latewood was about 3.5 times greater than that for earlywood. For the extreme values of tensile strength the ratio of the tensile strength of latewood to that of earlywood was over 17, (211/12). The ratio of the mean values of elasticity modulus of latewood to that of earlywood was 3.37, while for the extreme values it was 11.5 (27.7/2.4). The numbers illustrate high inhomogeneity of the wood studied, especially as regards the mechanical properties.

The inhomogeneity indices presented above refer to the whole plank studied. Tab. 4 presents values of the same parameters but for individual annual rings. As follows from these data, the wood inhomogeneity in density, tensile strength and elasticity modulus varies in individual annual rings. The greatest variation is observed in the tensile strength (the ratio of tensile strength in latewood to that of earlywood changes from about 2 in ring 59 to 10.8 in ring 27), less variation is noted in the elasticity modulus (the relevant ratio changes from about 2.5 in ring 59 to 8.7 in ring 9), and the lowest in wood density (the relevant ratio changes from 2.1 to 3.1).

As follows from the above data, the wood density is not the only determinant of its mechanical properties, which confirms the earlier observations (Raczkowski 1965, Zhang 1997, Cowdrey and Preston 1966 (after Cave and Walker 1994), Cave 1968, Walker and Woollons 1998, Bendtsen and Senft 1986). According to Roszyk et al. (2010) who studied spruce wood, the differences in wood density within individual rings of 2.7 times corresponds to 5-fold increase in the modulus of elasticity. The greater increase in wood tensile strength and modulus of elasticity than it would be implied by differences in density, indicates the significant effect of microfibril angle to the longitudinal cell axis, in particular in the section of the thickest S2 layer (MFA). Bendtsen and Senft (1986) as well as Cave and Walker (1994) claim that MFA is the main factor determining the stiffness and mechanical strength of wood in the longitudinal direction. Earlier Cave (1968) has shown that the stiffness of cell wall increases fivefold upon the mean MFA decrease from 40 to 10°. Via et al. (2009), who studied the influence of lignin and cellulose, MFA and sample position along the radius on mechanical strength parameters and stiffness of pine wood by IR spectroscopy and X-ray diffraction method, reported a fourfold increase in wood stiffness accompanying MFA decrease from 40 to 5°.

Tab. 4: Heterogeneity indices characterising wood density, tensile strength and modulus of elasticity of the resonance spruce wood studied.

The tested growth	**Inhomogeneity indices**		
	Density wood (ρ_{lw}/ρ_{ew})	**Tensile strength (TS_{lw}/TS_{ew})**	**Modulus of elasticity (MOE_{lw}/MOE_{ew})**
2	2.99	8.45	4.63
7	2.07	2.41	4.47
9	3.42	10.64	8.70
14	2.89	4.55	4.05
23	2.47	8.29	3.18
27	2.83	10.84	4.85
34	3.10	3.88	3.96
51	2.66	4.08	5.45
59	2.16	1.97	2.50
64	2.93	3.87	3.81
Average	**2.75**	**5.90**	**4.56**
Standard deviation	0.42	3.33	1.68

Much greater increase in the parameters of mechanical strength than it would follow from the changes in density is also apparent from the plots in Fig. 5, showing the tensile strength along the grains versus the modulus of elasticity for the samples studied. Assuming that these data can be well approximated by the power functions it can be estimated that an increase in wood density from 200 to 800 kg.m^{-3} corresponds to a tenfold increase in the tensile strength along the grains (on average 23.5 to 246 MPa). The same increase in wood density (from 200 to 800 kg.m^{-3}) gives an over sevenfold increase in the modulus of elasticity. Slightly smaller effect of wood density on the modulus of elasticity than on the mechanical strength suggests that the modulus of elasticity is to a lower degree dependent on MFA, which is consistent with the observations of Via et al. (2009).

Despite certain differences in the influence of wood density on MOE and TS, the correlation between the two latter parameters is linear (Fig. 6).

For the earlywood density of 215 kg.m^{-3}, and that of latewood of 590 kg.m^{-3} and the corresponding to them values of modulus of elasticity of 4.82 and 24.19 GPa, the damping of sound radiation was calculated for the two zones separately. Results of these calculations are presented in Tab. 5, which also includes the sound velocity (C) calculated according to the formulae given in Tab. 1.

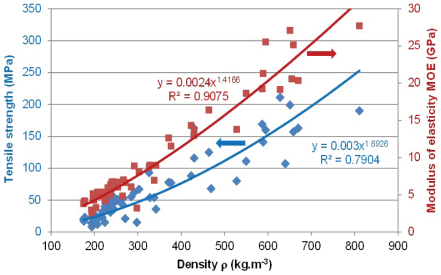

Fig. 5: Tensile strength along the grains versus the modulus of elasticity in the sample.

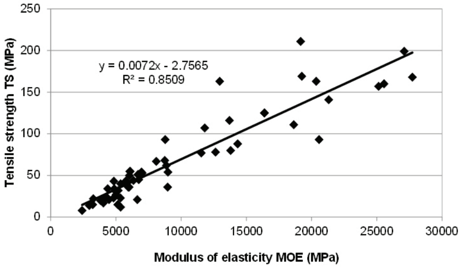

Fig. 6: Tensile strength of the samples measured versus their modulus of elasticity.

Tab. 5: The sound velocity along the grains and damping of sound radiation for the assumed densities of early- and latewood.

Zone of wood	Density (kg.m^{-3})	Modulus of elasticity (GPa)	Sound velocity along the grains (m.s^{-1})	Damping of sound radiation (m^4.kg^{-1}. s^{-1})
Earlywood	215	4.82	4736	22.08
Latewood	590	24.19	6403	10.85

On the basis of the modulus of elasticity values obtained for early- and latewood, taking into regard the law of reciprocal proportions and the average contribution of early- and latewood in a plank studied, the mean modulus of elasticity for the bulk wood was calculated as:

$$\text{MOE} = 4.82 \text{ GPa} \times 0.827 + 24.19 \text{ GPa} \times 0.173 = 3.99 \text{ GPa} + 4.18 \text{ GPa} = 8.17 \text{ GPa}$$

This value is close to that determined at the Chair of Wood Science, University of Technology, Zvolen (7.37 GPa). The fact that the value determined in our study is by 11 % higher can be explained by a slightly greater moisture content of wood when it was in Zvolen (10 %) than that the sample had at our laboratory (6-7 %).

CONCLUSIONS

Analysis of the results obtained in our studies has permitted drawing the following conclusions:

1. The profiles of changes in wood density, tensile strength and modulus of elasticity within individual annual rings are determined by the rings' widths and the contribution of latewood in them.
2. The variations in the heterogeneity index characterising tensile strength in individual annual rings was 2-11, in the modulus of elasticity it was 2.5-8.7, and in density – 2-3. Thus, an increase in wood density within individual ring from 200 (earlywood) to 800 (latewood) kg.m^{-3} corresponds to a 7-fold increase in the modulus of elasticity and 10-fold increase in the tensile strength along the grains.

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