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The impact of crosshead speed on the strength of spruce wood (*Picea abies* L.*)*

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Abstract: *The effect of crosshead speed on the strength of spruce wood (Picea abies L.).* This work examines the compression and tensile strength along the grain and bending perpendicularly to the grain of spruce wood was investigated at various crosshead speeds. The dependence of the immediate strength on the crosshead speed takes the form of an exponential function for compression and tension along the grain and bending perpendicular to the grain. The study showed that as the crosshead speed increases, the ultimate strength value increases regardless of the type of stress occurring. The bending strength is between the compression and tensile strength values. The strength for compression along the grain for the spruce wood tested is 50% of strength tension along grain length and 57% of the bending strength. The bending strength corresponds to 88% of the tensile strength.

Keywords: compression along the grain, tensile strength along the grain, bending perpendicularly to the grain, spruce wood, crosshead speed

INTRODUCTION

The wood used in structures works mainly in: compression, bending and tension. There is a certain correlation between these strengths, in which e.g. the compression strength is on average about 40% of the tensile strength tested in the same direction (Kollmann, 1943). The bent material is simultaneously compressed on the side of the applied load and stretched on the opposite side. The height of this strength is between the tensile and compression strength (Krzysik, 1970).

When determining the mechanical properties, in addition to the analysis of the influence of the material's physical properties, the parameters that determine the nature of the test itself are taken into account. These include the rate of deformation under dynamic loading and the duration of the test under static loading. An increase in the load rate usually results in higher strength. For example, the compressive strength along the grain increases by 25 percentage points when the load rate is tripled (Gerhards, 1977). It has also been observed that with long-term loading of the component and a decrease in strength below about 20%, damage to wood structures occurs (Wood, 1951).

In the research on the temporary strength of wood (Langendorf, et al., 1990, Madsen 1990, Bodig, Jayne, 1993, Nielsen 2007) and in tests carried out in accordance with current standards, static breaking load is applied at different speeds.

In the German standards, a maximum force of 1±0.5 minutes is required when testing compression strength (DIN 52 185), tensile strength (DIN 52 188) along the grain and bending perpendicular to grain (DIN 52 186). After conversion, the anticipated load on the specimen cross-section is from 20.0 MPa/min to 30.0 MPa/min for compressive strength, bending from 40.0 MPa/min to 50.0 MPa/min and tensile strength about 60.0 MPa/min. Similar ranges of requirements for the load build-up during wood strength testing are also found in French standards (NF B51-007, 1985; NF B51-008, 1987; NF B51-017, 1988).

In American Standard ASTM D4761-02a, it is recommended to perform strength tests in 1 minute, while specifying a load time for boundary conditions of 10 seconds to 10 minutes. In these tests, the tensile strength is determined at a crosshead speed of 12 MPa/min and the compressive strength at 30 MPa/min. In Swiss standards, the crosshead speed is one of the lowest – it is 2.0 to 3.0 MPa/min for the tensile strength, and 1.5 MPa/min for the bending strength, thus the elongation of the tests reaches 160 minutes (Kollmann, 1951).

According to Polish standards PN-77/D-04103, PN-79/D-04102, PN-81/D-04107, static tests of immediate strength properties are carried out at one speed, which equals 5.0 mm/min. In the standard EN 408:2010+A1, when testing of timber structures compression and tension strength parallel to the grain, the maximum load is reached within 3 to 7 minutes.

Due to the very different way of conducting strength tests, for many years now, there have been attempts to standardize the time and speed of the load of elements when determining the mechanical properties of wood (e.g. Kollmann, 1943). These include modern European standards on how to determine the bending moment strength (ISO 13061-3:2014), compression (ISO 13061-17:2017) and tension (ISO 13061-6:2014) of wood, which introduce continuous load at a rate that allows a destructive force to be obtained in 0.5 to 5.0 minutes.

The analysis of the range of crosshead speed changes during the tests of compressive strength, grain lengthwise tensile strength and static bending shows a significant variability of this parameter both in the requirements presented in the normative acts as well as in scientific studies on the mechanical properties of wood.

Therefore, the study was undertaken to determine the effect of crosshead speed on the compression and tensile strength along the grain and bending perpendicular to the planes of spruce wood (*Picea abies* L.).

Depending on the analyzed strength, several crosshead speeds were determined, respectively, and the method of testing itself was consistent with the guidelines of the Polish standards PN-81/D-04107, PN-79/D-04102 and PN-77/D-04103.

EXPERIMENTAL MATERIAL AND TEST METHODS

Samples for strength testing were cut from a single log of spruce wood (*Picea abies* L.). From them, samples with no defects were selected with parallel annual growth rings in relation to planes. The size and shape of the samples corresponded to the requirements presented in the standards for the determination of bending strength (PN-77/D-04103), compression (PN-79/D-04102) and tensile strength along the grain (PN-81/D-04107).

The determination of the physical properties of the material included the determination of the annual growth width, density and absolute humidity. All of these determinations were made on samples of dimensions corresponding to the compressive strength along the grain.

A comprehensive specialist system "WinDENDRO" was used to study the width of annual growth and the proportion of late and early wood, which consisted of a scanner together with the "WinDENDRO" software. After scanning the samples, a section of an appropriate length was determined on their surface, including several or more full annual growth rings. At the determined section of the sample, the width of each annual growth ring and the width of early and late wood were determined. On this basis, the average grain size and the share of early and late wood was calculated.

The proportion of late wood was calculated using the following formula:

$$U_p = \frac{\sum b_p}{\sum b_p + \sum b_w} \cdot 100\%$$

where:

$\sum b_p$ – sum of late wood widths (mm)

$\sum \mathrm{b_w}$ $\sum b_w$ – sum of early wood widths (mm)

$\mathrm{U_p}$ U_p – share of latewood (%)

The density of wood was determined in accordance with the guidelines of standard PN-77/D-04101. The absolute moisture content of the wood was determined using the weight-drying method, using the PN - 77/D - 4100 standard.

Determination of immediate strength

Tests of the immediate compression strength along the grain, static bending perpendicular to grain and tensile strength along the grain were carried out using the INSTRON 3382 machine with a 100 kN measuring head and with an advanced control and visualisation system.

Spruce wood samples were subjected to a force exerted under various loads until they were destroyed. The load speeds selected for the tests (for each strength) are included in terms of the speed range in the quoted standards. To unify the way of expressing the load speed, they were converted to mm/min. The crosshead speed ranged from 0.05 mm/min to 50.0 mm/min. For the compressive strength tests along grain, the speeds were used: 0.05 mm/min (A), 0.5 mm/min (B), 5.0 mm/min (E), 9.9 mm/min (F), 50.0 mm/min (H). The bending strength test perpendicular to grains at two sample support points and one thrust was performed at speed: 5.0 mm/min (E), 9.9 mm/min (F), 50.0 mm/min (H). The tensile strength test along the grain was carried out at the following speeds: 2.5 mm/min (C), 3.3 mm/min (D), 5.0 mm/min (E), 9.9 mm/min (F), 15.0 mm/min (G), 50.0 mm/min (H). The effect of each speed on the magnitude of the destructive force was checked on 10 specimens in compression and tension along the grain and 15 specimens in static bending perpendicular to planes.

After the strength tests, the type and extent of damage was documented by photographs of the breakages.

TEST RESULTS

Characteristics of the test material

The spruce wood used in the research was characterized by determining its basic physical properties, which included: moisture content, density, width of annual growth and the proportion of early and late wood.

Table 1. Physical properties of the tested spruce wood

Wood type	Density (kg/m^3)	Growth rings width (mm)	Late wood (%)	Early wood (%)	MC (%)
Fine-ringed	418	1.7	32	68	9.0
V* (%)	3.1	48.4	42	20	1.2

*) Coefficient of variation

The moisture content of the tested material was 9.0% (V=1.2%) and corresponded to the usable-dry range of wood.

The average density of spruce wood in the absolutely dry state was 418 kg/m^3 (coefficient of variation V=3.1%). With an annual growth width of 1.7 mm (V=48.4%), it was characterized by a late wood share of 32% (V=42%) (Tab. 1).

Immediate strength of spruce wood

The test of the temporary strength of spruce wood included the compressive and tensile strength along grain and the bending strength.

The determination of the immediate compressive strength along the grain was carried out at the following crosshead speeds: 0.05 mm/min (A), 0.5 mm/min (B), 5.0 mm/min (E), 9.9 mm/min (F), 50.0 mm/min (H).

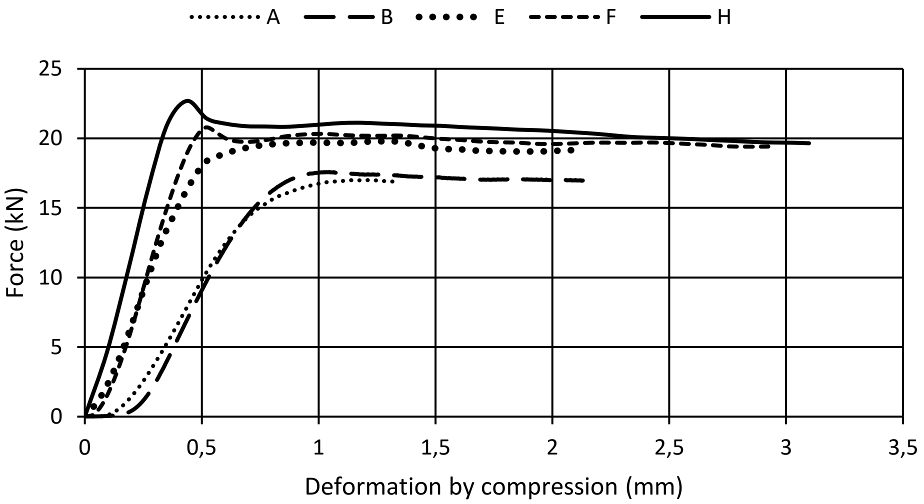


Figure 1: Influence of the crosshead speed on the increase in force and the amount of deformation produced during the compressive strength test along spruce wood grain at crosshead speeds: 0.05 mm/min (A), 0.5 mm/min (B), 5.0 mm/min (E), 9.9 mm/min (F), 50.0mm/min (H)

The type and size of the resulting deformation of the specimens during loading for the designated feed rates of the crosshead of the testing machine are shown in Fig. 1. Table 2 shows the obtained compressive strength for each feed rate.

Table 2: Immediate compression strength along the grain at different crosshead speeds of spruce wood samples

Crosshead speed (mm/min)	Compression strength (MPa)	Test time to destruction (s)	s* (MPa)	V** (%)
0.05	40.7	954	1.5	3.7
0.5	42.2	95	2.1	5.0
5.0	43.4	9	1.8	4.1
9.9	46.5	3	2.0	4.3
50.0	51.7	0,5	1.2	2.3

*) Standard deviation

**) Coefficient of variation

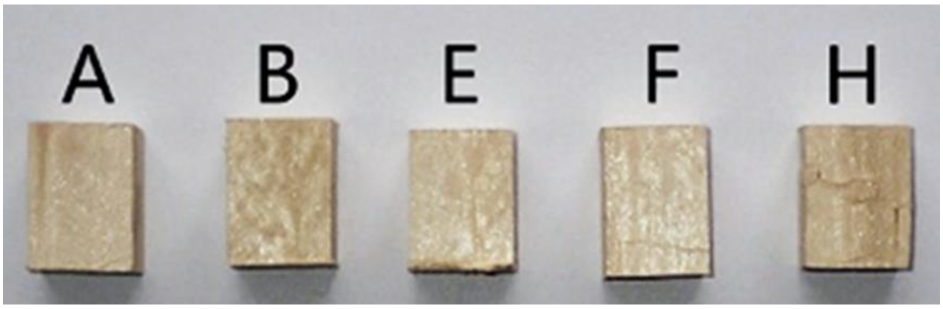


Figure 3: Characteristic failure of test specimens after the immediate compression test along the grain at the crosshead speeds: 0.05 mm/min (A), 0.5 mm/min (B), 5.0 mm/min (E), 9.9 mm/min (F), 50.0 mm/min (H)

Based on the results obtained, it was found that with increasing crosshead speed, the immediate compression strength along the grain increases. At 0.05 mm/min (A) the strength is over 40 MPa, and at 50.0 mm/min (H) it reaches almost 52 MPa.

The samples after the compression strength test along the grain (Fig. 3), regardless of the crosshead speed used, showed a visibly smaller dimension and a damaged inner structure, characterised by buckling of the grain and longitudinal cracks.

The test of the immediate tensile strength along the grain was analysed for equal crosshead speeds: 2.5 mm/min (C), 3.3 mm/min (D), 5.0 mm/min (E), 9.9 mm/min (F), 15.0 mm/min (G), 50.0 mm/min (H). The magnitude of the immediate tensile strength depending on the crosshead speed together with the coefficients of variation are shown in Table 3.

Table 3: Immediate tensile strength along the grain obtained at different crosshead speeds of spruce wood samples.

Crosshead speed (mm/min)	Tensile strength (MPa)	Test time to destruction (s)	s* (MPa)	V** (%)
2.5	76.8	768	8.6	11.2
3.3	78.3	458	5.9	7.5
5.0	92.3	379	13.9	15.1
9.9	103.5	166	16.3	15.7
15.0	91.7	119	9.1	9.9
50.0	99.3	36	15.2	15.3

*) Standard deviation
**) Coefficient of variation

It was found that at the highest crosshead speed of 50.0 mm/min (H) the tensile strength was nearly 100 MPa (V=15.3%) and the lowest about 77 MPa (V=11.2%) was obtained at 2.5 mm/min. The tensile strength along the grain in the tested crosshead speed range shows a significant irregularity, expressed by relatively high coefficients of variation and standard deviation (Table 3, Fig. 4).

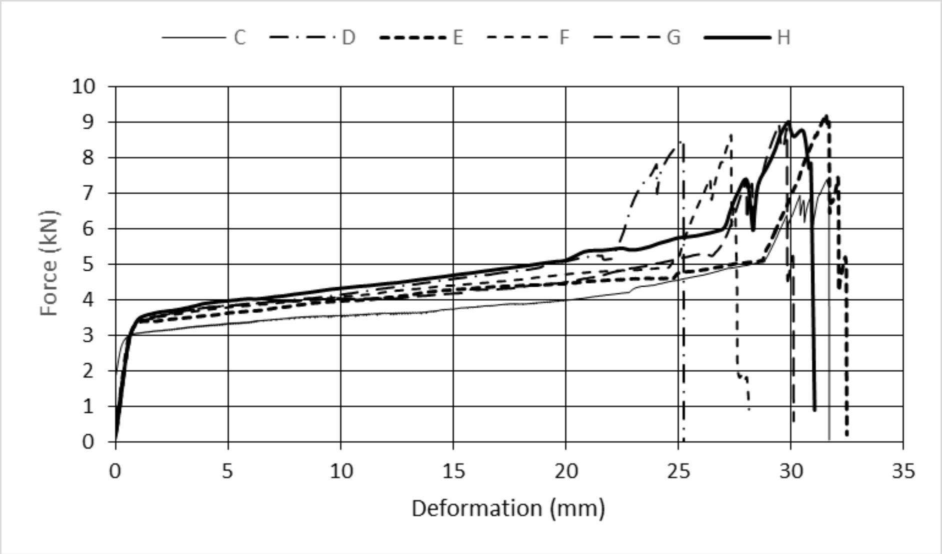


Figure 4: Influence of the crosshead speed on the increase in force and the amount of deformation produced during the tensile strength test along the grain of spruce wood at crosshead speeds: 2.5 mm/min (C), 3.3 mm/min (D), 5.0 mm/min (E), 9.9 mm/min (F), 15.0 mm/min (G), 50.0 mm/min (H)

With the increase in crosshead speed, a change in the structure of the resulting breakthroughs was observed. At the lowest speeds of 2.5 mm/min (C) and 3.333 mm/min (D), the breakages cover a large area of the narrowed part of the sample (Fig. 5). At higher speeds of 15.0 mm/min (G) and 50.0 mm/min (H), the breakthroughs are characterized by one short-grain, short-range failure. Fractures of samples tested at 9.9 mm/min (F) differ in their structure from the sections described so far. In this group of specimens in the middle part there are long fibrous scrapes around the plane determining the symmetry of the specimen, at the point most loaded with tensile forces.

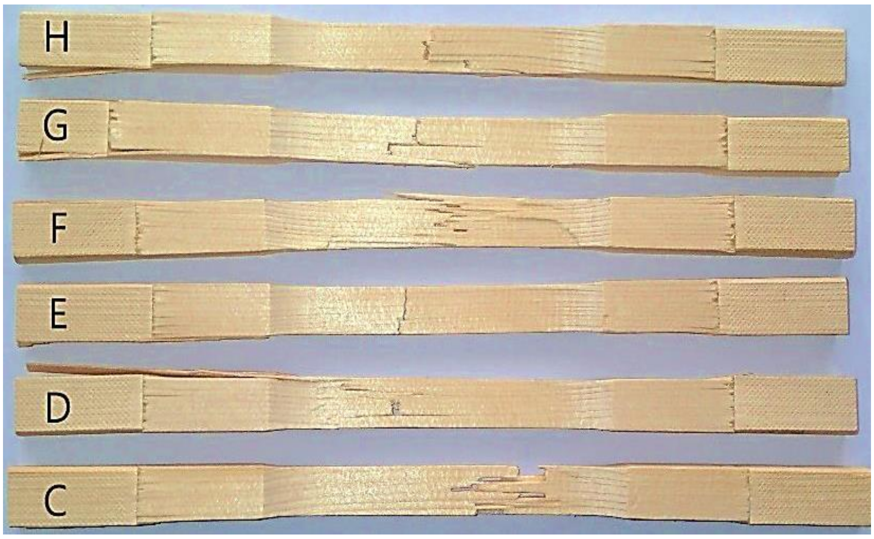


Figure 5: Characteristic specimen fractures after the grain longitudinal tensile strength test at crosshead speed of 2.5 mm/min (C), 3.3 mm/min (D), 5.0 mm/min (E), 9.9 mm/min (F), 15.0 mm/min (G), 50.0 mm/min (H)

The high irregularity of tensile strength was confirmed by the shape instability of the resulting breakages and high coefficients of variation (Table 3).

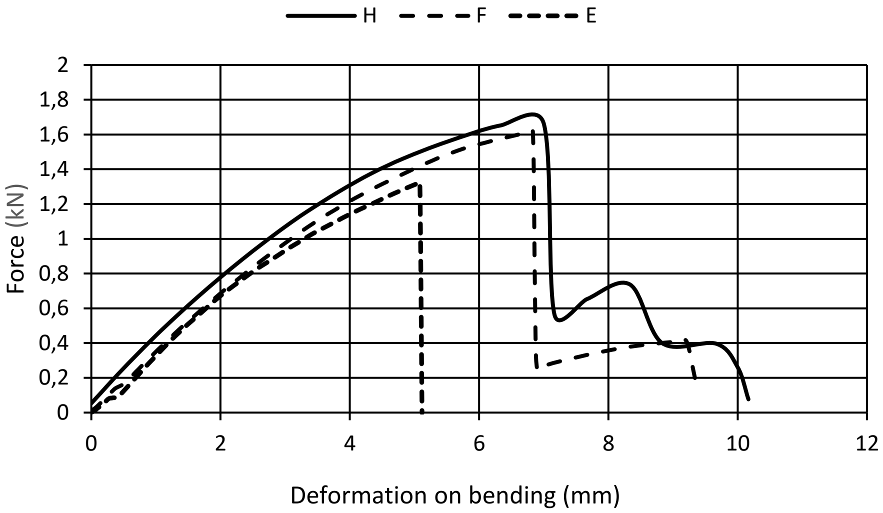


Figure 6: Influence of the crosshead speed on the increase in force and the magnitude of the resulting deformation when testing the bending strength of spruce wood at crosshead speeds: 5 mm/min (E), 9.9 mm/min (F) and 50 mm/min (H)

The bending strength was determined at three crosshead speeds: 5.0 mm/min, (E), 9.9 mm/min, (F) and 50.0 mm/min (H) (Fig. 6).

Table 4. Values of the immediate static bending strength at different crosshead speeds for spruce wood samples

Crosshead speed (mm/min)	Bending strength (MPa)	Test time to destruction (s)	s* (MPa)	V** (%)
5.0 (E)	74.0	61	2.2	3.0
9.9 (F)	78.2	41	2.5	3.2
50.0 (H)	82.7	9	3.3	4.0

*) Standard deviation
**) Coefficient of variation

During the test, the loading force was applied perpendicular to the tangential section. The obtained bending strength regardless of the crosshead speed was characterized by low coefficient of variation. As the crosshead speed increased, the bending strength increased (Tab. 4).

The highest bending strength of 82.7 MPa was obtained at a crosshead speed of 50.0 mm/min (H) and strength of 74.0 MPa at the lowest speed of 5.0 mm/min (E).

Figure 7: Characteristic specimen fractures after the immediate bending test at crosshead speeds of 5.0 mm/min (E), 9.9 mm/min (F) and 50.0 mm/min (H)

The specimen fractures after the immediate bending strength test were characterized by interrupted wood grain in the central part, which at a speed of 50.0 mm/min (H) were approximately in one plane (Fig. 7).

From further analysis of individual behaviours of force build-up in the area of elastic deformations, characteristic increases in the resulting deformations were found in the test of the immediate compressive and tensile strength along the grain (Fig. 8 and 9). For the immediate strength at a speed of 0.05 mm/min (A) in compression and 2.5 mm/min (C) and 3.333 mm/min (D) in tension, there was an intense increase in force due to the way the specimen section is loaded.

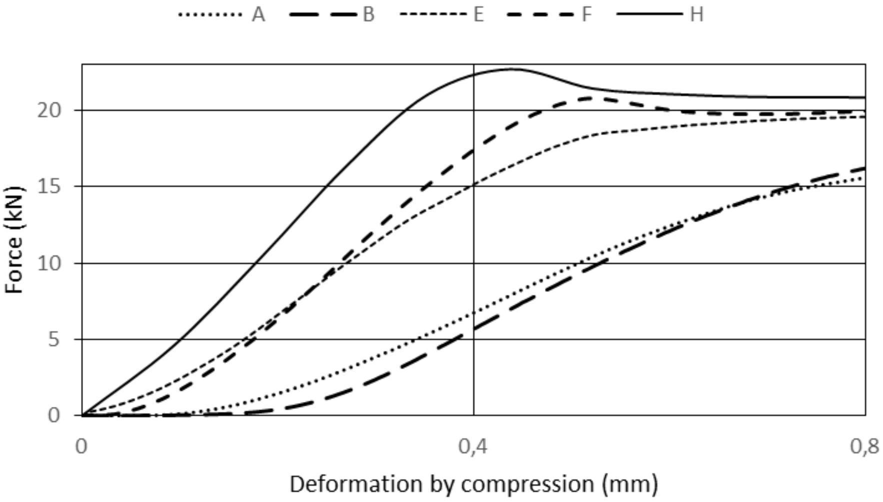


Figure 8: Force build-up from 0 kN to 25 kN and deformation in the area up to 0.8 mm, at each crosshead speed (A, B, E, F, H) for the instantaneous compression strength test along the grain

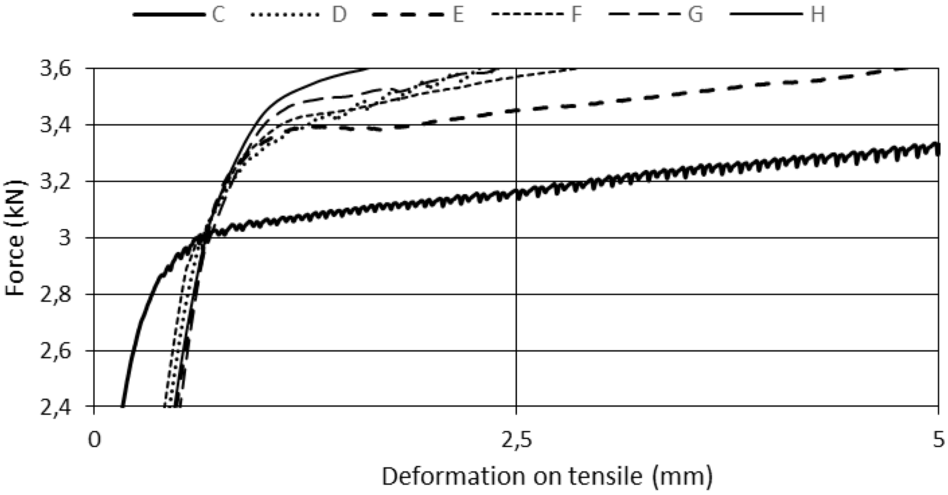


Figure 9: Force build-up from 2.4 kN to 3.6 kN and occurring in the deformation area up to 5,0 mm for each crosshead speed (C, D, E, F, G, H) for the instantaneous tensile strength test along the grain

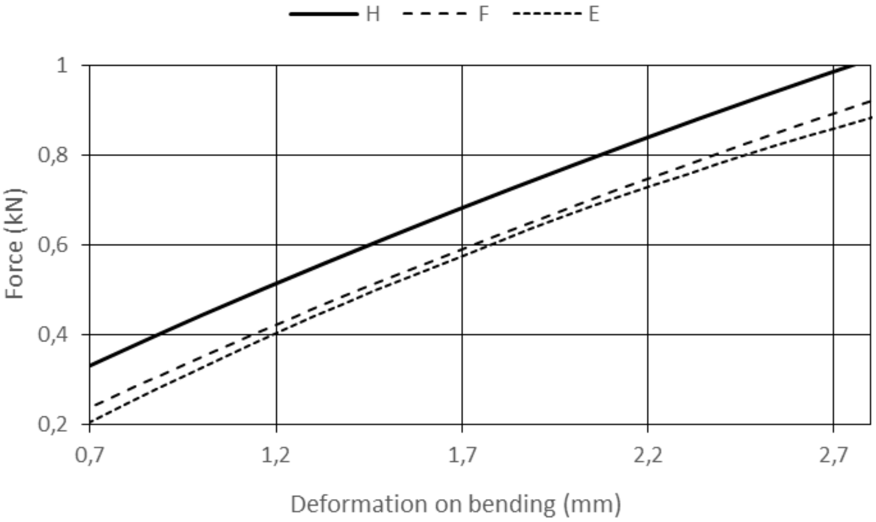
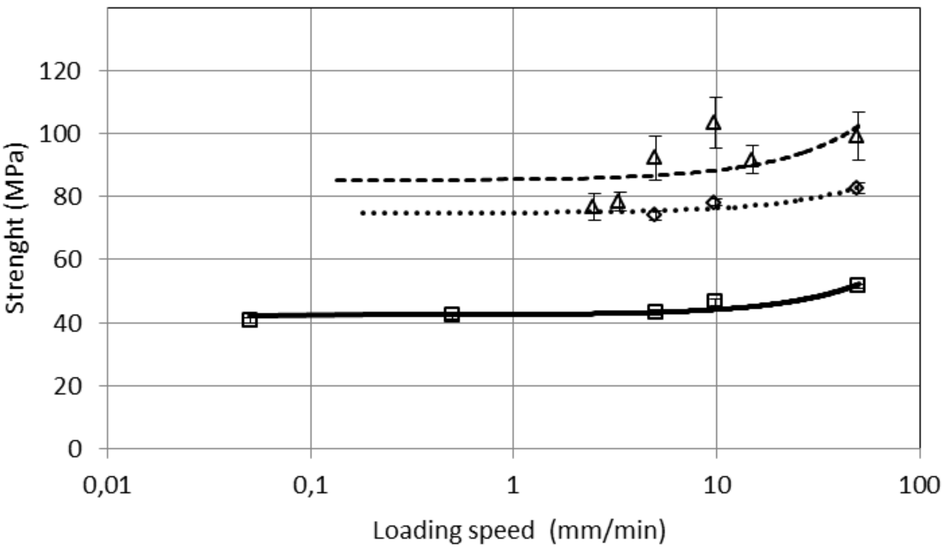


Figure 10: Force build-up from 0,2 kN to 1 kN and occurring in the deformation area up to 2.7 mm for each crosshead speed (H, E, F) when testing the ultimate bending strength perpendicular to the grain

At these speeds, the increasing internal stress in the material caused cracking of successive layers of early wood with lower strength, and then of late wood with higher strength (Kollmann, 1951, Krzysik, 1957, Kokociński 2004). A force increase during compression at 5 mm/min (E) and tension at 9.9 mm/min (F), resulted in an even distribution of internal stress, covering the entire cross-section, without any differentiation between early and late wood (Kollmann, 1951). An example of an increase in compressive forces in the range from 0 kN to 25 kN and tensile forces from 2.4 kN to 3.6 kN in the area of elastic deformations is presented in Fig. 8 and Fig. 9. The effect of their interaction was also the form and shape, as well as the place and extent of breakages produced in the compressed and stretched specimens (Fig. 3 E and 5 E, F).

The deformation force dependence for the bending test perpendicular to the grain (Fig. 10) did not show a similar dependence due to the direction of the loading force. However, it cannot be excluded that similar variations in force values (on the 'OY' axis) may occur at lower crosshead speeds which have not been tested.

The curves plotted on the basis of the strength test results (Fig. 11) determine the points of intersection with the "Y" axis and represent a situation where the crosshead speed for the specimen is low and thus the time of force application to the material is extended.



Strength

Tensile Δ----- $y = 85.138 \cdot e^{0.0037 \cdot x};\ r^2 = 0.3010$

Bending ◊········ $y = 74.818 \cdot e^{0,0021 \cdot x};\ r^2 = 0.8335$

Compression □——— $y = 42.399 \cdot e^{0.0024 \cdot x};\ r^2 = 0.8746$

Figure 11. The development of the change in compression and tensile strength along the grain and bending according to the crosshead speed

The correlation between the immediate compressive strength along the grain and the crosshead speed takes the form of an exponential function: $y = 42.4 \cdot e^{0.0024 \cdot x}$, with a determination factor of R^2=0.8736 (Fig. 11). From the theoretical analysis of the function behaviour describing this variability, assuming that the argument is aimed at values close to zero but greater than zero, it follows that the ordinate value of 42. Hypothetically, referring this interpretation to a test of spruce wood being loaded at a speed close to 0 mm/min, the value of the immediate compression strength interpreted on the basis of the above function will be approximate to 42.4 MPa.

For the immediate tensile strength along the grain despite large statistical variations, the curve expressed as an exponential function: $y = 85.1 \cdot e^{0.0037 \cdot x}$, is within the standard deviation of the results for each crosshead speed. Assuming, theoretically, that the arguments belonging to the function are positive and aim at zero and, at the same time, represent a crosshead speed of the test item close to 0 mm/min, the ordinates of the function and, thus, the tensile strength will be close to 85.1 MPa.

In the case of an immediate bending strength test, its dependence on the crosshead speed is approximated by a function: $y = 74.8 \cdot e^{0.0021 \cdot x}$, with a coefficient of determination equal to R^2=0.8335 (Fig. 11). The analysis of the function presenting the tested dependencies shows that with a positive argument close to zero, the ordinate value will aim at the value of 75. Assuming that the crosshead speed will be close to 0 mm/min, the immediate bending strength will aim at the value of 74.8 MPa.

Therefore, the strength of the spruce wood under investigation at compression accounts for 50% of tensile strength and 57% of bending strength. The bending strength corresponds to 88% of the strength occurring in tension.

Comparing the results obtained from the three strength tests depending on the crosshead speed and the functions characterizing their behaviour, two areas of test duration can be distinguished (Tables 2, 3, 4 and Fig. 11). The first one includes a relatively slow increase in force values, which is connected with a long test lasting up to a dozen or so minutes, and the second one is characterized by greater dynamics and times ranging from a fraction to several seconds.

CONCLUSIONS

On the basis of the analysis of the studies carried out, the following conclusions were drawn:

1. In addition to physical properties such as width of the annual growth rings, including the proportion of late and early wood, density and moisture content, the crosshead speed has a significant impact on mechanical properties such as the ultimate compression and tensile strength along the grain and bending perpendicular to the grain.
2. The crosshead speed influences the type and size of the resulting strength. When testing the tensile strength along the grain, low crosshead speeds cause uneven destructive stress distribution in the late and early wood, causing a gradual reduction in the size of the active cross-section, which is opposed to the acting force.
3. The correlation between the instantaneous strength and crosshead speed takes the form of an exponential function for each type of test: compression and tensile strength along the grain and bending perpendicular to the grain. The tendency to change is increasing and independent of the type of stress occurring.
4. The strength for compression along the grain for the spruce wood tested is 50% of strength tension along grain length and 57% of the bending strength. The bending strength corresponds to 88% of the tensile strength.

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Streszczenie: *Wpływ prędkości obciążania na wytrzymałości drewna świerkowego (Picea abies L.).* W pracy zbadano przy różnych prędkościach obciążania wytrzymałość doraźną na ściskanie i rozciąganie wzdłuż włókien oraz zginanie prostopadle do płaszczyzn drewna świerkowego. Zależność wytrzymałości doraźnej od prędkości obciążania przybiera postać funkcji wykładniczej dla ściskania oraz rozciągania wzdłuż włókien a także zginania prostopadłego do włókien. Badanie wykazało, że wraz ze wzrostem prędkości obciążania rośnie wartość wytrzymałości doraźnej, niezależnie od rodzaju występujących naprężeń. Wytrzymałość na zginanie zawiera się w przedziale pomiędzy wartościami wytrzymałości na ściskanie i rozciąganie. Wytrzymałość przy ściskaniu dla badanego drewna świerkowego stanowią 50% wytrzymałości występującej przy rozciąganiu i 57% przy zginaniu. Wytrzymałość przy zginaniu odpowiada 88% wytrzymałości przy rozciąganiu.

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