WOOD RESEARCH
59 (5): 2014
757-768

PREDICTION MODELS OF SLOVAKIAN STRUCTURAL TIMBER

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(Received August 2013)

ABSTRACT

The structural timber used in building construction is subjected to a strength grading. Grading requirements and methods are defined in European standards, obligatory for each country where the structural timber is used. The destructive bending tests are applied during the strength grading process in order to acquire bending strength ($f_{m,384}$), modulus of elasticity in bending ($E_{m,g,384}$) and wood density (ρ_{384}). These characteristics represent a basis for prediction modelsspecifying structural timber quality individually for each country.

Paper deals with a testing of structural spruce timber (*Picea abies*, Karst.) grown in three Slovakian regions. The parameters of prediction models were determined by destructive bending test (EN 408 2010) and evaluated by EN 384 2010. Results showed that all correlations were within the expected limits and in accordance with neighboring countries. Hence, moduli of elasticity in bending and wood density can be considered as the reliable indicators of structural timber strength.

The expected contribution of prediction models of Slovakian structural spruce timberis a further development of wood property database for timber construction.

KEYWORDS: Structural spruce timber, wood density, modulus of elasticity, bending strength, indication, prediction.

INTRODUCTION

The spruce timber (*Picea abies*, Karst.) of structural dimensions is commonly used in a building construction. High variability of properties, partially influenced by user environment (climatic conditions, character of loading), is considered to be its typical characteristic. Sawn timber built in construction is characterized by natural structure of wood and presence of defects (knots, splits). Timber quality represented by strength classes seems to be an important meanfor differentiation and assessment of individual characteristics (Gloss 1999, Deublein et al. 2010). These are defined in EN 338 2009. Methods and process of strength class determination are identicalin all countries. Although the harmonized European standards enable project and trade cooperation within European Union, further analyses and testing of structural timber properties based on country origin are needed. Therefore, national and international projects are implemented with the scope of reliable definition of timber properties from different countries. The property database of timber harvested in North and Central Europe is elaborated sufficiently, information about a timber from East European regions needs to be completed (Stapel and Denzler 2011). Different properties were confirmed between countries and also between regions (Pazlar et al. 2011, Krzosek et al. 2008, Friedrich and Denzler 2010, Rohanová et al. 2009, 2010).

The aim of strength grading is to enable that the structural timber built in construction is able to bear the design load. The system of strength classes with characteristic values (5^{th} percentile) has been adopted in order to secure it. European system of strength classes (EN 338 2009) determines the requirements for three basic properties: Bending strength and wood density (characteristic values), modulus of elasticity in bending (mean value). Destructive bending tests according to EN 408 2010 followed by result evaluation according to EN 384 2010 have to be performed in order to determine these values.

The system of strength classes based on bending strength, elastic properties in bending and density seems to be the most appropriate because bending is considered to be the most important type of load in timber structures. Hence, the bending strength is a critical strength property.

True structural timber strength can be determined only by a destructive test. Sawn timber is loaded until its rupture occurs, so it can no longer be used as a load bearing member. Results of destructive bending test and strength prediction are applied in non-destructive testing methods (Weidenhiller and Denzler 2009, Rohanová et al. 2009, Ziethén and Bengtsson 2010). Strength prediction of sawn timber by an indirect method leads to a certain inaccuracy, because the ability to predict strength by an indirect measurement can never be perfect and always contains the measurement faults. The uncertainty of strength (and others grade determining properties) prediction is corrected by the requirements for statistical distribution of strength determining properties. Sawn timber needs to meet the requirements for inclusion to a particular strength class (EN 14 081-1 2011). The development of strength class system in Europe necessitate to prove that required statistical properties determined non – destructively are enough reliable. The properties determined by non – destructive methods and used as a predictor of grade determining property are called grade indicating properties.

The linear regression model is used fora prediction of probability density function of certain structural timber property. It mentions two limit values of indicating properties: Modulus of elasticity and wood density. This model is created on the principle, that new information could continuously enter the model and allow upgrading the strength prediction. Following authors describes a theory of prediction model on timber (Kretschmann and Green 1999, Hanhijärvi et al. 2005, Köhler and Sandomeer 2007, Säll et al. 2007, Ziethén and Bengtsson 2010).

The quality of structural timber has been evaluated within EU countries in project "GRADEWOOD". Stampel- Denzler (2010) tested the structural timber of 5000 sawn timber pieces from ten European countries. Slovakia was included, but the number of spruce timber specimens was lowest (only n=100 pcs) among all countries. The contribution of project wasa creation of prediction model of structural timber properties, characteristic for each country (Baltrušaitis et al. 2010, Güntekin et al. 2011, Krzosek et al. 2008, Mišeikyte 2008, Pazlar et al. 2011, Ranta-Maunus et al. 2011, Stapel and Denzler 2010, Srpčič et al. 2010). Similarly in Slovakia, the parameters of spruce structural timber were studied within national projects. The results from one of the Slovak regions (Orava, n = 49) were presented in Edinburgh. Quality parameters using the bending test and ultrasound method were tested. Significant results were confirmed only by the bending test with high correlations. Results from two Slovak regions

(Žilina and Žarnovica, n = 144) were presented in project Gradewood (Friedrich and Denzler 2010).

The quality determination of Slovakian spruce timber by destructive and non-destructive methods is being actually upgraded; the results are published in Slovakia and abroad (Rohanová and Kúdela 2011, Rohanová et al. 2011, 2013).

The expected contribution of prediction of spruce structural timber parameters from Slovakia is a further development of wood property database for timber construction. Used testing methods guarantee objectivity and reliability of measurement results.

MATERIAL AND METHODS

The spruce timber (*Picea abies*, Karst.) was chosen from three Slovak forestry regions – West SK (Kysuce), North SK (Orava) and Central SK (Horehronie) (Fig. 1). Two types of log sawing patterns were selected: "Cant sawing" for Orava (13 pcs), Kysuce (12 pcs) and "sawing for grade" for Horehronie (25 pcs).

Specimens with dimensions of 50×120 (100) × 2360 (1900) mm were prepared from rough sawn timber of dimensions 55x200x5000 (4000) mm. The number of specimens was n=154 pieces. Average moisture content of specimens was approximately 12 %, measured in laboratory conditions. Moisture content was monitored and controlled using dielectric capacity moisture meter Hydromette HT 85 T.

Fig. 1: Regions of structural timber (Picea abies, Karst.) from Slovakia.

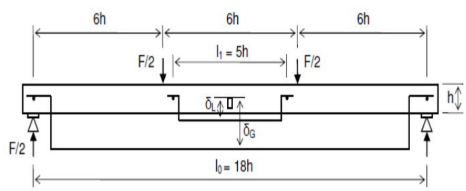

Fig. 2: Experimental scheme for determination of modulus of elasticity and bending strength according to STN EN 408 2010 (l_o - span, l_1 - length for modulus of elasticity (local), h - depth of cross section, F- load, δ - deformation)

The following properties of specimens were determined for creation of prediction models: bending strength, modulus of elasticity in bending – global and wood density.

Prediction models – methods and standards:

1. Destructive bending test: $E_{m,g,408}$, $f_{m,408}$ and ρ_{408} according to EN 408 2010 (Fig. 2).
2. Reduction: $E_{m,g,408}$, $f_{m,408}$ and ρ_{408} to $E_{m,g,384}$, $f_{m,384}$ and ρ_{384}.

The results of destructive bending tests are corrected according to EN 384 2010. The moisture content was corrected to w=12 % and the coefficient of cross section depth k_h was applied.

Determination of static modulus of elasticity – global ($E_{m,g,384}$)

1. Specimen was loaded by *4 point bending load*. The increase of load was determined from a regression line of force – strain diagram with a coefficient of correlation 0.99 or higher.

Global modulus of elasticity ($E_{m,g,408}$) was calculated from following equation:

$$E_{m,g,408} = \frac{3al^2 - 4a^3}{2bh^3\left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)} \quad (1)$$

where: $E_{m,g,408}$- global modulus of elasticity (MPa), applied in the calculation of $E_{m,g,384}$,
F_2 - F_1- increase of load (N),
w_2 -w_1- increase of deformation corresponding to F_2 - F_1 (mm),
a - distance between load point and the closest support point (mm),
b -width of cross section (mm),
l - support span (mm),
G - shear modulus (EN 408 2010 states G = 650 MPa).

2. Global modulus of elasticity $E_{m,g,384}$ was calculated from the equation:

$$E_{m,g,384} = \frac{E_{m,g,408}}{1 - \alpha(w - 12)} \quad (2)$$

where: $E_{m,g,384}$ - global modulus of elasticity corrected to w = 12 % (MPa),
α - correction coefficient of moisture content 0.01,
w - moisture content of wood during test (%).

Determination of bending strength – $f_{m,384}$

Specimen was loaded by 4 *point bending load* until its rupture occured (Fig. 2). Bending strength ($f_{m,408}$) was calculated as follows:

$$f_{m,408} = \frac{3Fa}{bh2} \quad (3)$$

where: F - maximum force (N),
a -distance between load point and the closest support point (mm),
b -width of cross section (mm),
h -depth of cross section (mm).

2. Bending strength $f_{m,384}$ was calculated from the equation:

$$f_{m,384} = \frac{f_{m,408}[1 + \alpha(w - 12)]}{k_h} \quad (4)$$

where: $f_{m,408}$ - bending strength for which rupture occurs (MPa),
α- correction coefficient of moisture content 0.01,
w -wood moisture (%),
k_h- coefficient of specimen depth k_h= $\left(\frac{150}{h}\right)^{0.2}$, correction to referential depth 150 mm,
h - depth of specimen cross section (mm).

Determination of wood density - ρ_{384}

The selection of specimen must represent the whole cross section of sawn timber without wood defects (40 x 40 x 100 -120 mm). Firstly, oven – dry density (ρ_0) was determined as follows:

$$\rho_0 = \frac{m_0}{V_0} \tag{5}$$

where: ρ_0- oven – dry density (kg.m^{-3}),
m_0 - weight of wood in absolutely dry state (kg),
V_0 - volume of specimen (m^3).

Wood density for moisture content w=12 % is calculated from following equation:

$$\rho_{12} = \rho_0 \frac{1+w}{1+0.933\rho_0 w} \tag{6}$$

where: $\rho_{12\,(384)}$ - wood density for moisture content w=12 % (kg.m^{-3}),
ρ_0 -wood density for w = 0 % (kg.m^{-3}),
w -moisture content of wood during test (g.g^{-1}).

RESULTS AND DISCUSSION

The results of destructive bending test (EN 408 2010) corrected to the referential conditions (EN 384 2010) are listed in Tab. 1. The basic statistical characteristics of three properties (wood density, modulus of elasticity and bending strength) represent the characteristics of spruce structural timber grown in Slovakia (3 regions). These characteristics create a basis for prediction models.

The recommended limit values for coefficients of variation of individual parameters ($f_{m,384}$, $E_{m,g,384}$ and ρ_{384}) are listed in EN 384 2010. The coefficients of variation determined in our work are in accordance to these values.

Tab. 1: Statistical summary of destructive bending test results – Slovakia (3 regions).

Characteristics	Parameters of predict model		
	Density wood ρ_{384} **(kg.m^{-3})**	**Modulus of elasticity** $E_{m,g,384}$ **(MPa)**	**Bending strength** $f_{m,384}$ **(MPa)**
Number of measurement	154		
Mean x	434	12 252	41
Maximum x_{max}	546	19 183	73
Minimum x_{min}	343	7 107	15
Standard deviation	39	2 331	12
Variation coefficient (%)	9	19	29

The prediction models need to be verified in each country on its domestic structural timber. The harmonization of European standards allows the compatibility of results. Tab. 2 lists the parameters of prediction models in selected countries and the results are compared with Slovakia.

Tab. 2: Properties of structural timber (Picea abies, Karst.) and coefficients of variations in selected countries.

Country	Parameters of predict models						
	N	Density of wood		Modulus of elasticity		Bending strength	
		ρ_{384} (kg.m^{-3})	COV (%)	$E_{m,g,384}$ (MPa)	COV (%)	$f_{m,384}$ (MPa)	COV (%)
Slovenia	1126	445	10	11200	21	43	31
Poland	443	440	11	10800	20	39	31
Ukraine	204	389	10	9600	19	36	29
Switzerland	563	472	7	12200	17	46	25
Finland1	111	428	10	11138	19	43	29
Finland2	589	448	9	12252	19	41	29
Slovakia-this work	154	434	9	12252	19	41	29

The values listed in Tab. 2 for Slovenia, Poland and Ukraine were obtained from a project Gradewood (Stapel and Denzler 2010). The results of spruce structural timber testing in Switzerland are listed by Arnold and Steiger (2007). The quality of structural timber in Finland was studied by Hanhijärvi et al. (2005) and Ranta-Maunus et al. (2001).

When considering the location of Slovakia in Europe (CNE), the properties of Slovakian spruce structural timber (Tab. 2) are in conformity with the presented countries.

Additionally, pine wood (*Pinus sylvestris* L.) is also used in building construction. Results of structural pine timber testing are listed by Krzosek et al. (2008), Baltrušaitis-Mišeikyté (2011), Stapel and Denzler (2011), Hanhijärvi et al. (2005), Ranta-Maunus et al. (2001).

Distribution parameters

The normality of distribution of measured prediction modelparameters was evaluated by three independent statistical tests (Kolmogorov – Smirnov, Lilliefors and Shapiro-Wilkov).

1. Distribution of bending strength is presented in Fig. 3.

Neither of tests denied null hypothesis about normal distribution of strength in bending. Up to 33 % of specimens had value of $f_{m,384}$ in the range from 40 to 50 MPa.

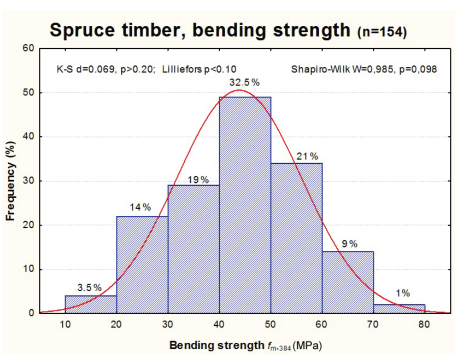

Fig. 3: Bending strength distribution.

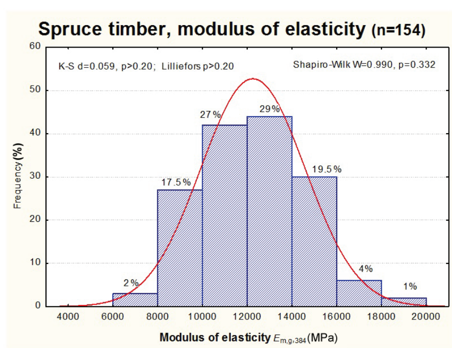

Fig. 4: Modulus of elasticity distribution.

2. Distribution of modulus of elasticity is presented in Fig. 4.

Neither of tests denied null hypothesis about normal distribution of modulus of elasticity in bending (global). Up to 56 % of specimens had value of $E_{m,g,384}$ in the range from 10 000 to 14 000 MPa.

3. Distribution of wood density is presented in Fig. 5.

Neither of tests denied null hypothesis about normal distribution of wood density. The majority of wood densities ranged from 400 to 450 kg.m^{-3} (cca 50 %).

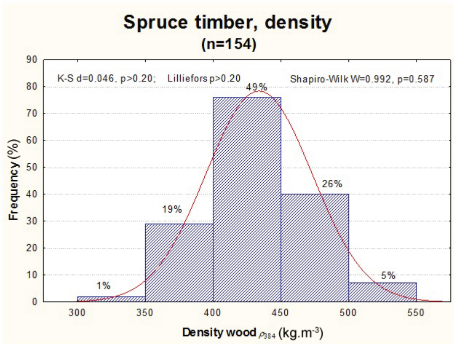

Fig. 5: Wood densities distribution.

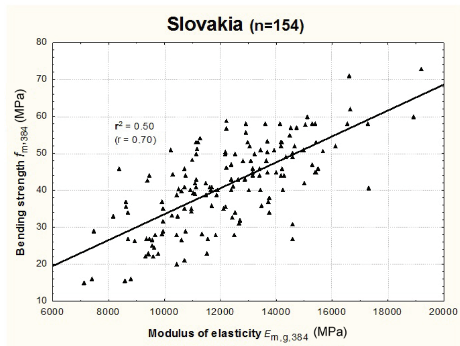

Fig. 6: Relationship between $E_{m,g,384}$ and $f_{m,384}$ from a bending test (Picea abies, Karst.).

Correlations between results

The distributions of structural timber properties represent a basis for prediction model proposal. Their objective is to predict timber bending strength via indicating parameters. The prediction of timber strength in bending is expressed by linear dependencies $E_{m,g,384}$~$f_{m,384}$ and ρ_{384} ~$f_{m,384}$.

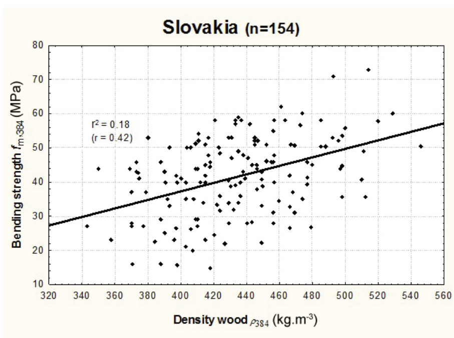

Fig. 7: Relationship between ρ_{384} and $f_{m,384}$ from a bending test (Picea abies, Karst.)

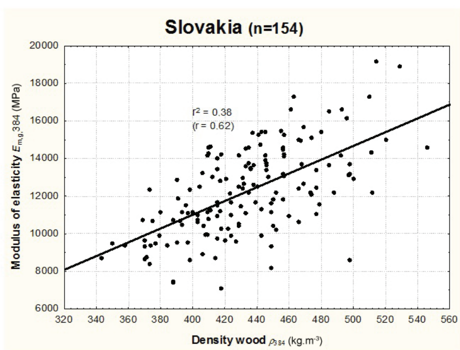

Fig. 8: Relationship between ρ_{384} and $E_{m,g,384}$ from a bending test (Picea abies, Karst.).

The bending test confirmed a dependence between $E_{m,g,384}$ and $f_{m,384}$ with a high coefficient of correlation r=0.7 (Fig. 6). The dependence is statistically significant with 50 % strength. Lower correlation was determined between ρ_{384} and $f_{m,384}$ (r = 0.42). The dependence is statistically significant with 18 % strength (Fig. 7). Higher correlation is between ρ_{384} and $E_{m,g,384}$ (r = 0.62), with 38 % strength (Fig. 8). These findings are applied in a multilevel prediction in non-destructive methods (NDT).

In the research also the influence and the number of Slovak regions on the quality parameters of the spruce lumber (n=1, 2 and 3) were analysed. However, the correlations between quality parameters are the same, the increased number of regions decreased the average values. The most significant decrease of 15 % is at f_m. It is supposed that the quality of spruce stands is influenced also by the uneven terrain as well as soil conditions in Slovakia.

Pazlar et al. (2011) studied correlations on Slovenian spruce timber. High correlation with r=0.816 (n=1074) was determined between $E_{m,g}$ and f_m. Lower correlation was confirmed between ρ_{12} and f_m with r = 0.553. For Finnish spruce timber, considered to be the one with the highest quality, high correlations were determined between $E_{m,g}$~ f_m(r = 0.82), ρ_{12}~ f_m(r= 0.61) and ρ_{12}~$E_{m,g}$ (r = 0.76), (n = 589) (Ranta-Maunus et al. 2001).

The values of coefficients of correlation determined on Slovak spruce timber are lower for all three studied dependencies comparing to neighboring countries. It is expected that these are influenced by different factors, e.g. sample size, regions. The results allow expending the property database of Slovak structural timber listed in project Gradewood (Friedrich and Denzler 2010).

CONCLUSIONS

Prediction model parameters $E_{m,g,384}$ and ρ_{384} of structural timber (*Picea abies*, Karst.) from Slovakia have a normal distribution. Presented properties of Slovak spruce timber are in accordance to listed countries when considering the location of SR in Europe (CNE).

The correlations in prediction models are within the expected limits. Moduli of elasticity in bending and wood density are reliable indicators of structural timber strength.

The prediction of parameters of structural spruce timber from locality Slovakia presupposes a contribution for future development of timber property database for building construction. Commercial application of results consists in a definition of setting parameters for grading devices based on various principles (EN 14081-4 2009).

ACKNOWLEDGMENT

This work was supported by the Ministry of education, science, research and sport of the Slovak republic under the contract. No. VEGA 1/0109/12.

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