Influence of Densification on Bending Strength of Laminated Beech Wood

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This paper reports the influence of densification and cyclic loading on the bending strength of laminated beech (*Fagus sylvatica* L.). There have been many studies dealing with the bending strength of solid or laminated wood; however, densification is much less explored with respect to its use in the production of laminated wood. Laminated beech wood was loaded using three different numbers of cycles (1000, 2000, and 3000 cycles). Bending strength values of the cyclically loaded laminated wood were compared with that of laminated wood that was not cyclically loaded. The laminated wood was formed by a combination of densified and non-densified veneers, as well as polyvinyl cholride (PVC) fabric. The results show that the laminated wood consisting of densified and non-densified veneers, eventually with PVC film included, reached higher values of bending strength in comparison with the traditional composition consisting of non-densified veneers. Densification had a strong impact on the bending strength. Laminated wood composed solely with densified veneers achieved by 17.4% higher bending strength compared to the reference. On the other hand, the number of cycles did not influence the bending strength to a meaningful extent.

Keywords: Bending strength; Densification; Cyclic loading; Veneer; Laminated wood; Beech; PVC fabric

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INTRODUCTION

Wood is a material with properties that make it almost 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 sometimes use only the application of force, or they may employ other factors. Densification is in an important option among such processes.

Wood densification is a process that achieves an increase of wood mass per volume unit (the density increases) by means of mechanical forces, mostly by compression, without pre-treatment or softening (Kamke 2006; Fang *et al*. 2012), or eventually by combinations of heat, steam, and pressure (*e.g*. thermo-hydro (TH) and thermo-hydro-mechanical (THM) method) (Inoue *et al*. 1993; Ito *et al*. 1998; Navi and Girardet 2000; Boonstra and Blomberg 2007; Welzbacher *et al*. 2008; Fekiač *et al*. 2015). The process of densification can be achieved in two basic ways: densification of the whole wood volume or densification of wood surface layers (surface densification) (Sandberg *et al*. 2013). Densification of the whole volume occurs in the process of wood shaping. But the main disadvantage is that in this process there is a loss of volume. This disadvantage can be partially eliminated by laminating of the densified wood with non-densified wood or other materials with the assistance of adhesives (Kutnar *et al*. 2008).

Due to the low thermal conductivity of wood, it is possible to impart densification mainly to the surface of the wood (Laine *et al*. 2014). During the surface densification, the wood surface is heated by hot plates and subsequently densified by non-heated plates. Consequently, the wood is heated again and the press remains closed. The process ends by slow cooling of wood (Fortino *et al*. 2013). Densification of the wood surface or thinner materials can be achieved by press rolling using heated or unheated rollers. During wood rolling, the strength required to densify the wood is supplied from a couple of rollers, which the wood passes between (Fig. 1), where h is the material's original thickness and h_1 is its thickness after the densification. This process is used for the densification of lamella for parquet flooring and flooring walkway layers.

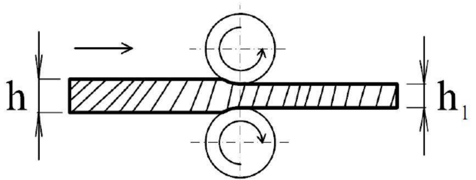

Fig. 1. Principle of densification by rolling

Densified wood can be used for flooring, staircases, wall paneling, and furniture parts, such as tabletop or worktop (Blomberg and Persson 2007; Laine *et al*. 2013). After densification, low-density woods can be used as an alternative to hardwood species, or hard-density woods have improved mechanical properties (Blomberg *et al*. 2005). In comparison with native wood, all mechanical properties of densified wood are better due to increased density. Another example of densified wood is compact pressed wood, known also as Lignostone. Lignostone is densified by pressure (from 10 to 28 MPa but mostly 7 to 15 MPa) at increased temperatures (between 160 and 180 °C) to densities around 1,400 kg/m^3. For example, the density of native beech is from 650 to 730 kg/m^3 and after compression the beech density was increased to 1,450 kg/m^3(Blomberg 2006).

Laminated veneer lumber (LVL) is a material produced from veneers or small-sized wood layers by bonding, while the parallel configuration of the layers is maintained with regard to the veneer or slat fibers (Aydin *et al.* 2004). For LVL, primarily hardwood species are used (Ozarska 1999) in conjunction with the use of urea-formaldehyde (UF) and phenol-formaldehyde (PF) adhesives. The layered veneer wood can be used for bearers, boards, partition structure rods, beams, purlins, partition structure strips, transportation vehicle floors, scaffolding boards, and prefabricated house structures. LVL is not only used for structural purposes, but also in furniture industry for sitting and bed furniture and also in carpentry for the fabrication of windows, stairs, and doors (Ozarska 1999).

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 (Gaff and Gáborík 2014). 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 close to the surface. 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 laminated beech wood. The laminated wood was formed by a combination of the three and five layers of densified and non-densified veneers, as well as PVC fabric. Cyclic loading was carried out at 1000, 2000, and 3000 cycles. All values of the bending strength of the cyclically loaded laminated wood were compared with that of non-cyclically loaded laminated wood.

EXPERIMENTAL

Materials

Veneer preparation

European beech trees (*Fagus sylvatica* L.) harvested from the Poľana region in the center of Slovakia were used for the experiments. The beech trunks, with diameter 700 mm, were steamed in an autoclave at 95 °C using hot water vapor. The veneers were made by rotary peeling of five steamed beech trunks. Sapwood veneers with annual rings 1.5 mm wide, located equidistant from the pith, were chosen for the experiment. The nominal thickness of the beech veneers was 1.7 mm. Veneers were cut to smaller strips with dimensions 1.7 mm × 60 mm × 700 mm. Subsequently, veneer straps were conditioned (ϕ = 65 ± 3% and t = 20 ± 2 ºC).

Densification

One group of veneers was intended for densification, while the second group consisted of non-densified veneers. A rolling densification machine was used to densify the veneers (Fig. 2). This machine operates by expelling the same amount of pressure on the both sides of the veneer by the means of two adversely located rollers. The pressure value was 30 MPa, which densified the veneers by an average value of 25%. The veneers were not additionally plasticized and heated, *i.e*. densification was carried out at temperature 20 °C. Each veneer was rolled five times in the machine to obtain the most exact and best results possible. This is because during single-rolling densification, higher pressure should be used, thus increasing the damaging probability if plasticizing is not used. After the densification, the veneers thickness changed from the original 1.7 mm to 1.3 mm.

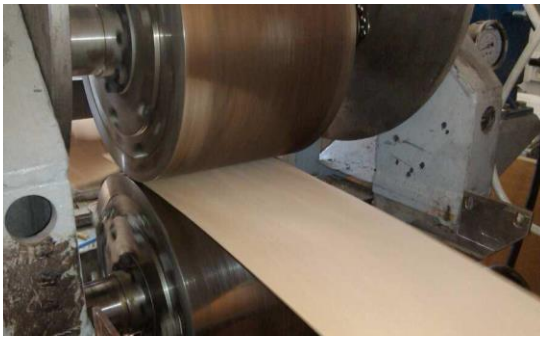

Fig. 2. Densification using the rolling process

Lamination

Defect-free, densified veneers and non-densified veneers (tangential width), and also 1 mm thick PVC foils, were used. The UF adhesive, Rakoll Isarit E1 (H. B. Fuller, USA) (Table 1), was used for the gluing. Approximately 150 g/m^2 of UF adhesive were manually spread on the loose side of veneer straps.

Subsequently, three and five veneer straps, plus PVC fabric, were put to each other with parallel fiber direction (without cross-banding) and pressed in one-story pressing machine JU 60 (Paul Ott GmbH, Austria) under the conditions specified in Table 2.

Table 1. Adhesive Properties

Open time at 20 °C (min.)	**Mixing ratio** (adhesive : water)	**Pressing temperature** (°C)	**Relative humidity** (%)	**Glue spread** (g/m^2)
15 -20	100 : 50 - 70	90 - 110	60 - 70	100 - 150

Table 2. Parameters of Pressing

Type of laminated wood	**Temperature** (°C)	**Time** (min)	**Specific pressure** (MPa)
Three-layer laminated wood	96	6	24
Five-layer laminated wood with PVC foil	96	9	32

The laminated woods were cut to final width of 50 mm and length of 650 mm, with thickness of 5 mm for the three-layer samples, and 8.5 mm for the five-layer samples. The clear laminated samples were conditioned in a conditioning room (relative humidity of air (ϕ) = 65 ± 3% and temperature (t) = 20 ± 2 ºC) for more than four months to achieve equilibrium moisture content (EMC).

There were 10 samples for each combination of laminated wood (Table 3 and Fig. 3) and number of cycles, so the whole investigation contained 200 samples.

Table 3. Composition of Laminated Wood

Laminated wood	**Description**
A	Three-layer laminated wood composed of non-densified veneers
B	Three-layer laminated wood composed of two non-densified outer and one densified inner veneers
C	Three-layer laminated wood composed of two densified outer and one non-densified inner veneers
D	Three-layer laminated wood composed of densified veneers
E	Five-layer laminated wood, composed of five non-densified veneers where the PVC fabric was applied under the outer veneers

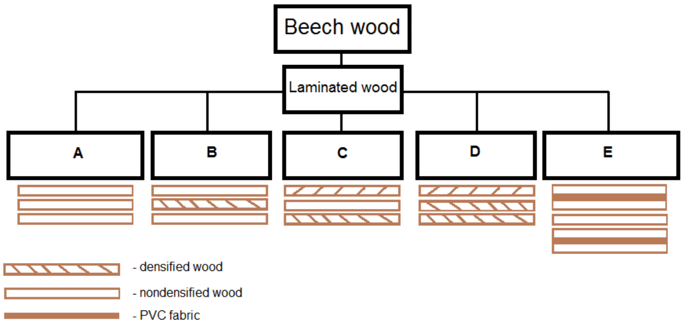

Fig. 3. Categorization of different composition of test samples

Procedure

Cyclic bend loading

The cyclic loading was carried out on a horizontal cycling machine (Fig. 4) based on uniaxial stress. 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 from exceeding 90% of the proportional limit during the loading (Table 4). The cyclic loading procedure took into account previous works by Gaff and Gáborík (2014) and Gaff *et al.* (2014).

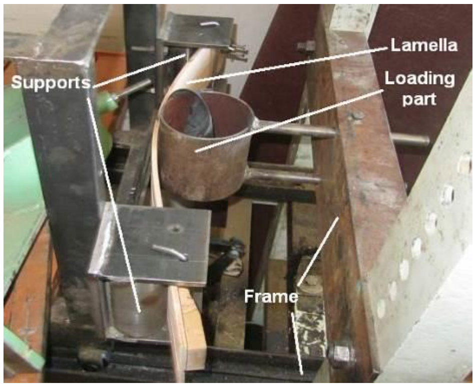

Fig. 4. Cycler machine

Table 4. Specific Parameters for Individual Thickness Group

Number of veneers	Thickness of laminated wood (mm)	Limit of proportionality (MPa)	90% of limit of proportionality (MPa)
3-layers	5	101.1	91.0
5-layers	8.5	104.8	94.4

Bending

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 standard tensile-pressing machine ZD 10/90 (VEB TIR Rauenstein; Germany) that contained a special jig for flexural tests, as well as a data logger for recording the maximum loading forces at the breaking points. Test samples were placed on supporting pins (l = 550 mm) so that the loading force acted in a perpendicular direction considering the length of the sample, and a load was applied until they broke.

Measurements

Values of the maximum loading forces were directly downloaded from the data logger onto 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 500-150-20 (Mitutoyo; Japan) to a precision of 0.1 mm.

Evaluation and Calculation

The influence of factors on bending strength was statistically evaluated using ANOVA, mainly by Fisher's F-test, in STATISTICA 12 software (Statsoft Inc.; USA).

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

$$\sigma_b = \frac{3F_{\max} l}{2bh^2} \tag{1}$$

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

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{2}$$

where ρ_w is the density of the test sample at moisture content w (kg/m^3); m_w is the mass (weight) of the test sample at moisture content w (kg); a_w, b_w, and l_w are dimensions of the test sample at moisture content w (m); and V_w is the volume of the test sample at moisture content w (m^3).

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

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{3}$$

where w is the moisture content of the samples (%); m_w is the mass (weight) of the test sample at moisture content w (kg); and m_0 is 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 of more than 0.1%. The accuracy of weighing was at least 0.5% of the mass of the test sample.

RESULTS AND DISCUSSION

Physical Properties

Results for the average equilibrium moisture content (EMC) as well as density of laminated wood types are shown in Table 5.

The present experiments identified an average density in beech wood of 704 kg/m^3. This value is similar to those quoted by other authors. Wagenführ (2000) stated the density of beech wood to be 720 kg/m^3, but Çolakoğlu *et al*. (2003) measured a lower density of 660 kg/m^3, and also Candan *et al*. (2012) found a density value of 630 kg/m^3 for beech.

Çolakoğlu *et al*. (2003) found that the density of beech LVL was 720 kg/m^3. However, Bal and Bektaş (2012), who investigated beech LVL bonded by UF adhesive, found a density of this LVL only 664 kg/m^3.

Table 5. Average Moisture Content and Density of Laminated Wood and Thickness of Veneers

Laminated wood	**Average veneer thickness** (mm)		**Equilibrium Moisture Content** (%)	**Average Density** (kg/m^3)
	Before densification	After densification		
A (3- ND. layers)	1.7 (2.11)	-	12.8	750 (3.10)
B (3-layers, 2ND + 1D.)	1.7 (3.04)	1.3 (2.81)	13.1	775 (1.92)
C (3-layers, 2D. + 1ND.)	1.7 (1.12)	1.3 (2.47)	12.6	765 (4.09)
D (3- D. layers)	1.7 (2.07)	1.3 (2.28)	12.9	820 (4.31)
E (5-ND. Layers + PVC)	1.7 (1.11)	-	13.4	790 (2.17)

Each mean density/moisture content (±SD) represents 20 wood samples
ND – non-densified veneers, D – densified veneers

Bending Strength

The statistical results revealed that the type of laminated wood was the only influence on the bending strength that was statistically significant (Table 6). On the other hand, number of cycles was statistically insignificant.

Table 6. 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	3,790,350	1	3,790,350	10,768	0,0001
Type of laminated material	24,732	4	6,183	18	0,0002
Number of cycles	592	3	197	1	0,6423
Type of lam. material × number of cycles	7,810	12	651	2	0,0441
Error	63,360	180	352		

The bending strengths of the individual laminated wood types are shown in Fig. 5. The differences in bending strength between the traditional composition consisting of three non-densified veneers (A) and the combinations of densified and non-densified veneers (B) were not great, although the values were lower by 5% approx. for type (B). The bending strength from densified veneers (C) was higher by 5% than that of non-densified veneers (A). However, for the laminated wood type (D), significant increase of the bending strength occurred, *i.e.*, by 21.6%. This means that the laminated wood consisting only of densified veneers had the highest values from among all the alternatives. On the other hand, the 5-layer laminated wood with PVC foil achieved bending strength values slightly lower than that of type D. In comparison with the 3-layer laminated wood samples with no densified veneers, the hypothesis of increasing bending strength with increasing material thickness (increasing number of veneers) was confirmed. Also, Schaffer *et al*. (1972) and Hoover *et al.* (1987) confirmed this fact in their studies. However, Fig. 5 shows only statistical evaluation where each value for the type of LVL is made of the values obtained with all types of cyclic loading (0, 1000, 2000, and 3000 cycles). Thus, as to the resulting value is the average value for a given type (A, B, C, or D).

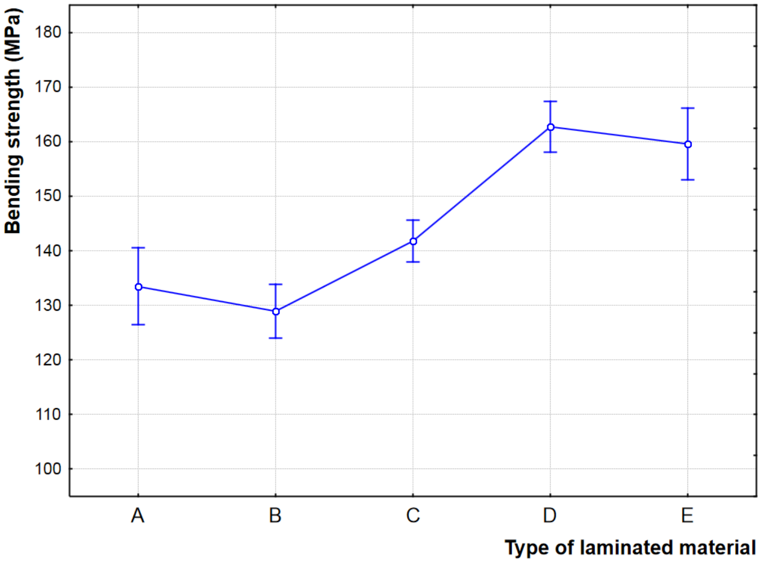

Fig. 5. Influence of type of laminated material on bending strength at the 95% confidence interval

No significant effect by the cyclic loading on the bending strength of the laminated woods was found (Fig. 6). Despite a slight increase in the bending strength (up to 2%) with the increase in the number of cycles, these differences were negligible. For greater differences, the number of cycles should be increased substantially.

Figure 7 shows the effect of the different laminated wood types and the number of cycles on the bending strength. The laminated wood with no cyclic loading achieved higher bending strength because of its composition change, while the lowest values were found for 3-layer laminated wood consisting of non-densified veneers (A). The bending strength increased for further combinations of non-densified and densified veneers (Fig. 7), where the highest values of the bending strength were achieved in the 3-layer laminated wood consisting only of densified veneers (D). In comparison with laminated wood of non-densified veneers, the values increased 17%. However, the highest bending strength values were in the 5-layer laminated wood with PVC foil (E). These values were 32% higher than that of the 3-layer laminated wood composed of non-densified veneers (A) and 13% higher than that of the 3-layer laminated wood composed of densified veneers (D).

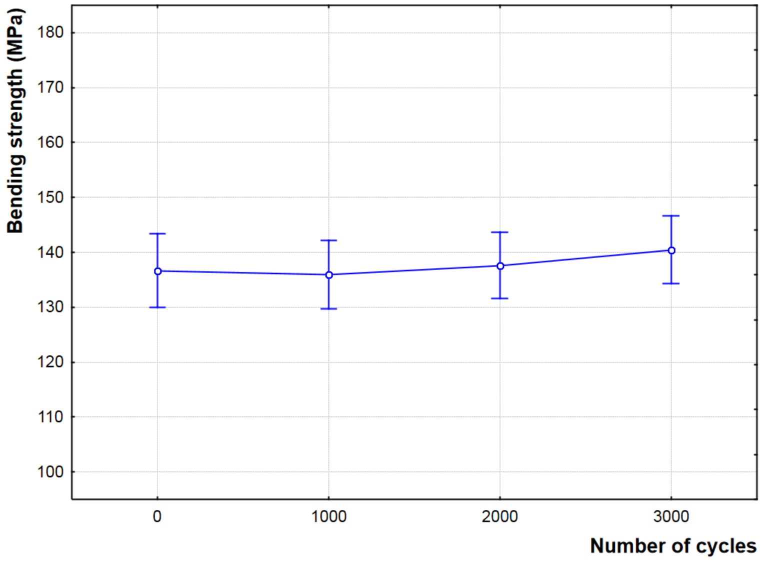

Fig. 6. The influence of number of cycles on bending strength at the 95% confidence interval

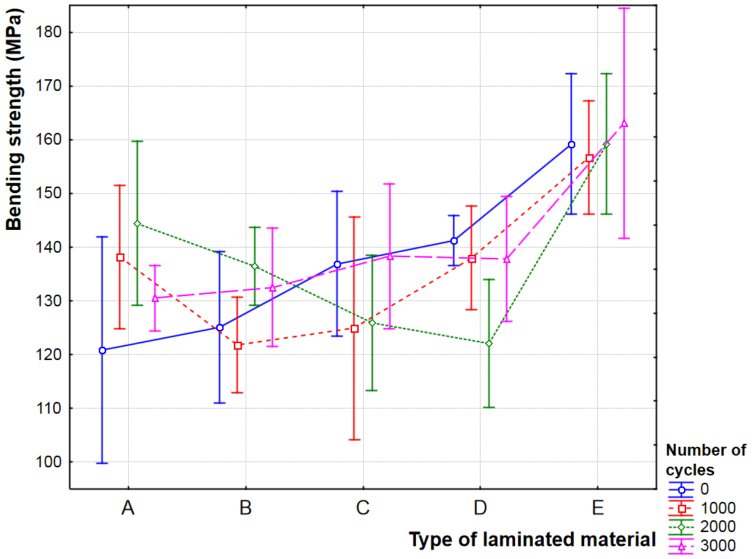

Fig. 7. The influence of type of laminated material and number of cycles on bending strength at the 95% confidence interval

The bending strength of the laminated wood composed of non-densified veneers and with no cyclic loading was 120.85 MPa, which is in accordance with other authors. Aydin *et al.* (2004), who examined 9-layer beech LVL, found its bending strength to be 118.3 MPa. Also, Çolakoğlu *et al.* (2003) found the bending strength equal to 111.5 MPa. However, Kiliç (2011), who investigated various compositions of 5-layer beech/poplar

LVL, found lower values of bending strength, *i.e.* 90.6 to 92 MPa for 5-mm thick veneers and 96.3 to 99 MPa for 4-mm thick veneers, respectively. On the other hand, Bal and Bektaş (2012) found the bending strength of 7-layer beech LVL to be 95.41 MPa.

The cyclic loading changed the behavior of the individual laminated wood types. Each composition showed different values at a certain number of cycles. This means that the increasing number of cycles did not change the bending strength proportionally. For 1,000 and 2,000 cycles, the laminated wood types B, C, and D had lower values of bending strength than that of type A (Table 7). For 3,000 cycles, the bending strength was similar to the behavior of laminated wood with no cyclic loading. Only the 5-layer laminated wood achieved the maximum values in all cases, however the number of layers (veneers plus PVC film) is also higher. Therefore, it is possible to conclude that the number of cycles almost did not affect the 5-layer wood, since the differences between its values at different numbers of cycles were the least. The different arrangement of veneers in the composition of LVL (at the edge or in center) led to different decreases in bending strength for each type of LVL during cyclic loading. This is probably caused by the fact that during the bending of LVL, the compressive pressure occurs on the inner side of the bend, while the tensile stress occurs on the outer side of the bend. For this reason, it is probably best to place densified veneers to the edges of LVL while non-densified should be at the center (due to shear stress, which occurs near the neutral axis).

Table 7. Average Values of Bending Strength

Type of Laminated Wood	**Number of cycles**	**Average bending strength (MPa)**	**Standard deviation**	**95% confidence interval**	
				Minimum	**Maximum**
A	**0**	120.85	9.337	99.73	141.98
	1000	138.16	5.912	124.79	151.54
	2000	144.43	6.734	129.20	159.66
	3000	130.52	2.703	124.40	136.63
B	**0**	125.08	6.244	110.95	139.20
	1000	121.78	3.939	112.87	130.69
	2000	136.49	3.203	129.24	143.73
	3000	132.55	4.850	121.57	143.52
C	**0**	136.92	5.966	123.42	150.41
	1000	124.93	9.159	104.22	145.65
	2000	125.91	5.572	113.31	138.52
	3000	138.31	5.952	124.85	151.78
D	**0**	141.27	2.061	136.61	145.94
	1000	137.98	4.251	128.36	147.60
	2000	122.06	5.250	110.19	133.94
	3000	137.83	5.164	126.15	149.51
E	**0**	159.21	5.790	146.11	172.31
	1000	156.73	4.653	146.21	167.26
	2000	159.21	5.790	146.11	172.31
	3000	163.07	9.473	141.64	184.50

Each mean value of bending strength represents 10 samples

CONCLUSIONS

1. In our research, the highest values of bending strength were found in five-layered laminated beech wood with PVC foil. For three-layered LVL, the combination of the densified veneers achieved the highest value of bending strength.
2. The number of cycles did not have a statistically significant effect on the bending strength of the samples. The decrease in bending strength, due to cyclic loading, was up to 2%.
3. Densification of veneers had a demonstrable impact on improving their bending strength. 3-ply LVL made entirely of densified of veneers had 17.4% higher bending strength than LVL of non-densified of veneers.

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