OVERVIEW OF SOME NON-DESTRUCTIVE METHODS FOR IN SITU ASSESSMENT OF STRUCTURAL TIMBER

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ABSTRACT

The need for structural health assessment of old buildings can emerge in order to assure or extend their service life. In renovating buildings it is essential to assess the condition of timber structures. Often there are situations where the wood structures need to be evaluated on site and visual assessment is confined. At this point the non-destructive methods can be used for evaluation. This research uses ultrasonic, resistance drilling and pilodyn methods for the assessment of timber samples taken from currently existing buildings of different ages. As bending being the most important loading mode and modulus of elasticity is a good indicator of strength in timber structures the results of non-destructive methods were compared with them. Individual arguments like ultrasound velocity, moisture content, drilling resistance and relative hardness used in the regression analysis did not give a correlation above average in prediction of the bending strength and modulus of elasticity of wood found in the standardized bending test. The correlation between the density of timber and the readings of the resistograph was the strongest, especially damaged by fungi and beetles. Thereby, when the age of wood increased, the strength of it decreased. The correlation between the readings of the resistograph and timber internal stresses was weak, meaning that the resistance of wood does not change significantly while loaded with longitudinal forces.

Key words: bending strength, modulus of elasticity, density, moisture content, acoustic measurement, resistance drilling, pilodyn

INTRODUCTION

In renovating buildings it is essential to assess the condition of timber structures. Historic timber structures must be preserved, in order to maintain their original structural purpose as much as possible, therewhile taking into account the safety aspect for the habitants of the building. Therefore, an accurate condition assessment is needed to evaluate the serviceability of timber structures. The most accurate way of determining the mechanical properties of timber is destructive methods, the most relevant results of which are given by compression, tension and bending tests. But for the sake of preserving the historical value of buildings, the aforementioned methods are not an option.

Going further: although the importance of visual assessment of structure elements is highly decisive, the results can be very subjective and dependent on the observers' experiences and skills. And often there are situations on site where visual assessment is constrained, since the timber structural member has one or many sides covered and/or its geometry does not enable the inspection. Therefore, a need for other methods to gain reliable results based on scientific research is grounded. At this point non-destructive methods can be used for assessing the condition of wood structures.

There are several non-destructive methods that can be used in the assessment and determination of the quality and properties of timber (Niemz, 2009):

- mechanical (drilling resistance, hardness, intrusion behaviour);
- electrical (correlation between electrical resistance and moisture, correlation between electrical resistance and fungal decay);
- acoustic (sound velocity, sound reflection, sound attenuation);
- thermal (heat radiation);
- electromagnetic waves (visible light, IR/NIR radiation, X-ray, neutron radiation, Synchrotron radiation).

The aim of this work was to investigate the non-destructive methods, the possibilities of using ultrasound, pilodyn and resistograph measurements to investigate the relationships of the physical-mechanical properties of timber. The comparable characteristics are the density and moisture content, because they have essential roles in the strength of wood.

NONDESTRUCTIVE METHODS AND TESTING

Ultrasound velocity method

In the assessment of the properties of wood, sound and ultrasound have been used rather widely. In general terms sound means an elastic wave that spreads in materials and its behaviour in various materials is different. For that reason we can give the acoustic properties for materials (Kettunen, 2006). If the distance of the wave transit is known, we can measure the time and therefore calculate the speed. This is how the technical properties of a material can be measured. Consequently, the correlation between the speed of sound and a certain property of the material such as stiffness can be made (Lempriere, 2002).

The longitudinal measuring method of sound speed is the most widely used. In the assessment of the properties of a material the unit of speed of sound is a common parameter. In the evaluation of the properties of timber the usage of the ultrasound method is far-spread in sawmills, where the longitudinal measuring method has been used to sort lumber into classes of strength.

As there is a need to assess wood structures on site an obstacle occurs, because in most cases both ends of a member are covered and the measurement cannot be conducted. The measurement can only be done when placing the transducers parallel on one side or across facing each other. But the latter way of measuring is not always possible, because of the inaccessibility of both sides. This kind of measuring method also gives us only the local parameters of wood assessing the local properties.

The main advantage of using ultrasound is that the bar will be undamaged and it can be used further – no deformations or destructions occur. Tests can be made on the same member repeatedly without any substantial variation in the results (Bucur, 2006).

There have been several investigations conducted in that field. Ultrasound wave propagation is directly related to the elastic properties of the material through where it propagates. If the material is damaged, its stiffness decreases. The wave speed is a function of the square root of material stiffness. Lower speed or longer propagation times are generally indicative of worse conditions of wood. It is assumed that the ultrasound pulse velocity can be an index of the quality of wood as it can detect defects like cracks, knots, decay and deviation on grain orientation. In spite of the inhomogeneous nature and anisotropy of wood, it is possible to correlate the efficiency of wave propagation with physical and mechanical wood properties (Drdacky and Kloiber, 2006).

The density and modulus of elasticity (MOE) of a material strongly affect the acoustic properties of wood. Bucur and Chivers (1991) stated that velocity decreases with increased density. Thus the propagation of sound varies in different species of timber. But in other investigations the results have shown that velocity increases for larger density values (Haines et al., 1996). On the contrary, Mishiro (1996) found in his research that velocity was not affected by density.

As wood is an anisotropic material, the speed of sound varies in different directions due to the cell structure (Kettunen, 2006). Transverse waves are scattered at every cell wall. More impacts of waves on wood cells in the transversal direction make them slower (Kotlinova et al., 2008). Ultrasound velocity is influenced by the width of annual rings only in radial direction, due to the macroscopic structure of wood, proportion of early and latewood and cell orientation in the growth ring (Drdacky and Kloiber, 2006).

Kotlinova et al. (2008) got the following results in measuring ultrasound velocity in wood members: in the longitudinal direction the velocity ranged from 3500 to 6500 m/s and 1000–2500 m/s across the grain. The ultrasound velocity decreases with increasing the moisture content (Drdacky and Kloiber, 2006). The velocity decreases dramatically with the moisture content up to the fibre saturation point, and thereafter the variation is very small (Bucur, 2006). It is also notable here that the moisture content over the fibre saturation point measured in the longitudinal direction does not have any significant effect on the ultrasound velocity (Machado et al., 2009).

Overall, the direct longitudinal measurement is fairly reliable method in the assessment of the strength of wood. However, according to the report of Machado et al. (2009) it is essential to note that an indirect measurement can give rather good results in determining the properties of stiffness and strength of wood. Furthermore, the results seem to indicate that as the distance (10 to 40 cm) between the transducers becomes larger the influence of deeper wood layers in the velocity of wave propagation increases. Therefore, in a situation where the wood structure is mostly covered and only one or two sides are accessible, it is possible to evaluate the strength of the member by the indirect measuring method. For wood the most favourable frequency range is between 20 kHz and 500 kHz because of the high attenuation of ultrasonic waves in wood at higher frequencies (ASTM 494-89, 1989; Tanasoiu et al., 2002).

Resistance drilling method

Resistance drilling (Resistograph) enables the inspection of timber through the depth of the member. Measurements are dependent on material resistance to drilling with the diameter of 1.5 to 3.0 mm. The resistograph has an electric motor and is battery-operated, which is very valuable for using in historic timber constructions. The drills are flexible and their length depends on type of the resistograph and manufacturer (Kotlinova et al., 2008).

The output of resistance drilling is graphical, the tops on output characterise higher resistance or density and bottoms vice versa. Thus, the internal defects and damage of the timber member can be detected.

Different properties like hardness, density, strength classes, residual cross-section and also biodeterioration and natural defects can be determined with the analysis of the resistograph

graphs. Also the width of the annual rings and structure can be measured. The aforementioned strength indicators can be used to calculate residual strength properties of the timber structure based on Eurocode 5 (Pilt, 2009).
According to the report of Kasal and Anthony (2004) the relationship of resistance drilling to the density of the wooden member is variable, ranging between $r^2 = 0.21\text{-}0.69$.
The main disadvantage is the locality of inspection. In order to get a total overview of the member condition a numerous amount of drilling tests have to be made. But that is often limited for the sake of keeping the material authenticity. Another issue involves the drilling needle, because of the small diameter of the drill, it can bend easily during the process of drilling into the element. Thus we can receive inaccurate readings.

Pilodyn method

As the resistograph enables the examination through the cross-sectional area, pilodyn gives only superficial results of the element. The mode of operation consists in the penetration of a tongue in the wood element by means of dynamic impact. The result of this method is penetration depth. The diameter of the tongue is of 2.5 mm and maximum penetration is of 40 mm (Kotlinova et al., 2008).
The density is well related to the hardness of wood (Bonamini, 1995; Kasal and Antony 2004). Superficial values of density can be predicted with this kind of portable method. The results got by Görlacher (1987) demonstrated good correlation between the penetration depth and density. Also the extent estimation of damaged areas of the wooden member is shown by the penetration depth of the needle to the inner layers, deeper penetration refers to a more damaged timber.
Hereby, it should be also mentioned that the moisture content and the penetration directions have effect on the results. The penetration depth is higher in radial direction than in tangential direction. In tangential direction the needle has to penetrate through different earlywood and latewood layers, but in radial direction the penetration happens only in one part of the annual ring.
When operating with this device it is very important to hold it perpendicular to the element and another issue is the vibration evoked by the needle strike, which can result in misleading estimates.

METHODOLOGY

The objective of the experiment was to measure the ultrasound velocity in wood members with certain distances between ultrasound transducers and on two main sections—the end and tangential surfaces. The distances were chosen according to the suggestions of the manual of the testing device for the maximum and minimal parameters. For the indirect measurements the distance was 0.1 to 0.6 m and for the direct measurements up to 1.5 m (Tico User Manual, 2008).
37 logs and beams dated from buildings with various uses were used for the present research. 124 members with dimensions of 50x50x1005–1100 mm were sawn out from the gathered. The chosen dimensions were based on the standard EN 408:2005, which means that the length of the member for the bending test should be at least 19 times the height of the cross-section. The specimens were graded into strength classes according to the Nordic standard of INSTA 142. Three strength classes were defined according to this standard: □C18, C18 and C24.
First of all a series of measurements with a *TICO Ultrasound Instrument* with 50 mm 54 kHz transducers were made with the number of 92 members.
Four different variants of measurements were conducted:

1) Five times with a spacing of 200 mm on the tangential surface at random early wood positions by using the indirect method (hereafter this characteristic is marked by "A");
2) Three times with a spacing of 600 mm on the tangential surface at random early wood positions by using the indirect method (hereafter this characteristic is marked by "B");
3) One time between the end surfaces in the longitudinal direction (hereafter this characteristic is marked by "C");
4) Five times in the radial direction by random selection in the direct method (hereafter this characteristic is marked by "D").

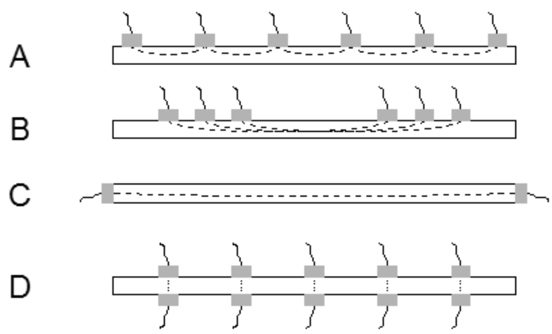

Figure 1. Schematic drawings of measurement methods applied with an ultrasound device: A - indirect measuring; B - indirect measuring; C - longitudinal direct measuring; D - transversal direct measuring.

The principle of this device is that it sends an ultrasound wave into the member by the transmitter probe and is picked up by the receiver probe with

the time of flight recorded in microseconds and also calculates the velocity when the length is entered.
The bending strengths of the test pieces were determined by an Instron 3369 device and based on the standard EN 408:2005. Here it should be noted that the force was set in the radial direction with younger annual rings facing upwards. With this experiment the modulus of elasticity in addition to the bending strength was stored.
After the destructive tests a resistance drilling was made using the resistograph Sibtech DmP that measures the resistance minimally at every 0.1 mm. If the resistance of wood is relatively low the interval of the recording data is even ten times longer. The drilling was made in the same direction as in loading force in the bending tests. There were done 5 drilling holes with the distance of 10...15 cm from each other and the spots were designated randomly free from knots and gaps.The superficial hardness was measured with Pilodyn 6J after micro drilling.
The moisture content (MC) and the density of the specimens were found according to standardized tests. In addition the resistance of wood with the resistograph was measured under different compression loads. All data processing including diagrams, correlation and regression analysis was conducted by MS Excel and R software.

RESULTS AND DISCUSSION

The characteristics determined by the experiments are shown in Table 1. The variation of the values of the indicators of density, bending strength and modulus of elasticity were relatively symmetrical, thus revealing that the variation by the main physical-mechanical indicators of the specimen were regular.
To describe the linear relationship between the individual characters of wood by the correlation coefficient Table 2 is presented here. The one-to-one correlation was between the maximum loading and bending strength, as this is a distinctive feature during the test causing the maximum bending strength with maximum force. That is why only the bending strength is taken into account hereafter.

Table 1

Characteristics of the statistical indicators

Main indicators / Characteristics	Max. bending strength, MPa	MOE, MPa	MC, %	Density, kg/m³
Mean	42.98	10156.3	8.85	443.12
Median	43.36	10370.8	8.95	434.48
Standard error	13.87	2321.5	1.76	54.01
Minimum	9.06	6317.2	5.34	329.61
Maximum	80.12	17115.6	11.41	596.53

The relationship between the maximum bending strength and modulus of elasticity is remarkably strong (r=0.72), which proves the latter to be an important argument in assessment of wood structures. There is also a strong relationship between the density and modulus of elasticity (r=0.8), which is about 0.3 higher than between the density and maximum bending strength. The results verify the well-known fact that stiffness is a more global property than bending strength and thus more dependent on density. Thus density can also be a good estimator of wood strength. In analysing the relationships between the ultrasound measurements and other characteristics the general relationship is reliably linear and the results of the longitudinal measurements characterise the most important strength and stiffness properties of wood moderately well (in case of bending strength r=0.42 and modulus of elasticity r=0.61).

Table 2

Correlation matrix of characteristics of specimens

Characteristics	A, m/s	B, m/s	C, m/s	D, m/s	Max. force, N	Max. bending strength, MPa	MOE, MPa	MC, %	Density, kg/m³
A, m/s	1								
B, m/s	0.63	1							
C, m/s	0.15	0.27	1						
D, m/s	0.32	0.05	-0.12	1					
Max. force, N	0.09	0.24	0.42	-0.29	1				
Max. bending strength, MPa	0.12	0.25	0.42	-0.25	1.00	1			
Modulus of elasticity, MPa	0.11	0.31	0.61	-0.38	0.72	0.72	1		
Moisture content, %	-0.23	-0.04	0.09	-0.78	0.35	0.31	0.30	1	
Density, kg/m³	-0.09	0.07	0.40	-0.31	0.50	0.51	0.80	0.16	1

Notes: figures marked grey indicate a moderate relationship (0.3 ≤ │r│ ≤ 0.7); figures marked dark grey indicate a strong relationship (│r│ ≥ 0.7).

According to the results of the indirect measurements (A and B) a moderate linear relationship to the modulus of elasticity occurs, the relationships with other characteristics are weak, except with each other, which was moderate (r=0.63). In investigating the relationships between the strength and ultrasound velocities Arriaga et al. (2006) found that a weak correlation between them was due to local defects having more influence on the strength than the general quality of the specimens. In that way the acquired results within this research are grounded.

A negative correlation occurs between the moisture content and ultrasound velocity (Bucur, 2006; Oliveira et al., 2005). In analysing the mentioned results within this paper the overall negative correlation is true, especially on the results of the transversal method (D), where there is a strong negative correlation (r=-0.78). As the measuring distances become bigger the moisture content also has a decreasing effect.

The correlations between the results of the density and the resistograph were found to be moderate and strong and statistically significant (p-value<0.05) in all groups shown in Table 3. The strongest value was obtained among the group of specimens with fungal and beetle damage. Higher correlations can be explained by the low number on specimen within these groups. Fig. 2 illustrates a moderate, but statistically insignificant correlation (r = 0,340; p = 0,071) between the bending strength and the time of harvesting. However, it can be concluded, that the strength of wood decreases with increased age of wood. The significant variety of bending strength within the same age can be explained by the variety of damage, knots and location (sap- and heartwood) of specimens sawn out from the material. According to Fig. 3 the internal stress increases with decreasing resistance of wood under compression force. However, due to the low value of the coefficient of determination the internal stress has a weak influence on the resistance of wood. The relationships between the results of Pilodyn and physical-mechanical properties were moderately strong (see Fig. 4 to 5).

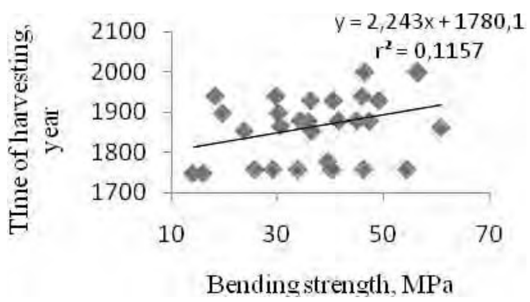

Figure 2. Relationship between bending strength and harvesting time.

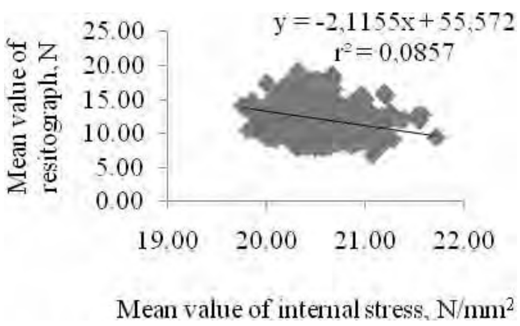

Figure 3. Relationship between resistance drilling and internal stresses.

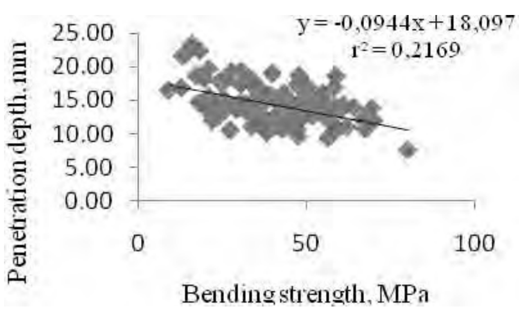

Figure 4. Relationship between penetration depth by Pilodyn and bending strength.

Table 3

Results of regression analysis of resistograph and density

Groups of specimens	Coefficient of correlation r	Coefficient of determination r^2	p-value	Number of specimens
All specimens	0,665	0,442	<0,001	124
Specimens in strength class of C24	0,568	0,322	<0,001	46
Specimens with knots of <250mm^2	0,805	0,649	<0,001	18
Specimens with knots of <1/4 and knot clusters of <1/3	0,614	0,378	<0,001	77
Specimens without cracks and fungal damage	0,733	0,537	<0,001	61
Specimens with fungal and beetle damage	0,850	0,722	<0,001	28

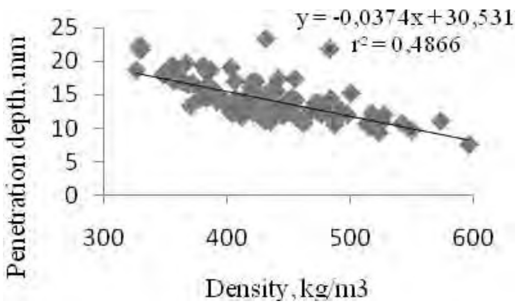

Figure 5. Relationship between penetration depth by Pilodyn and density.

The results concerning the relationship between the density and penetration depth obtained in this study confirm the findings of Görlacher (1987).

CONCLUSIONS

The main aim was to investigate the possibilities of applying some non-destructive measurements in assessment of the physical-mechanical properties of wood. For achieving this purpose series of measurements were done using the *TICO Ultrasound Instrument* with 54 kHz transducers, resistograph Sibtech DmP and Pilodyn devices to assess some characteristics in the wooden specimen. The analysis of ultrasound with different measurement techniques showed that the shorter the measured distance, the more local the evaluation for the wooden member. It turned out that the best arguments in prediction of the physical-mechanical properties were longitudinal (C) and indirect measurements with a distance of 600 mm (B) within the literature as well as in this study.

The possibilities of using resistance drilling and needle penetration in prediction of the density of wooden members are remarkable. In spite of the low number of specimen the resistograph showed strong relationship within the group of fungi and beetle damage. In comparison of the aforementioned methods both described density with the same accuracy within the total number of specimen.

There can be found mixed results about the influence of the age on the mechanical properties of wood from literature. This study showed moderate, but statistically insignificant correlation between the time of harvesting and bending strength.

The correlation of the drill resistance to the compressive force of the wooden members is negatively weak. Thus, it can be concluded that the resistance of wood does not change significantly while loaded with longitudinal forces.

The assessment of the strength of individual members by the aforementioned methods can always be somewhat imprecise, because of the imperfection of the results of measuring on site. Also, it is essential to note that it is not always possible to measure ultrasound velocities in the longitudinal direction. Therefore, it is essential to continue with the investigation in this field and to search for stronger relationships between indirect and direct measuring methods.

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