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CORRELATIONS AND DIFFERENCES BETWEEN METHODS FOR NON-DESTRUCTIVE EVALUATION OF TIMBER ELEMENTS

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ABSTRACT

The aim of this paper is to compare the results of evaluation of mechanical properties of timber by visual assessment, two grading machines, three devices for measuring in-situ and destructive tests. The most important result is the comparison of static and dynamic modulus of elasticity of timber, and further comparison of strength classes obtained by different measuring methods.

KEYWORDS: Strength class, visual assessment, acoustic method, machine grading, modulus of elasticity.

INTRODUCTION

As an organic material, timber has a wide range of physical and mechanical variables. Their detection in cut timber and in built timber elements is generally quite problematic. Usually, it is not possible to determine them with such precision as with plastic materials. In industry, the most used grading is visual and machine-operated. That is how elements are sorted into strength classes, which have clearly specified physical and mechanical properties. Mobile machines for assessment of inbuilt elements in-situ usually use destructive penetration methods and non-destructive acoustic methods. The aim of an in-situ or mechanical sorting measurement is to get information on timber density and modulus of elasticity, according to which strength class of timber could be stated with satisfactory precision. Among exact methods of modulus of elasticity and timber strength measurement belong destructive tests based on four-points bending. The results of timber selection by various methods often differ, which is why it is necessary to perform comparison and calibration processes.

Structural timber with rectangular cross section is sorted into strength classes based on visual or machine classification. The requirements are specified in the standards ČSN EN 14081-1+A1 (2011), ČSN EN 14081-2+A1 (2013), ČSN EN 14081-3 (2012) and ČSN EN 14081-4 (2009). Visual grading is older and cheaper method that takes into account the general morphology of the timber, i.e. the amount of knots and cracks, fibres diversion, width of tree rings, etc. Evaluation of cut timber by grading machines gives acceleration of process and decreases the influence of human factor. Grading machines are using various methods, for timber evaluation such as scanning, measuring the deflection of the timber element, vibrations, speed propagation of ultrasonic waves and also propagation of X-rays. But the most commonly used method is still visual grading, which, however, is not the most effective, especially in industry with large amount of timber. In terms of efficiency in the woodworking industry (e.g. during production of glue laminated timber, cross laminated timber (CLT) or solid structural timber (KVH)), use of mechanical sorting of cut timber is more favourable. Various non-destructive or semi-destructive methods are used for measuring in-situ. These methods provide information about the physical properties such as speed of propagation of the acoustic signal through material, energy required to penetrate the penetration tool (Kloiber et al. 2014), the resistance against passage of X-rays, the electrical conductivity of timber and finally weight of a timber sample. The values of these physical properties are the input information to determine material properties such as modulus of elasticity, bending strength and density of the timber. These properties define the strength class of structural timber according to standard ČSN EN 338 (2009). In literature you can find a variety of correlation values achieved between non-destructively measured values and results from destructive tests. Type of method, the number of samples, way of measurement or kind of wood significantly influence the correlation degree.

MATERIAL AND METHODS

Fourty Norway spruce (*Picea abies* L. Karst) laths, provided by Stora Ensa Wood Products Planá, Ltd., CR , with cross section of 35/70 mm and length 2.7 m were used for experiments. At first, laths were evaluated visually and sorted in strength classes according to standard ČSN 732824-1 (2015). Then they were mechanically graded (Goldeneye 702 and Metriguard HLT 7200).Three portable devices (Sylvatest, Fakopp and Timber Grader MTG) were used for measuring the speed of propagation of acoustic signal. The destructive tests were carried out according to standard ČSN EN 408 (2012) for comparison with non-destructive tests. Modulus of elasticity and bending strength were determined during the destructive tests.

Visual Sorting

Visual grading in Czech Republic is prescribed by the standard ČSN 732824-1 (2015) (identical DIN 4074-1: 2012), which is valid for regions of Central, Eastern and Northern Europe. The visual classes are transferred to strength classes according to standard ČSN EN 1912 (2012), as shown in Tab. 1. Among the crucial sorting criteria belong the size and number of knots, tree rings width, resin pockets length, fibres diversion, crack depth, curvature, colour and decay, the proportion of the pressure timber and insect damage. The sorting criteria are adjusted to moisture content of 20 %.Rules for squared timber were used for sorting to visual classes S7, S10 and S13. These rules are more accurate and better reflect requirements on timber elements loaded mainly in bending.

Tab. 1: Transfer of visual classes to strength classes according to ČSN EN 1912 (2012).

Visual class in Czech Rep.	Strength class
S7	C18
S10	C24
S13	C30

Machine grading

Machine grading of timber laths was performed on grading machines by Stora Enso Wood Products Plana, s.r.o.

Golddeneye 702

The first machine was Goldeneye 702 by Microtec which uses X-rays. The output values are the density of the timber element (minimum, maximum and average value), the dimensions of element and static modulus of elasticity. Modulus of elasticity is measured over the entire length of the element.

Metriguard HLT 7200

The second machine was Metriguard HLT 7200 (MGP10) (Fig. 1) which uses real bending deformation of timber element for calculating static modulus of elasticity. The measurement is continuous for all cross-sections at least 600 mm away from the edges of the timber element. Average and minimum value of modulus of elasticity in bending were used within each element for the next data processing. Achieved outputs are strength class, average and minimum recorded value of modulus of elasticity in bending.

Fig. 1: Grading machine Metriguard HLT 7200.

Non-destructive tests

Sylvatest

Sound waves propagation through material is good and proven method with a clear theoretical background. The speed of the wave is also used for the determination of internal damage to wood, where a lower speed indicates rot or other internal damage (Hasníková and Kuklík 2014). Nowadays, this method is used by machines for sorting cut timber and mobile devices determining the mechanical properties of inbuilt elements. Measurement of modulus of elasticity using Sylvatest device is based on the ultrasonic wave propagation between the measuring probes. When defining wood species (spruce, pine), cross section (squared, timber), element length and moisture content, the device classifies the element into strength classes (S7, S10 and S13) and also determines the value of the modulus of elasticity in bending. For the comparison of methods for determining modulus of elasticity, the time of ultrasonic wave propagation was recorded. Based on this time and density it is possible to calculate a dynamic modulus of elasticity. In this case, the density is not determined by device but is obtained by weighting. The modulus of elasticity in the direction parallel to grain is then determined by a simple relation:

$$E = \rho \cdot v^2, \tag{1}$$

where: E - modulus of elasticity (Pa),
ρ - density ($kg.m^{-3}$),
v - speed of ultrasonic signal ($m.s^{-1}$).

Fakopp microsecond timber

The Fakopp device measures the time of acoustic wave propagation through timber element, including the length of coaxial connections of probes. Therefore, it is necessary to subtract time of the propagation of acoustic signal through the probes connecting from measured time. The acoustic signal is created by a hammer strike on the acoustic probe. The calculation of the dynamic modulus of elasticity is the same as in the case of Sylvatest. The values of dynamic modulus of elasticity obtained from the two devices are very similar.

Timber grader MTG

Another device for detecting the mechanical properties is Timber Grader (Fig. 2) made in the Netherlands. This device is able to determine the strength class according to standard ČSN EN 338 (2009) and static modulus of elasticity. The input variables are mechanically created shock waves, sample size, moisture content and a mass of sample. The disadvantage is the necessity of measurement on the faces of the sample. It is often impossible with inbuilt samples.

Fig. 2: Measurement of sample by device timber grader.

Destructive tests

For the destructive tests the samples were adjusted according to the requirements of standard ČSN EN 408+A1 (2012). Three 700 mm long samples were prepared from each a 2.7 m long lath. The loading diagram is shown in Fig. 3. The loading of the timber sample was controlled by deformation. The progress of force and deformation was recorded for each sample. The aim of destructive tests was to obtain static modulus of elasticity and bending strength of the timber laths. The part of working diagram between 10 and 40 % of maximum power achieved at failure was used to calculate the modulus of elasticity. The strength was calculated as:

$$f_m = \frac{6 \,.\, F_{max} \,.c}{2 \,.b \,.h^2} \tag{2}$$

where: F_{max} - maximal load achieved during the test (N),
c - distance of forces from the support (mm),
b - width (mm),
h - height (mm).

The elastic modulus was calculated using the equation:

$$E_{stat} = \frac{3 \,.c \,.l^2 - 4 \,.c^3}{2 \,.b \,.h^3 \,.\left(2.\, \frac{\Delta w}{\Delta F}\right)} \tag{3}$$

where: ΔF- load increment in interval 0.1 F_{max} – 0.4 F_{max} (N),
Δw - increase of deflection corresponding to the load range 0.1 F_{max} – 0.4 F_{max} (mm).

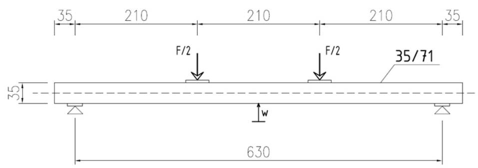

Fig. 3: Scheme of destructive test.

RESULTS AND DISCUSSION

The main output of machine grading, measurement by non-destructive methods and destructive tests is the modulus of elasticity (MoE). Machine grading, destructive tests and device Timber Grader MTG give a static modulus of elasticity. Acoustic non-destructive methods give a dynamic elastic modulus. The Timber Grader device also classifies elements into strength classes according to standard ČSN EN 338 (2009). The output of the visual grading is classification to the visual classes according to standard ČSN 732824-1 (2015) and subsequent transfer to the strength classes according to standard ČSN EN 1912 (2012) (Tab. 1). The bending strength was also obtained from destructive tests according to standard EN 408+A1 (2012), besides modulus of elasticity. These results were mutually compared and they showed linear regression.

Correlation between moduli of elasticity

Comparison of machine grading with real values of the destructive tests was done by determining the level of correlation between static modulus of elasticity (Fig. 4). The correlation coefficient (R) between the modulus of elasticity of the Metriguard HLT 7200 and the destructive tests reached a very high value of 0.94. The correlation coefficient between the modulus of elasticity of the Goldeneye 702 and the destructive tests was also high 0.80. Higher correlation with the Metriguard device is given by way of measurement, when the element is physically bent, while with the Goldeneye device modulus of elasticity is determined on the basis of the passage of X-ray through the element.

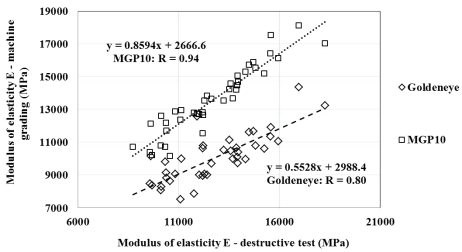

Fig. 4: Correlation between machine grading and destructive test.

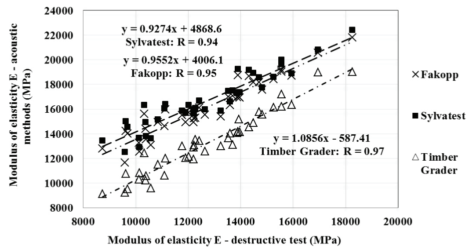

Fig. 5: Correlation between acoustic methods and destructive test.

Similarly, when evaluating the accuracy of non-destructive devices using acoustic methods, evaluation parameter is the correlations coefficient. These correlations have been proven between dynamic modulus of elasticity (Fakopp, Sylvatest) or static modulus of elasticity (Timber Grader) and static modulus of destructive tests (Fig. 5). The highest correlation coefficient achieves Timber Grader device. The main reason is that this device determines the modulus of elasticity based not only on the propagation of the acoustic signal, but also on the basis of wood species, moisture content, sample size and weight. In this case, the value of the correlation coefficient is 0.97. It indicates a very tight relationship. For Fakopp and Sylvatest the speed of propagation of an acoustic signal was obtained, and then the dynamic modulus of elasticity was calculated by Eq. 1. Even in these cases, the relationship is very tight. For Fakopp device the value of R is 0.95 and 0.94 for Sylvatest device. We can say that the acoustic method is appropriate for determining the modulus of elasticity, if the density of measured element is known. Many papers dealt with the degree of correlation between modulus of elasticity obtained by acoustic methods and real value of destructive tests. Mostly, authors also achieved high correlations. Wang et al. (2008) reported correlation in the interval 0.84 - 0.91 in paper describing four species of conifers. Pazlar et al. (2011) came to the correlation coefficient R = 0.87 for fir and spruce samples. Widmann (2011) tested samples of beech (R = 0.94). Johansson et al. (1996) found a correlation 0.92 (spruce). Íňiguez et al. (2007) tested pine samples and reported a correlation of 0.93. Ross and Pellerin (1991) presents a correlation coefficient in the interval 0.87-0.99, Dolejš (1997) 0.87, Kloiber (2008) 0.72 and Rohanová (2013) 0.98 for Sylvatest device.

Comparing the modulus of elasticity

For comparing the modulus of elasticity it is not only the degree of correlation that is important, but also the real value of modulus of elasticity. The curves comparing the obtained static modulus of elasticity are shown in Fig. 6. The full line represents the value of static modulus of elasticity obtained by the destructive tests. The modulus of elasticity obtained by Timber Grader MTG device most correspond with modulus of destructive tests. High degree of correlation confirms this fact. However, the average value of Timber Grader is approximately by 500 MPa higher than the average value of real modulus of elasticity of destructive tests. Similar results were also obtained for grading machine Metriguard. In this case, the average value of modulus of elasticity is higher by around 880 MPa. Only the values of modulus of elasticity given by machine Goldeneye 702 are lower by 2700 MPa on average. The results from this machine are thus reliable, even if the mutual coefficient of correlation 0.80 is lower than with Metriguard.

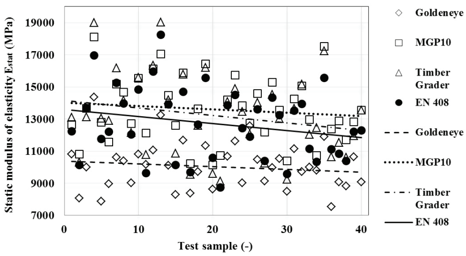

Fig. 6: Comparing the static modulus of elasticity.

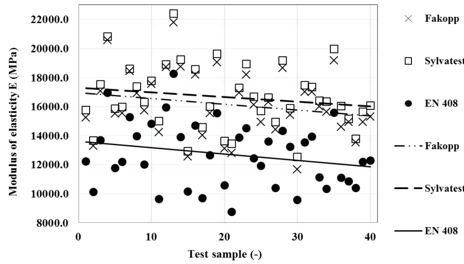

Fig. 7: Comparing the dynami cmodulus of elasticity with destructive tests.

The static modulus of elasticity which best defines class of timber, is usually approximately about 25 % lower than the dynamic modulus of elasticity. This is confirmed by values obtained from Sylvatest and Fakopp. The dynamic modulus of elasticity is higher than the static modulus from destructive tests (Fig. 7). The average value of modulus of elasticity is about 31 % higher with Sylvatest, which represents 3950 MPa. With Fakopp it is 27 % or 3450 MPa. In literature, there is no universal equation for conversion between dynamic and static modulus of elasticity. The conversion method depends on the method used, sample type, sample size, etc. It can be certainly said, that the resulting relations and correlations reported in the literature are very similar. Rohanová et al. (2011) gives the difference between dynamic and static modulus of elasticity observed for samples of spruce 17 % (1900MPa). Widmann (2011) presents the difference at beech samples 34 % (4900 MPa). Kim et al. (2011) state a difference of 39 % (3200 MPa). Baradit and Niemz (2011) present difference 33 % (2800 MPa) and Íñiguez et al. (2007) present 25 % (3300 MPa). It was always the dynamic modulus of elasticity measured by ultrasonic method.

Prediction of bending strength

Modulus of elasticity is closely related to strength. It could be said that it is the best indicator of strength, and thus classes of timber. Figs. 8 and 9 show the relationships between MoE detected by various methods and ultimate bending strength of the destructive test. As expected, the highest correlation coefficient was found between bending strength and modulus of elasticity of destructive tests (R = 0.92). From the other comparisons, the bending strength best correlates with the modulus of elasticity measured by Timber Grader (R = 0.86).

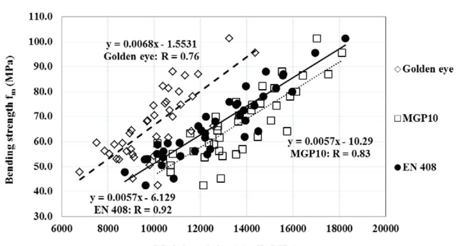

Fig. 8: The dependence of the bending strength on the modulus of elasticity – fading machine.

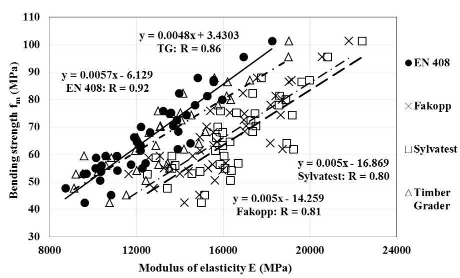

Fig. 9: The dependence of the bending strength on the modulus of elasticity – acoustic methods.

Correlation coefficients between static MoE from grading machines and bending strength from destructive tests are comparable with correlation coefficients between dynamic MoE from acoustic methods and bending strength (Goldeneye 702 – 0.76, Metriguard – 0.83, Sylvatest 0.80, Fakopp – 0.81). The results confirm the findings from the literature that the static MoE is a better indicator of strength than the dynamic MoE. Pazlar (2011) gives a correlation coefficient 0.82 for static MoE and interval of correlation coefficients 0.64 - 0.72 for dynamic MoE. Bucar et al. (2007) states 0.76 for static MoE and 0.64 for dynamic MoE. Faggiano (2013) also mentioned the correlation between strength and static modulus of elasticity (R = 0.69). The density is another suitable indicator of strength. Literature indicates correlation coefficients between 0.4 and 0.7 (Pazlar et al. 2011, Dolejš 1997, Rohanová et al. 2011, Bucar et al. 2007, Bartůňková 2011, Kuklík et al. 2014, Cruz and Machado 2013). The carried out experiments resulted in correlation coefficient 0.57 between density determined by weighing and strength from four bending tests.

CONCLUSIONS

The one of the aims of this paper was compare results from visual assessment with results from destructive tests. The correlation between strength classes determined by visual sorting and bending strength from the destructive tests reached 0.67. The correlation between modulus of elasticity corresponding to strength classes and modulus of elasticity from the destructive tests is 0.70. This confirms the good practical use of visual sorting.

The most important aim was to find the correlation between the MoE obtained by grading machines or devices for non-destructive evaluation in-situ and MoE from the destructive tests. The highest correlation coefficient was found for the Timber Grader device (Tab. 2). Other acoustic devices Sylvatest and Fakopp also show a tight relationship. However, we cannot overlook the fact that all three of these methods require the knowledge of density of timber element. Due to the high speed sorting and null input data, the correlation coefficients between values from grading machines and values from devices for non-destructive evaluation are comparable.

Tab. 2: The correlation coefficients between the modulus of elasticity from destructive tests and from other procedures.

	Goldeneye 702	Metriguard HLT 7200	Sylvatest	Fakopp	Timber grader
Coefficients of correlation R	0.80	0.94	0.94	0.95	0.97

Dynamic modulus of elasticity determined by acoustic methods (Sylvatest and Fakopp) came out about 31 and 27 % higher than the static modulus of elasticity from the bending test. This confirms the results from literature for spruce and other coniferous or deciduous timber.

The last aim was to find relationship between strength and density or MoE. The degree of correlation between density and bending strength reaches a value of 0.57. This is average value in comparison with the means of other papers. The modulus of elasticity has proven as the better predictor. For the static modulus of elasticity the correlation coefficient stands in the interval 0.76 - 0.86. The coefficient of correlation between strength and dynamic modulus of elasticity came out as 0.80 (Sylvatest) and as 0.81 (Fakopp). This confirms the findings from the literature that the static modulus of elasticity is a better indicator of strength than the dynamic.

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