WOOD RESEARCH
56 (2): 2011
157-168

STRENGTH AND STIFFNESS PROPERTIES OF THE LITHUANIAN GROWN SCOTS PINE (*PINUS SYLVESTRIS*): NON-DESTRUCTIVE TESTING METHODS VS. STATIC BENDING

A. Baltrušaitis, S. Mišeikytė
Kaunas University of Technology, Department of Mechanical Wood Technology
Kaunas, Lithuania

(Received April 2010)

ABSTRACT

In this paper, the comparisons of modulus of elasticity MOE and resulting modulus of rupture MOR, determined using different dynamic and static testing methods is presented. Those consisted of amplitude resonance (dynamic MOE) method, two approaches of long span bending method, and industrial Metriguard machine stress rating method. All these non-destructive testing results were compared with standard 4-points bending testing MOE and MOR. The uncertainties of bending and 3-point ASTM Long Span tests were evaluated and uncertainty of Metriguard method was derived from calibration certificate for validation the interrelations of received models describing Lithuanian grown pine strength and stiffness.

KEYWORDS: Sawn timber, non-destructive methods, bending test, measuring uncertainties, stiffness – strength of wood.

INTRODUCTION

The mechanical properties of wood and integrated data processing are analyzed from early 1900's. First researches were made using bending tests in order to predict wood strength and stiffness. Since that time wood industry became much more modern and the need of faster measurement of wood properties increased. For this reason the non-destructive methods were developed when wood properties are analyzed with the help of some special equipment. In this case, it is necessary to predict uncertainty of measurement, "because the capability of an indirect measurement to predict strength can never be perfect and always includes measurement errors" (Hanhijärvi et al. 2005).

The base of non-destructive tests is estimation and measurement of the secondary wood properties, like visual parameters (knots size), moisture content, natural frequency, slope of grain, density (Ross et al. 1996, Denzler 2007, Rajeshar et al. 1997). Where upon using standard and special formulas or software the strength of timber is calculated. Therefore many investigations are made in order to estimate the coefficient of determination between non-destructive methods and destructive tests (Divos and Tanaka 2005, Schafer 2000). The different species of softwood (Krzosek et al. 2008, Mišeikyte and Baltrušaitis 2009, Baltrušaitis and Pranskievičiene 2003) and hardwood (Ravenshorst et al. 2006, Baltrušaitis et al. 2009) are used in researches. In both cases good correlation between non-destructive and destructive tests were achieved.

This paper represents comparative study of three non-destructive tests using special equipment for modulus of elasticity (MOE): the Timber Grader MTG, Long Span stiffness bending test and Metriguard MSR machine, and 4-point edgewise bending test. Destructive bending test followed standard EN 408 stiffness testing (EN 338 2004, EN 408 2006). The uncertainties of MOE measurement were calculated for all tests results. The main target was to examine how timber specimen individual stiffness-strength reducing characteristics affect different NDT and static testing procedures and measured values uncertainties and variability.

MATERIAL AND METHODS

Lithuanian grown Scots pine (*Pinus sylvestris* L.) was tested in the current research. The average dimensions of specimen were 3006 (length) x 90 (width) x 35 (thickness) mm. Width and height were measured using calipers (accuracy ± 0.01 mm) and length was measured using ruler (accuracy ± 1 mm). They were numbered from 1 to 40 in random way. The specimens represented centre yield battens from 200 – 220 mm diameter logs. Then they were weighted using Kern scales (accuracy ± 0.01 kg), moisture content was measured using electronic moisture meter (accuracy ± 0.1 %).

The experiment contained 3 non-destructive tests equipment: the Timber Grader MTG, Long Span and Metriguard, and 4-point edge bending.

Firstly, dynamic MOE was determined with the MTG device measuring natural frequency of the timber specimens. All the information about species (length, width, thickness, weight and moisture content) was tabled to the computer program, which calculated density for 12 % moisture content. Whereupon the device (Fig. 1a) was attached to the end of specimen, the acoustic–wave was released, the intensity of it measured and the E calculated and sent to the computer (Rozema 2007). In the current research the uncertainty of this device is not calculated, as the formula of modulus of elasticity, as well data processing procedures which are used for calculating E, is unknown.

Secondly, the specimens were tested on the 3-point Long Span flat wise bending test equipment (Fig. 1b). After deflection by placing first constant loading mass (3.381 kg) in the specimen middle length initial deformation was fixed by calliper. In order to get linear relation between force and deflection the second loading mass (3.379 kg) is applied to force the specimen and to record the deformation value by the calliper. Then the MOE was calculated using standard 3-point bending formula (Mišeikyte and Baltrušaitis 2009, Baltrušaitis and Pranskievičiene 2003):

$$E_{ls} = \frac{9.81 m l^3}{4 h b^3 (\omega)} \text{ (MPa)} \tag{1}$$

where: m – the second constant loading mass (3.397 kg)
l – the span length (2980 mm)
h – the height of specimen (90 mm)
b – the width of specimen (35 mm)
ω – deflection of specimen (mm)

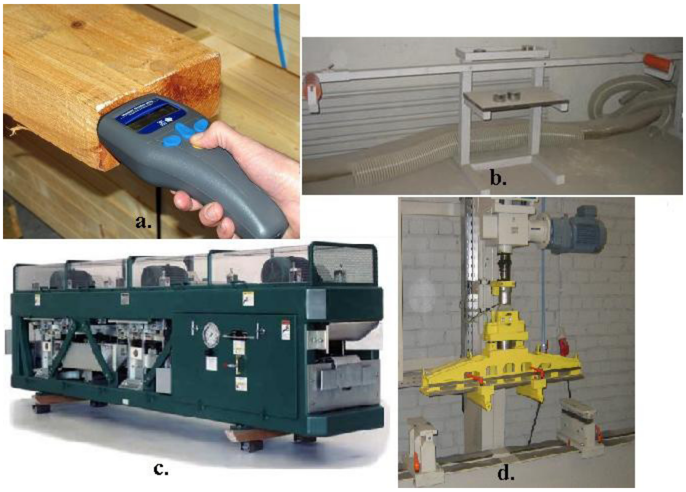

Fig. 1: Test equipment: a) Timber Grader MTG b) Long Span c) Metriguard d) Bending machine

As seen from formula width of the specimen has the main effect on the accuracy. The relative extended Long Span uncertainty may be expressed on the basis of (1) as:

$$u_E = 2 \cdot \sqrt{\sum_{i=2}^{3} (u_{mi} \cdot c_m)^2 + \sum_{i=1}^{3} (u_{li} \cdot c_l)^2 + \sum_{i=1}^{3} (u_{hi} \cdot c_h)^2 + \sum_{i=1}^{3} (u_{bi} \cdot c_b)^2 + \sum_{i=1}^{3} (u_{\omega i} \cdot c_{\omega})^2} \tag{2}$$

where: u_{mi}, u_{li}, u_{hi}, u_{bi} *and* $u_{\omega i}$ are the relative standard (corresponding to the load mass, specimen length, height, width and deflection) measurement uncertainties; c_x are the coefficients of influence (corresponding to the load mass, specimen length, height, width and deflection).

The relative standard measurement uncertainties consist from three types uncertainties, calculated as:

$$u_{x1} = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2}{2(n-1)}} \tag{3}$$

where: x_1, x_2 – measured parameter value (length, height, width and deflection);

$\bar{x}$ – the mean value of parameter (length, height, width and deflection);
n – the amount of measurements.

$$u_{x2} = \frac{U}{k} \tag{4}$$

where: U – the uncertainty from measurement device calibration certificate;
k – coefficient of variation principle from measurement device calibration certificate.

$$u_{x3} = \frac{a}{2\sqrt{3}} \tag{5}$$

where: a – section value of measurement device.

Coefficients of influence were calculated as:

$$\frac{\partial E_{ls}}{\partial m} = \frac{l^3}{4hb^3(w)\cdot 100} = c_m \frac{1}{\text{mm}^2} \tag{6}$$

$$\frac{\partial E_{ls}}{\partial l} = \frac{3ml^2}{4hb^3(w)\cdot 100} = c_l \frac{1}{\text{mm}^2} \tag{7}$$

$$\frac{\partial E_{ls}}{\partial h} = -\frac{ml^3}{4h^2b^3(w)\cdot 100} = -c_h \frac{1}{\text{mm}^2} \tag{8}$$

$$\frac{\partial E_{ls}}{\partial b} = -\frac{ml^3}{12hb^4(w)\cdot 100} = -c_b \frac{1}{\text{mm}^2} \tag{9}$$

$$\frac{\partial E_{ls}}{\partial \omega} = -\frac{ml^3}{4hb^3(w^2)\cdot 100} = -c_\omega \frac{1}{\text{mm}^2} \tag{10}$$

After calculating the uncertainties the main value of modulus of elasticity was written as:

$$E_{ls} \pm u_E (N\ .\ mm^{-2}) \tag{11}$$

Thirdly, the specimens were tested by passing specimens flat-wise through Metriguard machine (Fig. 1 c). This device has two load cells creating the pressure on the flat side of specimen. The software measures the deflection and calculates the MOE data. The uncertainty for this device was taken from calibration certificate.

Finally, the specimens were placed on the 4-point bending machine (Fig. 1 d). The limits of linear correlation between force and deflection were set at range 0.2 F_{max} – 0.4 F_{max} according to the standard EN 408. At this range loading was stopped and deflection calliper was used to measure deflection for further MOE calculation. Then force was added again till the specimens were broken and MOR calculated.

Accordingly to standard EN 408, modulus of elasticity was calculated using standard 4-point bending formula:

$$E_b = \frac{3al_1^2(F_2 - F_1)}{4bh^3(\omega_2 - \omega_1)} \tag{12}$$

where: a – distance between the loading position and nearest support in bending test (450 mm)
l_1 – gauge length for the determination of modulus of elasticity (1660 mm)
F_1-F_2 – is an increment of load in Newtons on the regression line with a correlation coefficient of 0.99 or better
ω_1-ω_2 – is the increment of deformation in millimetres corresponding to F_2-F_1
h – the height of specimen (90 mm)
b – the width of specimen (35 mm)

As seen from formula the specimen height has the main effect on the accuracy. The relative extended 4-point bending uncertainty may be expressed on the basis of (12) as:

$$u_E = 2 \cdot \sqrt{\sum_{i=1}^{3}(u_{F1i} \cdot c_1)^2 + \sum_{i=1}^{3}(u_{F2i} \cdot c_2)^2 + \sum_{i=1}^{3}(u_{\omega 1i} \cdot c_3)^2 + \sum_{i=1}^{3}(u_{\omega 2i} \cdot c_4)^2 + \sum_{i=1}^{3}(u_{hi} \cdot c_5)^2 + \sum_{i=1}^{3}(u_{bi} \cdot c_6)^2 + \sum_{i=1}^{3}(u_{ai} \cdot c_7)^2 + \sum_{i=1}^{3}(u_{l1i} \cdot c_8)^2} \tag{13}$$

where: u_{xi} are the relative standard (corresponding to the load, deflection, underlying length, distance between the load point and nearest support, specimen length, height and width) measurement uncertainties; c_y (y= 1...8) are the coefficients of influence (corresponding to the load, deflection, underlying length, distance between the load point and nearest support, specimen length, height and width).

The relative standard measurement uncertainties consist from three types uncertainties, calculated with (3), (4) and (5) formulas.

Coefficients of influence were calculated as:

$$\frac{\partial E_m}{\partial F_1} = \frac{3al_1^2}{4bh^3(w_2 - w_1)} = \mathrm{c}_1 \frac{1}{\mathrm{mm}^2} \tag{14}$$

$$\frac{\partial E_m}{\partial F_2} = -\frac{3al_1^2}{4bh^3(w_2 - w_1)} = -\mathrm{c}_2 \frac{1}{\mathrm{mm}^2} \tag{15}$$

$$\frac{\partial E_m}{\partial w_1} = -\frac{3al_1^2(F_2 - F_1)}{4bh^3 w_1^2} = -\mathrm{c}_3 \frac{1}{\mathrm{mm}^2}; \tag{16}$$

$$\frac{\partial E_m}{\partial w_2} = \frac{3al_1^2(F_2 - F_1)}{4bh^3 w_2^2} = \mathrm{c}_4 \frac{1}{\mathrm{mm}^2}; \tag{17}$$

$$\frac{\partial E_m}{\partial h} = \frac{(-3)3al_1^2(F_2 - F_1)}{4bh^4(w_2 - w_1)} = -\mathrm{c}_5 \frac{1}{\mathrm{mm}^2} \tag{18}$$

$$\frac{\partial E_m}{\partial b} = -\frac{3al_1^2(F_2 - F_1)}{4b^2h^3(w_2 - w_1)} = -c_6 \frac{1}{\mathrm{mm}^2} \tag{19}$$

$$\frac{\partial E_m}{\partial a} = \frac{3l_1^2(F_2 - F_1)}{4bh^3(w_2 - w_1)} = c_7 \frac{1}{\mathrm{mm}^2} \tag{20}$$

$$\frac{\partial E_m}{\partial l_1} = \frac{3al_1\,(F_2 - F_1)}{2bh^3(w_2 - w_1)} = c_8 \frac{1}{\mathrm{mm}^2} \tag{21}$$

After calculating the uncertainties the main value of modulus of elasticity was written as:

$$E_b \pm u_E (N\,.\,mm^{-2}) \tag{22}$$

When all possible uncertainties were calculated and the interval of modulus of elasticity was determined for all the tests, the non-destructive tests and 4-point bending test were compared and the conclusions were made.

RESULTS AND DISCUSSION

The experiment was made with three non-destructive tests: Timber Grader MTG, Metriguard, Long Span; and destructive 4-point bending test. The comparison of all results (Figs. 2 and 3) was made on purpose to establish Lithuanian grown pine (*Pinus sylvestris* L.) characteristics and strength classes as well as selection the best and accurate way to measure them is commented comparing coefficients of determination.

In the Fig. 2 is given correlation between modulus of elasticity (E) and ρ (density).

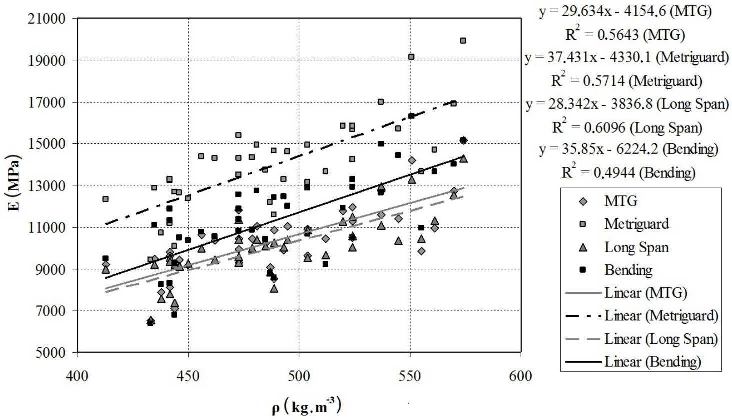

Fig. 2: Modulus of elasticity and density interrelation (all tests)

Fig. 2 shows that the lowest E = 6393 MPa was received in bending test for the same specimen density ρ = 433 $kg.m^{-3}$ (initial MC 16.2 %) as in non-destructive tests, whereas the highest E = 19890 MPa was when ρ = 574 $kg.m^{-3}$ and MC 13.9 % and it was obtained in test with Metriguard, while the highest value of E = 16301.7 MPa in bending was received when ρ = 551 $kg.m^{-3}$ and MC 12.4 %. Still the best coefficient of determination R^2 = 0.61 between E and ρ was gained in Long Span test. The worst – in bending test (R^2 = 0.49). The results are in line or slightly better than the commonly accepted average values of coefficients of determination R^2 = 0.4 – 0.6, (Denzler 2007). Prediction of stiffness based on density alone is highly variable and dependent on used NDT method. Additional problems appear in estimating and validation of reliability of those methods (Rozema 2007).

In order to specify the best and accurate non-destructive E-MOR prediction method, all methods and results were compared. As the best correlation is between E and MOR in static bending the 4-point static bending test MOR-E values were compared with the dynamic E out of Timber Grader MTG and flat-wise static bending E of Metriguard and Long Span (Fig. 3).

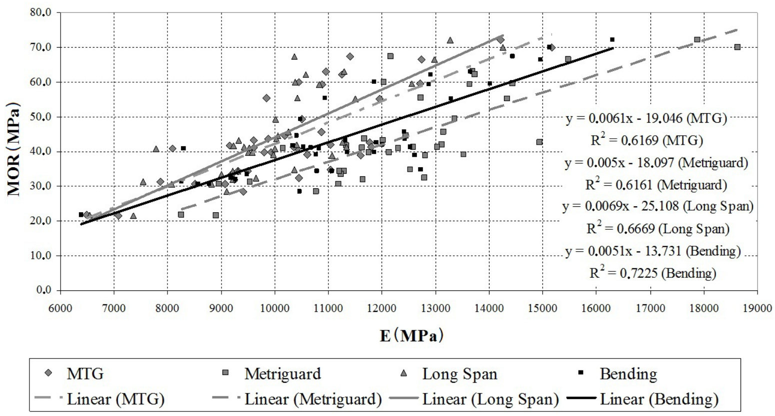

Fig. 3: Modulus of elasticity and modulus of rupture interrelation (all tests)

The best results were achieved with the Timber Grader MTG, as seen from Fig. 3. It is because that its linear model is closest to the static 4-point bending linear approximation. Long Span MOE values are slightly lower for the same MOR level. MOE values from Metriguard are on average higher by 10.6 % than those received from 4-point bending test, what makes better timber grading yield; on the other hand strength prediction is overestimated compared with the real strength of timber. Similar dataset is typical for static-dynamic E-MOR interrelations and strength prediction models; however, indirectly measurement uncertainties usually are not disclosed and commented (Ravenhorst et al. 2006, Krzosek et al. 2008).

To explain that phenomenon measurement uncertainties of Long Span and 4-point bending tests were calculated for determination realistic changing intervals of measured modulus of elasticity values. The uncertainty of device Timber Grader MTG is not calculated and the value is accepted as exact. Uncertainty of Metriguard machine is taken from calibration document. All results are given in Tab. 1.

Tab. 1: Statistics of measured parameters

	E				MOR
	MTG	**Metriguard**	**Long Span**	**Bending**	**Bending**
Mean (MPa)	10351	12478	10035.9	11323.5	44.3
Minimum, (MPa)	6488	9440	6554.1	6392.9	21.5
Maximum, (MPa)	15168	19890	14257.8	16301.7	72.2
Standard Deviation, (MPa)	1695.9	2128.6	1560.5	2191.8	13.2
COV	0.16	0.15	0.16	0.19	0.30
Standard Error (MPa)	268.2	336.6	246.7	346.6	2.1

Such standard statistics show only between-board E and MOR variation assuming separate measured results as accurate. However, each measured value possesses measurement uncertainty depending on measurement instruments accuracy (calibration) and also on calculation method (formula). Therefore, the uncertainties of Long Span and 4-point bending tests were calculated in order to determine the measuring uncertainties - variation intervals - of measured values for calculated modulus of elasticity. The uncertainty of device Timber Grader MTG was not calculated and the value was accepted as exact. Uncertainty of Metriguard machine is taken from calibration document. All results are given in Tab. 2.

Tab. 2: Uncertainties of modulus of elasticity

Method of measurement	**The mean MOE (MPa)**	**Uncertainty (MPa)**
Timber Grader MTG	10351	±0
Long Span	10035.9	±48.0
Metriguard	12478	±250
4-point bending	11323.5	±1014.1

Uncertainty of Long Span test was calculated using formulas for standard 3-point bending tests. The gained mean value was the best-received variation comparing with other tests. For bending test uncertainty was calculated using standard 4-point bending formula and it was the highest from all tests. This makes calibration of bending-type grading machines somehow indeterminate. The uncertainty of Metriguard machine was taken from calibration certificate based on bending test and thus also very much formula-related. The uncertainty of Timber Grader MTG is not calculated and modulus of elasticity is taken as exact.

The realistic intervals of average values of modulus of elasticity including measurement uncertainties for all tests are:

1. Long Span

$$9987.9 \le E_{ls} \le 10083.9 \; (MPa) \tag{23}$$

2. Metriguard

$$12228 \le E_{m} \le 12728 \; (MPa) \tag{24}$$

3. 4-point bending

$$10309.4 \le E_{b} \le 12337.6 \; (MPa) \tag{25}$$

4. Timbed Grander MTG

$$E_{mtg} = 10351 \; (MPa) \tag{26}$$

How it can be seen from formulas (23) – (25), E variation ranges for separate tests are: 96 MPa for Long Span; 500 MPa for Metriguard; 2028.2 MPa for 4-point bending (EN 408) and not applicable for Timber Grader MTG. Opposite to the routine statistical COV and dispersion calculation (Ross et al. 1996, Rajeshvar et al. 1997), estimation of measurement uncertainties emerge dramatically differences in realistic interval of measured values. Maximum value of Long Span gets into allowable values interval according to bending test; the minimum value of Long Span is lower than bending tests by 3.1 %. For Metriguard, as seen comparing formulas (24) and (25), minimal value of modulus of elasticity falls into interval of allowable bending tests values; though the maximal value is by 3.2 % bigger. The value of modulus of elasticity for Timber Grader MTG device, formula (26), is bigger than bending test minimal value (25) by 0.4 %.

Given intervals for mean E values received using different NDT method applies also for each separate measurement on single specimen. This way specifying and assigning strength class for separate timber piece bypassing realistic measurement uncertainties is highly relative and unsecured and confirms our earlier hypothesises (Baltrušaitis and Pranckevičienė 2003, Miseikyte et al. 2009). Similar is reported also by other authors (Poussa et al. 2007, Ravenhorst et al. 2004). According to our results, all tested non-destructive methods measure modulus of elasticity rather accurate and credibly for average values, but variation intervals are distinctively different. Moreover, Long Span test gives somehow lower values than outwardly similar Metriguard method. The latter machine is settings-dependent and therefore results vertically-movable accordingly to the machine-control settings uncertainties.

Finally, performed testing revealed the most accurate method when determining Lithuanian grown Scots pine stiffness – strength characteristics; it is device Timber Grader MTG, but that in turn implies again the fact that normal distribution of measured values with zero measuring uncertainty can be markedly obscure and unspecified. Determining strength classes and characteristics or design values it can result in largely inaccurate judgements.

CONCLUSIONS

1. Static and dynamic MOE/MOR measurements are dependent on calculation formula's complexity and accuracy specifying size, load, frequency, etc. parameters. While average measured values may be comparable and credible their real variation intervals could be distinctively different.
2. Considerable differences in realistic distribution of measured values are especially dangerous and could effect in fluctuations of ascertained MOE, strength classes and design values for timber structures.

3. All tested non-destructive methods estimate average modulus of elasticity accurately and credibly. However, the Long Span test gives little lower values and Metriguard - little higher ones. As accurate and efficient method and instrument to determine stiffness – strength characteristics could be recommended the Timber Grader MTG.
4. The best prediction and COV between modulus of rupture and modulus of elasticity was achieved with static Long Span method and lowest with the dynamic device Timber Grader MTG.
5. The Timber Grader MTG and Long Span test methods deviation gets bigger for higher modulus of elasticity, therefore they measure more accurate for the lower MOE values. The deviation between Metriguard and bending tests is constant in all MOR range, but the gained values are higher and strength prediction is overestimated compared with the real static timber strength.

REFERENCES

1. Baltrušaitis, A., Pranckevičienė, V., 2003: Strength grading of the structural timber. Medžiagotyra (Materials Science). Kaunas: Technologija 9 (3): 284-287.
2. Baltrušaitis, A., Laurinavičius, A., Ukvalbergienė, K., Pranckevičienė, V., Minelga, D., 2009: Acoustic and elastic properties of modified oak wood. Materials science. Kaunas University of Technology, Academy of Sciences of Lithuania. Kaunas: Technologija 15(4): 316-320. (ISI Web of Science).
3. Denzler, J. K., 2007: Machine strength grading – an overview over existing machines. COST Action E53 "Quality Control for Wood and Wood Products". Working Group 3. Meeting 14-15th May 2007, Hamburg, Germany, 26 pp.
4. Divos, F., Tanaka, T., 2005: Relation between static and dynamic modulus of elasticity of wood. Acta Silv. Lign. Hung. 1: 105-110.
5. Hanhijärvi, A., Ranta-Maunus, A., Turk, G., 2005: Potential of strength Grading of timber with combined measurement techniques. Report of the Combigrade – project – phase 1, VTT Technical Research Centre of Finland, 82 pp.
6. Krzosek, S., Grzeskiewicz, M., Bacher, M., 2008: Mechanical properties of Polish – grown *Pinus silvestris* L. structural sawn timber. The Netherlands, Conference COST E53. Pp 253 – 260.
7. Mišeikytė, S., Baltrušaitis, A., 2009: Timber elements strength-stiffness effects on the performance of glued laminated beams. Proceedings of the 5th meeting of the Nordic Baltic Network in Wood Material Science and Engineering (WSE), October 1-2, 2009, Copenhagen, Denmark. Ed. by A. Bergstedt. Copenhagen: Faculty of Life Sciences, University of Copenhagen. Pp 161-167.
8. Poussa, M., Tukiainen, P., Mitsuhashi, K., Auderisin, P., 2007: Destructive tension-, shear- and compression- (0° and 90°) strength-tests for finish sawn timber. Technical report Combi-T, Helsinki University of Technology, Laboratory of Structural Engineering and Building physics, 52 pp.
9. Rajeshwar, B., Bender, D. A., Bray, D. E., McDonald, K. A., 1997: An ultrasonic technique for predicting tensile strength of southern pine lumber. Transactions of the American Society of Agricultural Engineers, 40(4): 1153-1159.

10. Ravenshorst, G.J.P., Van de Kuilen, J.W.G., CNR, Ivalsa, 2006: An innovative species independent strength grading model. WCTE 2006 - 9th World Conference on Timber Engineering, Portland, OR, USA, August 6-10, 2006.
11. Ravenshorst, G.J.P., Van der Linden, M.L.R., Vrouwenvelder, A.C.W.M., Van de Kuilen, J.W.G., 2004: An economic method to determine the strength class of wood species. The Netherlands: HERON 49(4): 297-326.
12. Ross, R.J., McDonald, K.A., Green, D.W., Shad, K.C., 1996: Relationship between log and lumber modulus of elasticity. Forest Products Journal 47(2): 89–92.
13. Rozema, P., 2007: Timber Grader MTG.- Brookhuis Micro-Eletronics BV. The Netherlands.
14. Schafer, M.E., 2000: Ultrasound for defect detection and grading in wood and lumber. Perceptron, Inc. Ultrasound Technology Group, 5 185 Campus Drive, Plymouth Meeting, PA 19462. IEEE Ultrasonics symposium.
15. EN 408, 2006: Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties.
16. EN 338, 2004: Structural timber – Strength classes.

Antanas Baltrušaitis, Svajūnė Mišeikytė
Kaunas University of Technology
Department of Wood Technology
Studentų 56
Lt-51424 Kaunas
Lithuania
Corresponding author: antanas.baltrusaitis@ktu.lt
Phone: + 00-370-37-35-38-63