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ORIGINAL PAPER

Ultrasonic technique for evaluation of initial stadium of wood degradation in exterior conditions without ground contact

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Abstract

The experiment evaluate the possibility of using non-destructive measure techniques of the mechanical properties of wood using ultrasonic to determine the initial stages of degradation by biotic and abiotic factors in the outdoors without ground contact. Nine tree species were tested: spruce, pine, Douglas fir, larch, oak, black locust, maple, poplar and alder. Test specimens were exposed to the exterior according to EN 927-3, Prague-Suchdol in the Czech Republic. Measuring changes in velocity of ultrasonic using the apparatus Ultrasonic Timer and moisture content change were measured after 1, 2, 3, 4 and 6 months. Certain ways of detecting the initial stages of damage have been demonstrated to trees oak, larch and spruce. The initial stages of damage by molds at non-durable maple, alder and poplar had not a clear impact on the decrease in the speed of ultrasonic, as well as hairline surface cracks at the Douglas fir.

Key words: wood; exterior; biotic and abiotic degradation; detection; ultrasonic velocity

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1. Introduction

Exterior wood applications are widely used in building industry, in the garden architecture and for outdoor mobiliar, but also in various wood structures such as fences, wooden houses, bridges, etc. (Štefko & Reinprecht 2004). The advantages of wood as renewable raw material can be sorted by excellent workability, strength and structural characteristics in comparison with steel, ceramic and silicates (Požgaj et al. 1993). The downside is, particularly for non-durable wood species, the possibility of damage to the timber by biotic and abiotic factors. Especially fungi and insects are able to completely disrupt the static function of the timber element or the whole building in a relatively short period of several years (Schmidt 2006; Reinprecht 2008). Abiotic degradation, particularly atmospheric degradation is also not negligible detrimental factor for the function of wood in construction. First cause esthetic color changes (Evans 2008), but there is also a significant formation of cracks that allow deeper penetration of water into the timber. This creates better conditions for the subsequent attack by decay fungi, which are tied up with wood moisture above 20%. For proper function of wooden buildings and structures is required regular maintenance and inspection status. To determine the degree of damage to the timber is possible to use a variety of diagnostic procedures (Koiber & Drdácký 2015). The simplest is a visual assessment, which is necessarily subjective, so it is advisable to use instrumentation and technical methods. These methods can be destructive – based on assessment of mechanical tests and as well as non-destructive techniques nowadays used in industrial practice (Rohanová 2013). Besides the use of sound (Bucur 2006), optical methods, including the use of microscopy and SEM (Panek et al. 2009), of using radiography (Gardner et al. 1980) is available the use of ultrasonic.

Measurement of ultrasonic speed is suitable for determining the mechanical properties of wood and damage of the elements (Bucur 2006; Tippner et al. 2016). Relatively well-researched areas is detection of damage by wood-destroying fungi (Wilcox 1988; Reinprecht & Hybky 2011), or wood-destroying insects (Reinprecht & Panek 2013).

Non-destructive testing using ultrasonic would allow quick and efficient detection of incipient damage and predict the next stage of serious action of atmospheric factors causing cracks (Raczkowski 1980) and wood-destroying fungi causing white or brown rot (Wilcox 1988). Less explored area is the ability to detect damage to the timber at the initial stage of exposure outdoors (Raczkowski et al. 1999; Oberhofnerová et al. 2016). Raczkowski et al. (1999) have demonstrated that even at low mass loss <1% due to the decay can be used detection method combining acoustic emission perpendicular with the grain test compression in radial direction. Research Oberhofnerová et al. (2016) focused on testing spruce and oak exposed to weathering for four months. A trend of the decline in the velocity of propagation of ultrasonic was observed but was not statistically significant.

For the detection of damage of the timber by waves of ultrasonic are used mainly anatomical measurements of the transverse directions (Kloiber & Drdácký 2015). It comes both from the possibility of access to most of the built-in elements in wooden structures such as bridges, timber beams, poles etc. The cellular elements forming in transverse directions with more interconnections as it is known from wood anatomy (Wagenführ 2002), brings further advantage of this detection method. Higher amount of damaged cell walls, or

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cracks which arise mainly in the longitudinal direction may indicate attenuation of the ultrasonic velocity.

The aim of this experiment was to explore the possibility of using ultrasonic velocity in the radial direction for the determination of the early stages of degradation of wood in the exterior without contact with the ground (use class 3 according to EN 335-2013) with nine tree species: spruce, pine, Douglas fir, larch, oak, black locust, maple, poplar and alder.

2. Material and Methods

Samples of nine tree species (Table 1) with dimensions of 375 × 78 × 20 mm (L × R × T) with the initial moisture content of 12% were exposed to the exterior without contact with the ground in a rack at 45 degrees south according to EN 927- 3 (2006). Exposure place was Prague-Suchdol time from 15th December 2014 to 15th June 2015 and the climatic conditions during the experiment are shown in Table 2.

Measurement of ultrasonic velocity (v) with number of 12 measurements for each tree species was performed initially and after 1, 2, 3, 4, 6 months of exposure using the apparatus Fakopp Ultrasonic Timer in the radial direction (Fig. 1) and for the calculation was used equation (Eq. 1):

$$v = \frac{size\ (mm)}{time\ (\mu s)} \cdot 10^3 \ \ [\mathrm{m\ s^{-1}}] \qquad [1]$$

Size is 78 mm in this experiment.

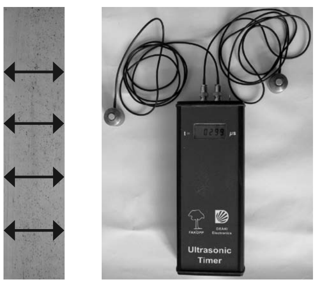

Fig. 1. Scheme of measurements and used testing equipment Fakopp Ultrasonic Timer.

To determine changes in velocity of ultrasonic in the experiment was used equation (Eq. 2):

$$\Delta v = \frac{v_1 - v_0}{v_0} \cdot 100 \ \ [\%] \qquad [2]$$

where subscript v_0 denotes the ultrasonic velocity values before exposure and v_1 denotes the values after exposure.

During the experiment was before each measurement determined moisture content of wood, which is an important factor affecting the speed of ultrasonic (Mishiro 1995). Moisture content was calculated by weight method according to the equation (Eq. 3):

$$MC = \frac{m_w - m_0}{m_0} \cdot 100 \ \ [\%] \qquad [3]$$

where m_w is the weight of wet wood and m_0 is the weight of absolutely dry wood.

Further was conducted a visual monitoring of evidence of cracks, molds and other damages with tenfold magnification.

For evaluation of the data with basic statistical characteristics, correlation tests and Duncan‘s test was used software Excell and Statistica.

3. Results

Results of the measurement of ultrasonic velocity changes are shown in Fig. 2 and 3. Moisture content changes during exposure, affecting the measurement results are shown in Fig. 4. The correlation between moisture content, occurrence of initial timber damage and the drop velocity of ultrasonic is analyzed in Fig. 5 and Table 3.

Figures 2 and 3 indicates for hardwoods and softwoods some similarities and differences. For all tested tree species, there were various Δv during exposure, therefore it is obvious that the decisive factors in addition to the length of exposure and the variation of moisture content (Fig. 3), or other factors that are further analyzed in Figs. 5 and Table 3. Overall, it can be deducted that for softwoods was a great variance of measured values (Fig. 2), making difficult correct interpretation of the results. By contrast for hardwoods were measured values Δv relatively low and the variability of the ave-

Table 1. Tested wood species and their initial characteristics (initial value of ultrasonic velocity in radial direction, density and natural durability against fungi).

Wood species	Latin name	Ultrasonic velocity [m s^{-1}]	Density [kg m^{-3}]	Natural durability against fungi (EN 350-2015)
Norway spruce	*Picea abies* L. Karst	858.75 (60.60)	533	4
Scots Pine	*Pinus sylvestris* L.	1095.47 (223.42)	698	3–4
Douglasce fir	*Pseudotsuga menziesii* (Mirb.) Franco	925.65 (29.03)	605	3
European larch	*Larix decidua* [Mill.]	854.06 (38.89)	559	3–4
English oak	*Quercus robur* L.	1451.34 (59.23)	710	2
Black locust	*Robinia pseudoacacia* L.	1367.57 (53.03)	827	1–2
Poplar	*Populus* sp.	1016.57 (20.77)	413	5
Sycamore maple	*Acer pseudoplatanus* L.	1183.61 (53.00)	599	5
Black alder	*Alnus glutinosa* (L.) Gaertn	1258.83 (203.05)	534	5

Note: Numbers in parentheses are standard deviations.

Table 2. An overview of climatic conditions during 12 months of natural weathering.

Variable/month	0–1	1–2	2–3	3–4	4–5	5–6
Average temperature [°C]	3.2	0.7	3.4	7.0	12.3	15.9
Average max. temperature [°C]	5.5	3.1	7.8	12.5	17.9	21.3
Average min. temperature [°C]	–0.3	–1.8	–1.1	1.5	6.4	10.7
Average RH [%]	76.1	78.4	70.7	63.5	60.7	62.2
Total precipitation [mm]	21.9	9.1	11.8	26.3	39.9	32.3
Average global solar rad. [kJ/m^2]	2086	3405	7453	12567	18164	19039

rage values of the individual exposure times was not as great as for most softwoods (Fig. 3).

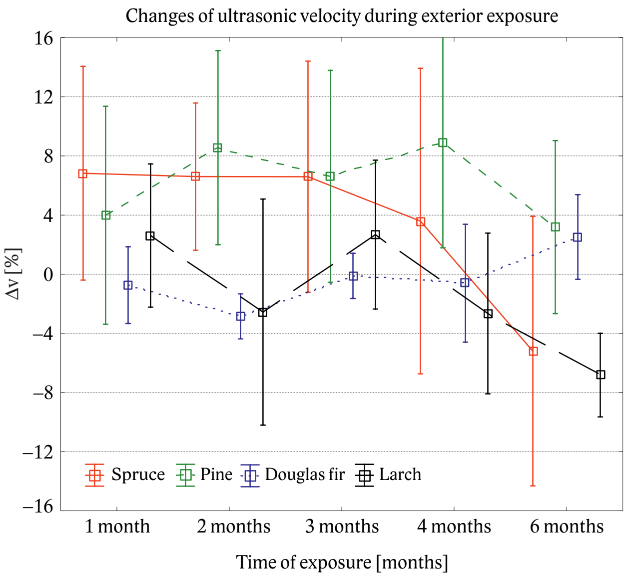

Fig. 2. Two sides confidence intervals of Δv in softwood species during exterior exposure.

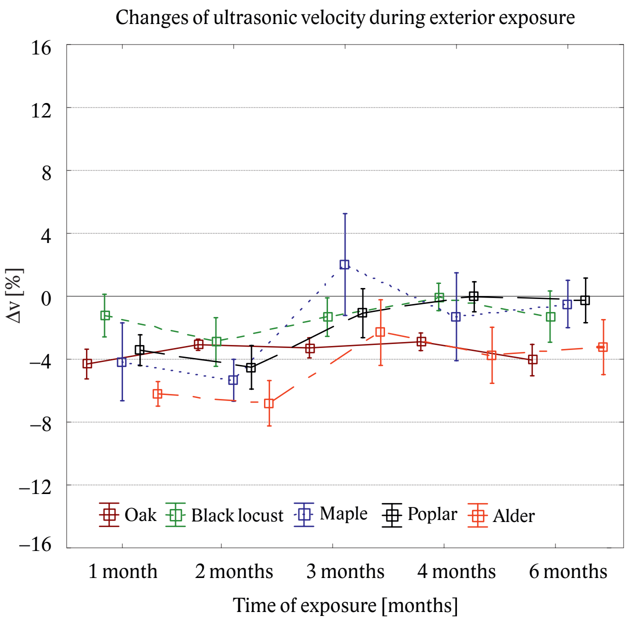

Fig. 3. Two sides confidence intervals of Δv in hardwood species during exterior exposure.

Moisture content of samples decreases mostly during exposure and naturally follows the effects of climate factors shown in the Table 2.

Visual evaluation of samples revealed the presence of molds or wood-stain fungi on non-durable hardwood species, maple, alder and poplar 3 months after exposure and gradually grew up. For Douglas fir wood occurred hairline surface cracks and the other woody species including the above mentioned there were changes of color, graying, which is on a wood exposed outdoors well known (Evans 2008).

Linear relationship between ΔV and MC for all of the trees is relatively low ($R^2 = 0.11$), what makes the assumption that changes in the velocity of propagation of ultrasonic to test tree species were affected mainly by other factors. Mainly by incipient degradation caused by atmospheric agents and biodegradation (Fig. 5).

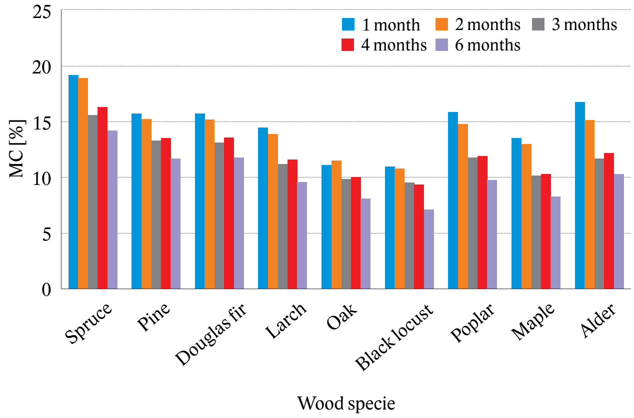

Fig. 4. Changes of moisture content (MC) of wooden samples during exterior exposition.

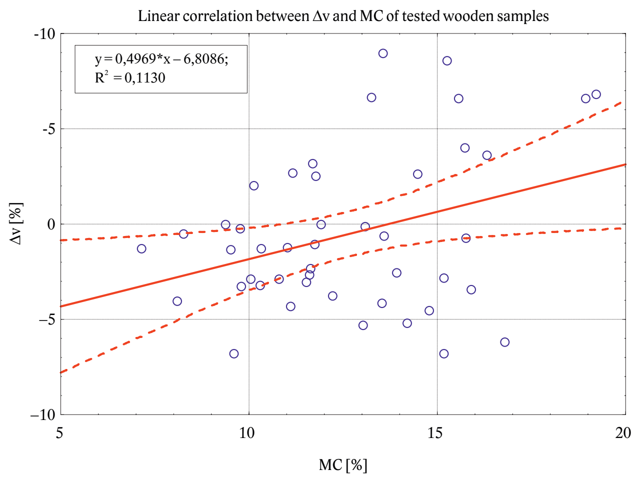

Fig. 5. Correlation between Δv and MC for all tested wood.

Separate analyses of each tested trees were conducted in next step (Table 3).

Table 3. Linear correlation between Δv and MC for each kind of wood and Duncan´s test for Δv changes after 1, 2, 3, 4 and 6 month of weathering.

Kind of wood	Linear correlation	Coeficient of determination [R^2]	Duncan test*
Spruce	$\Delta v = -26.05 + 1.76*MC$	0.56	d (only 6 months versus others c)
Pine	$\Delta v = 0.24 + 0.43*MC$	0.07	d (for all cases)
Douglas fir	$\Delta v = 13.26 - 0.98*MC$	0.67	—
Larch	$\Delta v = -14.63 + 1.09*MC$	0.30	d (only 6 months versus 1 and 3 months c)
Oak	$\Delta v = -4.67 + 0.11*MC$	0.06	d (only 1 months versus 2 and 3 monts c and versus 4 months b; 4 months versus 6 months c)
Black locust	$\Delta v = 0.79 - 0.22*MC$	0.12	—
Maple	$\Delta v = 9.89 - 1.06*MC$	0.62	—
Poplar	$\Delta v = 7.21 - 0.71*MC$	0.77	—
Alder	$\Delta v = 4.10 - 0.65*MC$	0.79	—

Note: Duncan´s tests for each kind of wood and months of exposition was done for wood species, which did not confirm decrease of ultrasonic velocity with increase of moisture content in range 0 – Fibre saturation point (FSP): 99.9% significance level (a); 99% significance level (b); 95% significance level (c); and less as 95% significance level at p ³ 0.05 (d).
"—": wood species, which confirmed decrease of ultrasonic velocity with increase of moisture content in range 0 – Fibre saturation point (FSP).

In Table 3 is analysed decreasing of ultrasonic velocity in dependence on the increase in moisture content. For wood maple, poplar, alder, black locust and Douglas fir, this dependence is confirmed (in addition to the black locust with high coefficient of determination), and therefore we can assume that it was the most important factor causing attenuation of ultrasonic. On the contrary, trees oak, spruce, pine and larch doesn't confirm this trend, which makes the assumption of superiority of other influences caused by the degradation of wood. Therefore, their significance was further analysed for each tree species separately using Duncan's test for different levels of significance (Table 3). For oak and pine was correlative dependence relatively low (see Coefficient of determination in Table 3), but for oak were found statistically significant decreases of ultrasonic velocity at lower moisture content after 6 months of exposure. The same results were also observed with spruce and larch, where have been recorded even higher coefficient of determination (Table 3).

4. Discussion

For wood we can assume that with a decrease in moisture content within 0 - FSP will increase the speed of ultrasonic (Mishiro 1995; Montero et al. 2015), what was confirmed for Douglas fir, black locust, maple, poplar and alder. Thus, for these kinds of wood, the ultrasonic cannot clearly detect the initial stages of damage. This was reflected mainly in non-durable trees maple, poplar and alder, which was visible mold or wood-stain fungi damaged, but did not show what is expected to drop of ultrasonic velocity. Conversely, simply copying the changes in humidity (Table 3). In Wilcox (1988) and a depth of Reinprecht (2011) was observed to reduce the speed of sound, but only at higher mass loss as 5 – 10% (Wilcox 1988). Such a big mass loss cannot be assumed after just short-term exposure and as effects of wood coloring fungus (Fojutowski 2004). Conversely Raczkowski et al. (1999) demonstrated the sensitivity of ultrasonic detection of damage to the timber by fungi already when the mass loss is less than 1%, but in combination with perpendicular to grain compression test in radial direction.

For woods spruce, pine, larch and oak cannot be assumed that the drop in moisture content led to an increase in velocity of ultrasonic (see linear correlation in Table 3). Interesting result is the significant decrease in velocity of ultrasonic in spruce after 6 months of exposure that may relate to the fact that out of the softwoods has the lowest natural durability (Table 1). Although there was not found the evidence of fungus infestation, spruce belongs to the class of durability 4 (EN 350). Exposure of spruce to outdoor applications - the use of class 3 (EN 335) – without a barrier or chemical protection is not recommended (EN 460). Ultrasonic propagation velocity changes in pine were not statistically significant for any of the tested months. For larch, like oak it is interesting to note that despite the low moisture content after 6 months of exterior exposure the velocity of ultrasonic in the radial direction was the lowest in several cases even significantly compared to the other values (Fig. 2 – 4 and Table 3). It is an interesting result because they are wood species with a relatively high natural durability (EN 350), which are often used in outdoor applications and they can withstand long term exposure of biotic factors (Reinprecht 2008). Explanation is possible by a high content of extractive substances in these woods, if larch arabinogalactans and in case of oak tannins (Bučko & Šutý 1988) which, after leaching from the cell walls caused the reduction of the velocity. This effect was confirmed also in work Farvardin et al. (2015) for persian silk wood. The effect of extractive substances leaching from some tree species has to be calculated using ultrasound as detection method in practice.

Oberhofnerová et al. (2016) investigated the effect of the exterior load of spruce and oak wood in outdoor areas without ground contact. There was observed a decrease in velocity of ultrasonic in native wood, but statistical significance was not demonstrated. It could be caused on the one hand by a shorter exposure time - only 4 months, on the other hand, the measurement in the longitudinal direction not so sensitively detects a beginning damage wood, due to fewer connection of cellular elements.

In contrast, the pine and Douglas fir resins and black locust extracts appearing to have stabilizing effect on the weather. On the basis of these results look out these extracts more stable as oak tannins.

Black locust belongs to a class of 1 – 2 natural durability (EN 350), and in pine wood is known relatively high content of water resistant resins (Bučko & Šuty 1988), which also provide some hydrophobic protecting (Oberhofnerová & Panek 2016). Douglas fir also contains extractive substances based resins but also biflavonoids dihydroquercetin, which causes a relatively high natural durability (Taylor et al. 2003).

From these results it is clear that the mere use of ultrasonic does not provide sufficiently accurate information about initial wood damage by biotic and abiotic factors. It is mainly due sensitivity of the method, which is probably better suited to the detection of more serious damage of structural timber, where the results are conclusive (Wilcox 1988). Initial stages are better diagnosed by the direct assessment of microscopic analyzes, which are visible hyphae infiltrating of cellular structure of wood (Pánek et al. 2009), or microruptures caused by the abiotic degradation (Masaryková et al. 2010). More sensitive detection method seems to be the use of destructive testing - impact strength in bending (Sonderegger et al. 2015). This sensitively respond even to wood-staining fungi that still does not significantly deform cell walls of wood (Fojutowski 2004).

The disadvantage of both methods is the need to remove test samples from the tested structure and their subsequent analysis in the laboratory. By this method can be created reliable overview of the state of the structure, but more precise and intensive measurements have to be done.

5. Conclusion

From the above experimental results, it is possible to provide the following conclusions:

1. The speed of ultrasonic in wood is affected during the initial stages of degradation of wood exposed outdoors without ground contact without shelter, although the changes are

relatively low. Statistically significant decrease was observed in some kinds of tested woods: spruce, larch and oak, especially after 6 months of exposure.
2. Considerable influence as a degradation of biotic and abiotic agents is in the early stages of exposure for most kinds of wood tested, has especially fluctuations in wood moisture content due to the local climatic conditions. Therefore, this factor has to be calculated at any non-destructive testing of structures using the ultrasonic.
3. There was not confirmed the possibility of using ultrasonic to determine the initial stages of fungal damages (Mainly by the molds or the wood-staining fungi) in non-durable woody species tested: maple, poplar and alder.
4. Based on these results it can be stated that the mere use of ultrasonic as a screening method of initial stages of timber damage is inadequate and does not provide a perfect idea of their range in wood. Analysis can be refined using microscopic analysis and SEM analysis of damage. Another option is providing of destructive analysis where, for example, impact strength in bending sensitively detects the already emerging biotic damage. The disadvantage of both is the higher effort, the need for the sampling and subsequent laboratory evaluation.

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