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STRENGTH GRADING OF STRUCTURAL TIMBER USING THE SINGLE MODE TRANSVERSE DAMPED VIBRATION METHOD

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ABSTRACT

This paper presents the preliminary results of strength grading of spruce structural timber based on non-destructive testing using the dynamic method – the single mode transverse damped vibration method. The main objective of this study was to evaluate the used method through the examination of correlations between the MOE_{dyn} determined by transverse damped vibration of simply supported edgewise oriented boards, global edgewise MOE_{stat}, and MOR. In the study the European standards dealing with the strength grading was also considered. The correlations between the investigated properties were identified to be within the range reported by other researchers. Numbers of correctly graded, upgraded and downgraded specimens were established according to the EN 14081-2 with the size matrix. 38 % of specimens were assigned correctly, 60 % of specimens were downgraded and only 3 % of specimens were upgraded. We can evaluate the used dynamic method as an entirely reliable method but for final statistically significant conclusions a larger pattern should be considered.

KEYWORDS: Spruce, nondestructive testing, structural timber, modulus of elasticity, vibration method.

INTRODUCTION

To determine the mechanical properties of structural wood only non-destructive methods can be used. Various non-destructive methods, their reliability, and correlations of testing results were researched and compared in numerous studies. Those studies have in common the aim of finding the most suitable, objective, and reliable non-destructive method to determinate the relevant wood properties. This method also has to be economic and fast.

Modulus of elasticity derived from bending tests correlates well with modulus of rupture (Steiger and Arnold 2009). Coefficients of correlation R up to 0.7–0.8 are reported in the literature (Glos 1995). Since modulus of elasticity can be derived by non-destructive tests, it is a very important parameter for machine grading. Modulus of elasticity can be determined either by static bending tests or dynamic methods (vibration, ultrasound,…) (Hearmon 1966, Kollmann and Krech 1960).

This paper presents the preliminary results of grading based on the non-destructive testing of structural timber using the transversal frequency response method. The objectives of this study were: firstly, to investigate the correlations between the MOE_{dyn} determined by the dynamic method (transversal damped vibration of simply supported edgewise oriented boards), global MOE_{stat} based on the classical 4-point banding test and the modulus of rupture MOR; and, secondly, to study the European standards dealing with the strength grading and determination of machine settings according to these standards. For this purpose the laboratory measuring equipment was set for the frequency response dynamic measurements.

Background

The modulus of elasticity is a material property which is important both from the design and construction aspect and also that of technology. Numerous authors have dealt with the determination of elasticity modulus of constructionally and technologically interesting natural and artificially designed materials in particular. One of the first was certainly Goens (1931) who determined the modulus of elasticity and shear modulus from transverse vibration of test samples. Noteworthy work was done by Hearmon (1958) and Huang (1961), who also determined the modulus of elasticity and shear modulus of freely oscillating free specimens. Later and Hearmon (1966) described the basic procedures for determining the modulus of elasticity and shear modulus on the basis of the measured self-frequencies of transverse, longitudinal and torsional vibration of prism shaped test samples. They were followed by numerous researchers who determined moduli on the basis of transverse and longitudinal vibration with emphasis on various details (Chui 1991, Haines et al. 1995, Ilic 2003).

The advantages of the dynamic response measurements in the acoustic domain are high degree of repeatability (Perstoper 1994), rapid and accurate means for determining MOE and also the low costs of equipment (Halabe et al. 1997). In the case of uniform specimens, including industrial size material, vibration methods have special advantages including simplicity, speed and convenience of use (Ilic 2001).

Jayne (1959) designed and conducted one of the earliest studies that utilized transverse vibration techniques of evaluating the strength of wood. He was successful in demonstrating the relationship between energy storage and dissipation properties, measured by forced transverse vibration techniques, and the static bending properties of small clear wood specimens. Since then transverse vibration techniques have received considerable attention for nondestructive evaluation applications. The summary of several research studies using the free transverse vibration nondestructive evaluation techniques and equipment for free transverse vibration techniques is listed in Pellerin and Ross (2002).

Damped vibration of simply supported thin cantilever

Dependences between natural frequencies of transverse vibrating prismatic elements and specific boundary conditions, such as free, simple and rigid clamping of test samples have been known for a long time (Weaver et al. 1990). In practice, the free end is the easiest to make, and therefore the majority of researchers who were engaged in experimental determination of modulus of elasticity used test samples with both their ends free, and in some cases simply supported. In general, in accordance with the Bernoulli-Euler theory of vibration of thin beams which does not take into account the effect of the moment of inertia or rotational inertia and shear deformations, we can express a time-dependant transverse vibration of a thin mechanical structure in the plane x, y which represents an axis of symmetry for any lateral cross-section of a structure with a differential equation.

$$\frac{\partial^2}{\partial x^2}\left(EI\,\frac{\partial^2 y}{\partial x^2}\right)dx = -\rho A dx\,\frac{\partial^2 y}{\partial t^2} \qquad (1)$$

In the equation (1), x denotes a coordinate along the vibrating structure, y denotes a lateral displacement of the structure, A and I are geometrical parameters determining the cross-sectional area and the moment of inertia of the structure cross-section, while E and ρ denote features of the relevant material, modulus of elasticity and density. If the bending rigidity of the structure (EI) does not vary along the x axes, the solution of the differential equation may be presented as follows:

$$y(x,t) = \sum_{i=1}^{\infty} u_i(x)\cdot q_i(t) \qquad (2)$$

where: u(x) is a function of mode shape (2), and q(t) is a function of the time-dependent modal coordinate. Index i applies to the i^{th} root of the frequency equation. The natural frequency of a certain vibration mode of a thin mechanical structure with a length of l can be expressed as follows:

$$\omega_i = (\eta_i l)^2 \sqrt{\frac{EI}{\rho A l^4}} \qquad (3)$$

whereby the product n_i l is the i^{th} root of the characteristic frequency equation.

MATERIAL AND METHODS

For the present research the sawn spruce wood (*Picea abies* Karst.) with two different cross sections were obtained from two middle-sized sawmills in Slovenia. The boards were visually graded according to the internal standards of sawmills and marked as appropriate for construction timber. The boards were kiln dried to an average final moisture content of 12 %. After drying, the boards were machined to the final dimensions 38 x 175 x 4 000 mm (99 boards – sample 1), or 20 x 130 x 4 000 mm (99 boards – sample 2), respectively.

Dynamic modulus of elasticity determined by the single mode transversal decayed vibration method

For nondestructive testing, the dynamic modulus of elasticity was determined by response of simply supported edgewise oriented boards excited in the natural flexural damped vibration modes. The laboratory equipment was set for this purpose (Fig. 1).

The edgewise oriented specimens were simply supported by two thin nylon wires located at 0.224 and 0.776 of length of the specimens. In preliminary test the specimen was excited mechanically and the response of the system was measured by microphone and to the sample attached accelerometer. We made the comparison of frequency spectra of the time signals obtained from both sensors. In accordance to our expectations, we did not find significant differences. In further investigation we use only the condenser microphone. Using a microphone, we applied a 10 Hz sampling frequency to monitor the signal of the pressure differences in the ambient medium which are caused by a transverse vibrating test sample. The values measured were captured by a personal computer with LabView software and an AT MIO 16E measurement card produced by National Instruments. The frequency structure of the captured time-dependent signal was determined by a FFT. On the basis of frequency data and the data of mass and dimensions of the specimens, the dynamic modulus was calculated using equation (4).

$$E_d = \frac{(2\pi\nu)^2 \times \rho \times A \times l^4}{(\eta_1 l)^4 \times I} \quad (Pa) \tag{4}$$

where:
E_d = dynamic modulus of elasticity ($N.mm^{-2}$),
I = moment of inertia (m^4),
ρ = density ($kg.m^{-3}$),
A = cross section area (m^2),
l = length of specimen (m),
υ = natural frequency (Hz).

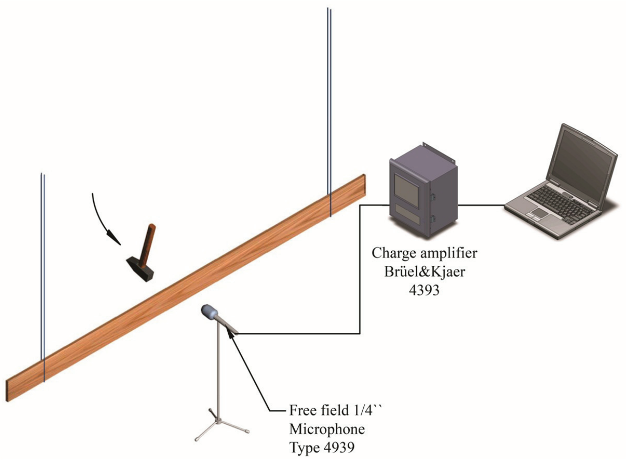

Fig. 1: Experimental system

Static modulus of elasticity and modulus of rupture

The global modulus of elasticity MOE_{stat} (classical 4-point bending test) was measured according to EN 408 standard. The specimens were tested edgewise. The actual bending strength (modulus of rupture, MOR) was also determined using the destructive method according to the EN 408 standard. The global static modulus of elasticity (MOE_{stat}) and the density of each board were then adjusted to the 12 % reference moisture content, and the bending strength was normalized to 150 mm depth as required in the EN 384 standard.

Grading into strength classes

The optimal grade, frequency and global cost matrices were made according to the EN 14081-2 standard. The grade determining properties, used for optimal grading, were: bending strength values (MOR), global static modulus of elasticity (MOE_{stat}) and density. Density was measured according to the ISO 3131 standard. The characteristic values of mechanical properties (5-percentile value MOR_{05}, mean characteristic modulus of elasticity $MOE_{stat\text{-}mean}$) and density (characteristic density ρ_{05}) were determined according to the EN 384 standard.

Each specimen was sorted on the basis of the grade determining properties into the highest possible grades. The modified characteristic values (MOR_{05}, $MOE_{stat\text{-}mean}$, ρ_{05}) meet the requirements of EN 338, EN 384 and EN 14081-2 standards. The grade thus determined for each specimen indicates its optimum grade. Each specimen was graded to the C30, C24, C16 class, or rejected.

The grades were assigned on the basis of the dynamic test results (MOE_{dyn}). The size matrix was made on the basis of the optimum grade and the assigned grade. The size matrix is given as the number of correctly graded, upgraded and downgraded specimens. The settings for our testing sets were calculated on the basis of the indicating property (MOE_{dyn}), the cost matrix and the characteristic values of assigned grades.

RESULTS AND DISCUSSION

Figs. 2 and 3 present the frequency distribution of the dynamic modulus of elasticity (MOE_{dyn}), which is our indicated property.

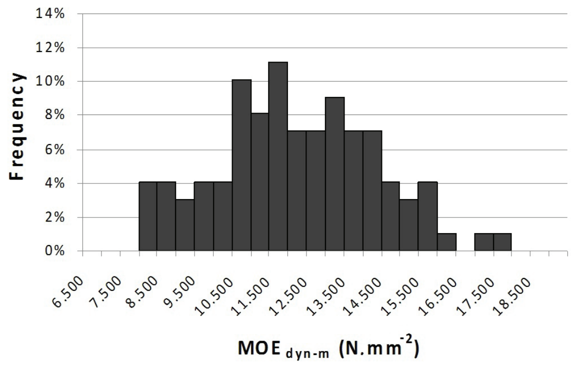

Fig. 2: Frequency plot of MOE_{dyn}, Sample 1

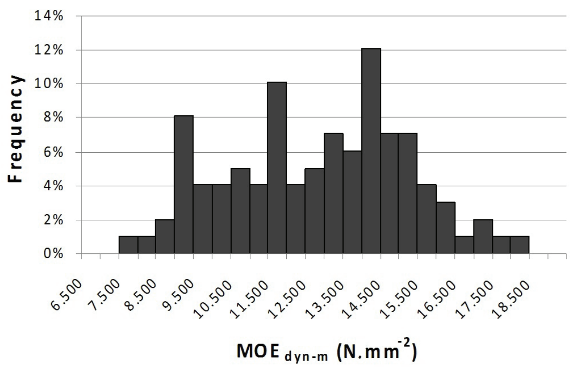

Fig. 3: Frequency plot of MOE_{dyn}, Sample 2

Comparing the results of the static bending test (MOE_{stat}) with the results of dynamic testing (MOE_{dyn}) presented in Tab. 1, we can see that MOE_{dyn} indicate higher values than the static ones, which is also reported by other authors (Kollmann and Cote 1984, Ilic 2001, Erikson et al. 2000, Divos and Tanaka 2005, Wang et al. 2004).

Tab.1: Dynamic (MOE_{dyn}) and static (MOE_{stat}) modulus of elasticity

	Sample 1		Sample 2	
	MOE_{dyn} (MPa)	MOE_{stat} (MPa)	MOE_{dyn} (MPa)	MOE_{stat} (MPa)
Mean	11753	10968	12365	11308
Max	17264	115563	18199	15413
Min	7630	6753	7544	7164
Stdev	2120	1889	2391	1977

Although the correlation between bending strength (MOR) and some other properties are known (Denzler et al. 2005, Gallingan and Kerns 2002) we evaluated the transverse vibration method by correlating the investigated properties (Tab.2). As we can see, there is a rather poor correlation between bending strength and density. The correlation coefficients for MOR versus the static MOE_{stat} were 0.66 and 0.82, and MOR versus dynamic MOE_{dyn} were 0.50 and 0.72, respectively. We confirmed the findings of Halabe et al. (1997) who also noticed that the MOR values correlate better with the statical defined modulus MOE_{stat} compared to the dynamical defined modulus MOE_{dyn}. They stated that the main reason for this was that the static bending was a direct measurement technique, whereas the NDT measurements were indirect. As shown in Figs. 4 and 5, the correlation between MOE_{stat} and MOE_{dyn} is very good and the coefficient of determination is 0.84 in case of sample 1 and 0.83 in case of sample 2. These coefficients of determination are within the range reported by other researchers (Denzler et al. 2005, Halabe et al. 1997, Steiger and Arnold 2009).

Tab. 2: Correlation coefficients of the investigated properties

	Sample 1				Sample 2			
	MOR	MOE_{stat}	density	MOE_{dyn}	MOR	MOE_{stat}	density	MOE_{dyn}
MOR	1				1			
MOE_{stat}	0.66	1			0.82	1		
density	0.33	0.68	1		0.41	0.57	1	
MOE_{dyn}	0.50	0.92	0.85	1	0.72	0.91	0.67	1

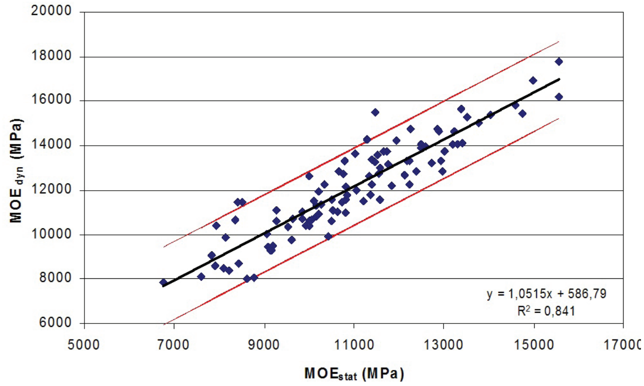

Fig. 4: Regression between dynamical defined modulus of elasticity MOE_{dyn} and modulus of elasticity defined by static bending tests MOE_{stat} with 95 % confidential limits (red lines) (Sample 1: n = 99, Stdev = 867.7 MPa)

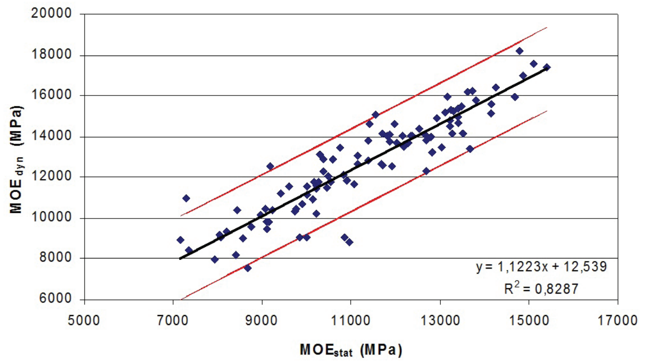

Fig. 5: Regression between dynamical defined modulus of elasticity MOE_{dyn} and modulus of elasticity defined by static bending tests MOE_{stat} with 95 % confidential limits (red lines) (Sample 2: n = 99, Stdev = 1013.8 MPa)

The settings for our grading device (set) were defined on the basis of the results of all investigated properties. All the specimens having a dynamic modulus of elasticity greater than 13 700 $N.mm^{-2}$ were graded to C30, specimens with MOE_{dyn} greater than 13 000 $N.mm^{-2}$ were graded to C24, and specimens with MOE_{dyn} greater than 8 900 $N.mm^{-2}$ were graded to C16 (Gornik Bučar et al. 2007).

Numbers of correctly graded, upgraded and downgraded specimens were established according to the EN 14081-2 with the size matrix. 38 % of specimens were assigned correctly, 60 % of specimens were downgraded and only 3 % of specimens were upgraded. The EN 14081-2 standard requires that the values in the global cost matrix cells, which indicate the incorrectly upgraded specimens, must not be greater than 0.2. In our case this criterion has been met in full.

On the basis of the results of the frequency and global cost matrix we can evaluate the dynamic method used – the response of the simply supported edgewise oriented boards excited in natural flexural damped vibration modes – as an entirely reliable method, but a bigger pattern should be considered for reaching final statistically significant conclusions.

CONCLUSION

In the present research, spruce structural timber were graded to three strength grades on the basis of the single mode transverse damped vibration method. The correlations between the investigated properties were identified to be within the range reported by other researchers. Correlation between MOE_{stat} and MOE_{dyn} is very good and the coefficient of determination is 0.84 in case of sample 1 and 0.83 in case of sample 2. The settings for equipment used were defined according to the EN 14081-2 standard. The grading procedure used is completely reliable and, we can say, even conservative. The research was performed in laboratory conditions, on small number of specimens. In the further investigations the possibility of applying the single mode transverse damped vibration method should be examined in industrial conditions, on a larger pattern and on green wood.

REFERENCES

1. Chui, Y. H., 1991: Simultaneous evaluation of bending and shear moduli of wood and the influence of knots on these parameters. Wood Science and Technology 25: 125-134.
2. Denzler, J.K., Diebold, R., Glos, P., 2005: Machine strength grading - commercially used grading machines - current developments. In: Proceedings of the 14th International Symposium on Nondestructive Testing of Wood. University of Applied Science, Eberswalde. Pp 11-16.
3. Divos, F., Tanaka. T., 2005: Relation between static and dynamic modulus of elasticity of wood. Acta Silv. Lign. Hung. 1: 105-110.
4. EN 338, 2003: Structural timber - Strength classes.
5. EN 384, 2004: Structural timber - Determination of characteristic values of mechanical properties and density.
6. EN 408, 2003: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties.
7. EN 14081-2, 2005: Timber structures - Strength graded structural timber with rectangular cross section - Part 2: Machine grading, additional requirements for initial type testing.
8. Erikson, R.G., Gorman, T.M., Green, D.W., Graham, D., 2000: Mechanical grading of lumber sawn from small-diameter lodgepole pine, ponderosa pine and grand fir trees from Northern Idaho. Forest Product Journal 50(7/8): 59-65.
9. Gallingan, W., Kerns, J., 2002: Mechanical grading of lumber. In : Pellerin, Ross: Nondestructive evaluation of wood. Madison, Forest Produts Society. Pp 93-128.
10. Glos, P., 1995: Step A6: Festigkeitssortierung. In: Holzbauwerke nach Eurocode 5. Step 1: Bemessung und Baustoffe, Informationsdienst Holz. Arbeitsgemeinschaft Holz e. V., Düsseldorf, Germany.
11. Goens, E. 1931: Über die Bestimmung des Elastizitätsmoduls von Stäben mit Hilfe von Biegungsschwingungen. Annalen der Physik 11: 649-678.

12. Gornik Bučar, D., Šega, B., Merhar, M., Čepon, M., Bučar, B., 2007: Strength grading of structural timber using the transverse frequency response method. Proceedings of the 15th International Symposium on Nondestructive Testing of Wood, September 10-12, 2007. Deluth, Minnesota, USA. Pp 79-84.
13. Haines, D. W., Leban, J. M., Herbé, C., 1995: Determination of Young´s modulus for spruce, fir and isotropis materials by the resonance flexure method with comparison to static flexure and other dynamic methods. Wood Science and Technology 30: 253-263.
14. Halabe, U. B., Bidigalu, G. M., Gangarao, H.V.S., Ross, R.J., 1997: Nondestructive evaluation of green wood using stress wave and transverse vibration techniques. Material Evalution 55(9): 1013-1018.
15. Hearmon, R. F. S., 1958: The influence of shear and rotary inertia on the free flexural vibration of wooden beams. British Journal of Applied Physics 9: 381-388.
16. Hearmon, R., 1966: Vibration testing of wood. Forest Product Journal 16 (8): 29-40.
17. Huang, T. C., 1961. The Effect of rotary inertia and of shear deformation on the frequency and shear deformation on the frequency and normal mode equations of uniform beams with simple end coditions. Journal of Applied Mechanics 28: 579-584.
18. ISO 3131, 1975: Wood – Determination of density for physical and mechanical tests.
19. Ilic, J. 2001: Relationship among the dynamic and static elastic properties of air-dry *Eucalyptus delegatensis*. R. Baker. Holz als Roh - und Werkstoff 59: 169-175.
20. Ilic, J., 2003. Dynamic MOE of 55 species using small wood beams. Holz als Roh- und Werkstoff 61: 167-172.
21. Jayne, B. 1959: Vibration properties of wood. Forest Product Journal 9(11): 413-416.
22. Kollmann F., Krech, H., 1960: Dynamische Messung der elastischen Holzeigenschaften und der Dämpfung. Holz als Roh- und Werkstoff 18(2): 41–54.
23. Kolmann, F., Cote. W.A., 1984: Principles of wood science and technology. Part I. Solid Wood; Springer – Verlag, Berlin, 302 pp.
24. Pellerin, R.F., Ross. R.J., 2002: Nondestructive evaluation of wood. Forest Prod. Soc., Madison, Wisconsin. Pp 13-35.
25. Perstoper, M., 1994: Strength and stiffness prediction of timber using conventional and dynamic methods. In: Proc. of the 1st European symposium on nondestructive evaluation of wood. Univ. of Sopron, Hungary. Pp 321-330.
26. Steiger R., Arnold, M., 2009: Strength grading of Norway spruce structural timber: revisiting property relationships used in EN 338 classification system. Wood Science and Technology (43): 259-278.
27. Wang, S.Y., Yang, T.H., Tsai. M.J., 2004: Evaluation of the mechanical properties of Duglas-fir lumber and it's structural glulam by non-destructive techniques. In: Proceedings of the 8th World Conference on Timber Engineering WCTE 2004. Volumen II. Pp 179-183.
28. Weaver, W., Timoshenko, S. P., Young, D. H., 1990. Vibration problems in engineering 5th Edition. New York, John Wiley & Sons, 610 pp.

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