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The influence of loading speed on the bending strength of beech (*Fagus sp.*) and birch (*Betula sp.*) wood

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Abstract: *The influence of loading speed on the bending strength of beech (Fagus sp.) and birch (Betula sp.) wood* The subject of this paper was to investigate the effect of loading speeds from 20 mm·min^{-1} to 200 mm·min^{-1} on the flexural strength and deformation of beech (*Fagus sp.)* and birch (*Betula sp.*) wood with moisture content close to the absolutely dry state and fibre saturation point. A GOM Aramis measuring system, operating with Digital Image Correlation (DIC) technology, was used in the study to record the displacement and deformation of the elements in real time. The results obtained for flexural strength, flexural modulus and the amount of deformation observed showed a relationship between material properties and loading rate. At higher moisture content, the bending strength and modulus of elasticity decreased with increasing deflexion. The highest bending strength and modulus of elasticity were achieved by the tested wood species at a loading rate of 200 mm·min^{-1}. Beech wood, compared to birch wood, showed higher bending strength and modulus of elasticity. Images obtained by means of DIC revealed, at moisture contents close to the dry state, a symmetrical distribution of compressive and tensile stresses relative to the neutral axis of the sample cross-section. At higher moisture contents, there was a significant asymmetry between the compressive and tensile stresses and an apparent shift of the neutral axis towards the tensile surface.

Keywords: wood bending strength, MOE, deflexion, strain, wood moisture content, loading speed, cross-section neutral axis

INTORDUCTION

Factors with significant influence on wood bending strength include the shape and dimensions of specimens, loading rate, moisture content and temperature (of the tested wood as well as the surroundings), the method of load transfer, and allowable defects in the timber. Consequently, the conditions under which wood is tested do have a significant impact on the variation in the values of the obtained measurements, which are characterised by large deviations that make comparisons difficult.

The strength of wood is particularly affected by its moisture content, mainly in the range from the dry state to the moisture content at the fibre saturation point. It has been noted that, in the hygroscopic interval, a 1 % change in wood moisture content causes an average decrease of about 4 % in static bending strength (Vorreiter 1949, Kollmann 1952, Fuchs 1963, Hänsel 2012, Hering et al. 2012).

When analysing compressive, tensile, flexural and shear strengths, and modulus of elasticity, a reduction of approximately 16% in mechanical parameters was found for ipe wood (*Tabebuia sp.*) and angelim wood (*Vataireopsis araroba*) when moisture content increased from 12% to above the fibre saturation point (Branco et al., 2014). Also, the change in moisture content of oak (*Quercus patraea* Liebl.) strands with moisture contents of 8%, 12%, 16%, 20% and above the fibre saturation point showed a statistically significant reduction in tensile, compressive and flexural strengths and elastic modulus (Gerhard 1982, Korkmaz et al. 2019). A similar relationship was observed when examining the physico-mechanical parameters of *Cedrelinga catenaeformis* wood (Soares et al. 2021). The test results for compressive and shear strength along the fibres, tensile strength along and across the fibres, static bending and splitting, and Young's modulus showed higher values at 12% moisture content compared to moisture content at the fibre saturation point.

Sometimes a reduction in the values of certain mechanical parameters of wood is a deliberate action. Wood with a lower Young's modulus will deform more when a lower force is applied, compared to wood with a higher Young's modulus.

Regarding the factors influencing the strength properties of wood, much research is currently focused on establishing a relationship between the loading rate and the amount of strain developed, the value of the elastic modulus and the strength achieved. For example, Rose 1965, Mohr 2001, Büyüksari 2017, Dobrowolska et al. 2020, Radmanović et al. 2021, found a direct relationship between the rate of load build-up and the change in the mechanical properties of wood.

An increase from 5.0 mm·min^{-1} to 50.0 mm·min^{-1} in loading speed resulted in an increase in the flexural strength of spruce wood (*Pinus sylvestris* L.). The relationship between loading rate and bending strength was described by an exponential function with a high coefficient of determination, showing a strong relationship between loading rate and wood strength (Dobrowolska et al. 2020). Even with small differences in loading rate, i.e. 2.0 mm·min^{-1}, 1.0 mm·min^{-1} and 0.5 mm·min^{-1}, changes in the magnitude of the obtained bending strengths of pine (*Pinus sylvestris* L.) wood were recorded, although according to author Büyüksari (2017), they were not statistically significant. They could have been due to other reasons, such as the shape and dimension of the samples. In the case of the static bending modulus, the differences between the obtained values at the above-mentioned loading speeds were statistically significant, and the static bending modulus itself increased with increasing loading speed (Büyüksari 2017). 1 000

In Radmanović et al. 2021, the longitudinal compressive strength and the modulus of elasticity of beech wood (*Fagus sp.*) were determined in two intervals of increasing loading rate: 10 mm·min^{-1}÷60 mm·min^{-1} and 100 mm·min^{-1}÷500 mm·min^{-1}. Based on the obtained results, the strength of the wood increases with increasing loading rate.

The loading rate has some influence on the development of the proportional limit between the deformation and the induced stress. It has been shown (Won Kang 2005) that as the loading rate of wood increases from 0.02 mm·min^{-1} to 2.00 mm·min^{-1}, the proportional limit of the wood increases. The relationship between the loading speed and the limit of Hooke's law applicability was described using a logarithmic function with a coefficient of determination of 0.3753. The low value of the coefficient of determination indicates the existence of a weak regression and may be due to insignificant differences between the selected loading speeds.

The results of the cited studies confirm the hypothesis that there is a relationship between loading speed, and the strength of wood and its moisture content. The analysis of the influence of the loading speed for wood elements with different moisture contents on wood strength properties may be of significant importance in determining practical technological parameters, which are connected with control systems for hydrothermal treatment processes and shaping by bending wooden elements.

The aim of the study was to analyse the influence of the loading rate and moisture content on bending strength and flexural modulu of woods. Beech (*Fagus sp.*) and birch (*Betula sp.*) wood with different moisture contents were tested. The distribution of stresses under bending load was determined using the GOM Aramis measuring system, which works with Digital Image Correlation (DIC) technology and records displacements and deformations of tested elements in real time.

MATERIALS AND METHODS

Material

The following wood species were selected for testing: beech (*Fagus sp.*) and birch (*Betula sp.*) These are among the most commonly used for the production of bentwood components and bentwood fittings (Starecki et al. 1989).

Determining the density of the test material

For the research 100 samples of each wood species were selected, with dimensions and shape (Figure. 1) complying with the requirements of ISO 13061-3 and ISO 13061-4.

The cross-sections dimensions of the samples were determined in the absolutely dry state of the wood, in the middle of the sample length, using a MICRO MAUa E1 150/0.01 electronic calliper with a resolution of 0.01 mm, with an accuracy equal to the resolution of the calliper.

The absolute dry weight of the samples was determined using a Radwag WPS 1200/C/2 laboratory balance with a resolution of 0.01 g, with an accuracy equal to the resolution of the balance.

The density of the samples was calculated according to the requirements of ISO 13061-2.

Moisture content of test material

Samples of the tested wood species were randomly assigned to two groups grup 1 had the samples with an absolute moisture content equal to W_0=6%, group 2 - with a moisture content at the fibre saturation point, which was initially set at W_w=30% (at a temperature of 20°C) for both wood species.

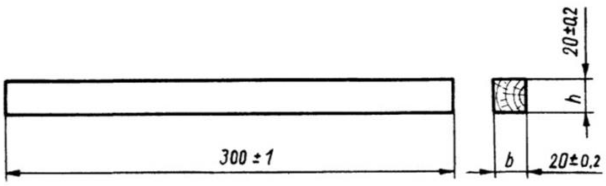

Figure 1. The shape and dimensions of the test specimen for the static flexural strength test (ISO 13061-3)

Figure. 2. A sample prepared for testing, with a sticker with reference points applied to the surface of the sample

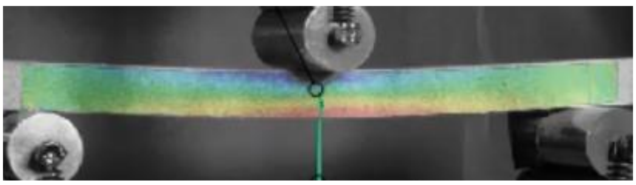

Figure 3. A visualisation of the deformations produced in the specimen during bending, using the GOM Aramis measurement system, which allows real-time recording of deformations

Figure 4. Placing a sample in the MTS Acumen 12 A/T testing machine in accordance with ISO 13061-3

Some of the samples of both wood species were placed in a Wamed KBK-60W climate chamber at a temperature of 26°C and a relative humidity of 30% to obtain equivalent humidity of W_0=6% (Dobrowolska et al. 2016). During conditioning, the samples were systematically inspected and, based on weighing, the actual moisture content was calculated until the required value was obtained.

The other part of the specimens was placed in water for a period of 120 h, and then transferred to an ACS DM340 SR climate chamber, where the air had a temperature of 15°C and relative humidity of 98%. Under these conditions, wood moisture equilibration to equivalent humidity of W_w=27% took place (Dobrowolska et al. 2016). *Static flexural strength and deflection test*

Static bending strength tests, modulus of elasticity and amount of deflection developed was carried out at three loading speeds: 20 mm·min^{-1}, 40 mm·min^{-1}, 200 mm·min^{-1}.

An MTS Acumen 12 A/T testing machine with software was used to read and aggregate data from individual tests (Figure 4). The dimensions of the supports and the distances between them were taken in accordance with the ISO 13061-3 standard. The measured deviation in the parallelism of the supports was 0.02 mm. The magnitudes of the deflection arrows, used to calculate the elastic modulus, were read from the points on the graphs, drawn from the measurement results. The range of the Hooke’s law applicability was assumed to be between 100 N and 500 N. A GOM Aramis measurement system was used to measure the nature and magnitude of the deformations, allowing them to be recorded in real time (Figure 5).

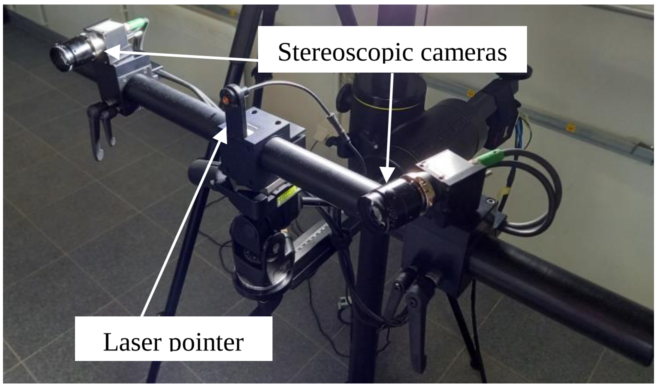

Figure 5. GOM Aramis stereoscopic cameras

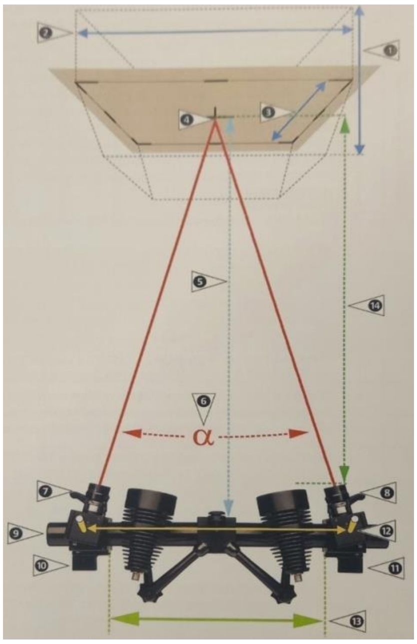

Figure 6. The schematic of the GOM Aramis measurement system (materials provided by the manufacturer) 1. height H of the measurement space; 2. length L of the measurement space; 3. width W of the measurement space; 4. centre of measuring space; 5. measuring distance; 6. camera angle of view; 7. left camera; 8. right camera; 9. support; 10. left slider; 11. right slider; 12. camera body spacing; 13. slider span; 14. light width.

The basic elements of this measurement system are stereoscopic cameras recording the displacement of discrete points (Figures 5, 6). Immediately prior to measurement, a so-called pattern, i.e. black points on a white background, was applied to the surface of the specimens

(Figure 2). The points were read by the software coupled to the video-extensometer as discrete points whose displacement was recorded by the measurement system. The resulting changes in the position of the discrete points were the basis for digital imaging of the displacements and deformations in the bent specimens (Figure 3).

Statistical analysis of test results

The results obtained in the form of .txt files were statistically processed in Microsoft Excel 2007. The mean values of deflection M_f at maximum failure force were determined from each measurement series. Observations outside the interval $<M_f - 1\sigma; M_f + 1\sigma>$ were discarded.

The static bending strength was calculated based on the ISO 13061-3 guidelines.

Next, an interval was determined in which there are observations that are not greater than the average static bending strength minus the standard deviation, and not greater than the static bending strength plus the standard deviation.

The static bending modulus was determined based on a formula in ISO 13061-4.

The values of the ME modulus of elasticity that were used for further analysis were within the range $<M_E - 1\sigma; M_E + 1\sigma>$.

On this basis, an analysis was carried out of how wood moisture content and the rate of load build-up influence the mechanical properties of wood, mainly its flexural strength and the flexural modulus. Beech (*Fagus sp.*) and birch (*Betula sp.*) wood with different moisture contents were tested.

RESULTS

The study showed that the average density of beech wood was 743 kg/m³, with a coefficient of variation of 3.3%. Birch wood had a lower average density of 620 kg/m³, with a coefficient of variation of 5.5% (Table).

Table. Density and moisture content of beech and birch wood

Wood species	Density [$kg \cdot m^{-3}$]		Humidity [%]			
			After conditioning		After soaking and conditioning	
		CV [%]	W_0	CV [%]	W_w	CV [%]
Beech	743	3.3	6.0	2.0	26.0	7.0
Birch	620	5.5	6.0	2.0	25.0	6.0

CV – Coefficient of variation

The conditioning of the wood resulted in a material with a homogeneous moisture content of W_0 in the dry state and W_w in the wet state. In the dry state, the moisture content of the wood was 6% (V=2.0%), while after soaking and conditioning it was approximately 26%, with a very low coefficient of variation (Table).

At both moisture contents, beech as well as birch wood showed an increase in static bending strength and static bending modulus with increasing loading rate from 20 $mm \cdot min^{-1}$ to 200 $mm \cdot min^{-1}$ (Figures 7÷10).

Changing the moisture content of the tested wood species from W_0 to W_w resulted in a decrease in flexural strength and flexural modulus.

Dry beech wood with a moisture content of W_0 achieved a flexural strength of 146.8 MPa at a loading rate of 20 $mm \cdot min^{-1}$, which increased to 154.7 MPa at a loading speed of 200 $mm \cdot min^{-1}$ (Figure 7). For birch wood at the same moisture content, the flexural strength was lower compared to beech wood. At a loading rate of 20 $mm \cdot min^{-1}$, it reached 123.1 MPa, and increased to 138.6 MPa at 200 $mm \cdot min^{-1}$ (Figure 8).

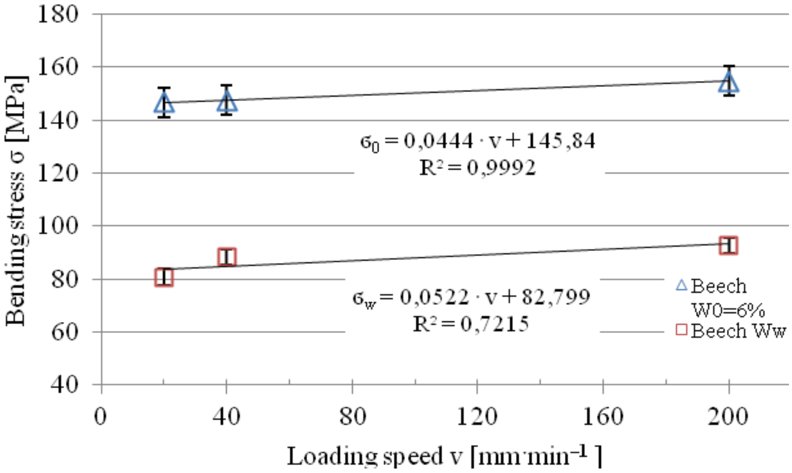

Figure 7. The influence of a loading rate in the range of 20 mm·min^{-1} to 200 mm·min^{-1} on the bending strength of beech wood with moisture content W_0 and W_w

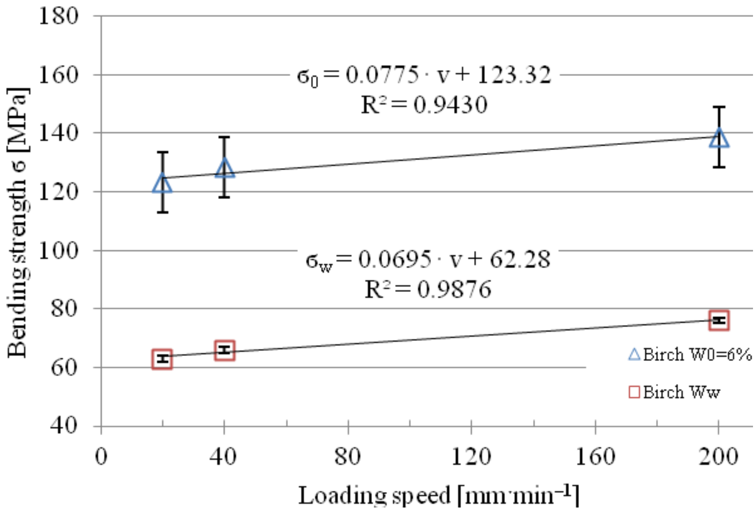

Figure 8. The influence of a loading rate from 20 mm·min^{-1} to 200 mm·min^{-1} on the bending strength of birch wood with moisture content W_0 and W_w.

Further tests showed that, with increasing loading speed (Figures 9, 10), there is an increase in the modulus of elasticity (E_0 and E_w) when bending both beech and birch wood with moisture content W_0 and W_w,. For dry beech wood (W_0), the value of the modulus of elasticity was 11.9 GPa at 20 mm·min^{-1} and 12.9 GPa at 200 mm·min^{-1}. At the same time, a 7% decrease in the modulus of elasticity was recorded for beech wood in the moist state, (W_w) compared to its value in the dry state (W_0) (Figure 4).The modulus of elasticity of birch wood at moisture content W_0 in the investigated velocity range ranged from 13.4 GPa to 14.9 GPa, and was on average 14% lower at moisture content W_w (Figure 10).

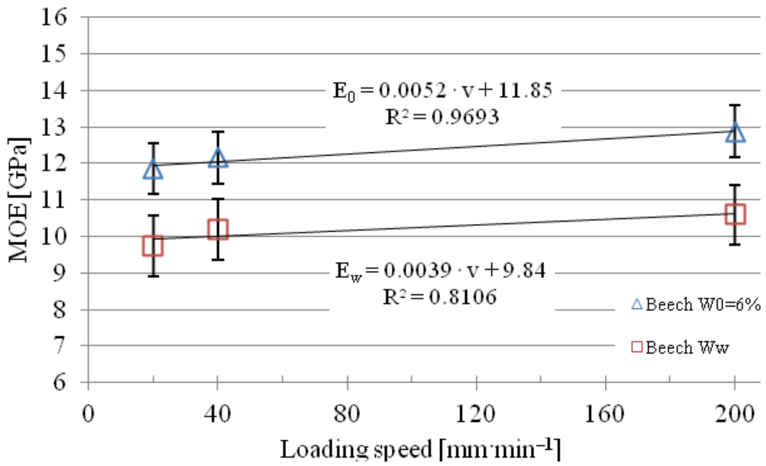

Figure 9. The effect of a loading rate on the modulus of elasticity of beech wood with moisture content W_0 and W_w in the loading rate range from 20 mm·min^{-1} to 200 mm·min^{-1}.

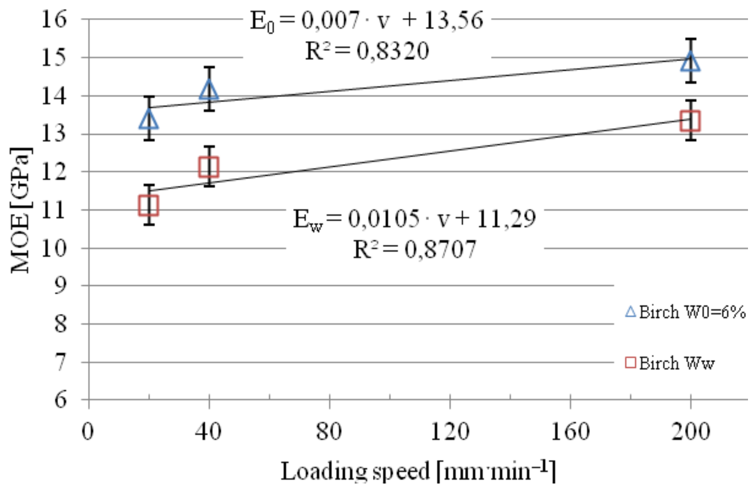

Figure 10. The effect of a loading rate on the modulus of elasticity of birch wood with moisture content W_0 and W_w in the range of loading rates from 20 mm·min^{-1} to 200 mm·min^{-1}.

On the basis of the results obtained, it was found that the proportionality limit changes significantly as a function of loading speed only for dry beech and birch wood (W_0) (Figure. 11 and 12). The highest force occurring at a loading rate of 200 mm·min^{-1}, were 1351.79 N for beech wood and 1658.05 N for birch wood.

The speed of 20 mm·min^{-1} was associated with the lowest stesses: 519.92 N for beech wood and 512.11 N for birch wood.

For dry wood, the changing limits of Hooke's law application (R_{h0}) as a function of loading rate (v) were described by linear regression equations with high coefficients of determination (Figures 11 and 12).

For moist (W_w) beech and birch wood, the stress magnitudes at the proportional limit (R_{hWw}) did not change as a function of loading speed (v). Compared to dry wood, there was a decrease, which was particularly pronounced at a loading rate of 200 mm·min^{-1}, as it was over 50%.

The linear function equations describing this relationship (R_{hw}) are characterised by high coefficients of determination with an almost parallel course to the X axis, resulting from the low values of the directional coefficients of the regression equations (Figures 11 and 12).

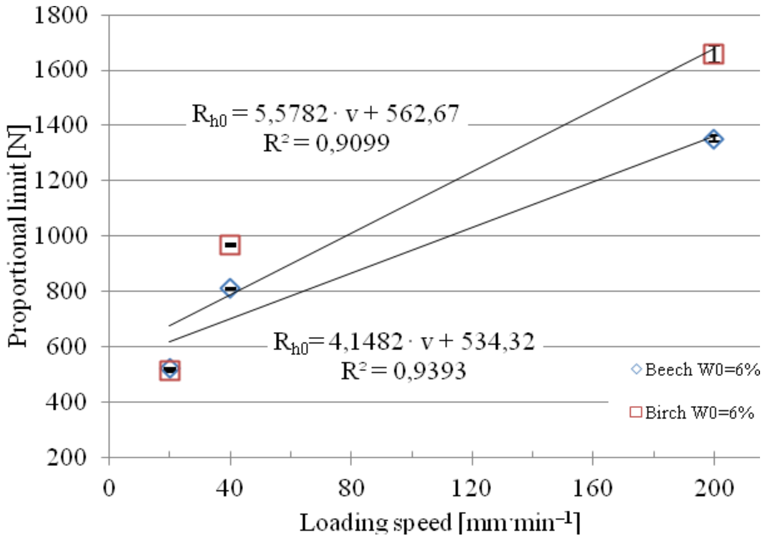

Figure 11. The influence of a loading rate on the proportional limit of beech and birch wood with moisture content W_0 in the loading rate range from 20 mm·min^{-1} to 200 mm·min^{-1}.

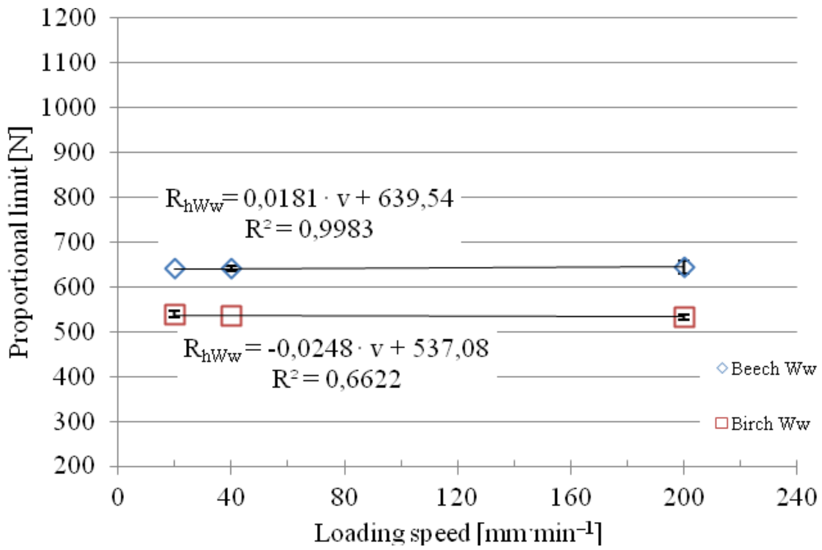

Figure 12. The effect ofa loading rate on the proportionality limit of beech and birch wood with W_w moisture content in the loading rate range from 20 mm·min^{-1} to 200 mm·min^{-1}.

Figures 13 to 16 show the types and magnitudes of stresses and strains developed in beech and birch wood samples with moisture content W_0 and W_w, depending on the loading rate.

The analysis shows that the deformations of bent beech and birch wood samples with moisture content W_0 do not show significant differences in the distribution of stresses or the magnitude of deflection, despite increasing loading speed (Figure 13 A, B, C and 14 A, B, C).

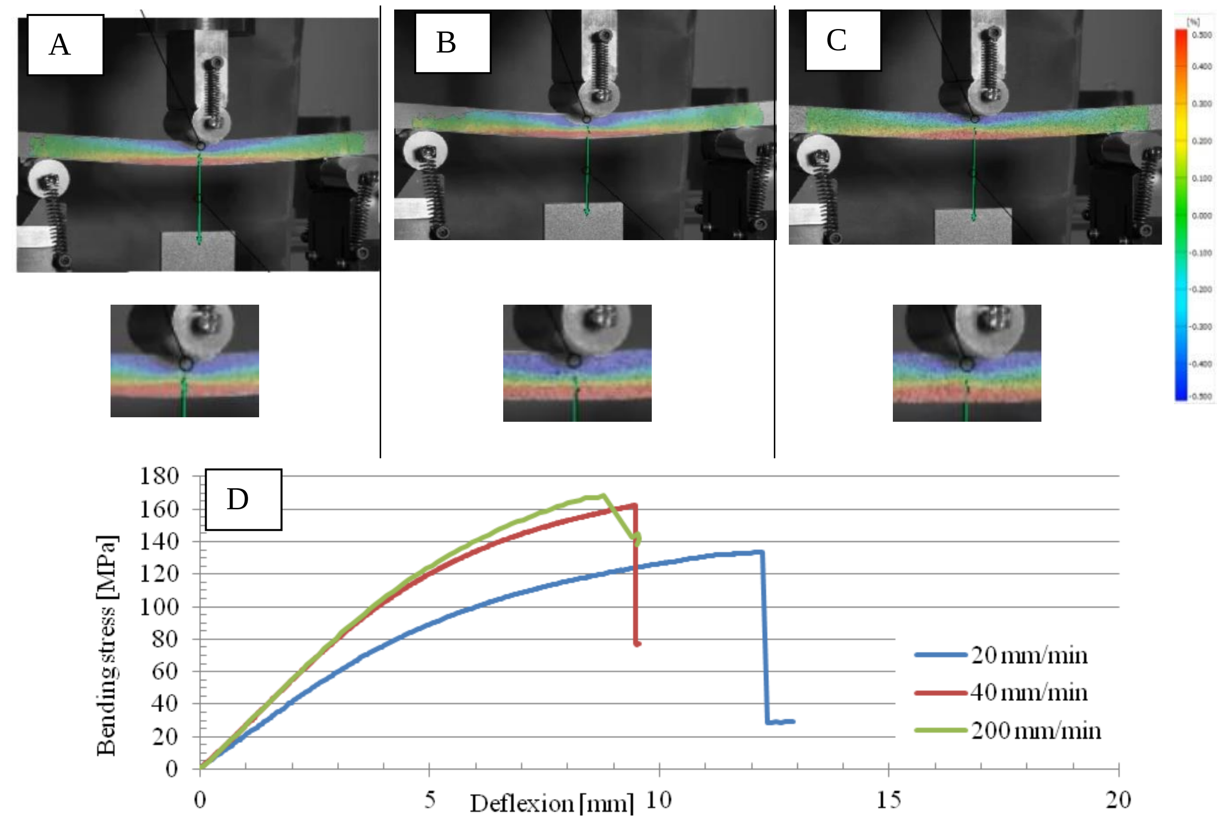

Figure 13. Strain and stress distribution developed in the samples during bending strength testing of beech wood with moisture content W_0 at loading rates of 20 mm·min^{-1} (A), 40 mm·min^{-1} (B) and 200 mm·min^{-1} (C). Course of stress changes during bending of beech wood with moisture content W_0, depending on the loading rate (D).

The compressive stress zones (blue) are symmetrical to the tensile stress zones (red), while the symmetry axis of the samples coincides with the neutral axis (green) of the bent sample cross-section. The highlighted stress zones do not undergo significant displacement at the tested loading rates for wood with moisture content W_0 (Figure13 A, B, C and 14 A, B, C).

The relationship between stress (σ) and strain for both wood species with moisture content W_0 is shown in Figures. 13 D and 14 D. The loading speed had no significant effect on the distribution and magnitude of the resulting stresses. From the analysis of their course, it can be seen that noticeable differences relate to the lowest and highest loading velocity, in which case, at 200 mm·min^{-1} the failure of the samples occurs faster and at a higher stress, compared to a loading velocity of 20 mm·min^{-1}.

For birch wood, the nature of the stresses and strains occurring are similar, but both values are lower compared to beech wood.

The relationship between stress (σ) and strain for both wood species with moisture content W_0 is shown in Figures. 13 D and 14 D. The loading speed had no significant effect on the distribution and the magnitude of the resulting stresses. From the analysis of their course, it can be seen that noticeable differences relate to the lowest and highest loading velocity, in which case, at 200 mm·min^{-1} the failure of the samples occurs faster and at a higher stress, compared to a loading velocity of 20 mm·min^{-1}.

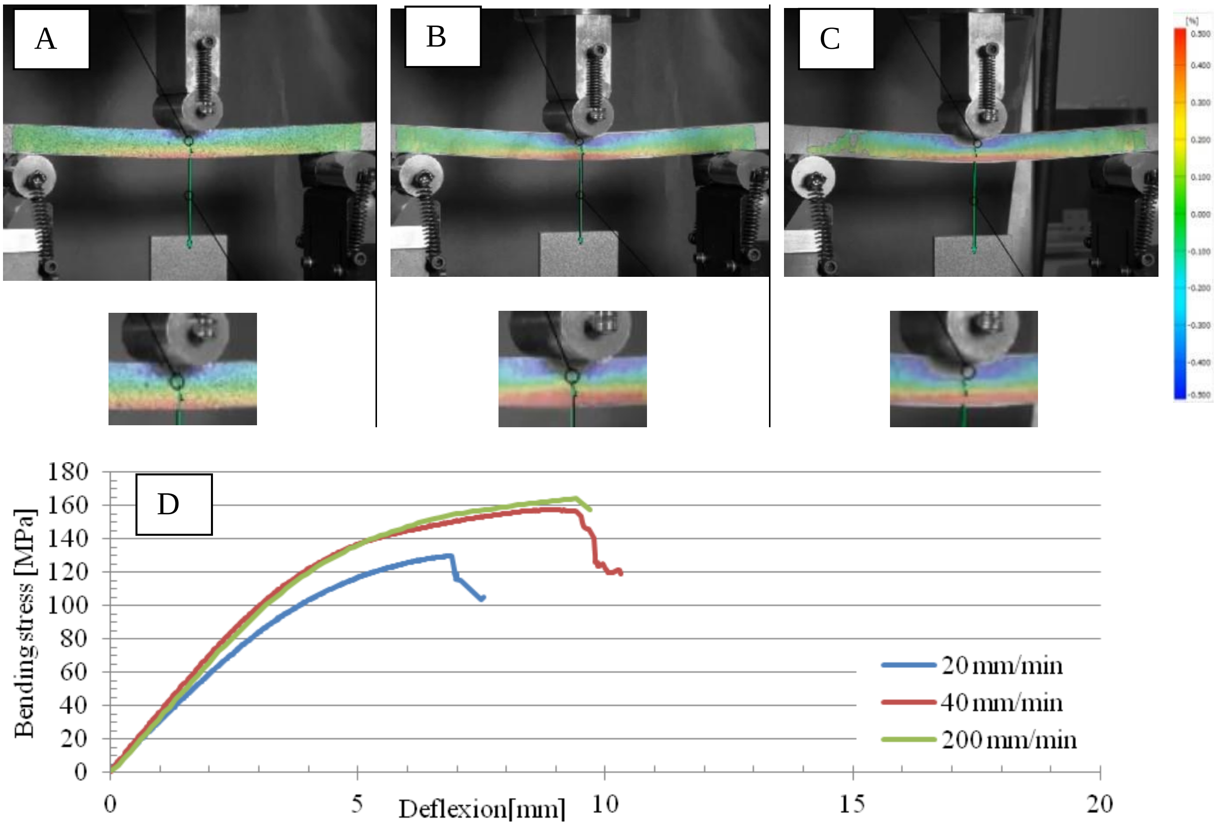

Figure 14. Strain and stress distribution developed in the specimen during bending strength testing of birch wood with moisture content W0 at loading rates of 20 mm·min^{-1} (A), 40 mm·min^{-1} (B) and 200 mm·min^{-1} (C). The course of stress changes during bending of birch wood with moisture content W_0, depending on the loading rate (D)

For birch wood, the nature of the stresses and strains occurring are similar, but both values are lower compared to beech wood.

As a result of increasing loading rates for beech and birch wood with a moisture content of W_w (Figure 15 A, B, C and 16 A, B, C), the resulting stresses and the magnitude of deflection have a different pattern compared to the changes occurring when bending wood with a moisture content of W_0. The analysis of the relationship between stress magnitude and deflection at W_w moisture content reveals a clear asymmetry in the occurrence of compressive (blue) and tensile (red) stress zones, as well as a shift in the neutral axis of the bending section (green) towards the tensile planes. Compressive stresses occupy a greater part of the height of the flexural of the specimens' cross-section compared to tensile stresses. For both wood species, the nature of the occurring changes is very similar. The observed differences are only slightly dependent on the loading speed. At the tested speeds, there is a slight variation in the magnitude of the stress at the same deflection size.

From the analysis of the resulting sample deflections for both wood species with moisture content W_w, it can be seen that, at the initial stage, the strain only slightly increases proportionally to the increase in stress. Then, with a further relatively small increase in stress, an intensive increase in strain magnitude takes place (15 D and 16 D).

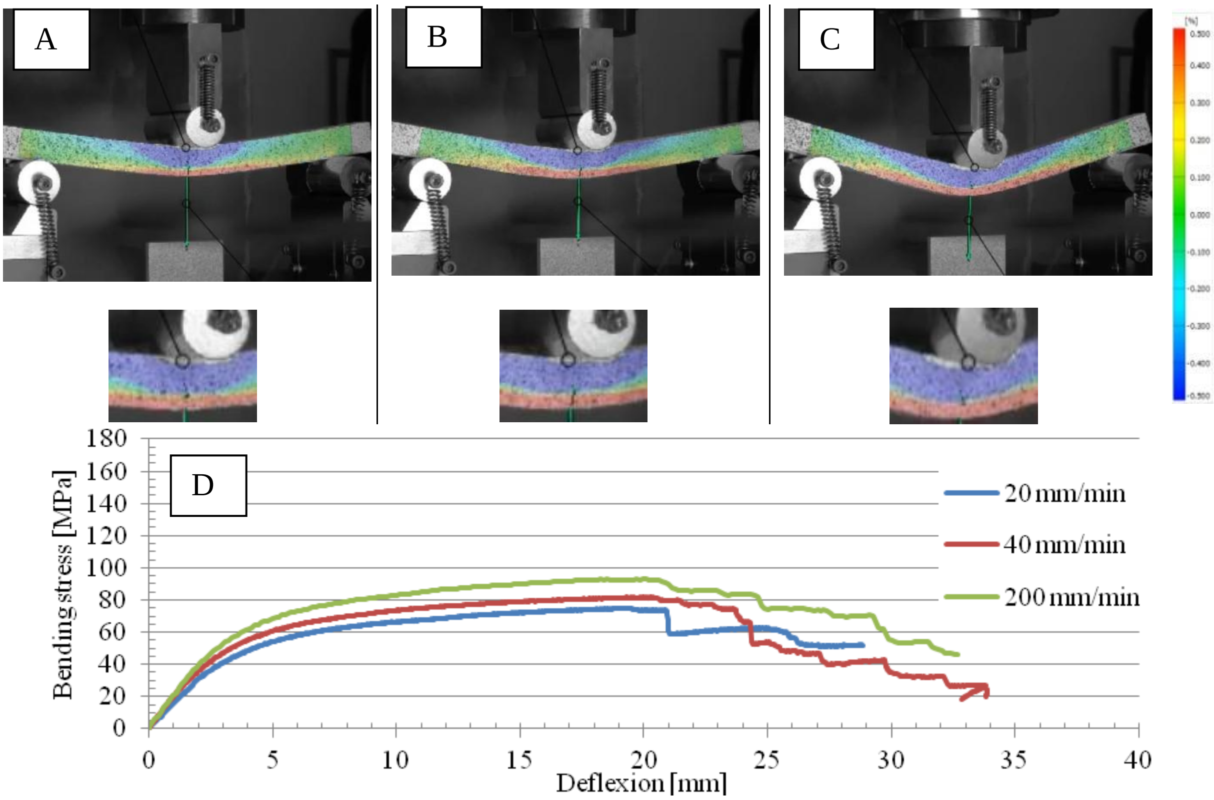

Figure 15. Deformation and stress distribution during bending strength testing of beech wood with moisture content W_w at loading rates of 20 mm·min^{-1} (A), 40 mm·min^{-1} (B) and 200 mm·min^{-1} (C). The course of stress changes during bending of beech wood with moisture content W_w, as a function of loading rate (D).

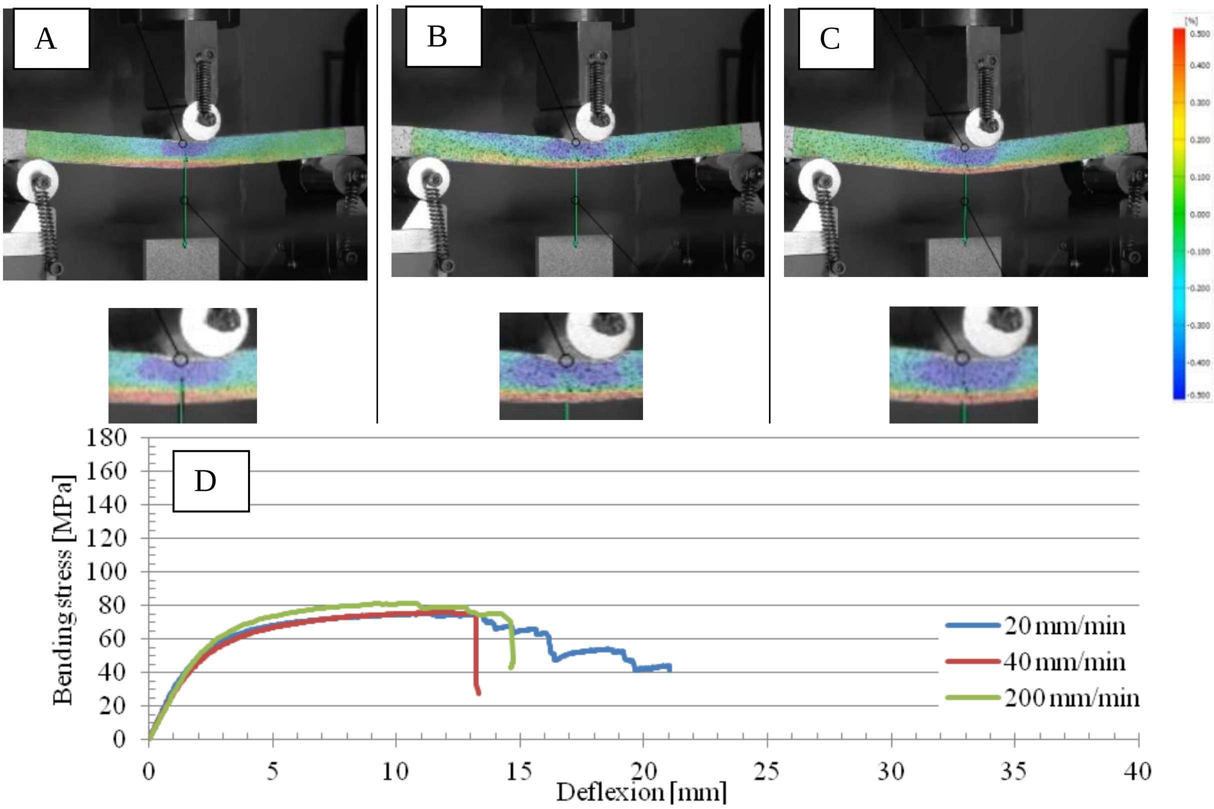

Figure 16. Strain and stress distribution during bending strength testing of birch wood with moisture content W_0 at loading rates of 20 mm·min^{-1} (A), 40 mm·min^{-1} (B) and 200 mm·min^{-1} (C). Course of stress changes during bending of birch wood with moisture content W0, as a function of loading rate (D).

CONCLUSIONS

Based on the study, it was found that loading rates of 20 mm·min^{-1}, 40 mm·min^{-1} and 200 mm·min^{-1} have an effect on the bending strength of beech and birch wood at dry W_0 and wet W_w.

The highest bending strengths and moduli of elasticity for both wood species at moisture content W_0 were achieved at a loading rate of 200 mm·min^{-1}.

With moistening to a moisture content of W_w, there was a significant reduction in the flexural strength by 58% for beech wood and 48% for birch wood. The modulus of elasticity of beech wood decreased by 7% and that of birch wood by 14%. With higher moisture content, there was a significant increase in the cross-sectional strain of the specimen with increasing loading speed.

For beech and birch wood with a moisture content of W_0, the proportionality limit increased with increasing loading speed. Beech wood with a moisture content of W_0 and W_w had a higher proportional limit compared to birch wood.

At the higher moisture content, there was a decrease in the proportional limit stresses compared to dry wood, which was particularly pronounced for beech wood and amounted to more than 50% at a loading rate of 200 mm·min^{-1}. The proportional limit for wood of both species with higher moisture content did not change under the influence of the loading rate.

The distribution of compressive and tensile stresses and the position of the neutral axis on the cross-section of the bending specimen was determined from the tests carried out using the GOM Aramis measurement system, which works with Digital Image Correlation (DIC) technology and records the displacements and deformations of the elements in real time.

It was found that during bending loading of the specimens, the magnitude of the resulting deformations in beech and birch wood with moisture content W_0 showed a symmetrical distribution of compressive and tensile stresses, despite increasing loading speed, and that the neutral axis coincided with the symmetry axis of the specimen cross-section.

At higher moisture content W_w, there was an increase in the compressive stress zone and a decrease in the magnitude of the tensile stress zone as the neutral axis moved towards the tensile stress zone. This change in the stress distribution on the cross-section of beech and birch wood samples with higher moisture content W_w resulted in a decrease in flexural strength.

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Streszczenie: *Wpływ prędkości obciążania na wytrzymałość na zginanie drewna buka (Fagus sp.) i brzozy (Betula sp.).* Przedmiotem pracy było zbadanie wpływu prędkości obciążania od 20 mm·min^{-1} do 200 mm·min^{-1} na wytrzymałość na zginanie i odkształcenie drewna buka (*Fagus sp.*) i brzozy (*Betula sp.*) o wilgotności bliskiej stanowi absolutnie suchemu i punktowi nasycenia włókien. W badaniach został wykorzystany systemu pomiarowego GOM Aramis, pracujący w technologii Digital Image Correlation (DIC) i rejestrujący przemieszczenia i odkształcenia elementów w czasie rzeczywistym. Uzyskane wyniki wytrzymałości na zginanie, moduł sprężystości przy zginaniu oraz wielkość powstającego odkształcenia wykazały związek między właściwościami materiału a prędkością obciążania. Przy wyższej wilgotności wytrzymałość na zginanie i moduł sprężystości ulegały obniżeniu, przy rosnącym odkształceniu. Najwyższą wytrzymałość na zginanie i moduł sprężystości badane gatunki drewna osiągnęły przy prędkości obciążania wynoszącej 200 mm·min^{-1}.

Wyższymi badanymi właściwościami charakteryzowało się drewno buka w porównaniu z drewnem brzozy. Obrazowanie przebiegu obciążania zginającego wykazało przy wilgotności bliskiej stanowi suchemu symetryczny rozkład naprężeń ściskających i rozciągających względem osi obojętnej przekroju próbki. Przy wyższej wilgotności nastąpiła znacząca asymetria między naprężeniem ściskającym i rozciągającym oraz widoczne przesunięcie osi obojętnej w stronę powierzchni rozciąganej.

Słowa kluczowe: wytrzymałość drewna na zginanie, moduł sprężystości przy zginaniu, ugięcie, odkształcenie, wilgotność drewna, prędkość obciążania, oś obojętna przekroju

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