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INFLUENCE OF DENSIFICATION ON BENDING STRENGTH OF BEECH WOOD

Miroslav Gašparík, Milan Gaff
Czech University of Life Sciences, Faculty of Forestry
and Wood Sciences
Department of Wood Processing
Prague, Czech Republic

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ABSTRACT

This paper reports the influence of densification and cyclic loading on bending strength of beech (*Fagus sylvatica* L.). There are many studies dealing with the bending strength of native wood but densified wood is much less explored. Beech wood was loaded by three different numbers of cycles (1 000, 2 000, and 3 000 cycles). Bending strength values of cyclically loaded densified wood were compared with cyclically non-loaded wood. The densified wood had, in average, bending strength values higher by 5.7 % than the non-densified wood. However, the number of cycles did not influence the bending strength unambiguously and essentially.

KEYWORDS: Bending strength, beech, densification, cyclic loading.

INTRODUCTION

Wood is a material with properties that make it ideal for various uses. On the other hand, in the wood industry there are efforts to improve certain properties of wood to match those of other materials. Basic processes to change the properties of wood use only the force application, or factors, such as heat and humidity. Densification is ranking among such processes.

Wood densification is a process that achieves an increase of wood mass per volume unit (the density increases) by the means of a pressing force, or eventually by other factors, such as changes in temperature and moisture, or additions of chemical agents (Chuchrjanskij 1949). Various methods of densification are known, such as uniaxial, biaxial, peripheral, and 3-D pressing, as well as wood rolling. During wood rolling, the strength required to densify the wood is supplied from a couple of rollers, which the wood passes in between (Fig. 1), where h is the material's original thickness and h_1 is its thickness after the densification.

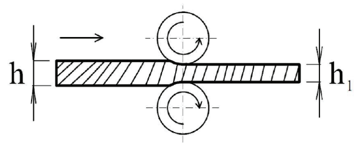

Fig. 1: Principle of densification by rolling.

This process is used for the densification of lamella for flooring and flooring walkway layers. Densified wood is used as an alternative to hard wood species, plastic materials, and metals. It is also used for shuttles in the textile industry, foundry patterns, music instruments (as an alternative to exotic wood species), and for sliding elements in the mechanical industry, such as special bearings for dusty environments and skids. Densified wood can also be utilized for flooring and furniture in countries that have a lack of hard wood species (Kafka et al. 1989).

For pressing, beech and birch wood is used. In comparison with native wood, all the properties of pressed wood are better. The density of native beech is 730 kg.m^{-3} and that of pressed beech is as high as 1 300 to 1 450 kg.m^{-3}. The strength of pressed wood is approximately equal to that of aluminum (Babiak and Dubovský 2001). Compact pressed wood, known also as Lignostone, is densified by pressure (from 10 to 28 MPa) at increased temperatures (between 130 and 160°C) to densities between 1 000 and 1 400 kg.m^{-3}. This is aimed to obtain a material that is 50 to 200 % stronger than the original wood (Eisner et al. 1983).

The radial bending perpendicular to the fibers is the most frequently examined feature for the furniture elements loaded during their use. This is because this feature is the most useful in practice for beams and balks, as well as for lamella elements, which are used in difference types of furniture pieces. If a wooden beam is loaded for bending, the deformation can be observed while compressive stresses appear on the inner side, and tensile stresses appear on the outer side. The non-deformable portion is observed on the cross section and this portion is called the neutral layer S. The farther from the neutral layer toward the edges, the more the layers are deformed and greater stress appears. Maximum values are achieved in the marginal fibers. For materials with a Young's modulus (E) equal in both compression and tension, with relatively high proportional limit values, the stress is distributed symmetrically alongside the neutral axis located in the middle of the cross section. The stress course is linear alongside the cross section (Požgaj et al. 1997).

This research focused on the bending strength of beech wood. The main goal was to find the influence of densification, and also cyclic loading, on the bending strength of beech wood. Cyclic loading was carried out at 1000, 2000, and 3000 cycles. All values of the bending strength of the cyclically loaded wood were compared with that of non-cyclically loaded wood. It has likewise been compared bending strength of non-densified and densified wood.

MATERIAL AND METHODS

Material

European beech trees (*Fagus sylvatica* L.) harvested from the Poľana region, in the center of Slovakia were used for the experiments. Sapwood zone, with annual rings 1.5 mm wide, located equidistant from the pith, was chosen for the experiment. Average beech density was 704 kg.m^{-3}. Sapwood boards were cut to test pieces.

The one group of samples was densified by the rolling densification machine (Fig. 2). This machine actuates with the same pressure on the both sides of the sample by the mean of two adversely located rolls. The pressure average value was 30 MPa, which densified the wood by an average value of 25 %. The samples were not pre-plasticized. Each sample was rolled 5 times in the machine in order to obtain as exact and as good result as possible because during single-rolling densification, higher pressure should be used, thus increasing the damaging probability. Densification was carried out at a temperature 20°C.

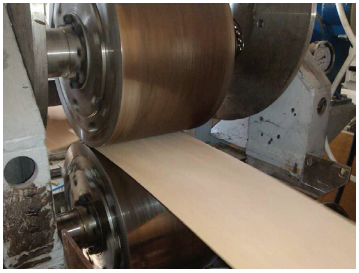

Fig. 2: Densification using the rolling machine.

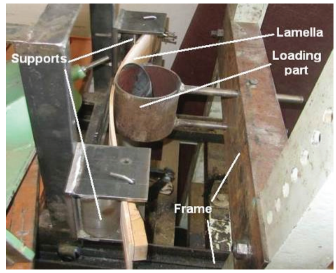

Fig. 3: Cycler machine.

Clear densified and non-densified samples, with dimensions 5 × 50 × 650 mm, were conditioned in a conditioning room (moisture content (ϕ) = 65 ± 3 % and temperature (t) = 20 ± 2°C) for more than four months to achieve equilibrium moisture content (EMC). The moisture content of samples after conditioning was 12 %.

Ten samples were used for each combination of wood type and number of cycles, so the whole investigation contained 80 samples.

Procedures

The cyclic loading was carried out on a horizontal cycling machine based on uniaxial stress (Fig. 3). The samples underwent 1 000, 2 000, and 3 000 cycles and were compared with samples without cyclic loading (0 cycles). During preliminary bending tests, the maximum strengths and proportional limits for the given materials were measured. These values were necessary for cyclic loading to avoid the sample load exceeding 90 % of the proportional limit during the loading. The cyclic loading procedure took into account previous works by Gaff and Gáborík (2014) and Gaff et al. (2014).

The samples were bent by the free-bending principle without a bending (tension) strap (i.e., three-point bending test) according to ISO 3133 (1975). The bending was carried out in a universal testing machine ZD 10/90, manufacturer VEB TIR Rauenstein (Germany), which contained a special jig for flexural tests and a data logger for recording the maximum loading forces at the breaking point. Test samples were placed on supporting pins (l = 600 mm) so that loading force acted in the perpendicular direction considering the length of the sample, and a load was applied until they broke.

Measurements

The values of maximum loading forces were directly downloaded from the data logger on a personal computer, and the bending strength (MOR) was calculated.

The dimensions of the samples, used for calculating the moisture content, were measured with a digital caliper from Mitutoyo company to a precision of 0.1 mm.

Calculations and evaluation

The influence of factors on bending strength was statistically evaluated using ANOVA analysis, mainly by Fisher's F-test, in STATISTICA 12 software.

The bending strength (MOR) of the samples was calculated after cyclic loading. These calculations were carried out according to ISO 3133 (1975) and Eq. 1:

$$\sigma_b = \frac{3F_{max} l}{2bh^2} \quad \text{(MPa)} \tag{1}$$

where: σ_b - the (ultimate) bending strength of wood (MPa),
F_{max} - the maximum (breaking) force (N),
l - the distance between supporting pins (mm),
b - the width of the test sample (mm),
h - the height (thickness) of the test sample (mm).

The density was determined as an auxiliary indicator. Density was calculated according to Eq. 2 from ISO 3131 (1975).

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \quad \text{(kg.m}^{-3}\text{)} \tag{2}$$

where: ρw - the density of the test sample at moisture content w (kg.m^{-3});
m_w - the mass (weight) of the test sample at moisture content w (kg);
a_w, b_w, l_w - dimensions of the test sample at moisture content w (m);
V_w - the volume of the test sample at moisture content w (m^3).

The moisture content of samples was determined and verified before and after thermal treatment. These calculations were carried out according to ISO 3130 (1975) and Eq. 3,

$$w = \frac{m_w - m_0}{m_0} * 100 \quad (\%) \tag{3}$$

where: w - the moisture content of the samples (%);
m_w - the mass (weight) of the test sample at moisture content w (kg);
m_0 - the mass (weight) of the oven-dry test sample (kg).

Drying to oven-dry state was also carried out according to ISO 3130 (1975), using the following procedure: Wood samples were placed in the drying oven at a temperature of 103 ± 2°C until a constant mass was reached. Constant mass is considered to be reached if the loss between two successive measurements carried out at an interval of 6 h is equal to or less than 0.5 % of the mass of the test sample. After cooling the test samples to approximately room temperature in a desiccator, the samples were weighed rapidly enough to avoid an increase in moisture content by more than 0.1 %. The accuracy of weighing was at least 0.5 % of the mass of the test sample.

RESULTS AND DISCUSSION

Bending strength

The statistical results revealed that the only influence of material type was statistically significant (Tab. 1). On the other hand, number of cycles was statistically insignificant.

Tab. 1: Influence of individual factors and their interaction on bending strength.

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	2 132.595	1	2132.595	7 800	0.000
Type of material	1.451	1	1.451	5	0.024
Number of cycles	294	3	98	0	0.783
Type of material type × Number of cycles	496	3	165	1	0.614
Error	19.687	72	273		

The bending strength of the individual types of material is shown in the Fig. 4. While comparing the individual types, it is evident that the bending strength of the densified wood was higher by 5.7 % in average than that one of the non-densified wood. These results confirm the fact of higher densified wood strength than that of the non-densified wood. This fact was confirmed also by the research of Schaffer et al. (1972) and Hoover et al. (1987).

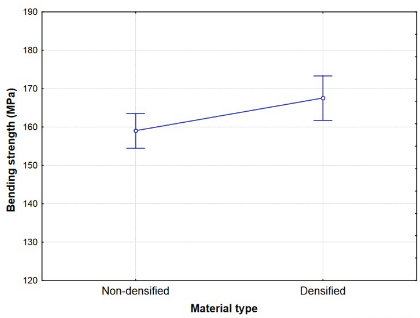

Fig. 4: The influence of type of laminated material on bending strength at the 95 % confidence interval.

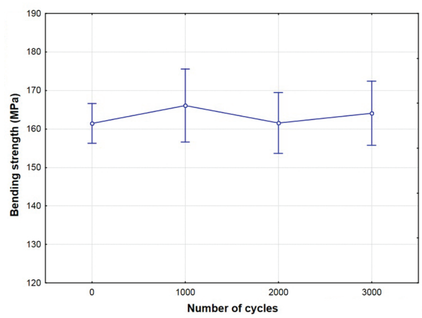

Fig. 5: The influence of number of cycles on bending strength at the 95 % confidence interval.

No significant effect of the cyclic loading on the bending stress of the laminated wood was proven (Fig. 5). With the increase in the number of cycles there was a slight fluctuation in flexural strength. Probably, for the significant difference would be necessary to substantially increase the number of cycles.

Fig. 6 shows the effect of the material type and number of cycles on the bending strength. For non-densified wood, the cyclic loading impact is negligible, although slightly higher than for wood without cyclic loading. On the other hand, slight increase of bending strength has been observed for the densified wood, mainly at 1.000 and 2.000 cycles. This fact could be explained by too low given number of cycles to be able to weaken the densified wood structure. On the contrary, due to the cyclic loading, local density might increase in the densified wood, thus resulting in slight increase of the bending strength. As confirmed by Pařil et al. (2014) the density increase improves directly some mechanical properties. He also states that density, which is affected by the densification degree, is determining the bending parameters. Pařil et al. (2014), who densified the beech wood, found an average bending strength of 160 MPa, which is a value similar to our results. However, it is necessary to mention that the bending strength values maximum increase was 3.7 % at 1.000 cycles. The fact of densified wood bending strength being less affected by cyclic loading than in case of non-densified wood is important. The individual values of the bending strength are shown in Tab. 2.

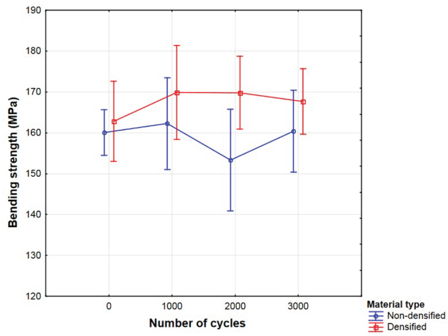

Fig. 6: The influence of material type and number of cycle on bending strength at the 95 % confidence interval.

Tab. 2: Average values of bending strength.

Material type	Number of cycles	Average bending strength (MPa)	Standard deviation	95 % confidence interval	
				Minimum	Maximum
Non-densified	0	160.08	2.48	154.46	165.70
	1000	162.24	4.97	151.01	173.47
	2000	153.31	5.51	140.85	175.78
	3000	160.40	4.44	150.36	170.43
Densified	0	162.80	4.33	153.00	172.59
	1000	169.88	7.72	152.43	187.33
	2000	169.77	3.94	160.87	178.68
	3000	167.65	6.64	152.63	182.67

Each mean value of bending strength represents 10 samples

In our research, the bending strength values were lower than those specified by other authors for densified wood. For example, Fang et al. (2012) found out an increased bending strength for maple by 50 % after its densification. In our case, the increase was just by 5.7 %. When comparing the non-densified wood results, ours were similar to those in their research. However, the wood in their research was densified at 180 and 200°C with the use of steam. These differences of values are caused by different densification methods and therefore by different nature of the densified wood. While heated and plasticized wood is more elastic and shapeable, the cold-densified (at 20°C) wood more susceptible to the structure breaking. Another factor is the densification method; in our case, continuous roll pressing repeated 5 times was used.

CONCLUSIONS

In general, densified wood had all values of bending strength higher in comparison with non-densified wood. The highest values of bending strength were found in densified beech wood after 1000-cycles loading.

The number of cycles did not have a statistically significant effect on the bending strength of non-densified and densified wood, respectively.

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Miroslav Gašparík*, Milan Gaff
Czech University of Life Sciences
Faculty of Forestry and Wood Sciences
Department of Wood Processing
Kamýcká 1176
Cz-165 21 Prague 6 - Suchdol
Czech Republic
Phone: +420 224 383 828
Corresponding author: gathiss@gmail.com