

Theses of the Dissertation

STRENGTH OF STRUCTURAL LUMBERS IN RELATION TO
PHYSICAL PROPERTIES

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Theses of the Dissertation
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Symbols and Abbreviations

<i>bend1MOE</i> :	dynamic modulus of elasticity calculated from bending vibration in mode number 1 [GPa]
<i>CKDR</i> :	concentrated knot diameter ratio
<i>CKDRE</i> :	concentrated knot diameter ratio on edge
<i>Damp</i> .	logarithmic decrement (Λ) x 1000
E_{larch} :	predicting formula of the static modulus of elasticity of larch [GPa]
$E_{predicted}$:	predicting formula of the static modulus of elasticity [GPa]
E_{spruce} :	predicting formula of the static modulus of elasticity of spruce
<i>KAR</i> :	knot area ratio
<i>KARE</i> :	knot area ratio on edge
<i>long1MOE</i> :	dynamic modulus of elasticity calculated from longitudinal vibration in mode number 1 [GPa]
<i>MC</i>	moisture content [%]
<i>R</i> :	correlation coefficient
<i>Static MOE</i>	static modulus of elasticity [GPa]
σ_{larch} :	predicting formula of bending strength of larch [MPa]
$\sigma_{predicted}$:	predicting formula of bending strength [MPa]
σ_{spruce} :	predicting formula of bending strength of spruce [MPa]
$\sigma_{\bar{x}}$:	standard error

1 Introduction

The non-destructive testing of wood has decades of history. From very early on, research projects usually aimed at the estimation of strength properties. The goal of the non-destructive testing of solid wood is to measure quickly and precisely the parameters of logs or lumbers that are in connection with the mechanical properties. These physical features, sometimes referred to as *non-destructive parameters*, then can be related to strength and elasticity via mathematical, statistical models with good accuracy.

1.1 Objective

The general research objectives included the evaluation and selection of those non-destructive parameters that have the strongest influence on the static bending strength and modulus of elasticity. Thus, based on the measurements of these parameters the estimation of strength and stiffness properties with the possible highest precision may be achieved.

During the course of the project, I have performed non-destructive and destructive tests on 1307 pieces of coniferous specimens. The characteristic dimensions of the spruce (*Picea abies*) and larch (*Larix decidua*) planks were 5×10 cm in cross sections and 2 – 6 m in length.

The measured parameters included growth ring structure related measurements: such as average growth ring width and maximum growth ring width. Additionally, several knot parameters like knot area ratio, knot area ratio on edge, knot diameter ratio, knot diameter ratio on edge were also assessed. Furthermore, different vibration frequencies helped to evaluate the dynamic moduli of elasticity, damping characteristics and densities. After measuring the non-destructive parameters, we performed a 4-point proof load test measuring the static modulus of elasticity and the bending strength according to MSZ EN 408.

1.2 Actuality of the Subject

From 2010, instead of the Hungarian standard MSZ 15025 (Design of load bearing structures of buildings in Hungary), the timber structures have to be sized and designed according to Eurocode 5 (Design of timber structures) that is already in force.

Eurocode 5 specifies the use of strength graded structural lumber and the grading follows the recommendations of the MSZ EN 338 standard. Since 1994 MSZ EN 338 is a naturalized standard in Hungary, and it has been modified several times. The current version was published in 2010. The MSZ EN 338 standard divides wood species into two groups: group C includes coniferous species and poplars. Group D includes deciduous species, within which the standard determines different strength classes. It significantly differs from the present Hungarian practices, as the 'old' Hungarian standard differentiates 3 wood species (low density angiosperms, high density angiosperms, gymnosperms) and 4 strength classes (0, I, II, III), while the 'new' European standard differentiates 2 groups of wood species (C and D) and 12 strength classes in group C and 6 strength classes in group D. Therefore, the developed data base may aid designers to conform the new standard.

2 Materials and Methods

2.1 Materials

During my measurements, I differentiated 3 groups according to species and growth areas. The groups were as follows:

- Group I: spruce from Slovakia
- Group II: larch from Russia
- Group III: larch from Slovakia

Table 2.1 contains the specifications of lumbers involved in the investigations.

Table 2.1: Division of Specimen Groups

	Cross-section (cm)	Length [m]	Species	Growth area	Number of specimens [pcs]	
					Non-destructive	Destructive
I.	5x10	2	spruce	Slovakia	432	432
II.	5x10	2	larch	Russia	432	432
III.	5x10	2	larch	Slovakia	143	143
	5x10	4			41	0
	5x10	4			51	51
	7,5x15	6			50	0
	7,5x15	3			100	100
	10x10	4			58	58
Total:					1307	1216

Source: own design

Out of the evaluated 1307 specimen, 1216 were tested destructively as well. The difference in numbers is due to that lumber in line 4 and 6 of the table were of 4 and 6 m. First I performed non-destructive tests on the 4 and 6 m long specimens, then cutting them into two, I repeated the non-destructive tests, and finally I performed the static measurements. It was necessary for examining the size effect. In all cases the materials were sawn planks or beams in cross sections.

2.2 Non-destructive Measurements

The non-destructive testing and evaluation included the following procedures, measurements and visual assessments:

- dynamic modulus of elasticity calculated from bending vibration in mode number 1
- dynamic modulus of elasticity calculated from longitudinal vibration in mode number 1
- logarithmic decrement
- different knot parameters
 - knot area ratio (GTA)
 - knot area ratio on edge (SZGTA)
 - concentrated knot diameter ratio (CKDR)
 - concentrated knot diameter ratio on edge (SZCKDR)

2.3 Destructive tests

Destructive tests were performed for:

- static modulus of elasticity
- bending strength

The determination of bending strength and modulus of elasticity happened by 4-point bending, according to the specifications of the MSZ EN 408 standard.

3 Summary of the Results

The ultimate purpose of my research was to determine the mechanical properties of the lumber by non-destructive methods as precisely as possible. Furthermore, finding the best algorithms to measure and to estimate these properties were also targeted. The most important parameters among the mechanical properties are the modulus of elasticity and the bending strength for structural design. I statistically analysed the measured data using the STATISTICA software and determined those formulas that resulted in the best correlation and the smallest standard error. Groups in *Table Table 2.1* were separately investigated. In this Theses-book, only the best estimating/predicting formulas are discussed.

3.1 Results of Group I

Group I contained 5×10 cm cross-section and 2 m long spruce planks from Slovakia, having 13±2% moisture content.

The best model for estimating the static modulus of elasticity was provided by using the dynamic bending modulus of elasticity and the damping, according to the equation below:

$$E_{predicted} = 0,863 \cdot bend1MOE - 0,043 \cdot Damp. + 2,512 \quad [3.1]$$

The relationship between the estimated and the measured static modulus of elasticity can be seen on *Figure Figure 3.1*. The standard error of prediction was of 0,51 GPa.

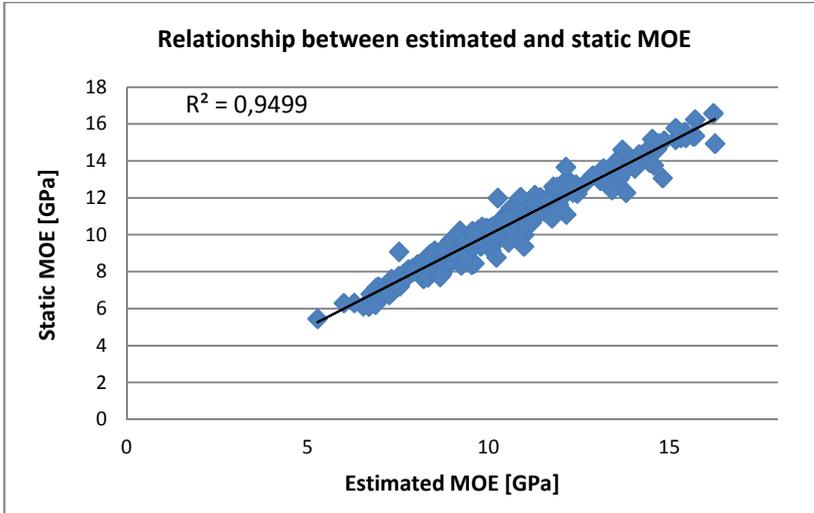


Figure 3.1: Relationship between estimated and static modulus of elasticity
Source: own design

The best formula for approximation of bending strengths from the non-destructive parameters turned out to be as follows:

$$\sigma_{predicted} = 2,946 \cdot bend1MOE - 16,103 \cdot KAR - 10,423 \cdot KARE - 0,547 \cdot Damp. + 29,760 \quad [3.2]$$

Figure Figure 3.2 shows the relation between the estimated and the actual bending strength. The detected standard error of prediction was 6,82 MPa.

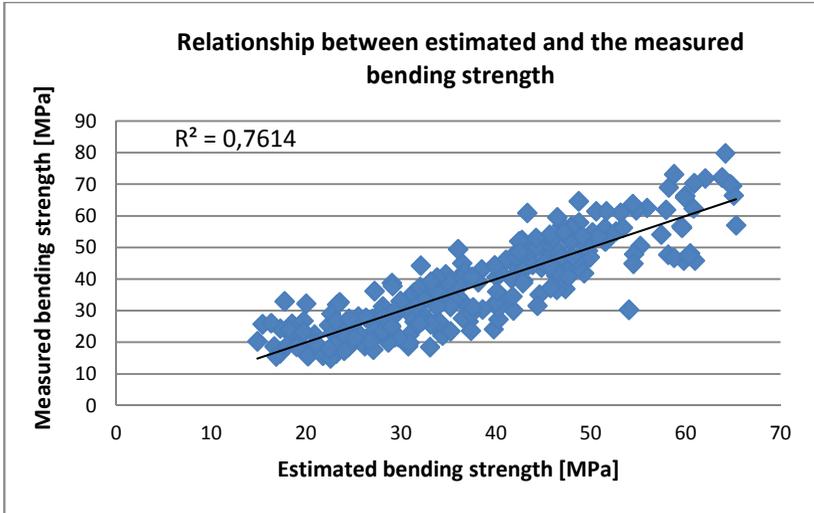


Figure 3.2: Relationship between estimated and measured bending strength
Source: own design

3.2 Results of Group II

Group II contained 5×10 cm cross-section and 2 m long Russian larch planks, conditioned similarly to that of group I to 13±3% MC.

For this group, the best prediction model of the static modulus of elasticity involved the dynamic bending modulus of elasticity and the CKDR. The resultant regression equation is as follows:

$$E_{predicted} = 0,937 \cdot bend1MOE - 1,683 \cdot CKDR + 0,536 \quad [3.3]$$

Figure Figure 3.3 shows the relationship between the estimated and the static modulus of elasticity in bending. The standard error of prediction was about 0,75 GPa.

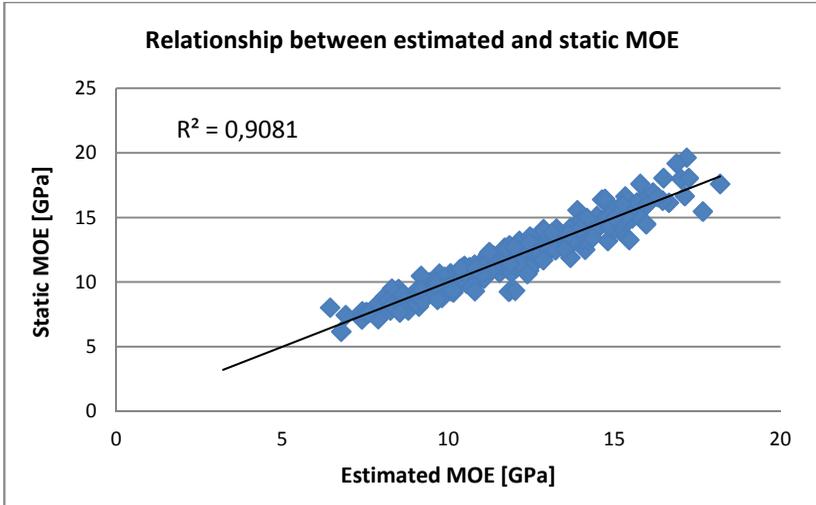


Figure 3.3: Relationship between estimated and static modulus of elasticity
Source: own design

The equation, to approximate the bending strength includes the bending vibration parameter with the following form:

$$\sigma_{predicted} = 3,909 \cdot bend1MOE - 43,676 \cdot CKDR + 10,191 \quad [3.4]$$

Figure 3.4 shows the relation between the estimated and the actual bending strength, with 11,62 MPa standard error of prediction.

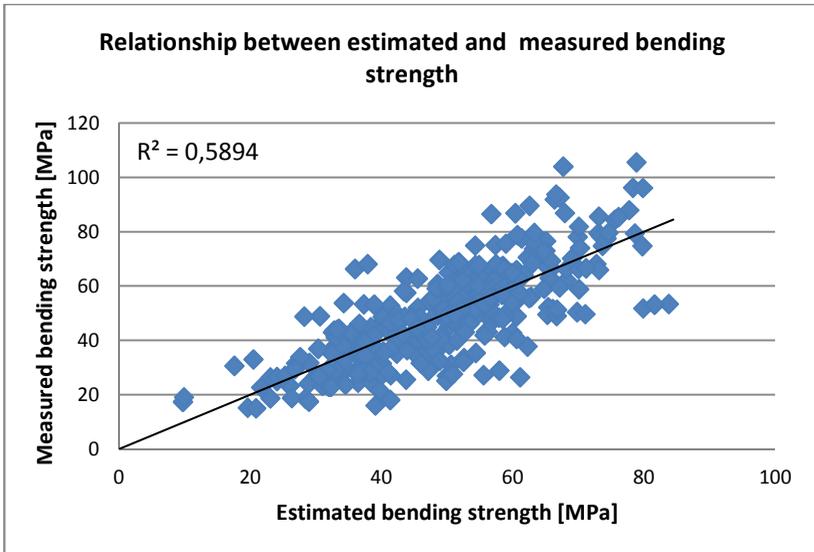


Figure 3.4: Relationship between estimated and measured bending strength
Source: own design

During the next step, for practical reasons, the simplest (one parameter) linear regression models were developed. The simplification is justified by fact that the results of the dynamic MOE (long1MOE) single factor models are close agreement with the “best” models’ predictions. The determination of long1MOE is quick and does not require involved calculations and transformations of data. In the next section the comparisons of two species groups are based on these new equations.

3.3 Comparing Group I and II

Analyses of data revealed that the average strength and MOE values of Russian larch are higher than that of Slovakian spruce. However, this statement is valid only for the average values. The overall relationships are demonstrated in Figures 3.5 and 3.6.

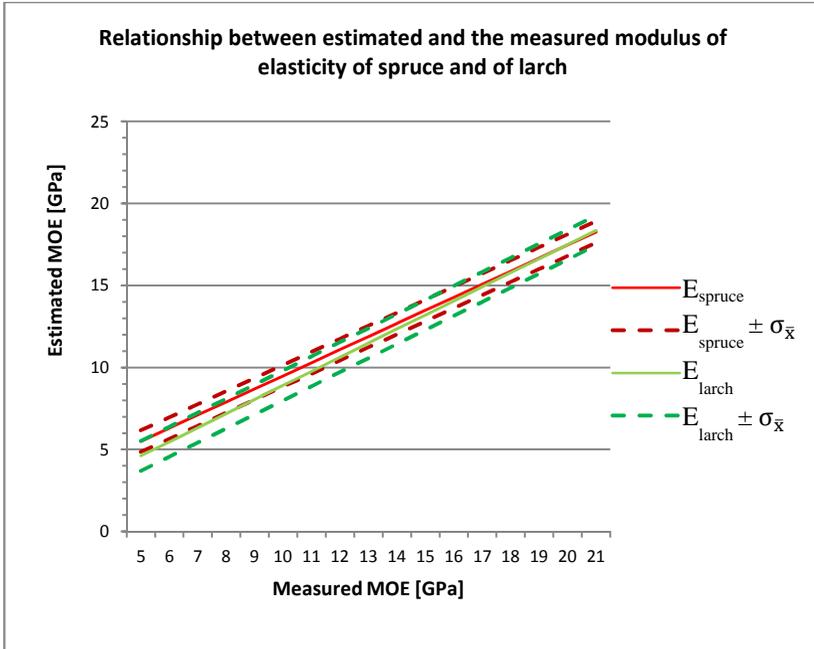


Figure 3.5: Relationship between estimated and the measured modulus of elasticity of spruce and of larch

Source: own design

In *Figure Figure 3.5* E_{luc} and $E_{\text{vörös}}$ represent the linear regression equations for modulus of elasticity of spruce and larch, respectively. These linear models (Eqs. [3.5] and [3.6]) were as follows:

$$E_{\text{spruce}} = 0,797 \cdot \text{long1MOE} + 1,520 \quad [3.5]$$

$$E_{\text{larch}} = 0,859 \cdot \text{long1MOE} + 0,317 \quad [3.6]$$

$E_{\text{luc}} \pm \sigma_{\bar{x}}$ and $E_{\text{vörös}} \pm \sigma_{\bar{x}}$ are the distances of ± 1 standard error from the predicted values. The values of $\sigma_{\bar{x}}$ for spruce and larch are $\pm 0,657$ GPa and $\pm 0,911$ GPa, respectively.

The diagrams start from 5 GPa, because I plot the values only throughout that domain in which I performed measurements (5-21GPa). The interpretation of the graph is justifiable from the 7 GPa value. The MSZ EN

338 specifies that structural wood having less than 7 GPa MOE is substandard and needs to be rejected. The deviation patterns are partly covering each other. In addition from 7 GPa the difference of the two estimated values is only 0,77 GPa, which is covered by the error of the two estimates. Moving towards the higher values the difference of the two values practically disappears.

The estimated bending strength values demonstrated similar patterns (Fig. 3.6).

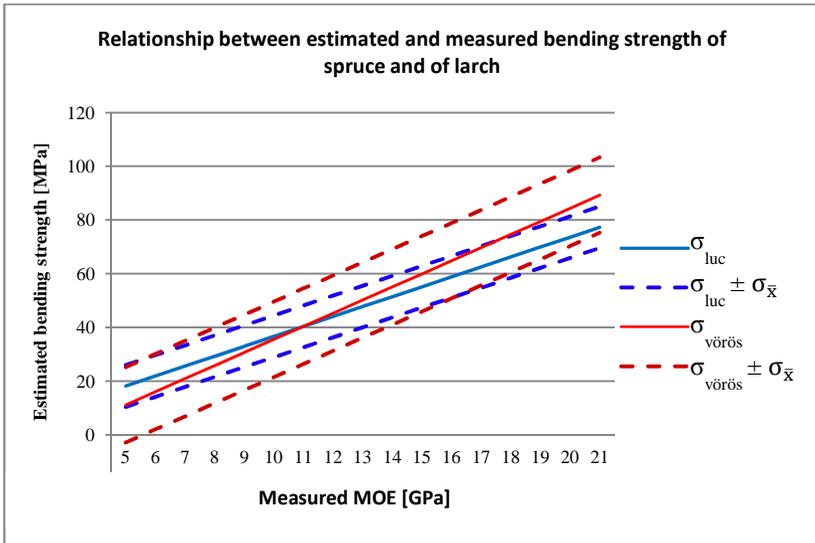


Figure 3.6: Relationship between estimated and measured bending strength of spruce and of larch

Source: own design

σ_{luc} , and $\sigma_{vörös}$ in *Figure Figure 3.6* represent the equations [3.7] and [3.8] for predicting the bending strength of spruce and of larch, respectively:

$$\sigma_{spruce} = 3,696 \cdot \log 1MOE - 0,306 \quad [3.7]$$

$$\sigma_{larch} = 4,8827 \cdot \log 1MOE - 13,306 \quad [3.8]$$

Similarly to that of MOE, $\sigma_{\text{luc}} \pm \sigma_{\bar{x}}$ and $\sigma_{\text{vörös}} \pm \sigma_{\bar{x}}$ are the distances of ± 1 standard error from the predicted values. The numerical values are $\pm 7,760$ MPa for bending strength of spruce and $\pm 14,056$ MPa for larch.

Again, I determined both equations by linear regression analysis, using only the modulus of elasticity calculated from the longitudinal vibration (i.e., long1MOE). Likewise, plots deal with the 5-21 GPa independent variable domain. The deviation patterns are covering each other well enough, here too. In case of higher strength values they slightly deviate from each other, but this value is still inside the margin of error. The highest difference between the estimated values does not exceed 12 MPa.

According to the MSZ EN 338 standard, conifers belong to one group (group D). However, the machine stress rating of structural lumber is regulated by the MSZ EN 14081 standard. The specifications require the evaluation of several hundreds of specimens by species and growing sites. Thus, the grading is very expensive, because it based on the tests results of more than a thousand specimens.

During this research two different species from several growing sites were examined. Results confirmed that the developed prediction equations do not differ significantly.

3.4 Results of Group III

In Group III, I tested planks and beams of different cross-sections and lengths at $12 \pm 4\%$ MC. The purpose of these evaluations was to investigate the size effects on structurally dimensioned elements. Table 2.1 contains the sectional dimensions and sample sizes. The comparison of small scale (5x10 cm and 2 m) and structural size beams and lumbers may have significance in safe and economic design.

First, the non-destructive parameters were assessed on full size elements, followed by destructive static bending. The 4 and 6 m long specimens were cut half in length, measured for dynamic MOE, that were calculated from the longitudinal vibration (long1MOE) for both prior and after halving. The bending strength and MOE were assessed in accordance with the relevant standard on the half-length specimens. Because the full size specimens were not tested destructively, the dynamic moduli of

elasticity were compared. Results of these analyses are represented by the box-plot diagrams (Fig. 3.7).

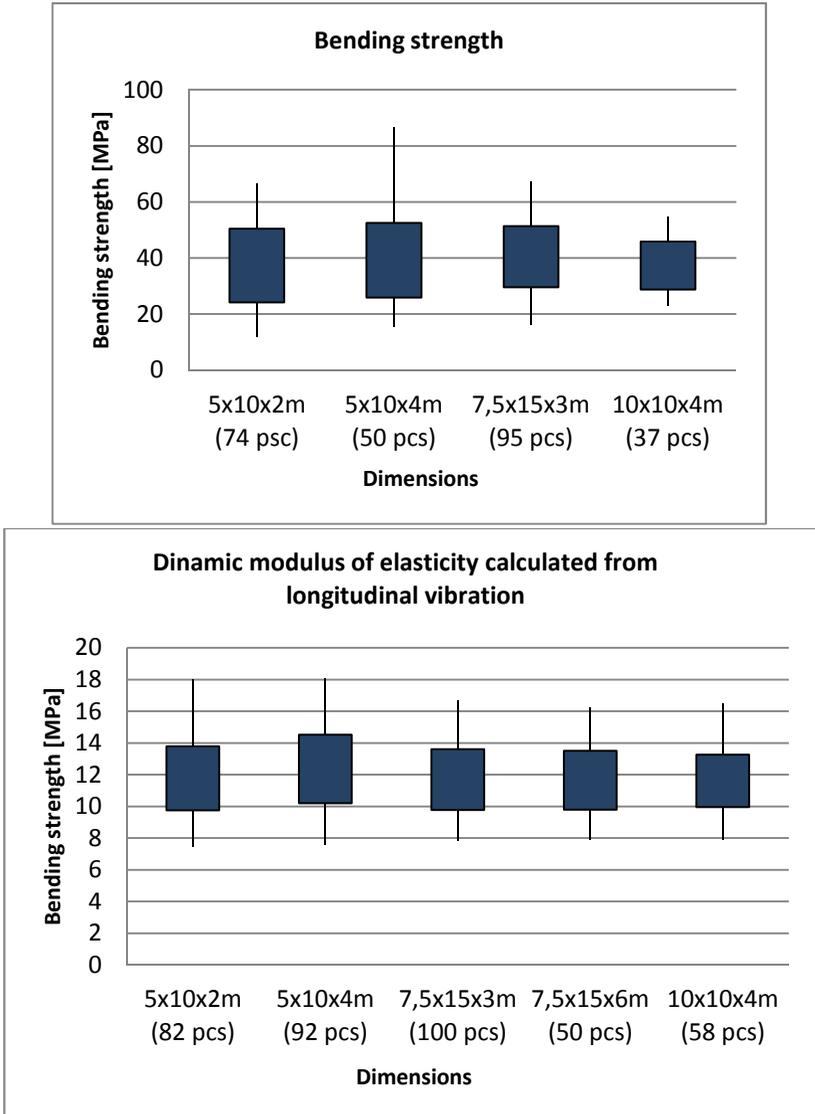


Figure 3.7: Mean, deviation, minimum and maximum of the mechanical properties
Source: own design

The upper and lower margins of the boxes in *Figure Figure 3.7* show the deviation around the mean, the thin lines show the minimum and maximum values. Numbers in parenthesis denote sample sizes.

Results confirmed that no size effect exists among the examined length and cross-sectional dimension for Slovakian larch. The measured mean values are very comparable and the spread of data is similar to each other.

This encourages the use of mechanical properties, determined on short and smaller cross sectional specimens, during the design of full size structural elements.

4 Summary

Throughout the course of my research, I have performed non-destructive and destructive measurements on 1307 pieces of spruce and larch planks and beams of different cross-section and length. The characteristic dimensions were 5×10 cm cross section and 2 m length.

The measured parameters included – among others – growth ring structure related measurements such as the so-called average growth ring width, maximum growth ring width, several knot parameters such as the so-called knot area ratio, knot area ratio on edge, knot diameter ratio, knot diameter ratio on edge, dynamic moduli of elasticity determined by different vibration frequencies, so-called bending and longitudinal vibrations, damping, moisture content and density.

Among the determined indicators damping (logarithmic decrement) and Knot Area Ratio on edge introduced by me were proved to be the best estimate parameters. Using the best prediction formula, the static modulus of elasticity was forecasted with a standard error of $\pm 0,51$ GPa and the bending strength of $\pm 6,82$ MPa in case of spruce. The static modulus of elasticity was estimated with a standard error of $\pm 0,75$ GPa and the bending strength of $\pm 11,62$ MPa in case of larch.

Additionally, the results of this research confirmed that the data of the tests on real size smaller specimens (5×10 cm cross-section, 2 m long) can be used on larger cross-section and length as well (5×10 cm cross-section, 4 m long; 7,5×15 cm cross-section, 3 and 6 m long; 10×10 cm cross-section, 4 m long). The size effect proved to be negligible.

One of the noteworthy outcome of this work is that the determined formulas to Siberian larch and Slovak spruce do not deviate from each other significantly, so combining the species according to MSZ EN 338 (that is every softwood species belongs to one group – Group C) is reasonable, but the requirement of MSZ EN 14081 that specifies the differentiation according to species and growth area seems to be unsubstantiated.

3. thesis

I derived an empiric formula to estimate the bending strength ($\sigma_{\text{predicted}}$). I found that besides the dynamic modulus of elasticity, calculated from the frequency of bending vibration in mode number 1 (*bendIMOE*), the logarithmic decrement measured in mode number 1 (*Damp.*) as an independent parameter helps in estimating the bending strength ($\sigma_{\text{predicted}}$) the most efficiently in case of 5×10 cm cross-section, 2 m long spruce planks, at 13±2% moisture content.

$$\sigma_{\text{predicted}} = 3,265 \cdot \underset{(198)}{\text{bendIMOE}} - 0,826 \cdot \underset{(108)}{\text{Damp.}} + 28,414 \quad [5.3] \\ \underset{(4,390)}{}$$

This formula can estimate the bending strength with a standard error of 7 MPa in the 15-80 MPa domain. Standard errors of the parameters are in parentheses.

4. thesis

I derived an empiric formula to estimate the bending strength ($\sigma_{\text{predicted}}$). I found that besides the dynamic modulus of elasticity calculated from the frequency of longitudinal vibration in mode number 1 (*longIMOE*), the Concentrated Knot Diameter Ratio (*CKDR*) as an independent parameter helps in estimating the bending strength ($\sigma_{\text{predicted}}$) the most efficiently in case of 5×10 cm cross-section, 2 m long spruce planks of 13±2% moisture content.

$$\sigma_{\text{predicted}} = 3,160 \cdot \underset{(153)}{\text{longIMOE}} - 24,122 \cdot \underset{(2,914)}{\text{CKDR}} + 10,938 \quad [5.4] \\ \underset{(2,021)}{}$$

This formula can estimate the bending strength with a standard error of 7,14 MPa in the 15-80 MPa domain. The standard errors of the given parameter are in parentheses.

5. thesis

I derived an empiric formula to estimate the bending strength ($\sigma_{\text{predicted}}$). I found that besides the dynamic modulus of elasticity calculated from the frequency of bending vibration in mode number 1 (*bendIMOE*), the logarithmic decrement measured in mode number 1 (*Damp.*), the Knot Area Ratio (KAR) and the Knot Area Ratio on Edge (KARE) as independent parameters in the empiric formula help in estimating the bending strength ($\sigma_{\text{predicted}}$) with the smallest error in case of 5×10 cm cross-section, 2 m long spruce planks, at 13±2% moisture content.

$$\sigma_{\text{predicted}} = \underset{(213)}{2,946} \cdot \text{bendIMOE} - \underset{(4,219)}{16,103} \cdot \text{KAR} - \underset{(3,499)}{10,423} \cdot \text{KARE} - \underset{(137)}{0,547} \cdot \text{Damp.} + \underset{(5,011)}{29,760} \quad [5.5]$$

The above formula can estimate the bending strength with a standard error of 6,82 MPa in the 15-80 MPa domain. The numbers in parentheses under the coefficients of the formula show the standard errors of the given parameter (the digits are written according to the place values).

6. thesis

I derived an empiric formula to estimate the static modulus of elasticity ($E_{\text{predicted}}$). I found that besides the dynamic modulus of elasticity calculated from the frequency of longitudinal vibration in mode number 1 (*longIMOE*), the Concentrated Knot Diameter Ratio (CKDR) as an independent parameter helps in estimating the static modulus of elasticity ($E_{\text{predicted}}$) the most efficiently in case of 5×10 cm cross-section, 2 m long larch planks, at 13±3% moisture content.

$$E_{\text{predicted}} = \underset{(19)}{0,819} \cdot \text{longIMOE} - \underset{(404)}{1,981} \cdot \text{CKDR} + \underset{(306)}{1,158} \quad [5.6]$$

This formula can estimate the static modulus of elasticity with a standard error of 0,88 GPa in the 6-21 GPa domain. The numbers in parentheses under the coefficients of the formula show the standard errors of the given parameter (the digits are written according to the place values).

6 References

MSZ 15025: Építmények teherhordó faszerkezeteinek erőtani tervezése

MSZ EN 14081: Faszerkezetek. Szilárdság szerint osztályozott, négyszög keresztmetszetű szerkezeti fa.

MSZ EN 338: Szerkezeti fa. Szilárdsági osztályok

MSZ EN 408: Faszerkezetek. Szerkezeti fa és rétegelt-ragasztolt fa. Egyes fizikai és mechanikai tulajdonságok meghatározása

MSZ EN 1995-1-1: Eurocode 5. Faszerkezetek tervezése

7 Publications from the Topic of the Dissertation

In Hungarian:

1. Sismándy-Kiss, F., Divós, F., 2011: Szerkezeti fa szilárdsági osztályozása (Hordozható fűrészáru osztályozó berendezés minősítése az EN14081 szerint), Brassó - Sopron Faipari Tudományos és Diákköri Konferencia, Sopron, Magyarország, 2011. július 18-24, (*Proceedings and oral presentation*)
2. Sismándy-Kiss, F., Divós, F., 2010: Szerkezeti fa szilárdsági osztályozása/Göcsök szerepe, Faipar LVIII. évf. 2010/2. szám:19-25

In English:

3. Divos, F., Sismándy-Kiss, F., 2011: Strength Grading of Structural Lumber – Effect of Damping and Knots, 17th International Nondestructive Testing and Evaluation of Wood Symposium, Sopron, Magyarország, 2011. 09. 14-16, (*Proceedings and oral presentation*)
4. Divos, F., Sismandy Kiss, F., 2010: Strength Grading of Structural Lumber by Portable Lumber Grading - effect of knots, The Final Conference of COST Action E53, The Future of Quality Control for Wood & Wood Products, Edinburgh, UK, 2010. 05. 4-7, (*Proceedings and oral presentation*)

Link:

<http://www.coste53.net/downloads/Edinburgh/Edinburgh-Presentation/19.pdf>

Oral presentations and posters:

5. Sismándy Kiss, F., Divós, F., 2011: Fűrészáru szilárdsága és fizikai tulajdonságainak kapcsolata, Nyugat-magyarországi Egyetem Faipari Mérnöki Kar Cziráki József Faanyagtudomány és Technológiák Doktori Iskola Doktorandusz Konferencia, Sopron, Magyarország, 2011. 06. 03., (*Proceedings and oral presentation*)

6. Sismándy-Kiss, F., 2010: Fűrészáru szilárdság szerinti osztályozása, "Aktualitások a fűrésziparban" című továbbképző tanfolyam, Sopron, Magyarország, 2010. 11. 23., (*Oral presentation*)
7. Sismándy Kiss, F., Divós, F., 2010: Fűrészáru szilárdsága és fizikai tulajdonságainak kapcsolata, Nyugat-magyarországi Egyetem Faipari Mérnöki Kar Cziráki József Faanyagtudomány és Technológiák Doktori Iskola Doktorandusz Konferencia, Sopron, Magyarország, 2010. 06. 04., (*Proceedings and oral presentation*)

Other related publications

8. Divos, F., Sismándy Kiss, F., Takats, P., 2011: Evaluation of historical wooden structures using nondestructive methods, SHATIS'11 International Conference on Structural Health Assessment of Timber Structures, Lisszabon, Portugália, 2011. 06. 16-17, (*Proceedings*)
9. Sismándy-Kiss, F., Divós F., 2010: Forgácslap rugalmas tulajdonságainak meghatározása dinamikus méréssel, A fa, mint fenntartható fejlődés alapanyaga konferencia, InnoLignum Erdészeti és Faipari Szakvásár és Rendezvénysorozat Sopron, Magyarország, 2010 09. 10. (*Proceedings and poster*)
10. Fassola, H. E., Sismándy-Kiss, F., Divos, F., 2012: Factibilidad de uso de la transformación rápida de Fouries (FFT) para la determinación del modulo de elasticidad dinamico a bajo costo, 15as Jornadas Técnicas Forestales y Ambientales. Facultad de Ciencias Forestales, UNaM - EEA Montecarlo, INTA., Eldorado, Misiones, Argentina, 2012. 06. 7-9, (*Proceedings and oral presentation*)