THE TYPE AND DEGREE OF DECAY IN SPRUCE WOOD ANALYZED BY THE ULTRASONIC METHOD IN THREE ANATOMICAL DIRECTIONS

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Norway spruce specimens 50x30x30mm with initially determined ultrasonic characteristics in the longitudinal, radial, and tangential directions were subjected to bio-attacks with the brown-rot fungi *Serpula lacrymans, Coniophora puteana*, or *Gloeophyllum trabeum*, and the white-rot fungus *Trametes versicolor*, respectively. Bio-attacks lasted 4, 8, 12, or 16 weeks. Decreases of the ultrasonic wave velocities (Δc) and the dynamic modulus of elasticity (ΔMOE_d) depended more or less closely on the enlarged degrees of rot in the spruce wood, and as the dynamic modulus of elasticity decreased approx. 1.7 to 2.3 times more than corresponding weights (Δm from 2.01 to 42.35%) or 2.1-3.4 times more than corresponding densities ($\Delta \rho$ from 2.42 to 26.63%). Two sample t-test analyses of slopes "*a*" in the linear regressions Δc *or* $\Delta MOE_d = a.(\Delta m)$ *or* $a.(\Delta \rho)$ showed that drops of the ultrasonic and elastic characteristics of wood having the brown rot were not influenced by the fungus species. On the other hand, the velocity of ultrasonic waves in the longitudinal direction and the dynamic modulus of elasticity appeared to be suitable for distinguishing the brown rot from the white rot at known decreases of wood density. The anatomical direction of wood was a significant factor only for the white rot, when approx. 2-times higher decrease of the ultrasonic wave velocities was determined in the radial and tangential directions compared to the longitudinal one.

Keywords: Anatomical directions; Brown-rot; Modulus of elasticity; Spruce; Ultrasonic tests; White-rot

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INTRODUCTION

Fungal rots, insect galleries, reaction wood, cracks, chemical corrosions, and some other damages in wooden structures can usually be established visually. However, some of them remain more or less hidden. For their detection and for determination of their degree and extent there are various convenient instrumental techniques, including destructive (DT), semi-destructive (SDT), or non-destructive (NDT) ones (Adam et al. 2010). When analyzing defects in standing trees, logs, poles, built-in materials – e.g. beams in wooden roofs, ceilings, log-cabins, bridges, etc., the NDTs such as ultrasonic or other acoustic diagnoses, e.g. sonic velocity, modal frequency, amplitude, damping, or travelling time of sound in wood, have become common in wood testing (Arita et al. 1986; Sandoz and Lorin 1994; Bucur 1995; Raczkowski et al. 1999; Sandoz et al. 2000;

Pellerin and Ross 2002; Huang et al. 2003; Wang et al. 2004; Dzbeński and Wiktorski 2009; Reinprecht 2009; da Costa et al. 2010; Roohnia 2011). In general, ultrasonic and other acoustic tests are simpler, quicker, and cheaper than other NDT tests, e.g. X-ray digital scanning and other radiographic, microwave, thermographic, molecular, or computer-tomographic ones (Unger et al. 2001). By the ultrasonic or frequency measurements it is well possible to detect the location of failures (Morrell and Rhatigan 2002; Machek and Militz 2004; Reinprecht and Vidholdová 2007; Roohnia 2011) and also their degree (Marčok et al. 1997; Faraji et al. 2004). For example, according to Pellerin and Ross (2002), a 30% decrease in the velocity of ultrasonic waves indicates severely decayed wood with an approximately 50% loss in strength. These authors also reported that ultrasonic measurements are better for finding non-homogenous decay in wooden beams in the transversal directions compared to the longitudinal one, because parallel-to-grain travel paths of waves can bypass regions of decay.

In practice, the ultrasonic characteristics, e.g. the velocity of the ultrasonic waves along fibres ($c_{||}$) or perpendicularly to fibres ($c_{\perp}$) and the calculated dynamic modulus of elasticity ($MOE_d = c_{||}^2.\rho$) at a known density (ρ), are often used to evaluate the presence, extent, and degree of various bio-defects in wood. For these objectives, the ultrasonic analysis can be used – for standardized laboratory and field tests to assess the durability of wood or the efficiency of biocides (Grinda and Goller 2005) – to evaluate practically fungal rot and insect attacks in wooden products and structures (Reinprecht and Hrivnák 2010). However, despite the advantages listed above, the ultrasonic method usually gives insufficient information about the type of wood damage; i.e. it is usually a less sensitive test for determination of the exact type of rot, insect gallery, or other type of damage.

Results obtained from ultrasonic measurements often depend also on environmental and measuring factors, e.g. on the moisture and temperature of wood (Sakai et al. 1990; Pellerin and Ross 2002; Larnoy et al. 2006), on the anatomical direction of ultrasound signal transmission in damaged wood (Kotlínová et al. 2010), or on the chemical structure of lignin and other polymers in cell walls of wood (Horvath et al. 2010a). Generally, the ultrasonic and other acoustic tests of the sound and decayed wood elements can be influenced mainly by the following factors: frequency level, where transducers with a frequency of about 100-200 kHz are usually used (Beall 2002); orientation of annual rings in wood (Pellerin and Ross 2002); reaction wood (Saadat-Nia et al. 2011); genetic group of wood species, e.g. with different lignin content or its ratio syringyl/guaiacyl (Horvath et al. 2010a, 2010b); moisture contents of wood below and above the fibre saturation point (Wang et al. 2002; Larnoy et al. 2006; Nicholas et al. 2009; Hasegawa et al. 2011); the presence of biocides and other preservatives in wood (Pellerin and Ross 2002; Machek et al. 2004; Alfredsen et al. 2006; Larnoy et al. 2006); the type of rot (Faraji et al. 2004); and the location of rot or other failures in wood (Morrell and Rhatigan 2002; Machek and Militz 2004; Reinprecht and Vidholdová 2007).

The aim of this study was to analyze the impact of different types and degrees of brown and white rots in the Norway spruce wood in laboratory tests (with the assumption that when using these tests a quite homogenous rot in the whole volume of the specimens can be achieved) on its ultrasonic characteristics measured strictly in three anatomical directions – longitudinal, radial, or tangential – and also on its dynamic modulus of elasticity.

EXPERIMENTAL

Materials

160 sound Norway spruce (*Picea abies* Karst. L.) specimens with a dimension of 50 mm x 30 mm x 30 mm (longitudinal x radial x tangential) were prepared and selected from five conditioned boards (containing both sap-wood and heart-wood) 1200 mm x 100 mm x 36 mm. From each board we prepared 60 specimens, and then 32 of the best ones without knots, cracks, etc. were selected for experiments. For each type of fungal attack (16 attacks = 4 fungi x 4 times) two specimens from each board were used, i.e. totally 10 specimens. These original sound specimens were without fungal rots, insect galleries, cracks, knots, or other inhomogeneities. Their densities (ρ) at a moisture content level of 12 ± 1% (after conditioning at 20°C/RH65%/4weeks) varied in the range from 398 to 559 $kg.m^{-3}$. Ultrasonic analyses were carried out before and after subjecting the spruce specimens to fungal attacks.

Fungal Attacks of Spruce Specimens with Wood-Destroying Fungi

The fungal attack of the spruce specimens into various stages of rot was performed with one of the following brown-rot fungi: *Serpula lacrymans* (Wulfen) J. Schröt, *Coniophora puteana* (Schumach.) P. Karst., *Gloeophyllum trabeum* (Persoon) Murrill., or with the white-rot fungus *Trametes versicolor* (L.) Pilát.

Firstly, original sound spruce specimens with known densities and ultrasonic characteristics at approximate moisture of 12% were dried and sterilized during 8 hours at a temperature of 103 ± 2ºC, and then cooled in desiccators and weighed in a sterile laboratory room in the oven-dry state with an accuracy of 0.001 g (m_0).

Next, the bio-attack of specimens with rotting fungi was started. Specimens were conditioned 1 week in sterile desiccators above a water solution of NaCl (20°C, RH 76%), then dipped in sterilized distilled water for 15 minutes with the aim to achieve their moisture above 20-30%, and then placed in 1-litre Kolle's flasks containing malt-agar soil in which a mycelium of the testing fungus had already expanded. Incubation of the individual series of spruce specimens in climatic chamber lasted 4, 8, 12, or 16 weeks at a temperature of 22°C and at a relative humidity of 80 ± 3%. After incubation, the specimens were taken out of the Kolle's flasks, cleaned free of the fungal mycelia, and subjected to the two-phase drying process using air seasoning 20-25°C/RH60-70%/100h and then kiln-seasoning 60°C/1h, 80°C/1h and 103±2°C/8h (Reinprecht et al. 2007) into the oven-dry state ($m_{0\text{-decayed}}$), with the aim to suppress creation of cracks.

Decayed specimens with determined weight losses were conditioned 4 weeks with the aim of achieving moisture content levels of approx. 12% (moistures were from 12 ± 1% at small degrees of rot to 9% at high degrees of brown rot). Then their dimensions with an accuracy of 1 mm, densities (ρ_{decayed}), and ultrasonic characteristics were measured. The actual volumes of decayed specimens, used for calculation of their densities (ρ_{decayed} = [weight at a moisture of 12% with an accuracy of 0.00001 kg] / [volume at a moisture of 12% with an accuracy of 0.0000001 m^3]), were determined by the volumetric method (it is suitable for decayed specimens with deformations or cracks), i.e. by their short immersion into a graduated cylinder with toluene for approx. 5 seconds.

The weight losses (Δm) and density decreases ($\Delta \rho$) of the decayed spruce specimens were evaluated with Equations (1) and (2):

$$\Delta m = [(m_0 - m_{0-decayed}) / m_0].100 \qquad [\%] \qquad (1)$$

$$\Delta \rho = [(\rho - \rho_{decayed}) / \rho].100 \qquad [\%] \qquad (2)$$

Ultrasonic Measurements

Each spruce specimen with an approx. moisture content of 12% was subjected to ultrasonic analyzes before and after fungal attack. The velocities of ultrasonic waves (UW) in the sound specimens (c) and in the decayed ones ($c_{decayed}$) were measured by a Pundit-plus device (CNS FARNELL Limited, England) at 150 kHz frequency using transducers of 25 mm in a diameter (Fig. 1). The set up parameter was the dimension of the specimen in millimeters in a direction of its ultrasonic measurement (i.e., in the longitudinal, radial, or tangential). Output of the ultrasonic measurements was in meters per seconds [m/s]. On the opposite surfaces of specimens the ultra-phonic conductivity gel "Aquagel C" was used, and also the out-side pressure was approx. 0.1 MPa (Fig. 1) with the aim of improving the contact between the transducers and the test timber. The UW measurements were made at a temperature of 20°C and a relative humidity of 65% in three anatomical directions, i.e. in the longitudinal (L $\Rightarrow c_{\parallel}$), radial (R $\Rightarrow c_{\perp R}$), and tangential (T $\Rightarrow c_{\perp T}$), on the same places indicated before decay.

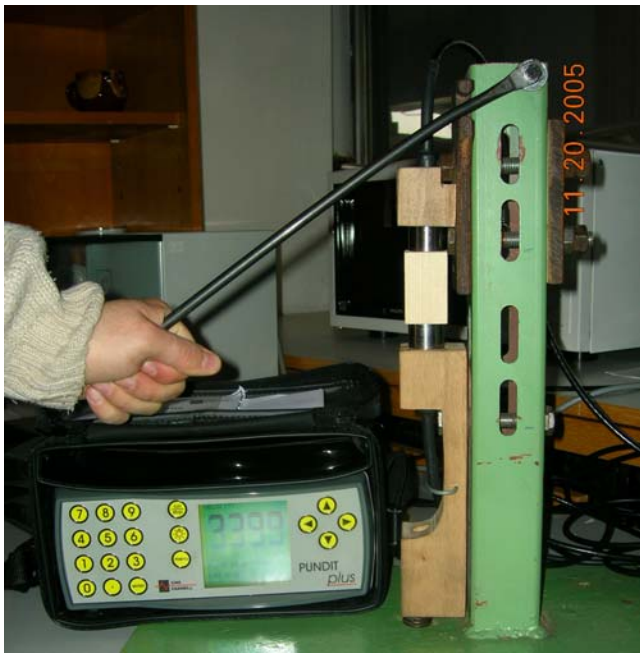

Fig. 1. Measurement of the UW velocity in the longitudinal direction of a spruce specimen using constant pressure on the transducers mounted in a wooden-metal stand

It should be noted that a constant pressure (approx. 0.1 MPa) was created on the transducers, and then this also was achieved on the spruce specimen in the wooden-metal stand by using the hand lever, i.e. by making sure that the deformation of the compressive spring at the bottom of a wooden-metal stand was constant.

The percentage decrease of the UW velocity through the decayed specimen (Δc) was calculated separately for each direction (i.e. for L, R, and T) using Equation (3):

$$\Delta c = [(c - c_{decayed}) / c].100 \qquad [\%] \tag{3}$$

In total, 960 measurements (1 shape of the specimen; 3 anatomical directions; 4 species of the rotting fungi; 4 times of rotting; 10 replicates in one test group; 2 healthy conditions of the specimen → sound before rotting and decayed after rotting) of the velocity of UW were carried out in the experiment.

Calculation of the Dynamic Modulus of Elasticity

Values of the dynamic moduli of elasticity for the sound (MOE_d) and decayed ($MOE_{d\text{-}decayed}$) spruce specimens, with known densities (ρ or $\rho_{decayed}$ [kg.m^{-3}]) and UW velocities in the longitudinal direction ($c_{\|}$ or $c_{decayed\|}$ [m.s^{-1}]), were calculated from the fundamental Christoffel's equation (Horvath et al. 2010b), i.e. by Equations (4a and 4b):

$$MOE_d = \rho . c_{\|}^2 \tag{4a}$$

$$MOE_{d-decayed} = \rho_{decayed} . c_{decayed\|}^2 \tag{4b}$$

The percentage decreases of the dynamic modulus of elasticity of the decayed spruce specimens (ΔMOE_d) were evaluated with Equation (5):

$$\Delta MOE_d = [(MOE_d - MOE_{d-decayed}) / MOE_d].100 \tag{5}$$

Data Analysis

Basic statistical analyses of the weight losses, density decreases, ultrasonic wave velocity changes, and dynamic modulus of elasticity changes of the decayed spruce wood were evaluated using the software STATISTICA 7.

Relations between the percentage changes of the ultrasonic wave velocities or the dynamic modulus of elasticity "Δy" and the higher degrees of rot "Δx" (expressed by the weight losses or density decreases) were studied by linear regression analysis ($y = a.x$) using the software STATISTICA 7. For comparison of two slopes "a" in the linear equations, the two-sample t-test for two independent slopes was used with help the software EXCEL 2003, applying Equation (6) by Andel (1985):

$$t = \frac{a_1 - a_2}{\sqrt{(SE_1^2 + SE_2^2)}} \tag{6}$$

where: a_1 – slope in the linear equation 1, a_2 – slope in the linear equation 2, SE_1 – standard error of the slope of equation 1, SE_2 – standard error of the slope of equation 2.

RESULTS AND DISCUSSION

Weight Losses and Density Decreases Caused by Rotting Fungi

The weight losses (Δm) of the spruce specimens were observed to increase proportionally with the time of bio-attacks lasting from 4 to 16 weeks (Table 1). For individual specimens the values of Δm ranged from 2.01 to 42.35% (Table 2, Fig. 2). The enzymatic activity of all used rotting fungi was sufficient, when after 16 weeks of rotting the mean weight losses of specimens were above 20% (Table 1). However, the aggressiveness of the brown-rot fungi *G. trabeum* and *C. puteana* was sometimes higher in comparison with the brown-rot fungus *S. lacrymans* or the white-rot fungus *T. versicolor* (Tables 1, 2, and 3).

The density decreases ($\Delta\rho$) of spruce specimens biodegraded with the brown rot were approximately 2-times smaller than their weight losses (Tables 1, and 3). On the other hand, a notable drop of their densities was caused by the white-rot fungus *T. versicolor*, when the density decreases were similar with the weight losses. For individual specimens the values of $\Delta\rho$ ranged from 2.42 to 26.63% (Table 3, Fig. 2).

Velocity of Ultrasonic Waves in 3 Anatomical Directions of Rotten Spruce

The ultrasonic waves (UW) spread significantly more slowly through the decayed spruce specimens than through the sound ones (Tables 1, 2, and 3). Average values of the UW velocities determined for 16 selected groups of the sound specimens with 10 replicates in each group (Table 1: $c_{\parallel}$ = from 4510 to 5180 m.s^{-1}; $c_{\perp R}$ = from 1490 to 1810 m.s^{-1}; $c_{\perp T}$ = from 1010 to 1570 m.s^{-1}) were in the same range with those reported by other researchers (e.g. Marčok et al. 1997; Pellerin and Ross 2002; Wang and Ross 2002; Kloiber and Bláha 2005).

UW velocities in the decayed spruce wood decreased proportionally with an extension of decay time, i.e. with increased degrees of rot defined for specimens on the basis of higher weight losses Δm and density decreases $\Delta\rho$ (Tables 1, 2, and 3). This trend was observed in all anatomical directions, i.e. for $\Delta c_{\parallel}$, $\Delta c_{\perp R}$, and $\Delta c_{\perp T}$.

After enzymatic attack with the brown-rot fungi *S. lacrymans*, *C. puteana*, or *G. trabeum* on the spruce specimens, the percentage decrease of UW velocities (Δc) was comparable in all three anatomical directions – longitudinal (L), radial (R), and tangential (T) (see Tables 1, 2, and 3). The velocity (Δc) decreases represented a 0.8 to 1.0 multiple of the weight losses (Δm) (Table 2), or a 1.4 to 1.8 multiple of the density decreases ($\Delta\rho$) (Table 3). By highlighting the linear regressions between the measured variables for the brown rots ($\Delta c = a.\Delta m$; and $\Delta c = a.\Delta\rho$), there were more or less strong relationships observed between the UW velocity retardation and the higher degrees of rot (see the coefficients of determination in the Tables 2 and 3: R^2 = from 0.215 to 0.386 – very weak relation; R^2 = from 0.408 to 0.536 – weak relation; R^2 = from 0.693 to 0.722 – moderate relation).

Table 1. Basic Ultrasonic and Structural Characteristics of the Norway Spruce Specimens Before and After Fungal Attacks Lasting 4-16 weeks and Their Percentage Change Decreases after Decay

Property of spruce	**Fungal attack (weeks)**															
	Serpula lacrymans				*Coniophora puteana*				*Gloeophyllum trabeum*				*Trametes versicolor*			
	4	8	12	16	4	8	12	16	4	8	12	16	4	8	12	16
Before decay																
$c_{\parallel}$ (km.s^{-1})	5.05	5.18	5.14	5.10	4.76	4.86	4.77	4.84	4.89	4.92	4.85	4.79	4.55	4.51	4.61	4.63
$c_{\perp R}$ (km.s^{-1})	1.51	1.68	1.60	1.68	1.55	1.80	1.74	1.81	1.70	1.67	1.50	1.49	1.75	1.78	1.71	1.78
$c_{\perp T}$ (km.s^{-1})	1.05	1.12	1.11	1.20	1.03	1.19	1.23	1.17	1.01	1.14	1.15	1.16	1.26	1.29	1.15	1.57
MOE$_d$ (GPa)	12.5	13.1	12.9	12.7	11.4	12.0	11.7	11.4	11.7	12.1	11.4	11.3	10.1	10.0	10.4	10.7
After decay																
$c_{d\parallel}$ (km.s^{-1})	4.60	4.42	4.09	4.01	4.51	4.08	4.06	3.67	4.52	4.00	3.41	3.13	4.34	4.18	4.10	3.47
$c_{d\perp R}$ (km.s^{-1})	1.42	1.44	1.31	1.29	1.44	1.50	1.32	1.29	1.56	1.34	1.18	0.97	1.62	1.57	1.36	1.29
$c_{d\perp T}$ (km.s^{-1})	0.99	0.91	0.89	0.96	0.93	0.99	0.96	0.87	0.91	0.92	0.89	0.84	1.11	1.11	0.94	0.96
MOE$_{d\text{-decayed}}$ (GPa)	9.9	8.4	7.2	6.7	9.6	7.7	7.5	5.5	9.5	7.1	4.8	3.9	8.6	7.8	7.1	7.1
Decrease after decay (%)																
Δm	4.8	13.2	17.9	22.7	9.6	18.3	23.0	27.4	8.3	22.3	27.8	36.5	5.3	9.8	14.9	25.5
	(1.2)	(2.3)	(2.7)	(3.1)	(2.6)	(2.1)	(2.5)	(3.9)	(1.5)	(2.0)	(2.5)	(4.3)	(2.0)	(1.2)	(3.2)	(-)
$\Delta\rho$	4.6	11.3	12.3	14.9	6.5	9.2	11.2	15.4	5.9	11.7	14.6	19.9	6.6	9.7	14.3	24.6
	(1.8)	(1.4)	(2.3)	(1.8)	(2.0)	(1.1)	(1.6)	(3.0)	(0.6)	(2.4)	(2.3)	(3.8)	(1.4)	(0.9)	(3.4)	(-)
$\Delta c_{\parallel}$	8.6	14.7	20.3	21.3	5.3	15.9	14.8	24.0	7.4	18.6	29.5	34.1	4.6	7.2	10.8	25.0
	(3.1)	(3.7)	(5.6)	(4.8)	(4.8)	(4.1)	(5.1)	(5.2)	(4.5)	(5.5)	(3.7)	(7.3)	(3.8)	(3.7)	(7.8)	(-)
$\Delta c_{\perp R}$	6.1	15.4	17.3	23.0	7.4	16.8	24.0	28.1	8.1	19.2	20.9	34.8	7.5	11.7	19.9	27.6
	(3.4)	(5.2)	(6.3)	(8.7)	(3.8)	(9.2)	(8.0)	(6.3)	(7.2)	(11.4)	(6.4)	(12.1)	(5.9)	(7.2)	(6.5)	(-)
$\Delta c_{\perp T}$	5.4	17.8	19.6	19.4	10.5	16.9	20.9	24.6	10.0	18.6	22.0	27.0	10.9	13.8	18.0	38.7
	(4.1)	(4.7)	(4.5)	(8.7)	(5.6)	(6.9)	(7.5)	(7.3)	(5.1)	(4.1)	(7.3)	(10.0)	(8.3)	(11.1)	(8.7)	(-)
ΔMOE$_d$	20.0	35.2	43.8	47.1	15.9	35.6	35.3	50.9	19.1	41.1	57.5	64.7	14.9	22.2	31.3	33.3
	(6.3)	(7.0)	(4.2)	(6.7)	(9.1)	(6.1)	(8.4)	(7.0)	(7.8)	(8.7)	(4.8)	(13.4)	(6.9)	(6.1)	(12.5)	(-)

Notes:

- Results are presented as arithmetic mean values of 10 replicates, respectively for the *T. versicolor* at the 16 weeks of decay only of 1 replicate (see also Tables 2, 3, and 4)
- Standard deviations are shown in parentheses

After action of the white-rot fungus *T. versicolor*, the drop of UW velocities in the decayed spruce specimens was higher in the transversal directions – radial and tangential ($\Delta c_{\perp}$ = approx. 1.3 multiple of Δm or $\Delta\rho$) – than in the longitudinal one ($\Delta c_{\parallel}$ = approx. 0.76 multiple of Δm or $\Delta\rho$). However, for the white rot only weak linear relationships between the retardation of UW propagation and the higher degrees of rot were found, with small coefficients of determination R^2 from 0.133 to 0.297 (see Tables 2 and 3). Volumes of the decayed spruce specimens with a typical erosive white rot changed minimally compared with the original sound ones. On this basis, the velocity decreases Δc could be reduced similarly in relation to weight losses Δm, and also in relation to density decreases $\Delta\rho$ (Tables 2 and 3).

Table 2. Linear Relationships between the UW Velocity Decreases (Δc) and the Weight Losses (Δm) for Spruce Wood Attacked by Selected Rotting Fungi *S. lacrymans, C. puteana, G. trabeum,* or *T. versicolor* during 4-16 weeks, and Statistical Analysis of these Relationships

Linear equations $\Delta c = a.\Delta m$		**Two sample t-test for slopes "a" (TSTT)** *S. lacrymans*	*C. puteana*	*G. trabeum*	*T. versicolor*
Serpula lacrymans					
(Δm = from 3.48 to 28.62 %; n = 40)					
$\Delta c_{\parallel}$ = 1.038 . Δm	R^2 = 0.454	-	3.949***	1.500	2.751**
$\Delta c_{\perp R}$ = 1.010 . Δm	R^2 = 0.453	-	0.344	1.485	1.454
$\Delta c_{\perp T}$ = 0.989 . Δm	R^2 = 0.348	-	0.979	2.548*	1.989
Coniophora puteana					
(Δm = from 5.65 to 35.86 %; n = 40)					
$\Delta c_{\parallel}$ = 0.775 . Δm	R^2 = 0.536	3.949***	-	2.930**	0.152
$\Delta c_{\perp R}$ = 0.978 . Δm	R^2 = 0.386	0.344	-	1.109	1.646
$\Delta c_{\perp T}$ = 0.902 . Δm	R^2 = 0.274	0.979	-	1.677	2.583*
Gloeophyllum trabeum					
(Δm = from 5.66 to 42.35 %; n = 40)					
$\Delta c_{\parallel}$ = 0.943 . Δm	R^2 = 0.722	1.500	2.930**	-	1.919
$\Delta c_{\perp R}$ = 0.879 . Δm	R^2 = 0.494	1.485	1.109	-	2.292*
$\Delta c_{\perp T}$ = 0.781 . Δm	R^2 = 0.408	2.548*	1.677	-	3.414**
Trametes versicolor					
(Δm = from 2.01 to 25.46 %; n = 31)					
$\Delta c_{\parallel}$ = 0.760 . Δm	R^2 = 0.297	2.751**	0.152	1.919	-
$\Delta c_{\perp R}$ = 1.248 . Δm	R^2 = 0.149	1.454	1.646	2.292*	-
$\Delta c_{\perp T}$ = 1.318 . Δm	R^2 = 0.189	1.989	2.583*	3.414**	-

Note: Two sample t-test (TSTT) analysis for slopes "*a*" in the linear equations, evaluated on significance levels of α = 95 % (* TSTT $\geq$ 2.021), α = 99 % (** TSTT $\geq$ 2.705), and α = 99.9 % (*** TSTT $\geq$ 3.551)

The two-sample t-tests, carried out for testing the steepness of slopes *"a"* in the linear equations between the slowing of UW velocities and the enlarged degrees of rot in the spruce wood ($\Delta c = a.\Delta m$; or $\Delta c = a.\Delta \rho$), confirmed that there were no more significant differences between ultrasonic measurements performed for three types of brown rots caused by the *Serpula lacrymans*, *Coniophora puteana*, or *Gloeophyllum trabeum* (Tables 2 and 3). On the other hand, at statistical analysis of slopes *"a"* in the linear equations $\Delta c_{\parallel} = a.\Delta \rho$, a high significance level α = 99.9 % was observed for the apparent difference of slopes *"a"* between ultrasonic measurements of wood damaged with the white-rot fungus *T. versicolor* and with the brown-rot fungi *S. lacrymans*, *C. puteana,* or *G. trabeum* (Table 3).

Table 3. Linear Relationships between the UW Velocity Decreases (Δc) and the Density Decreases ($\Delta\rho$) for Spruce Wood Attacked by Selected Rotting Fungi *S. lacrymans, C. puteana, G. trabeum*, or *T. versicolor* during 4-16 weeks, and Statistical Analysis of these Relationships

Linear equations $\Delta c = a.\Delta\rho$		Two sample t-test for slopes "a" (TSTT) *S. lacrymans*	*C. puteana*	*G. trabeum*	*T. versicolor*
Serpula lacrymans					
($\Delta\rho$ = from 2.42 to 18.31 %; n = 40)					
$\Delta c_{\parallel} = 1.466 . \Delta\rho$	$R^2 = 0.508$	-	0.328	2.543*	6.310***
$\Delta c_{\perp R} = 1.437 . \Delta\rho$	$R^2 = 0.505$	-	2.505*	1.188	0.589
$\Delta c_{\perp T} = 1.403 . \Delta\rho$	$R^2 = 0.381$	-	1.837	0.196	0.425
Coniophora puteana					
($\Delta\rho$ = from 3.99 to 22.36 %; n = 40)					
$\Delta c_{\parallel} = 1.431 . \Delta\rho$	$R^2 = 0.485$	0.328	-	2.600*	5.488***
$\Delta c_{\perp R} = 1.819 . \Delta\rho$	$R^2 = 0.386$	2.505*	-	1.289	2.687*
$\Delta c_{\perp T} = 1.667 . \Delta\rho$	$R^2 = 0.215$	1.837	-	1.752	1.815
Gloeophyllum trabeum					
($\Delta\rho$ = from 5.09 to 26.63 %; n = 40)					
$\Delta c_{\parallel} = 1.720 . \Delta\rho$	$R^2 = 0.693$	2.543*	2.600*	-	8.351***
$\Delta c_{\perp R} = 1.605 . \Delta\rho$	$R^2 = 0.480$	1.188	1.289	-	1.552
$\Delta c_{\perp T} = 1.427 . \Delta\rho$	$R^2 = 0.386$	0.196	1.752	-	0.579
Trametes versicolor					
($\Delta\rho$ = from 3.04 to 24.58 %; n = 31)					
$\Delta c_{\parallel} = 0.759 . \Delta\rho$	$R^2 = 0.282$	6.310***	5.488***	8.351***	-
$\Delta c_{\perp R} = 1.348 . \Delta\rho$	$R^2 = 0.254$	0.589	2.687*	1.552	-
$\Delta c_{\perp T} = 1.326 . \Delta\rho$	$R^2 = 0.133$	0.425	1.815	0.579	-

Note: Two sample t-test (TSTT) analysis for slopes "a" in the linear equations, evaluated on significance levels of α = 95 % (* TSTT ≥ 2.021), α = 99 % (** TSTT ≥ 2.705), and α = 99.9 % (*** TSTT ≥ 3.551)

No obvious differences were found between the linear equations $\Delta c = f(\Delta m)$ (or between $\Delta c = f(\Delta\rho)$) determined separately for the longitudinal, tangential, and radial anatomical directions, except in the case of the white rot caused by the fungus *T. versicolor*. For this particular case, the UW velocities in the transversal directions decreased significantly more than in the longitudinal one (see Tables 2 and 3).

Generally, coming out from the results of stake tests, it can be claimed that the ultrasonic technique is suitable for detection of the different degrees of so-called “homogenous” brown or white rots in a spruce wood. This knowledge is valid for propagation of the UW in the longitudinal (parallel-to-grain) direction and also in the transversal (perpendicular-to-grain) directions.

The anatomical direction of the decayed spruce specimens in terms of changes of the UW propagation proved to be significant only in the case of the white rot caused by the fungus *T. versicolor*. For this rot the slope “*a*” in the linear equations was approximately 42% smaller for the longitudinal direction ($\Delta c_{\parallel} = a.\Delta m$, or $\Delta c_{\parallel} = a.\Delta\rho$) as for the radial and tangential directions (Tables 2 and 3). This result is in good agreement with the work of Faraji et al. (2004), in which the white-rot fungus *T. versicolor* had an apparent higher influence on decreasing the UW velocity in the transversal direction than in the longitudinal one.

On the other hand, the ultrasonic technique cannot be considered to be a convenient method (or in some cases as partly convenient, but with no systematic effect) for determination of the exact type of brown rots. However, it can be applied for distinguishing of the brown rots from the white rots, preferentially on the basis of different slopes “*a*” in the equation $\Delta c_{\parallel} = a.\Delta\rho$. This means in practice that the slope “*a*” can be an approximately 2-times higher in the case of brown rots, relative to white rots (Table 3).

The achieved results, comparing the Δc and Δm values only (see Table 2), confirmed also the outlook and the following hypotheses of Faraji et al. (2004): 1) in the longitudinal direction of ultrasonic measurements, the brown cubic rot causes a partly higher decrease of the UW velocity than the white erosive rot, because at the brown rot the role of cellulose chains (arranged longitudinally in the S_2 layer of cell walls) in transmission of the UW is more apparently decreased after major depolymerization processes; 2) in the transversal directions of ultrasonic measurements, the white erosive rot causes a higher decrease of the UW velocity than the brown cubic rot, because in the case of white rot the role of bio-deteriorated lignin or lignin-polycarbohydrate part in the network of wooden cells in transmission of the UW is decreased, while in the case of the brown rot the role of lignin does not change.

Dynamic Modulus of Elasticity of Rotten Spruce

The dynamic modulus of elasticity of the decayed spruce specimens decreased proportionally with their weight losses ($\Delta MOE_d = a.\Delta m$) and density decreases ($\Delta MOE_d = a.\Delta\rho$) (Tables 1 and 4, Fig. 2). In these linear relationships a more or less strong connection was found between the tested variables, i.e. between the ΔMOE_d, and the Δm or $\Delta\rho$ (R^2 = from 0.211 to 0.266 – very weak for *T. versicolor*; R^2 = from 0.457 to 0.636 – weak for *S. lacrymans* and *C. puteana*; R^2 = from 0.735 to 0.751 – moderate for *G. trabeum*). The percentage drops of the dynamic modulus of elasticity (ΔMOE_d) of the decayed spruce specimens represented an approximately 1.7 to 2.3 multiple of their weigh losses (Δm), or approximately 2.1 till 3.4 multiple of their density decreases ($\Delta\rho$) (Table 4, Fig. 2). Marčok et al. (1997) determined similar, or only moderately smaller, decreases of the dynamic modulus of elasticity ($\Delta MOE_d = 1.79.\Delta m$, $R^2 = 0.603$; ΔMOE_d

= 2.75.$\Delta\rho$, R^2 = 0.576) for spruce specimens 120 mm x 10 mm x 10 mm (LxRxT) bio-damaged by the brown-rot fungus *S. lacrymans* during 1-9 weeks.

Table 4. Linear Relationships between the Dynamic Modulus of Elasticity Decreases (ΔMOE_d) and the Weight losses (Δm) or Density Decreases ($\Delta\rho$) for Spruce Wood Attacked by Selected Rotting Fungi *S. lacrymans, C. puteana, G. trabeum,* or *T. versicolor* during 4-16 Weeks (see also Fig. 2), and Statistical Analysis of these Relationships

Linear equations $\Delta MOE_d = a.\Delta m$ $\Delta MOE_d = a.\Delta\rho$		Two sample t-test for slopes "a" (TSTT)			
		S. lacrymans	*C. puteana*	*G. trabeum*	*T. versicolor*
Serpula lacrymans *(n = 40)*					
$\Delta MOE_d = 2.312 . \Delta m$	$R^2 = 0.457$	-	4.884***	3.982***	1.570
$\Delta MOE_d = 3.286 . \Delta\rho$	$R^2 = 0.636$	-	0.328	0.822	6.661***
Coniophora puteana *(n = 40)*					
$\Delta MOE_d = 1.743 . \Delta m$	$R^2 = 0.636$	4.884***	-	1.388	1.686
$\Delta MOE_d = 3.230 . \Delta\rho$	$R^2 = 0.600$	0.328	-	1.069	5.908***
Gloeophyllum trabeum *(n = 40)*					
$\Delta MOE_d = 1.868 . \Delta m$	$R^2 = 0.751$	3.982***	1.388	-	0.968
$\Delta MOE_d = 3.415 . \Delta\rho$	$R^2 = 0.735$	0.822	1.069	-	7.308***
Trametes versicolor *(n = 31)*					
$\Delta MOE_d = 2.028 . \Delta m$	$R^2 = 0.211$	1.570	1.686	0.968	-
$\Delta MOE_d = 2.051 . \Delta\rho$	$R^2 = 0.266$	6.661***	5.908***	7.308***	-

Note: Two sample t-test (TSTT) analysis for slopes "*a*" in the linear equations, evaluated on significance levels of α = 95 % (* TSTT $\geq$ 2.021), α = 99 % (** TSTT $\geq$ 2.705), and α = 99.9 % (*** TSTT $\geq$ 3.551)

A statistical analysis of the linear equations ($\Delta MOE_d = a.\Delta m$, or $\Delta MOE_d = a.\Delta\rho$), carried out with the two-sample t-test with the aim to evaluate differences in the intensity of the dynamic modulus of elasticity decreases as a result of different types of rot (Table 4), repeatedly confirmed that the ultrasonic method is convenient only for distinguishing the white rot (in experiment caused by *T. versicolor*) from the brown rots (in experiment caused by *S. lacrymans*, *C. puteana,* or *G. trabeum*), provided that the density decreases $\Delta\rho$ are known. Comparing the linear equations $\Delta MOE_d = a.\Delta\rho$, there on a high significance level α = 99.9 % was found an evident difference between ultrasonic determination of the white rot and the brown rots (Table 4, Fig. 2).

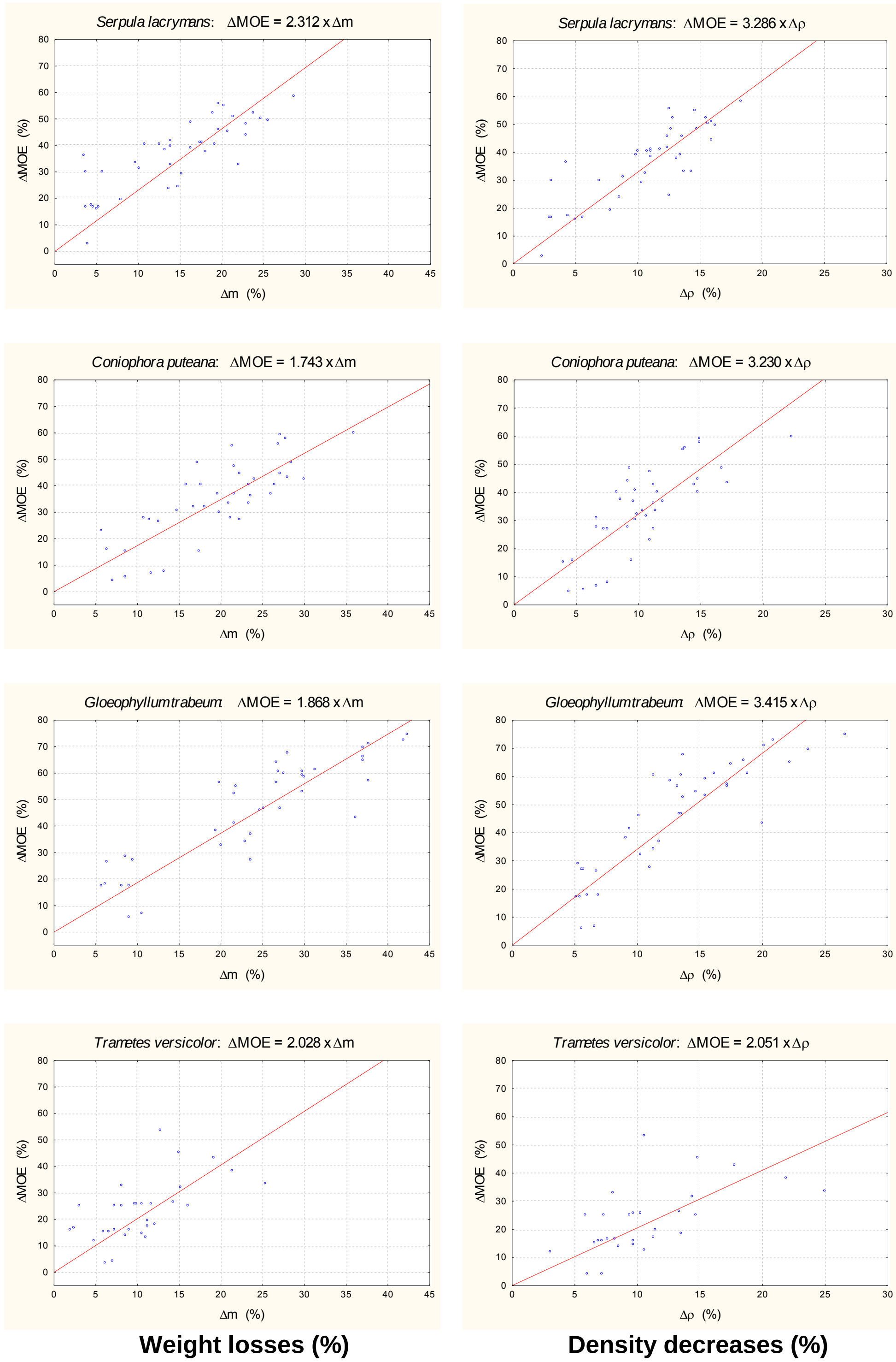

Fig. 2. Linear regressions between the dynamic modulus of elasticity decreases (ΔMOE_d) and the weight losses (Δm) or density decreases ($\Delta \rho$) of the Norway spruce specimens attacked by selected wood-destroying fungi during 4-16 weeks
Note: The coefficients of determination R^2 are in the Table 4.

CONCLUSIONS

The locations and degrees of fungal rots, insect galleries, cracks, thermo-chemical, or other degradations of wooden structures are often determined by ultrasonic techniques, evaluating the velocities of ultrasonic waves and the dynamic modulus of elasticity, respectively. However, practical results are in more cases influenced by additional factors, such as the type of damage, the un-homogeneity of rots or other failures in wood, the positioning of ultrasonic transducers relative to failures in wood, the direction of ultrasonic measurement, i.e. in the radial, tangential, longitudinal or strictly undefined direction, the density of wood and its actual moisture content, etc. Based on the results obtained in this particular research, the following conclusions can be drawn:

1. Ultrasonic characteristics of spruce specimens attacked by rotting fungi (brown-rot: *Serpula lacrymans*, *Coniophora puteana,* or *Gloeophyllum trabeum*; white-rot: *Trametes versicolor*) were significantly affected by the degrees of rot, i.e. by the weight losses or density decreases.
2. Ultrasonic diagnoses were judged to be inappropriate for distinguishing spruce wood decays caused by various species of brown-rot fungi.
3. It was also judged to be feasible to differentiate the occurrence of white rot from brown rot. This can be done preferentially by measuring the ultrasonic waves in the longitudinal direction of rotten wood along with the density decrease. Smaller changes of the UW velocities and the dynamic MOE were observed on specimens exposed to the white rot than at those exposed to the brown rot, at their same density decreases.
4. In terms of different influence of rotting fungi on the propagation of UW along the three basic anatomical directions of the wood specimens, only the white-rot fungus *T. versicolor* showed a marked preferential influence for one of the directions. In this case, white-rot fungus caused a sharper decrease in UW velocities along the radial and tangential directions than along the longitudinal one.

The following practical recommendations can be made based on the results:

I. The degree of homogenous rot in wooden elements can be assessed by both modes of ultrasonic measurements – parallel or transversally to grains.
II. Ultrasonic measurements performed in the transverse directions appear to be more sensitive and effective in detecting white rots than brown rots. Conversely, ultrasonic measurements performed in the longitudinal direction appear to be more effective in detecting brown rots than white rots.
III. Ultrasonic methods are not suitable for distinguishing different types of brown rot; however, they can be useful for differentiating between white rots and brown rots.

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