IMPACT OF THE LOAD RATE ON THE ELASTIC PROPERTIES OF BEECH WOOD SAMPLES AT COMPRESSION TEST IN THE LONGITUDINAL AND TANGENTIAL DIRECTION

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ABSTRACT
Knowledge of dynamic elastic properties of wood is an important precondition for rational and effective exploitation of wood raw material. In this paper, the impact of the load rate on the elastic properties of wood at the compression test in the longitudinal and tangential directions is analyzed. Elastic properties which were determined in this research are the modulus of elasticity, stress and strain at the point of proportionality and specific energy and power of elastic deformation. The research was carried out on beech samples that were prepared with smaller dimensions than prescribed in the norm (DIN EN 408) in order to achieve a more accurate determination of the specific energy and power of elastic deformation. The load rate was varied from 2 to 50 mm/min.

Key words: wood, Stress, strain, elastic area, load rate.

1. INTRODUCTION
Wood is a natural material that is despite the growing presence of synthetic alternatives remained an integral part of human life. The use of wood is varied, from construction, making plate of chopped wood and wood composite materials, use of wood for making energy products, to the production of furniture. Due to increasingly stringent technological requirements, knowledge of the mechanical properties of wood is of high importance. Mechanical properties are dependent on several factors, and one of these factors is the rate of load (Mathew *et al*. 1982). Measurement of mechanical properties of wood is prescribed by the norm (DIN EN 408) in which the load rate is defined as $v = 0{,}0005 \cdot l_0$ m/s (l_0 is the initial dimension of the sample). However, the wood because of its various uses often could be exposed to much higher load rates. The mechanical properties measured by standard load rate are called static properties, and if the load rate in the measurement is higher than the load rate prescribed by the norm, the measured mechanical properties are called dynamic. Knowledge of the dynamic properties of the wood is exceptionally important in the wood processing (Radmanovic 2015) but also during the use of final wood products. In this paper, the impact of the load rate on the dynamic elastic properties of wood in the longitudinal and tangential directions is analyzed. The elastic properties of wood determined in this work are: modulus of elasticity, stress and strain at the point of proportionality, and specific energy and power of elastic strain.

2. EXPERIMENTAL METHODS
The experimental research was carried out in two phases. In the first phase, wood samples were selected and prepared and in the second phase, the elastic properties of wood samples were measured in the longitudinal and tangential directions. Testing of

elastic properties of wood samples was carried out in the accredited Wood Laboratory for Construction at the Faculty of Forestry of the University of Zagreb.

Determination of the dependence of elastic properties on the load rates was carried out on beech wood samples (*Fagus Sylvatica*), as the most common tree species in Croatia. It is known that the elastic properties of wood depend on the dimensions of the examined samples, or on the composition of the wood samples (Horvat and Krpan 1967). To determine as precisely as possible, the energy required for the elastic strain of the unit volume, the aim was to do compression tests with the samples of dimensions as small as possible for good quality of measurement on the testing machine. Selected samples were free of visible defects that could have a significant impact on the measurement results. The dimensions of samples were $a = b =$ 1.5 cm and $c =$ 3 cm (Fig. 1), and the resistance hygrometer measured the moisture content of 9%.

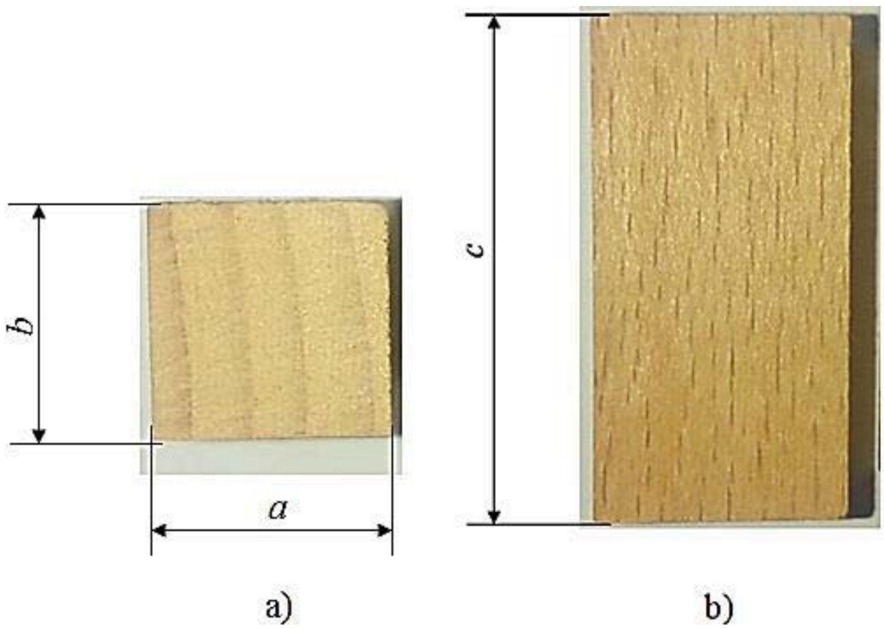

Figure 1: Beech wood samples: a) Cross section; *a* - length of the beech sample, *b* - width of the beech sample; b) radial cross section; *c* – height of the beech sample

2.1. METHODS

In the second phase of the experiment, the elastic properties of the beech samples were measured depending on the load rate at the compression tests in the longitudinal and tangential directions. Fig. 2 shows the cross-section (Fig. 2.a) and radial section (Fig.2.b) of the samples with dimensions before and after application of the load. In Fig. 2.a, the force (F) acts in the tangential, and in Fig. 2.b in the longitudinal direction. The forces in the longitudinal and tangential directions with corresponding displacements ($\Delta c = c - c'$ and $\Delta b = b - b'$) were measured on a Shimadzu drill, type Autograph AG-X equipped with a dynamometer with nominal force of 10000 N. The flow and test procedure is programmed with the corresponding Trapezium X software. The displacement measurement in the longitudinal direction (Δc) was performed until the force reached its maximum value, and the displacement in tangential direction (Δb) was measured to a deformation of 6 %.

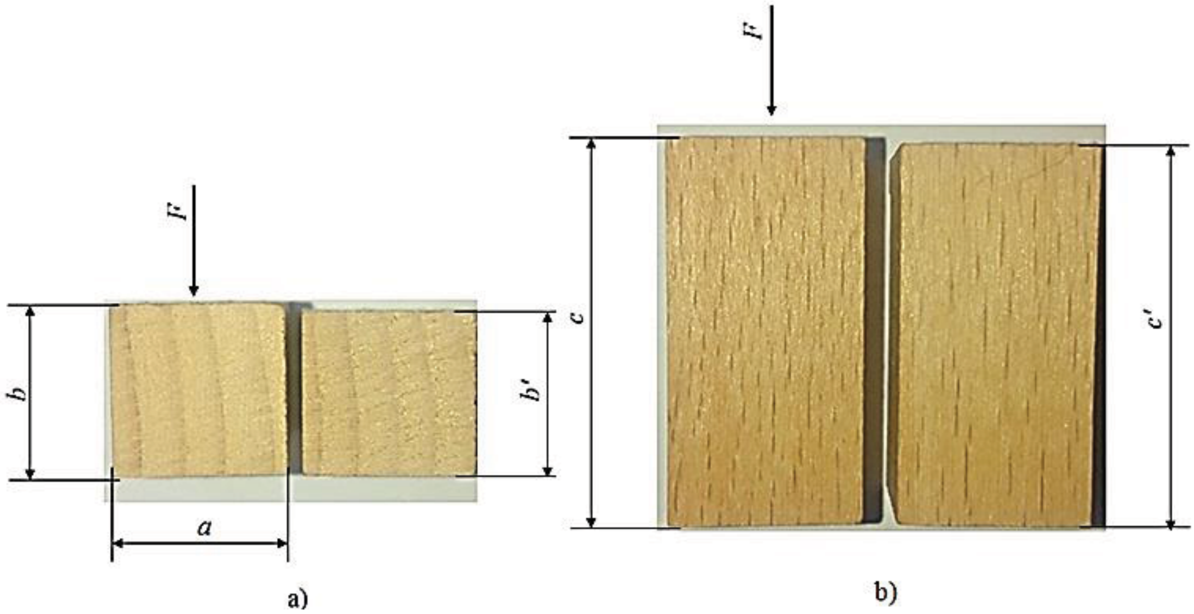

Figure 2: The force action on the beech samples: a) The force action on the beech samples in tangential direction: *a* - sample length, *b* - sample width before action of the force, *b* '- sample width after action of the force, b) The force action on the beech samples in longitudinal direction: *c* - sample height before action of the force, *c*' - sample height after action of the force

The elastic properties of the beech samples were determined depending on the load rate and the chosen load rates were: v = (2, 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50) mm/min. The data of measured force and displacement are processed in Sigmaplot v.10.0. Compressive stress in the longitudinal direction is determined according to the expression

$$\sigma_x = \frac{F_x}{a \cdot b}. \qquad \textbf{(1)}$$

where: σ_x – stress in longitudinal direction, F_x – force in longitudinal direction, *a*- sample length, *b* - sample width. The corresponding strain in the longitudinal direction is determined according to the expression

$$\varepsilon_x = \frac{\Delta c}{c}. \qquad \textbf{(2)}$$

where: ε_x – relative strain in longitudinal direction, Δc – change in height of the samples, c – initial height of the sample. Compressive stress in the tangential direction is determined by the expression

$$\sigma_y = \frac{F_y}{a \cdot c}. \qquad \textbf{(3)}$$

where: σ_y – stress in tangential direction, F_y – the force in tangential direction, *a* – sample length, c – sample height. The corresponding strain in the tangential direction is determined according to the expression

$$\varepsilon_y = \frac{\Delta b}{b}. \qquad \textbf{(4)}$$

where: ε_y – relative strain in the tangential direction, Δ*b* – change in width of the sample, c – initial width of the sample. After calculating the compression stress and the corresponding strain, the stress – strain diagrams were plotted. The stress – strain diagram for the longitudinal direction of the force is shown in Fig. 3.a and for the tangential direction in Fig. 3.b. Diagram parameters in the longitudinal direction are marked with index x and in tangential direction with index y. In the Fig. 3. it is evident that after the initial nonlinear part comes linear part of the stress – strain curve. Initial nonlinearity is due to the fact that in the beginning of the action of the force, in addition to compression, the sample adjustment is due to micro unevenness on its surface, which causes deformation ε_0 as the beginning of elastic deformation (Fig. 3.a and 3.b). The area in which the stress and strain relationship is linear is called the elastic area (FPL 1999). The point of proportionality (TP) indicates the end of the elastic area and the beginning of the plastic area.

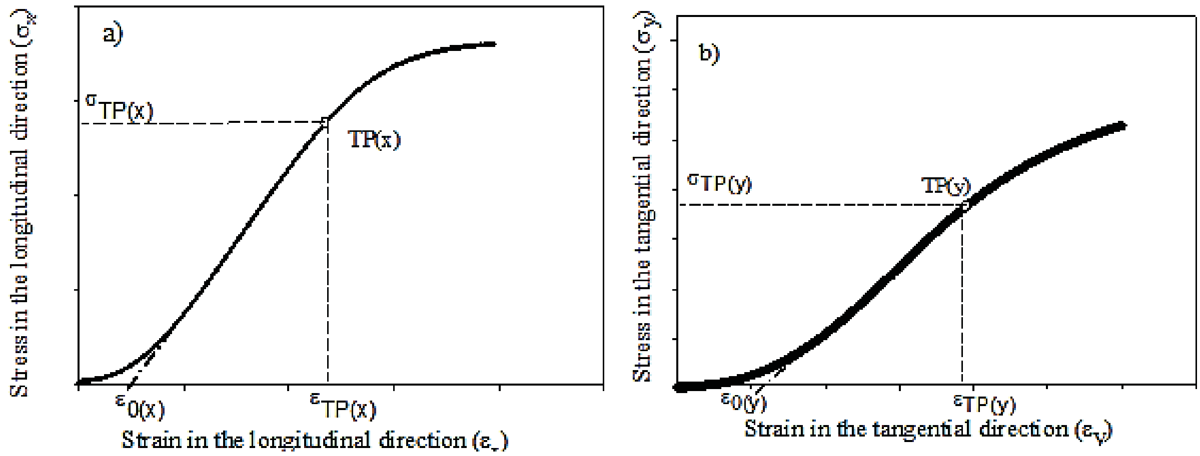

Figure 3: a) Stress – strain diagram in the longitudinal direction; TP (x) – point of proportionality in the longitudinal direction, $\varepsilon_{0(x)}$ - initial strain in the longitudinal direction,, $\varepsilon_{TP\,(x)}$ – strain at the point of proportionality in the longitudinal direction, $\sigma_{TP\,(x)}$ – stress at the point of proportionality in the longitudinal direction. b) Stress – strain diagram in tangential direction; TP (y) – point of proportionality in the tangential direction, $\varepsilon_{0(y)}$ – initial strain in the tangential direction,, $\varepsilon_{TP\,(y)}$ – strain at the point of proportionality in the tangential direction, $\sigma_{TP\,(y)}$ – stress at the point of proportionality in the tangential direction

During one test, the load rate was constant and it can be defined as

$$v_x = \frac{|\Delta c|}{\Delta t_x} = \frac{|\Delta c_0|}{t_{0(x)}} = \frac{|\Delta c_{TP}|}{t_{TP(x)}}. \qquad (5)$$

where: v_x – load rate in longitudinal direction, Δc – displacement in the longitudinal direction, Δt_x – time of force action in the longitudinal direction, $t_{0(x)}$ – the time required to achieve initial strain in longitudinal direction, Δc_{TP} – displacement at the point of proportionality in longitudinal direction, $t_{TP(x)}$ – the time required to achieve strain at the point of proportionality in longitudinal direction. Considering that during a test, load rate in the tangential direction was constant, that means

$$v_y = \frac{|\Delta b|}{\Delta t_y} = \frac{|\Delta b_0|}{t_{0(y)}} = \frac{|\Delta b_{TP}|}{t_{TP(y)}}. \qquad (6)$$

where: v_y – load rate in the tangential direction, Δb – displacement in the tangential direction, Δt_y – time of force action in the tangential direction, $t_{0(y)}$ – the time required to achieve initial strain in tangential direction, Δb_{TP} – displacement at the point of proportionality in tangential direction, $t_{TP(y)}$ – the time required to achieve strain at the point of proportionality in tangential direction.

2.1.1. Determination of modulus of elasticity

The force acting on the beech sample changes the size and shape of the sample. This change can be elastic or plastic, i.e. the shape change consists of reversible or elastic strain and irreversible or plastic strain. In elastic changes of shape, upon ending of external force action, the sample returns to its original form. The modulus of elasticity is the elasticity ratio, i.e. the relationship between stress and strain in the elastic area of the stress - strain diagram (Bodig and Jayne 1993). According to Tkalec and Prekrat (2000), the modulus of elasticity in the tangential direction, at 15% moisture content, amounts to only 1/11 to 1/40 of the elastic modulus in the longitudinal direction. The elastic field considerations are identical for both observed directions, and for simplicity, the general terms associated with index x for longitudinal and index y for tangential direction will be presented. The relationship between stress and strain in the elastic region can be described by linear function (Požgaj 1993)

$$\sigma_{el} = \sigma_0 + E \cdot \varepsilon_{el} \,. \qquad (7)$$

where σ_{el} denotes any stress less than σ_{TP}, and ε_{el} each strain for which $\varepsilon_0 \leq \varepsilon_{el} \leq \varepsilon_{TP}$, σ_0 denotes a section of the linear function in the ordinate and E is the modulus of elasticity (slope of linear function in relation to strain axis). The modulus of elasticity (E) and the section of the linear function in the ordinate (σ_0) were determined by fitting experimentally obtained data in the linear part of stress – strain diagram to expression (7). Fig. 4.a shows stress – strain diagram in longitudinal direction (index x), and Fig. 4.b shows stress – strain diagram in tangential direction (index y) with adjusted linear function in elastic area.

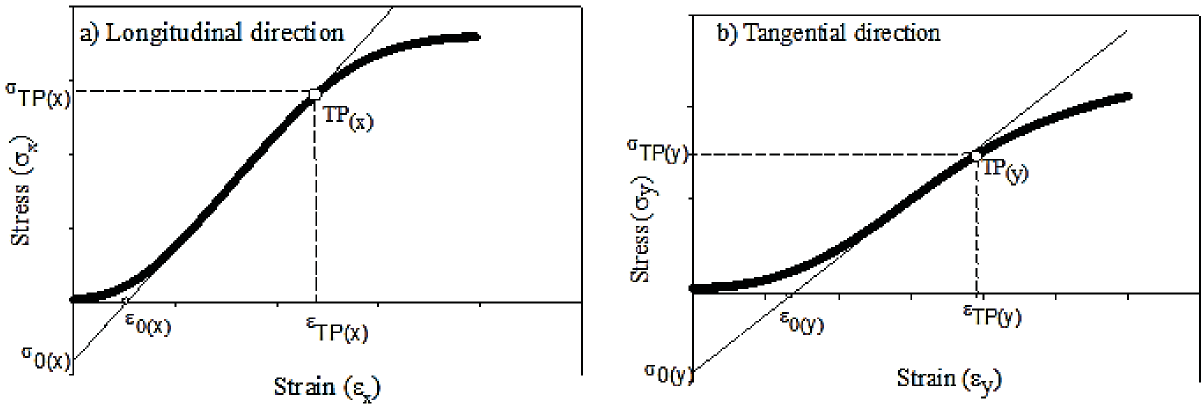

Figure 4: a) Stress – strain diagram with fitted function in the longitudinal direction; TP (x) – point of proportionality in the longitudinal direction, $\varepsilon_{0(x)}$ – initial strain in the longitudinal direction, $\sigma_{0(x)}$ – section of the linear function in the ordinate in longitudinal direction, $\varepsilon_{TP\,(x)}$ – strain at the point of proportionality in the longitudinal direction, $\sigma_{TP\,(x)}$ – stress at the point of proportionality in the longitudinal direction. b) Stress – strain diagram with fitted function in the tangential direction; TP (y) – point of proportionality in the tangential direction, $\varepsilon_{0(y)}$ – initial strain in the tangential direction, $\sigma_{0(y)}$ – section of the linear function in the ordinate in tangential direction, $\varepsilon_{TP\,(y)}$ – strain at the point of proportionality in the tangential direction, $\sigma_{TP\,(y)}$ – stress at the point of proportionality in the tangential direction

2.1.2. Determination of specific energy and strength of elastic strain

In the process of the beech sample deformation forces have to perform a certain work. Part of this work accumulates in the material as a potential energy deformation. If the losses due to conversion to other forms of energy are neglected, all outsourced power work turns into the potential energy of the beech sample. This energy is within the limits of elastic behavior returning, which means that upon ending of the force action the beech sample can perform mechanical work equal to the stored elastic energy. The elemental deformation work invested on the elastic deformation of the unit volume is called the specific energy of elastic deformation, and is defined by the expression

$$e_{el} = \int_{\varepsilon_0}^{\varepsilon_{TP}} \sigma_{el} d\varepsilon_{el} = \sigma_0 \cdot \left(\varepsilon_{TP} - \varepsilon_0\right) + \frac{E}{2} \cdot \left(\varepsilon_{TP}^2 - \varepsilon_0^2\right) \quad \textbf{(8)}$$

where: e_{el} – specific energy of elastic strain, ε_0 – initial strain, ε_{TP} - strain at the point of proportionality, ε_{el} – elastic strain, σ_0 – section of the linear function in the ordinate, σ_{el} – elastic stress, E – modulus of elasticity.

Specific power of elastic strain (p_{el}) is rate of transmission the specific elastic energy, and is defined by the expression

$$p_{el} = \frac{e_{el}}{t_{TP} - t_0} \quad . \quad \textbf{(9)}$$

where: p_{el} –- specific power of elastic strain, e_{el} – specific energy of elastic strain, t_0 – the time required to achieve initial strain, t_{TP} – the time required to achieve strain at the point of proportionality. From the expressions (8) and (9) it follows that for determining the specific elastic energy and power of elastic strain it is necessary to know the parameters that limit the elastic area on the strain axis (ε_0 and ε_{TP}) and stress axis (σ_0) and the time required to achieve initial strain and strain at the point of proportionality (t_0 and t_{TP}). The strain ε_0 is determined by equating the expression (7) with the zero

$$\sigma_0 + E \cdot \varepsilon_0 = 0 \Rightarrow \varepsilon_0 = -\frac{\sigma_0}{E} \quad . \quad \textbf{(10)}$$

where: ε_0 – initial strain, σ_0 – section of the linear function in the ordinate, E – modulus of elasticity. By combining the terms (2), (5) and (10), time (t_0) is determined by expression

$$t_0 = -\frac{\sigma_0 \cdot c}{E \cdot v} \quad . \quad \textbf{(11)}$$

where: t_0 – the time required to achieve initial strain, σ_0 – section of the linear function in the ordinate, E – modulus of elasticity, v – load rate, c – height of the beech sample. The expression (11) shows that the time required for the achievement of initial strain ε_0, reverse proportionally depends on the modulus of elasticity (E) and load rate and proportionally on the height of the sample (c) and the section of the linear function in the ordinate (σ_0). The strain at the point of proportionality is read out from stress – strain diagram, and the time required to achieve strain at the point of proportionality is determined by the combination of expression (2) and (5) for the longitudinal direction

$$t_{TP(x)} = \frac{\varepsilon_{TP(x)} \cdot c}{v_x} \quad . \quad \textbf{(12)}$$

where: $t_{TP(x)}$ – the time required to achieve strain at the point of proportionality in longitudinal direction, $\varepsilon_{TP(x)}$ – strain at the point of proportionality in the longitudinal direction, v_x – load rate in the longitudinal direction, c – height of the sample. With the combination of expression (4) and (6) the time required to achieve strain at the point of proportionality in tangential direction is determined

$$t_{TP(y)} = \frac{\varepsilon_{TP(y)} \cdot b}{v_y} \quad . \quad \textbf{(13)}$$

where: $t_{TP(y)}$ – the time required to achieve strain at the point of proportionality in tangential direction, $\varepsilon_{TP(x)}$ – strain at the point of proportionality in tangential direction, v_y – load rate in tangential direction, b – width of the sample.

3. RESULTSAND DISCUSSION

The measurement data were processed in SigmaPlot v.10.0. The experiment was repeated five times under the same conditions, after which the mean value of the measured data was determined with the corresponding standard deviation. Given the small number of repeated measurements, the data were not tested by statistical tests.

3.1. THE RESULTS OF DETERMINING PARAMETERS THAT LIMIT THE ELASTIC AREA OF THE STRESS – STRAIN DIAGRAM IN THE LONGITUDINAL AND TANGENTIAL DIRECTIONS

Fig. 5 shows diagrams of dependence of the mean value of stress in the point of proportionality on the load rate with the corresponding standard deviations in the longitudinal and tangential direction. As can be seen in Fig. 5, the mean value of stress at the point of proportionality follows the tendency of growth with an increase of load rate, which means that faster loads result in higher material resistance.

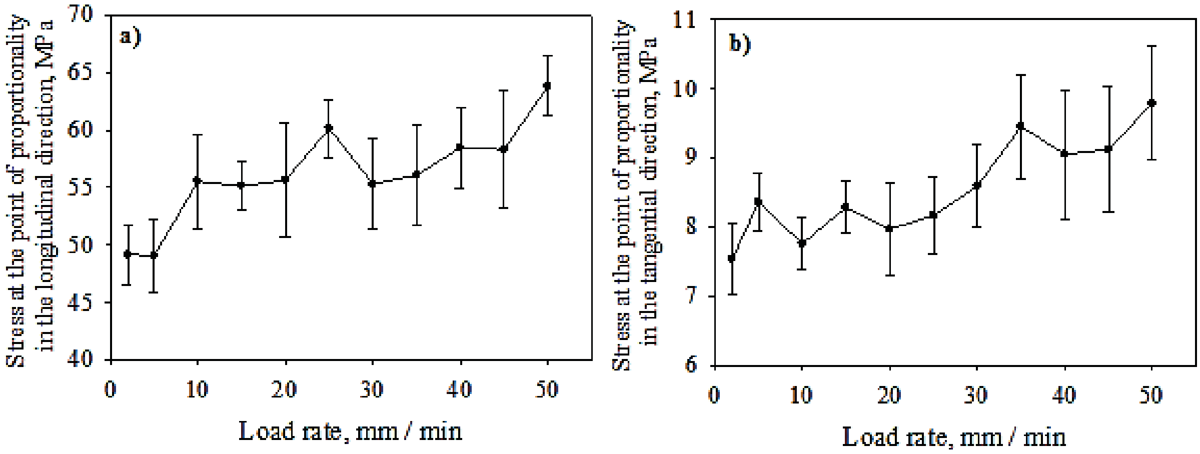

Figure 5: Dependence of the mean value of stress at the point of proportionality on the load rate with the corresponding standard deviations a) longitudinal direction ($\sigma_{TP(x)}$), and b) tangential direction ($\sigma_{TP(y)}$)

Fig. 6 shows diagrams of the dependence of mean values of characteristic deformations ($\varepsilon_{0(x)}$, $\varepsilon_{TP(x)}$, $\varepsilon_{0(y)}$, $\varepsilon_{TP(y)}$) on load rate in the longitudinal and tangential directions with corresponding standard deviations. In Fig.6, there is a noticeable increase in mean value of strain with higher load rate, which is consistent with the results of conducted research of mechanical properties of wood (Wouts et al. 2016). It is also obvious that the mean values of initial strain and strain at point of proportionality have larger values in the tangential direction than in the longitudinal direction for all observed load rates

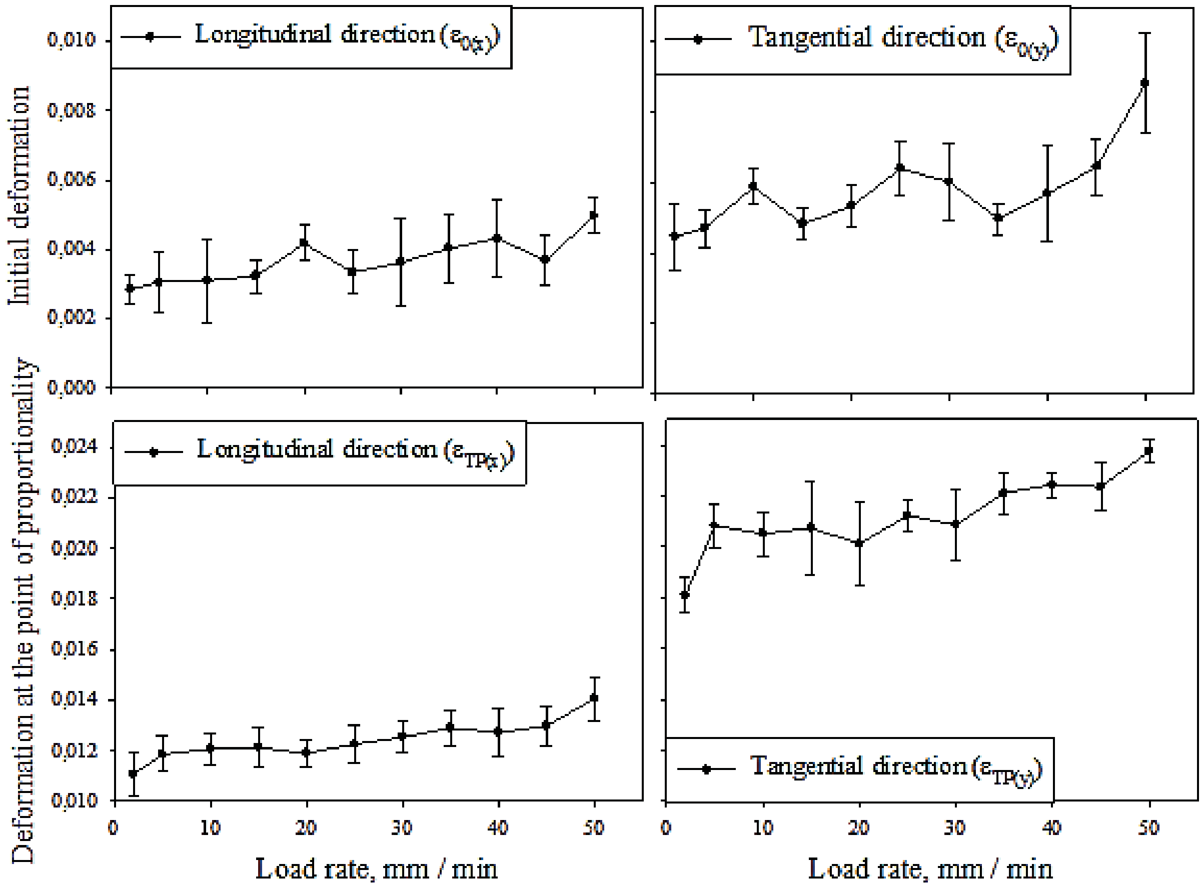

Figure 6: Dependence of the mean value of initial strain ($\varepsilon_{0(x)}$ and $\varepsilon_{0(y)}$) and the strain at point of proportionality ($\varepsilon_{TP(x)}$ and $\varepsilon_{TP(y)}$) on the load rate with the corresponding standard deviations

3.2. RESULTS OF DETERMINATION OF MODULUS OF ELASTICITY IN THE LONGITUDINAL AND TANGENTIAL DIRECTIONS

Fig. 7 shows a diagram of the dependence of mean values of the modulus of elasticity in the longitudinal (E_x) and tangential (E_y) direction on the load rate with the corresponding standard deviations. By increasing the load rate the upward trend in the mean values of modulus of elasticity is visible, that is consistent with the results of the research of mechanical properties of wood (Sliker 1972). The increase of the mean value of the modulus of elasticity with increasing the load rate is more pronounced in the longitudinal direction.

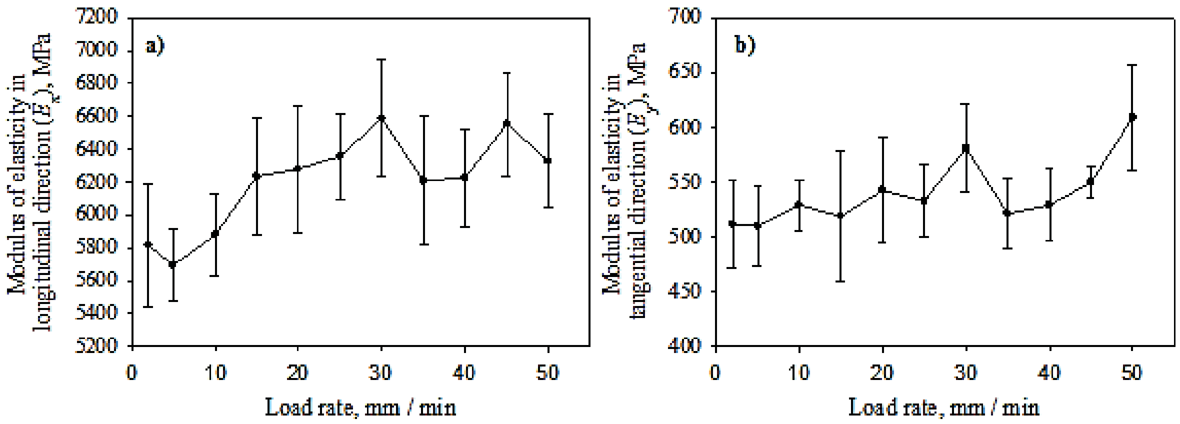

Figure 7: Dependence of the mean values of the modulus of elasticity on load rate with the corresponding standard deviations a) longitudinal direction (E_x) and b) tangential direction (E_y)

3.3. RESULTS OF DETERMINATION OF SPECIFIC ENERGY AND SPECIFIC POWER OF ELASTIC STRAIN IN THE LONGITUDINAL AND TANGENTIAL DIRECTIONS

Fig. 8 shows the dependence of the mean values of the specific energy of elastic strain in the longitudinal ($e_{el(x)}$) and tangential ($e_{el(y)}$) direction on load rate with the corresponding standard deviations. By increasing load rate the upward trend in the mean values of the specific energy of elastic strain in longitudinal direction can be noticed, while in tangential direction a clear trend can not be established.

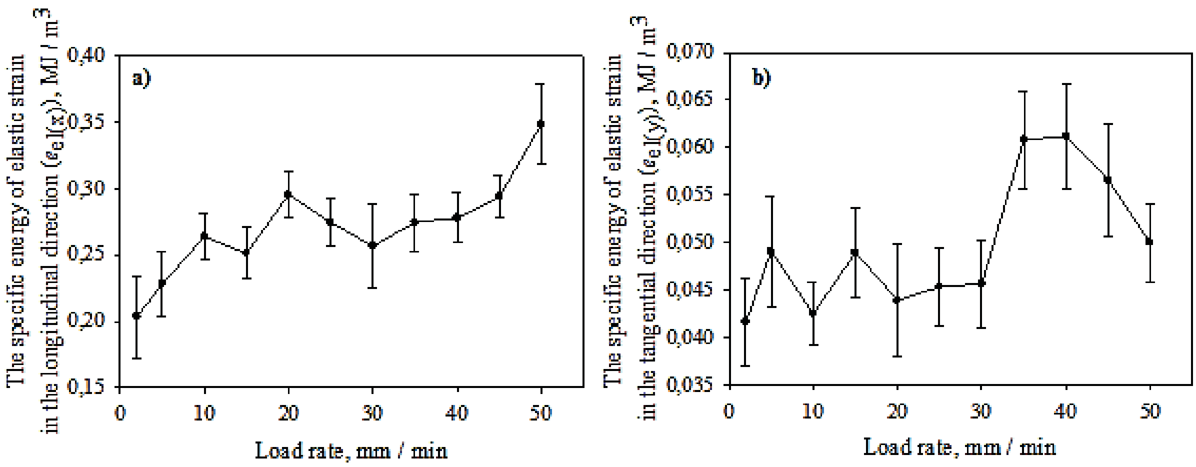

Figure 8: Diagram of dependence the mean value of the specific energy of elastic strain on load rate with the corresponding standard deviations. a) longitudinal direction ($e_{el(x)}$) and b) tangential direction ($e_{el(y)}$)

Increasing the load rate increases also the specific power of elastic strain in both observed directions (Fig. 9). The increase of the specific power of elastic strain by increasing the load rate is more pronounced in the longitudinal direction (up to 50 MW/m^3), while in the tangential direction the increase is significantly less (up to 8.5 MW/m^3).

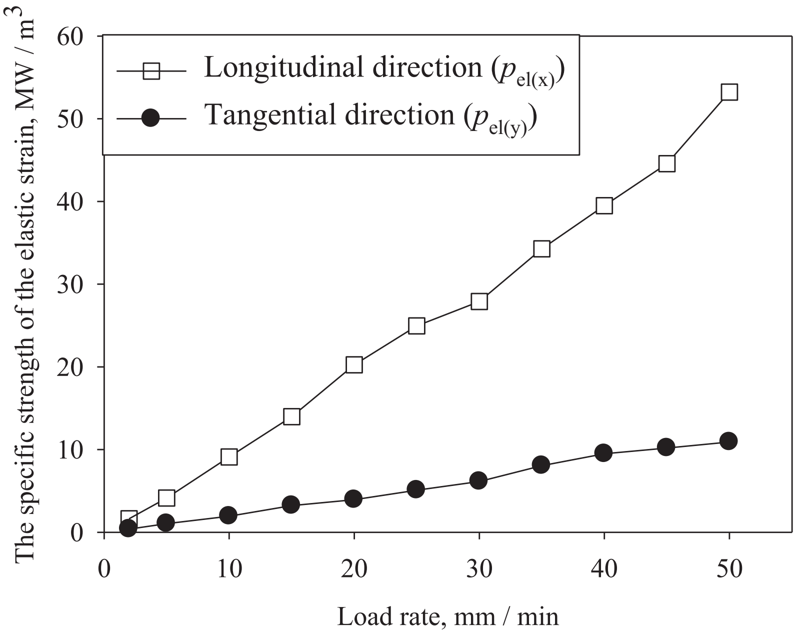

Figure 9: Dependenceof the mean value of the specific power of the elastic strain on the load rate in the longitudinal ($p_{el(x)}$) and tangential ($p_{el(y)}$) direction

4. CONCLUSIONS

1. The load rate has effects affects on the measured elastic properties of beech wood samples in both observed directions.
2. The mean values of parameters that limiting the elastic area of stress - strain diagrams show an increasing tendency with the increase of load rates in both observed directions.
3. The mean value of modulus of elasticity increases with the increase of load rates in both observed directions. This means that at higher load rates the beech wood provides higher resistance to force action. Increase of mean values of modulus of elasticity in the longitudinal direction is greater than in tangential.
4. The mean values of the specific energy of elastic strain in longitudinal direction increases with the increase of the load rates, while in tangential direction a clear trend can not be established. But, the increase of specific power of elastic strain by increasing load rate is obvious in both directions, although the increase is more significant in longitudinal direction.

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