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Adjustments of dynamic MoE on referent moisture content of wood and temperature in grading of small-sized samples

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Subject review

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Adjustments of dynamic MoE on referent moisture content of wood and temperature in grading of small-sized samples

Mathematical dependences are derived for non-destructive testing (NDT) and destructive testing (DT) of three timber sets, each with six beams made of soft and hard structural timber. Very strong correlations were established between elastic moduli (e-moduli) determined by non-destructive testing, from dynamic ultrasound testing with direct propagation and static testing to bending action, and the correlation of e-moduli with bending strengths. The effects of adjustment of NDT results to reference values of moisture and temperature, and statistical significance of regression parameters, were evaluated from the standpoint of use in the initial classification of a small number of samples.

Key words:
structural timber, combined tests, referent moisture content, direct ultrasound propagation

Pregledni rad

Adriana Bjelanović, Tomislav Franković, Ivana Štimac Grandić

Učinci prilagodbi dinamičkog E-modula drva na referentne sadržaje vlage i temperaturu u razredbi malobrojnih uzoraka

Izvedene su matematičke ovisnosti rezultata nerazornih (NDT) i razornih (DT) testova triju setova s po šest greda od mekog i tvrdog konstrukcijskog drva. Uspostavljene su vrlo jake korelacije modula elastičnosti (E-modula) određenih nerazorno, iz dinamičkih ultrazvučnih testova izravnog valovanja i statičkih testova na savijanje, te korelacije E-modula s čvrstoćama na savijanje. Učinci prilagodbe rezultata NDT na referentne vrijednosti udjela vlage i temperature te statističko značenje parametara izvedenih regresija vrednovani su sa stajališta primjene u početnoj razredbi malobrojnih uzoraka.

Ključne riječi:
konstrukcijsko drvo, kombinirani testovi, referentni sadržaj vlage, ultrazvučno izravno valovanje

Übersichtsarbeit

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Auswirkungen der Anpassung des dynamischen E-Moduls des Holzes an die Referenzfeuchteanteile und die Temperatur bei der Einstufung einer kleineren Anzahl an Proben

Durchgeführt wurden mathematische Abhängigkeiten des Ergebnisses zerstörungsfreier (NDT) und zerstörender (DT) Tests dreier Sets von jeweils sechs Balken aus weichem und hartem Bauholz. Es wurden sehr starke Korrelationen des Elastizitätsmoduls (E-Modul) festgestellt, die zerstörungsfrei bestimmt wurden, aus dynamischen Ultraschalltests der direkten Wellen und statische Tests auf Verbiegen, wie auch die Korrelation des E-Moduls mit Biegefestigkeiten. Die Auswirkungen der Anpassung der Ergebnisse des NDT auf die Referenzwerte des Feuchteanteils und der Temperatur sowie die statistische Bedeutung der Parameter, die aus der Regression ermittelt wurden, wurden vom Standpunkt der Anwendung in der Anfangseinstufung der kleinen Anzahl an Proben bewertet.

Schlüsselwörter:
Bauholz, kombinierte Tests, referent Feuchtigkeitsgehalt, direkte Ultraschallwelle

1. Introduction

Wood is a nonhomogeneous and anisotropic material of natural origin, sensitive to environmental influences. These properties have significance influence on usage of wood in construction, so, it is important reliably determine mechanical properties and the density of existing structural members and new wood products [1]. Non-destructive tests (NDT) have been researched, evaluated and improved for decades [2-4] to widening of their application for industrial purpose, in quality estimation and grading [5, 6] and for "in situ" assessment of structural members [7-13]. Numerous successful combinations of NDT, mutually and with destructive tests (DT) were reported [12-16]. Due to prevailing intermediary character, the results are often starting points in determining some property rather than final information about it, while the implementation of NDT in structural health evaluating has also its additional challenges (e.g. sampling and deterioration of the material). The growing interest for wood construction imposes requirements to assure production quality and reliability of strength classification based on combined implementation of NDT [17, 18] and DT, with standardized procedures for sampling, setting and performing of destructive tests, with accompanying rules for interpretation of their results [19] and calculation of characteristic and mean values [20, 21]. Visual classification precedes the machine strength-grading, whose parameters are adjusted according to the results of proof DT of part of the (production) series, and the declared values of properties for the assigned strength class are often significantly lower than those determined for majority of series. The accuracy of measurements and potential of measured properties for strength prediction significantly influence efficacy of the system of classification [22-28]. Therefore, to improve the results of classification, two areas are key: reliability of predicting the strength by measuring other properties (Table 1) and accuracy of measuring these indicators [29, 30].

Recent researches deal with possible standardization of NDT and NDE, which requires meeting a series of prerequisite, like compiling results of numerous studies (different techniques, scopes and goals of conducted research), creating a database with the results and proposing factors of adjustment for harmonisation the data, and standardizing mathematical models of correlation of the results [13, 31, 32]. From the latest studies, performed on greater number of large specimens, it is possible to recognize possible guidelines for standardization of NDT and the need for defining factors of adjustment of measured parameters on reference values of moisture content, temperature, dimension of cross-section and length of specimens, and also finding way of taking into account other parameters influencing on the results derived from acoustic tests [22, 26, 27], comparable with results of DT (e.g. influences of the position of sensors, the angle of inclination of fibres and anomalies of growth) [33-42].

This paper is the result of a preliminary study conducted on a limited number of wooden samples, spruce beams and oak billets with the assumption that the adjustments of the dynamic parameters of direct ultrasonic wave-test on reference values would improve the accuracy of results of the initial type classification. Factors of the adjustments of the stress-wave velocity and dynamic E- module (MoE) for the independent effects of deviations of measured moisture content of the wood and the temperature of the reference values are taken from the literature. We proposed our own simplified expression for combined effect of these deviations on the velocity of longitudinal waving, assuming its applicability due to small differences between measured and reference values.

Table 1. Correlation of grading parameters in evaluating the potential of strength predicting [23]

Granding parameter	Correlation with bending strength and strenghts of axial tension and compression		
	f_m	$f_{t,0}$	$f_{c,0}$
Knots	0.5	0.6	0.4
Nagib vlakana	0.2	0.2	0.1
Density	0.5	0.5	0.6
Ring width	0.4	0.5	0.5
Knots + ring width	0.5	0.6	0.5
konts + density	0.7 - 0.8	0.7 - 0.8	0.7 - 0.8
Modulus of elasticity, E	0.7 - 0.8	0.7 - 0.8	0.7 - 0.8
E + density	0.7 - 0.8	0.7 - 0.8	0.7 - 0.8
E + knots	> 0.8	> 0.8	> 0.8

Regression models for dependency of dynamic and static MoE and also results of NDT and DT were developed and then validated on the basis of established correlations and statistic significance of regression parameters. Adequacy of implemented NDT and efficacy of adjusted results in bending strength predicting were evaluated within classification procedure, where the characteristic values were corrected taking into account a small number of specimens.

Figure 1. Specimens of structural softwood and hardwood for testing phases from 1 to 4: a) and b) spruce beams (grouped into samples I. and III.); c) oak billets (grouped into II. sample)

Table 2. Experimental programme – important data, test outcomes and calculated properties

Type of test, phase and used technique			Used standards	Test outcomes – calculated properties
NDT	0	Visual inspection	EN 1912:2012 [40] EN 14081-1:2005 [15]	Qualitative assessment of irregularities of growth[1], cross-section[1] and shape[1]
NDT	1-1	Geometric measurement and weighing	EN 384:2015 [18] EN 14358:2013 [17]	Dimensions (b, h, L); mass (m) – density, corrected and referent density (ρ), (ρ_{corr}), (ρ_{12})[2]
NDT	1-2	Hygroscopic test	EN 13183-2:2002 [41]	Moisture content (u%) and temperature (T)[2]
NDT	2	Ultrasound stress-wave test (longitudinal / direct)	–	Time-of-flight (t_i) – mean velocity of wave propagation (v_{mean}) and dynamic E-modules (E_{dyn^*})[3]
NDT	3	Static bending test (proof load)	EN 408:2010 + A1:2011 [16]	Midspan deflection and displacements on support – static E-module ($E_{m,0}$)[3]
DT	4	Destructive 4-pt bending test		Failure force (F_L) – bending strength ($f_{m,0}$)[3]

[1] Assessment of anomalies of qrowth (presences of knots, cracks and fibre irregularities, discolorations and reaction wood), properties of cross-section (width of rings) and shape (bending, twisting, warping) etc.
[2] Table 2.
[3] Table 3.

2. Materials and methods

2.1. Specimens and samples

After initial visual inspection, specimens of structural softwood and hardwood were grouped in samples, by quality, botanic species and average dimensions (Figure 1): spruce beams of the length L = 1600 mm and cross-section of b/h = 100/100 mm were grouped in samples I. and III., and oak billets of the length L = 650 mm and b/h = 40/40 mm in sample II. The cross-section of the width b and height h, and the axial spans (l = 18h ± 6h) [16] of specimens were adapted to perform the static tests of the phases 3 and 4.

2.2. Experimental programme, procedures and results of combined tests

Experimental programme (Table 2) was conducted in four phases, which were preceded by the initial visual inspection (phase 0). Specimens of the softwood were visually classified into strength classes above C18 (upper strength class, representative for the structural timber of low quality), and according to the qualitative criteria (Table 2) grouped in samples I. and III. of high and low quality, while average quality was assigned to the oak billets (Figure 1).

Figure 2. Conducting test phases 1-1 and 1-2 (Table 2)

During three weeks before testing in Laboratories for structures and materials at Faculty of Civil Engineering of Rijeka, samples were conditioned in suitable rooms, where humidity didn't exceed 65 %. Measured moisture contents of tested specimens were between 9.5 % and 13.5 % (Table 3), while the range of their temperature was from 21 °C up to 27 °C. Cracking, changes of colour, presence of reaction wood and mechanical damages on specimens were not noticed. Specimens grouped into III. sample had noticeable knots, and on two among them, small geometric problems of end-grain cross-section or very slight fibre inclination (≤ 3°) outside the area of knots were noticed. Greater deviations of fibre slopes on the oak specimens were noticed, although they didn't exceed 10° in the middle third of their length. The influence of perceived anomalies on the results is not the subject of this paper. Upon completion of ND tests (Table 2), all specimens were tested up to failure, and the results of destructive testing are given in Tables 3 and 4. Average densities of all specimens were calculated from three measurements (Table 4) of their dimensions (at the ends and in the middle of length) and masses. Due to weighing test, densities were corrected with factor k = 1.05 for softwood, and k = 1.0 for hardwood, while the values u_{corr} were calculated from the expression (1) [18]. Electrical resistant hygrometer (AB Brookuis Micro-Electronics BV with accuracy of reading 0.1 %, and digital correction for the botanic species) was used to measure the moisture content, u. Reference density, ρ_{ref} adapted to reference value u < 28 %, was calculated from the expression (2) [45], using the adjustment factor of 0.0042 (which is close to correction of 0.5 %, according to the norm ISO 3131) for every 1 % deviation of measured moisture content from referent value u = 12 %.

$$\rho_{u,corr} = \rho_u / k \tag{1}$$

$$\rho_{ref} = \frac{\rho_{u,corr}}{1 + 0,0042\,(u - 12)} \tag{2}$$

Method, based on the ultrasonic runtime measurement is often used in quality estimating and timber strength grading, and the theoretical base [46] is improved for industrial and in situ application [4, 25, 47]. Smaller velocity of wave propagation signals to inner anomalies and the higher moisture content. SylvaTest Trio portable device (based on low-frequencies excitation) was used for direct ultrasonic stress-wave test (phase 2). Piezoelectric transducers with blunt tip were positioned in end grains of specimens in 10 mm long cavities drilled in the middle and thirds of depths (Figure 3). From the registered time-of-flight, t_i, mean speed v_{mean}, was

Table 3. Results of tests phase 1 and calculated densities

Specimens		Phase 1-1			Phase 1-2		Gustoće		
		b [mm]	**h** [mm]	**m** [g]	**u** [%]	**T** [°C]	ρ_u [kg/m³]	$\rho_{u,corr}$ [kg/m³]	ρ_{ref} [kg/m³]
L = 1600 [mm]	I.-1	92.76	93.32	6525.0	9.70	27	471.11	448.68	452.99
	I.-2	92.33	93.90	6430.0	10.30	27	463.54	441.46	444.64
	I.-3	92.66	93.64	6125.0	10.10	27	441.20	420.19	423.57
	I.-4	93.08	93.65	6040.0	9.90	27	433.06	412.44	416.17
	I.-5	92.91	93.29	6370.0	10.40	27	459.33	437.45	440.48
	I.-6	93.20	93.36	6200.0	9.70	27	445.34	424.14	428.27
L = 650 [mm]	II.-1	40.66	41.54	755.0	13.10	22	687.70	687.70	684.54
	II.-2	40.43	40.57	830.0	13.43	22	778.50	778.50	773.84
	II.-3	40.28	40.59	750.0	11.97	22	705.73	705.73	705.83
	II.-4	40.46	41.22	810.0	11.53	22	747.20	747.20	748.67
	II.-5	40.42	40.44	680.0	11.30	22	640.01	640.01	641.90
	II.-6	40.45	41.45	739.6	10.80	22	678.64	678.64	682.08
L = 1600 [mm]	III.-1	96.51	99.87	5610.0	11.10	21	363.78	346.45	347.77
	III.-2	97.38	100.21	6650.0	12.00	21	425.91	405.63	405.63
	III.-3	97.19	99.70	6045.0	10.80	21	389.91	371.34	373.22
	III.-4	97.52	100.25	6675.0	12.00	21	426.73	406.41	406.41
	III.-5	98.53	99.38	6330.0	11.10	21	404.03	384.79	386.25
	III.-6	97.52	97.67	6995.0	11.50	21	459.00	437.14	438.06

calculated from three measurements (Table 1). The corresponding reference value v_{ref} (Table 4) is the mean speed, v_{mean}, corrected with factors k_u = 0.0062 [45] and k_T = 0.01 [16], taking into account the effects of moisture content *u* and temperature *T* from Table 3. The adequacy of the proposed expression (3), which describes in simplified way their mutual effect, is evaluated in this research.

$$v_{ref} = \frac{v_{mean}}{1-0{,}0062\,(u-12)} \cdot \frac{1}{1+0{,}01(T-20)} \tag{3}$$

Dynamic *E*-modules (Table 3) are calculated using the expressions from (5) to (7), with adjustments of wave speed and/or the density to reference *u* = 12 %, *T* = 20 °C, and directly, from the expression (8), with the factor k_{ref} = 0.078 for the adjustment on reference *u* [45]. The expressions are adjustments of theoretical dynamic MoE from the expression (4) [46], where $\rho_u = \rho$ and $v_{mean} = v$, are calculated mean values for density of specimen and velocity of wave propagation.

$$E_{dyn} = \rho_u \cdot v_{mean} \tag{4}$$

$$E_{dyn,\rho ref} = \rho_{ref} \cdot v_{mean} \tag{5}$$

$$E_{dyn,vref} = \rho_{u,corr} \cdot v_{ref} \tag{6}$$

$$E_{dyn,\,\rho ref,vref} = \rho_{ref} \cdot v_{ref} \tag{7}$$

$$E_{dyn,ref} = \frac{\rho_{u,corr} \cdot v^2_{mean}}{1-0{,}0078\ (u-12)} \tag{8}$$

In the static NDT (phase 3), the specimens were supported on steel plates positioned on their axial spans of *l* = 1500 mm (16*h*, for beams) and *l* = 600mm (15*h*, for billets). On the symmetrically placed suspensions of equal mass and spaced for *a* = 6*h* were gradually adding the weights (Figure 3) of 20 kg and 5 kg up to 2x265 kg (for beams) and 2x41.5 kg (for billets), i.e. about 25 % estimated failure force for beam and about 10% for billets (the cases, the chains and suspensions were previously weighed). Displacements (w_A and w_C on supports and w_B in the midspan) for unloaded specimens, loading phase (eight, for the beams

Figure 3. ND tests – a) ultrasonic stress-wave (longitudinal) test (phase 2) i b) static bending test (phase 3)

Figure 4. Destructive bending tests (phase 4) and corresponding failure types

Table 4. Results of test phases from 2 to 4, calculated *E*-modules and bending strengths, $f_{m,0}$

Specimen	v_{mean}	v_{ref}	E_{dyn}	$E_{dyn.\rho ref}$	$E_{dyn.vref}$	$E_{dyn.\rho ref.vref}$	$E_{dyn.ref}$	$E_{m.0}$	$E_{m.0.ref}$	$F_{m.0}$	$f_{m.0}$
		(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)		(11)
	[μm/s]		[kN/mm²]							[kN]	[N/mm²]
I.-1	5948.0	5899.2	16.67	16.03	15.61	15.76	15.60	13.17	12.87	21.73	37.93
I.-2	5619.3	5592.0	14.64	14.04	13.80	13.90	13.76	11.16	10.97	17.73	30.59
I.-3	5978.0	5941.8	15.77	15.14	14.83	14.95	14.80	13.36	13.10	22.32	38.66
I.-4	5760.0	5717.2	14.37	13.81	13.48	13.60	13.46	11.75	11.50	19.11	32.94
I.-5	5978.0	5951.2	16.41	15.74	15.49	15.60	15.44	13.68	13.46	22.06	38.47
I.-6	5771.3	5722.8	14.83	14.27	13.89	14.03	13.88	11.86	11.59	19.32	33.53
II.-1	4632.7	4670.5	14.76	14.69	15.00	14.93	14.89	13.57	13.72	7.65	57.35
II.-2	4412.7	4457.6	15.16	15.07	15.47	15.38	15.33	13.25	13.44	7.23	58.14
II.-3	4876.0	4882.4	16.78	16.78	16.82	16.83	16.77	15.39	15.38	7.93	63.91
II.-4	4756.7	4750.5	16.91	16.94	16.86	16.90	16.85	15.61	15.54	8.42	64.81
II.-5	4660.7	4648.2	13.90	13.94	13.83	13.87	13.83	13.75	13.66	7.04	57.11
II.-6	4938.0	4910.1	16.55	16.63	16.36	16.44	16.39	15.92	15.73	8.88	67.30
III.-1	5788.7	5761.9	12.19	11.65	11.50	11.55	11.53	11.17	11.07	22.03	30.92
III.-2	5680.7	5684.9	13.74	13.09	13.11	13.11	13.09	11.05	11.05	22.19	30.59
III.-3	5264.7	5231.0	10.81	10.34	10.16	10.21	10.20	8.56	8.46	15.76	22.07
III.-4	5416.7	5420.7	12.52	11.92	11.94	11.94	11.92	9.85	9.85	20.02	27.53
III.-5	5456.7	5431.4	12.03	11.50	11.35	11.39	11.38	9.39	9.31	18.30	25.50
III.-6	5473.3	5461.1	13.75	13.12	13.04	13.06	13.05	10.71	10.66	20.21	29.79

and four, for the billets), and for the offloading phase (Figure 3) were measured with dial gages (Mitutoyo 2052). Static MoE, $E_{m,0}$ was calculated according to the expression (9) [19], from the difference of displacements $w_2 - w_1$ to load increment of $F_2 - F_1$ on regression line, with shifts w_1 and w_2, calculated as the difference of measured displacements ($w_B - (w_A + w_C)/2$), and reference $E_{m,0,ref}$ for u = 12 % from equation (10) [21].

$$E_{m,0} = \frac{3a \cdot l^2 - 4a^3}{4 \cdot bh^3} \cdot \frac{F_2 - F_1}{w_2 - w_1} \tag{9}$$

$$E_{m,0,ref} = E_{m,0} \cdot \left[1 + 0{,}01\,(u - 12)\right] \tag{10}$$

In the destructive bending test (phase 4) with controlled increase of force, the specimens of spans *l* were symmetrically loaded on the distance α. The failure developed in tensile zone (Figure 4), with appearance of cracks in the zone of knots. The test was conducted without external measuring instruments, so the results of the tests were only failure force of specimens, $F_{m,0}$, while the bending strength bending were calculated from the expression (11) [19].

$$f_{m,0} = \frac{3F_{m,0} \cdot a}{bh^2} \tag{11}$$

The probable causes of small differences between v_{ref} and v_{mean} are narrow ranges of measured values u (0.7 % and 1.2 % for I. and III., and 2.63 % for II. sample) and mean values close to references (with deviations from 1.99 % and 0.58 % for I. and III., and 0.02 % for II. sample), while temperature *T* deviate 7 % at most and 1 % at least from references (Table 2 and 5). Despite being approximate, recommended expression (3) for v_{ref} could be considered satisfactory for this level of research and because the effects of deviation *T* from the reference is smaller than those for *u* [22, 32-36]. Illustratively, using expression (3), mean values population of *u* and *T*, decrease the value v_{mean} for 16.81 % for I., and 4.43 % for III. sample (with effect of deviations of 11 %, i.e. 3.47 %), while the decrease of 1.84 % for II. sample is negligible. Results of applying expressions (3) on deviations of mean values of MoE are given in Table 6.

Table 5. Statistic distribution of the results of tests phases 1-2 and 2

Samples		*u* [%]	*T* [°C]	v_{mean} [μm/s]	v_{ref} [μm/s]
I.	min	9.70	27	5619.33	5591.55
	mean	10.01		5842.44	5804.03
	max	10.40		5978.00	5951.23
	St.dev	0.29	0.00	148.00	147.52
	CoV	2.62 %	0.00 %	2.31 %	2.32 %
II.	min	10.80	22	4412.67	4457.63
	mean	12.02		4712.78	4719.86
	max	13.43		4938.00	4910.07
	St.dev	1.04	0.00	188.94	167.25
	CoV	7.90 %	0.00 %	3.66 %	3.23 %
III.	min	10.80	21	5264.67	5230.96
	mean	11.42		5513.44	5498.50
	max	12.00		5788.67	5761.90
	St.dev	0.50	0.00	189.63	193.73
	CoV	4.03 %	0.00 %	3.14 %	3.22 %

Table 6. Ratios of mean values of populations of *E*-modules (MoE)*,**

Ratios of mean values of populations, y_{mean} [%]						
Set	(5)/(4)	(6)/(4)	(7)/(4)	(8)/(4)	(9)/(4)	(10)/(4)
I.	- 3.96	-6.01	-5.22	-6.22	-19.09	-20.70
II.	- 0.0	+0.31	+0.79	- 0.0	-6.97	-7.00
III.	-4.54	-5.25	-6.80	-5.17	-19.06	-19.52
Set	(4)/(10)	(5)/(10)	(6)/(10)	(7)/(10)	(8)/(10)	(9)/(10)
I.	+26.10	+21.11	+18.53	+19.52	+18.26	+2.03
II.	+6.28	+6.29	+6.61	+7.12	+6.29	+0.02
III.	+25.16	+19.48	+18.59	+16.64	+18.69	+0.56

* For populations of MoE calculated from equations (5) do (9) and E_{dyn} and $_{m.0.ref}$ from eq. (4) and (10)
** see Table 7
Note: Negative percentages refer to discussed value smaller than comparative.

3. Evaluation of regressions and their usage in grading of small-sized samples

3.1. Derived regression models and effects of adjustments on referent moisture content and temperature

In many studies conducted on a great number of specimens (of different dimensions, botanic species and origin), a model of adequacy of linear regression for interdependency of mechanical properties was proved [7, 15, 23, 25, 28, 30, 33, 47-50]. Due to differences between frequencies used for excitement, the effects of using of different acoustic tests (based on runtime measurement or oscillations) on dynamic MoE of beam specimens were also estimated [5, 29, 45]. This research is focused on evaluations of both, the regression model derived for small-sized samples of beams and billets (Figure 2 to 4) and the effect of adjusted values of *u* and *T* on the results (Table 4 to 6). Correlation strengths of dynamic MoE-s (Figure 5 to 7) are valued, not only by correlation coefficients, but also by the criterion of significance of reference velocity v_{ref}, as isolated indicator of regressions (Table 7), where statistical analysis ANOVA (Excel) was conducted using confidence interval of 75% and reliability level of 95% (ρ = 0,05) [20, 51, 52]. Qualitatively, the results of performed statistical analysis confirm the adequacy of specimens because *F*-test values are > 1 and sig. *F* are < *F* (*P*-values or factor of significance), as measures of variability when verifying the model, indicate to the relation of correlation coefficient *r* with changes of regression parameter [53, 54]. The qualitative evaluation precisely shows the following:

- for all samples and developed regression models, reference velocity v_{ref} has got better statistical significance than v_{mean}
- acceptability of linear relationship of velocities with static MOE-s and strengths, because all *P*- values < α
- very strong correlation and *P*-values < α for I. sample both confirm initial assumption about suitability of linear regressions of velocities and dynamic MoE-s, while with *P*-values > α = 0,05 deficiently explain linearity of relationship for II. and III. samples (which consist of specimens of lower quality)
- equality of correlation and statistical significance of regression models for MoE, $E_{dyn\rho ref,vref}$ and $E_{dyn,ref}$.

Very strong correlations (*r* > 0.85) with static MoE and strength confirm efficacy of implemented NDT (Table 7, Figure 5 to 8), and measurable effects of adjustments according to expression from (1) to (8) which have been applied in process of initial type classification (Table 6 and 8).

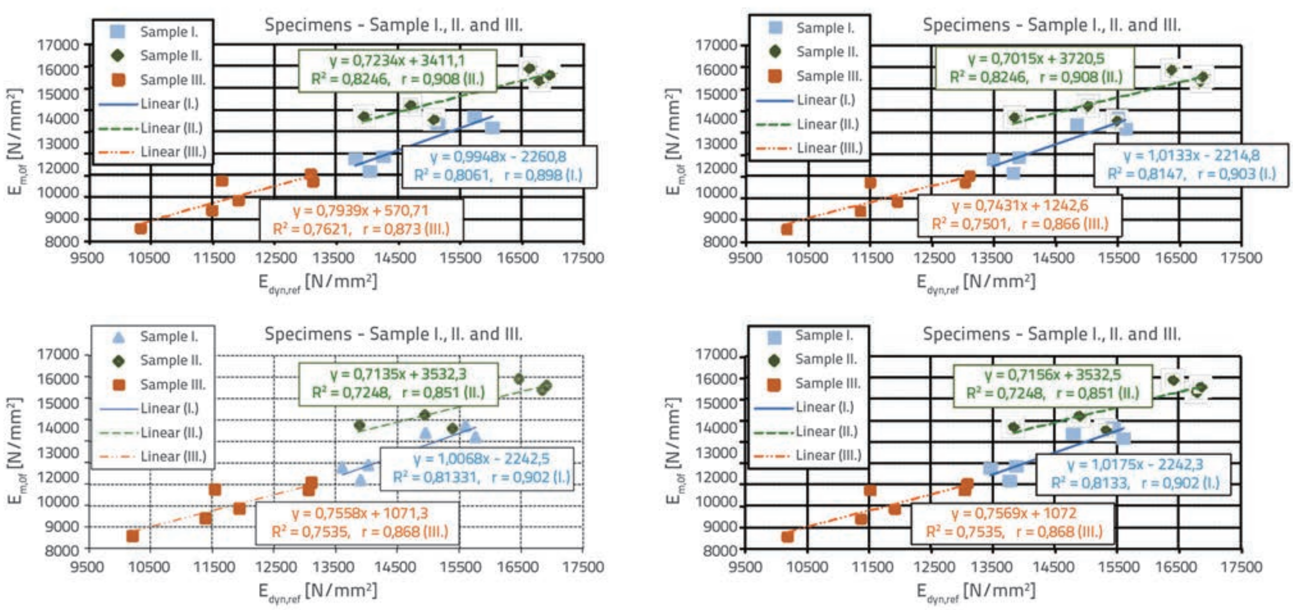

Figure 5. Regressions of dynamic and static *E*-modules (MoE)

Table 7. Evaluations of derived regressions for MoE and bending strength with referent wave velocity*

Set	Regression model $y = a \cdot x + b$	Determination coeff.* R^2		Correlation coeff.* r		Significance of regression* sig.F (P-value)	$F > 1$
I.	$E_{dyn} = 5.678 v_{ref} - 17510$	**0.743**	(0.735)	**0.862**	(0.857)	0.027 (0.029)	11.54 (11.09)
	$E_{dyn.rref} = 5.444 v_{ref} - 16758$	**0.742**	(0.737)	**0.862**	(0.858)	0.027 (0.029)	11.53 (11.20)
	$E_{dyn.vref} = 5.365 v_{ref} - 16618$	**0.740**	(0.726)	**0.860**	(0.852)	0.028 (0.031)	11.40 (10.62)
	$E_{dyn.rref.vref} = 5.4 v_{ref} - 16700$	**0.742**	(0.730)	**0.861**	(0.854)	0.028 (0.030)	11.48 (10.81)
	$E_{dyn.ref} = 5.343 v_{ref} - 16525$	**0.742**	(0.730)	**0.861**	(0.854)	0.028 (0.030)	11.48 (10.81)
	$E_{m.0} = 6.947 v_{ref} - 27823$	**0.985**	(0.969)	**0.992**	(0.984)	**0.000** (0.000)	260.62 (125.08)
	$E_{m.0.ref} = 6.836 v_{ref} - 27426$	**0.978**	(0.958)	**0.989**	(0.979)	**0.000** (0.001)	176.92 (90.24)
	$f_{m.0} = 0.023 v_{ref} - 99.441$	**0.993**	(0.992)	**0.996**	(0.996)	**0.000** (0.000)	559.48 (474.36)
II.	$E_{dyn} = 4.940 v_{ref} - 7641$	**0.441**	(0.409)	**0.664**	(0.639)	0.150 (0.172)	3.15 (2.76)
	$E_{dyn.rref} = 5.237 v_{ref} - 9042.6$	**0.475**	(0.447)	**0.689**	(0.669)	0.130 (0.146)	3.62 (3.24)
	$E_{dyn.vref} = 4.098 v_{ref} - 3618.6$	**0.331**	(0.290)	**0.575**	(0.539)	0.232 (0.270)	1.98 (1.63)
	$E_{dyn.rref.vref} = 4.398 v_{ref} - 5033.6$	**0.371**	(0.332)	**0.609**	(0.576)	0.200 (0.231)	2.36 (1.99)
	$E_{dyn.ref} = 4.385 v_{ref} - 5021.1$	**0.371**	(0.332)	**0.609**	(0.576)	0.199 (0.231)	2.36 (1.99)
	$E_{m.0} = 5.3974 v_{ref} - 10711$	**0.795**	(0.785)	**0.891**	(0.886)	**0.017** (0.019)	15.46 (14.62)
	$E_{m.0.ref} = 4.742 v_{ref} - 7632.9$	**0.742**	(0.713)	**0.861**	(0.844)	**0.028** (0.035)	11.50 (9.92)
	$f_{m.0} = 0.0238 v_{ref} - 51.561$	**0.837**	(0.814)	**0.915**	(0.902)	**0.011** (0.014)	20.53 (17.56)
III.	$E_{dyn} = 3.124 v_{ref} - 4671.8$	**0.291**	(0.237)	**0.539**	(0.487)	0.269 (0.327)	1.641 (1.25)
	$E_{dyn.rref} = 2.924 v_{ref} - 4237.1$	**0.293**	(0.240)	**0.541**	(0.541)	0.267 (0.324)	1.658 (1.26)
	$E_{dyn.vref} = 3.074 v_{ref} - 5052.2$	**0.285**	(0.230)	**0.534**	(0.480)	0.275 (0.336)	1.593 (1.19)
	$E_{dyn.rref.vref} = 3.041 v_{ref} - 4843.2$	**0.287**	(0.232)	**0.536**	(0.482)	0.273 (0.333)	1.610 (1.21)
	$E_{dyn.ref} = 3.037 v_{ref} - 4836.9$	**0.287**	(0.232)	**0.536**	(0.482)	0.273 (0.333)	1.610 (1.21)
	$E_{m.0} = 4.2543 v_{ref} - 13343$	**0.741**	(0.691)	**0.861**	(0.831)	**0.028** (0.041)	11.44 (8.95)
	$E_{m.0.ref} = 4.3061 v_{ref} - 13685$	**0.724**	(0.669)	**0.851**	(0.818)	**0.032** (0.047)	10.48 (8.09)
	$f_{m.0} = 0.0159 v_{ref} - 59.508$	**0.791**	(0.746)	**0.889**	(0.864)	**0.018** (0.028)	14.97 (11.26)

* Values in brackets are given for regressions with mean velocity v_{mean}. Correlation coeff. v_{ref} with v_{mean} for I.. II. & III. are: $r = 0.998$, $r = 0.994$ i $r = 0.997$.

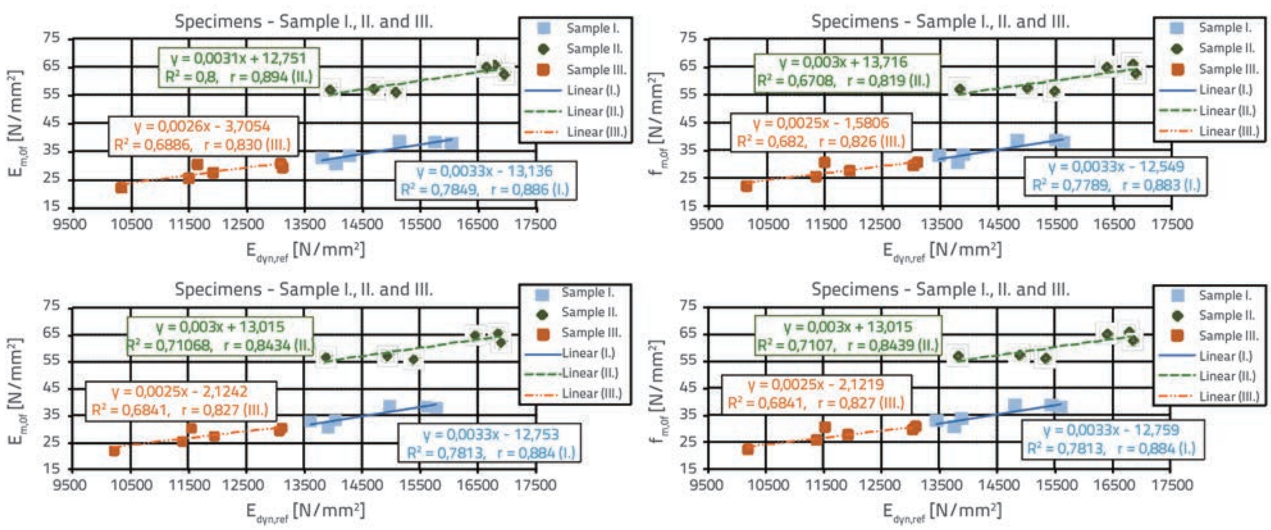

Figure 6. Regressions of theoretical *E*-module with static *E*-module and bending strength

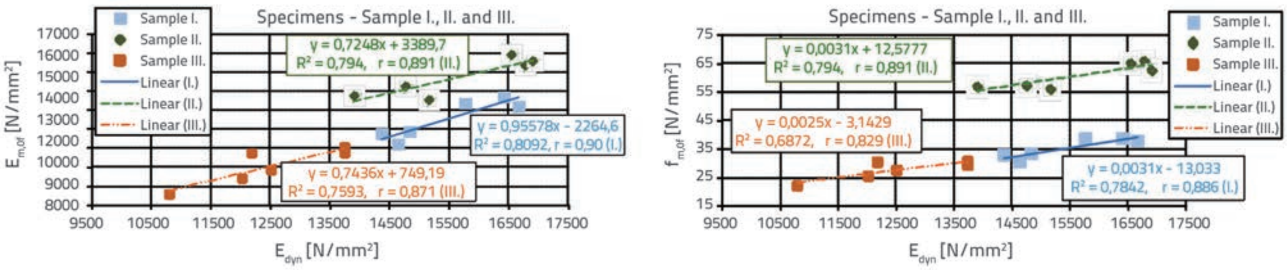

Figure 7. Regressions of dynamic *E*-modules with bending strength

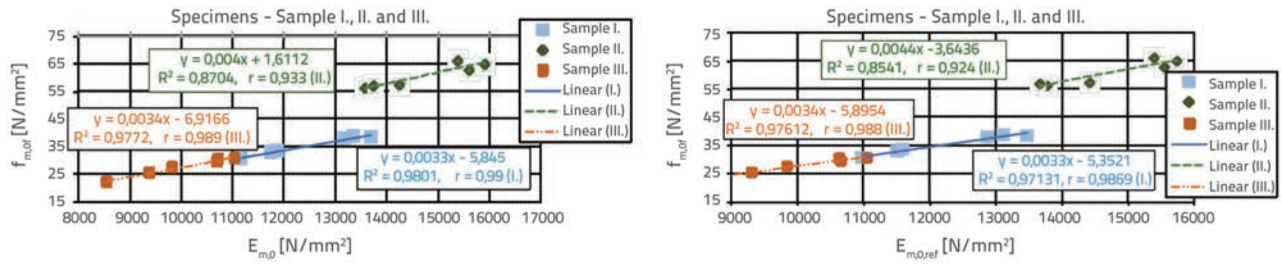

Figure 8. Regression models and parameters of static *E*-modules with bending strength

3.2. Effects of applied adjustments within grading of small-sized samples into strength classes

For the initial type classification, the parametric calculation of mean and characteristics values of properties for samples with $n < 40$, for reliability level of 95 % and confidence interval, γ = 75 %, where influence of real number of specimens (n) on characteristic property is taking into account by factor $k_{s(n)}$ [51, 52], calculated from equation (12) [20].

$$k_{s(n)} = \begin{cases} \dfrac{0,78}{n^{0,53}} = 0,302 & \text{for } E_{mean,k} \\ \dfrac{6,5n+6}{3,7n-3} = 2,344 & \text{for } E_{mean,k} \text{ and } \rho_k \end{cases} \tag{12}$$

$$m_k = \begin{cases} y_{mean} - k_{s(n)} s_y & \text{for } E_{mean,k} \text{ and } \rho_k \\ \exp(y_{mean} - k_{s(n)} s_y) & \text{for } E_{mean,k} \end{cases} \tag{13}$$

Table 8. Classification of specimens and assigned strength classes according to EN 338:2105

Grading parameter**		$\rho_{u.corr}$	ρ_{ref}	E_{dyn}	$E_{dyn.\rho ref}$	$E_{dyn.vref}$	$E_{dyn.\rho ref.vref}$	$E_{dyn.ref}$	$E_{m.0}$	$E_{m.0.ref}$	$f_{m.0}$
		(1)	(2)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		[kg/m³]		[kN/mm²]							[N/mm²]
I.	y_{mean}	434.4	430.7	15.45	14.84	14.52	14.64	14.49	12.50	12.25	3.56*
	s_y	21.7	21.5	0.97	0.93	0.92	0.93	0.92	1.03	1.02	0.10*
	m_k	383.5	380.3	15.15	14.55	14.24	14.36	14.21	12.19	11.94 < 12	27.94
	CoV [%]	2.95	2.93	5.74	5.73	5.78	5.73	5.77	7.54	7.60	8.88
	Razred	C30	C30	C45	C40	C40	C40	C40	C30	C27	C27
II.	y_{mean}	706.3	706.1	15.68	15.68	15.72	15.80	15.68	14.58	14.58	4.12*
	s_y	49.8	48.1	1.24	1.27	1.19	1.51	1.20	1.18	1.07	0.07*
	m_k	589.6	593.4	15.30	15.29	15.36	15.35	15.31	14.45	14.47	51.29
	CoV [%]	6.43	6.22	7.25	7.40	6.91	7.01	7.01	6.26	5.70	6.54
	Razred	D45	D45	D50	D50	D50	D50	D50	D50	D50	D50
III.	y_{mean}	392.0	392.9	12.51	11.94	11.85	11.66	11.86	10.15	10.10	3.32*
	s_y	31.6	31.2	1.12	1.05	1.12	1.30	1.10	1.07	1.09	0.13*
	m_k	318.0	319.9	12.17	11.62	11.51	11.26 < 11.5	11.53	9.76	9.70	20.37
	CoV [%]	7.35	7.24	8.19	8.05	8.60	8.45	8.45	8.70	8.96	11.0
	Razred	C18	C18	C30	C27	C27	C24	C27	C20	C20	C20

* for lognormal distribution. ** differences between results are highlighted by underlining – assigned strength class is based on appropriate m_k

Table 9. Ratios of characteristic and mean vales for populations of *E*-modules

Referent E-module $E_{m.0.ref}$						
m_k	(4)/(10)	(5)/(10)	(6)/(10)	(7)/(10)	(8)/(10)	(9)/(10)
I.	+ 26.9 %	+21.9 %	+19.3 %	+20.3 %	+19.0 %	+2.0 %
II.	+5.7 %	+5.7 %	+6.2 %	+6.0 %	+5.8 %	-0.2 %
III.	+25.5 %	+19.9 %	+18.7 %	+16.2 %	+18.9 %	+0.7 %
Theoretical E-module E_{dyn}						
m_k	(5)/(4)	(6)/(4)	(7)/(4)	(8)/(4)	(9)/(4)	(10)/(4)
I.	-4.0 %	-6.0 %	-5.2 %	-6.2 %	-19.6 %	-21.2 %
II.	+0.0 %	+0.4 %	+0.3 %	+0.1 %	-5.6 %	-5.4 %
III.	-4.5 %	-5.4 %	-7.4 %	-5.3 %	-19.8 %	-20.3 %

Characteristic values m_k are determined from the expression (13) [20], for mean values of homogeneous populations, y_{mean}, and standard deviations, $s_y \geq 0.05$ (for $f_{m,k}$) and $s_y \geq 0.05 y_{mean}$ (for $E_{mean,k}$ and ρ_k). From the regression charts (Figure 5 to 8) it is notably that points deviate negligently from the line between the first and third quartiles. Therefore, additional verifications of the character of distribution (using probability diagram or other statistic methods) were not conducted, and the normal distribution of the density properties and stiffness, as well as lognormal for strength are adopted [1].

3.3. Discussion of derived regressions and effects of adjustments within initial type grading

Results reported in recent studies point to similar, but not unique regression parameters which depend of applied NDT and influence of other factors (the number, specie, size and/or type of considered specimens and etc.). Many research based on method of ultrasonic runtime measurement and performed on large and numerous specimens of known densities, reported correlations between dynamic and static E-modules, as the strongest, with achieved regression coefficients of 0.84 – 0.91 for four species of softwood [30], 0.93 for pine beams [47] and 0.87 for fir and spruce specimens [48], wherein dynamic *E*-modules are between 15 % and 35 % higher than static MoE [45, 47, 49, 50]. Reported data are comparable to those we achieved within conducted research (Table 6 and 9). Due to very strong correlations, close to ones in listed sources, potentials of dynamic MoE for predicting of static MoE and bending strengths (Figure 5 to 7) can be confirmed as high, and linear regressions as adequate (with *P* - values that are significantly lower from limit value, $\alpha = 0.05$). Although the strength of correlations for all derived regressions models are mutually similar (Figure 5), and close to those for theoretical MoE, E_{dyn} (Figure 6), the strongest correlation (with coefficients $r = 0.903$ and $r = 0.902$, for regression with E_{dyn}, v_{ref} and $E_{dyn,\ ref}$) was achieved for I. sample, where the differences between reference and measured values of *u* and *T* are the biggest, variations of density are the lowest (Table 5 and 9), and the statistic significance of reference velocity, v_{ref}, the best (Table 7). For other samples, correlation were strongest for regressions of static MoE with reference module $E_{dyn,\rho ref}$ (with $r = 0.908$, for II., and $r = 0.873$, for III. sample), and the weakest with the module $E_{dyn,vref}$ (with $r = 0.825$ and $r = 0.866$), while the corresponding strengths of regression with module E_{dyn}, are described with $r = 0{,}891$ and $r = 0.871$ (Figure 6). For both samples, mean values of populations v_{mean} and v_{ref} (Table 5) are close, variations of densities are bigger, while deviations of mean values of populations *u* and *T* of references is negligible, and statistic significances of wave velocities are weaker than values for I. sample (Table 7). For developed regressions of static MoE and strengths (Figure 5 and 7) with dynamic MoE $E_{dyn,\rho ref}$, v_{ref} and $E_{dyn,ref}$, correlation coefficients are mostly equalized for all samples, confirming that all combined adjustments can be described with one linear function. Effects of these adjustments therefore can be considered as satisfactory for application in initial type classification (Table 8 and 9). For spruce samples (I. and III.), the values m_k for dynamic MoE from expressions from (5) to (8) are lower than comparative ones for theoretical MoE, E_{dyn} from equation (4), and assigned strength classes are not so over-estimated, while the effects of adjustments are negligible for II. sample, what is also connectable to data given in Table 5 and 6. The smallest differences between values of m_k had been found for population of $E_{dyn,\rho ref}$ and E_{dyn}, so, the adjustments of velocity should be considered as more significant from those for density. Many studies of big-sized samples also marked the density (even when they vary a little) as worse indicator for MoE, with $0.3 < r < 0{,}7$ [15, 23, 29, 48, 49]. Static MoE is the best indicator for bending strength (Figure 8, Table 8 and 9). Achieved correlation coefficients ($r = 0.99$, for I. and III. samples, and $r = 0.93$, for II.) are higher than those for regressions with adjusted dynamic MoE and the module E_{dyn} (Figure 7), where $r_{max} = 0.89$ for I. and II. samples, and $r_{min} = 0.83$ for III. sample, and mutually differences of correlations coefficients derived for $E_{dyn,ref}$ and E_{dyn} are negligible. Results are comparable with those from literature [15, 23, 29, 48, 49], with $r > 0.8$ for dynamic, and $r > 0.9$ for static MoE.

4. Conclusions

Although this research was performed on samples consisted of small number of specimens, and the deviations of results of test phases 1 and 3 (Table 4 and 5) from reference values are small, the following can be noted:

- density, velocities of ultrasonic stress-waves and dynamic MoE are sensitive to effects of moisture content *u* and temperature *T*, whose adjustments to reference, improve results of NDT (Table 6 and 7),
- to be applied in strength grading procedure is primary purpose of the adjustments, and the effects are visible even also for relatively small deviations of considered parameters from reference values of *u* and *T* (Table 8 and 9),
- for the method based on runtime measuring of longitudinal ultrasound stress-waves, dynamic MoE can be defined using the adjustments of density or velocity, as well as combining both, but also as average adjusted value, according to the expressions from (5) to (8),
- combined effects of adjustment of density of specimens and stress-wave velocity to dynamic MoE, $E_{dyn,\rho ref,vref}$, can

be described with one linear function for the module $E_{dyn,ref}$ (Figure 5 to 7),

- linear regression models can be established for mechanical properties determined by combined tests (Figure 5 to 8), and static MoE has the highest potential of predicting the bending strength (Table 8),
- efficiency evaluation of regression model should cover not only the correlation strength, but also the verifying of the statistic significance of regression parameters as additional criterion for checking relationship between variables and measure of variability (Table 7, Figure 5 to 7),
- it is possible to establish linear regression models of static MoE, $E_{m,0}$ and bending strength, f_m with velocities of longitudinal ultrasonic stress-waves (Table 7),
- in comparison with mean velocity, v_{mean}, reference velocity v_{ref} (Table 7), determined from proposed simplified expression (3), is more reliable parameter of derived regression with $E_{m,0}$ and $f_{m,0}$.

Evaluations of statistic significance of reference speed v_{ref} and strength of correlations (Table 7, chapters 3.1 and 3.3) point to following possible improvements the representativeness of results and guidelines for future research:

- verifying the adequacy of the expression (3) for bigger deviations of parameters u and T of reference values, and defining the limits of its application,
- correction of velocity for additional influence of fibre inclination on longitudinal wave propagation
- establishing the models of multiple regressions in order to include additional influence of presence of knots
- establishing the models of multiple regression taking in consideration the influence of density, and making conclusions from results of the tests on greater number of specimens, selected on the basis of detail visual inspection and apply other available techniques to determine static MoE.

The results of conducted research indicate the high potential of dynamic MoE determined by this ND method in predicting mechanical properties and the appropriateness of applied adjustments in strength grading process. By evaluating effect of adjustments to samples of different quality and botanic species, the limitations of the applied approach and analysed parameters have been noted and listed as possible guidelines for its improvement.

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