Bending Characteristics of Multilayered Soft and Hardwood Materials

Tomáš Svoboda, Daniel Ruman,* Milan Gaff, Miroslav Gašparík, Elena Miftieva, and Ľubomír Dundek

The influence of selected factors, such as wood species, veneer combinations, and loading cycles, on the bending strength and modulus of elasticity of glued laminated wood was investigated after cyclic loading of 0, 1000, 3000, and 7000 cycles with European beech (*Fagus sylvatica* (L.)) and Eurasian aspen (*Populus tremula* (L.)) The laminated woods were created by a combination of densified and non-densified veneers. The 30% densification was carried out by cold rolling. All factors and their interactions had statistically significant influence on the modulus of elasticity. Similarly, the influence of all factors on bending strength was statistically significant. However, the mutual interaction of all factors had no significant effect.

Keywords: Cyclic loading; Densification; Laminated wood; Bending strength; Modulus of elasticity; Beech; Aspen

Contact information: Department of Wood Processing, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521 Czech Republic;
** Corresponding author: dano.ruman@gmail.com*

INTRODUCTION

Most of wood's physical and mechanical properties can be improved by means of controlled changes. New applications of wood products in uncommon areas are being researched (Kurjatko *et al.* 2010). Wood densification is a modification process that changes the wood's volume and density by rolling (Kamke 2006). In the Czech Republic this process is most frequently used in the furniture industry, whereas abroad it is mostly used in the construction industry (Blomberg and Persson 2007; Laine *et al.* 2013; Gaff and Gašparík 2014). In the densification process, a qualitative change in the wood's properties is possible, and the obtained material may have better properties than the original solid wood. After the densification, softwood species are able to substitute for hardwood (Blomberg *et al*. 2005). The densified wood can be used as upper flooring elements, stairs, walls facing, and furniture elements such as some bed parts (Blomberg and Persson 2007; Laine *et al*. 2013; Gašparík and Gaff 2015).

Laminated veneer lumber (LVL) is manufactured by the gluing of veneer pieces in parallel layers to each other (Aydin *et al.* 2004). Laminated veneer lumber was designed as a substitute for solid wood (Erdil *et al.* 2009). It has excellent mechanical properties and dimensional stability. Urea-formaldehyde (UF), phenol formaldehyde (PF), melamine-urea-formaldehyde (MUF), and, to a lesser extent, polyvinyl acetate (PVAc) glues are used for LVL production (Ozarska 1999; Uysal and Kurt 2006).

Layered-veneer wood is used in the construction industry as beams, rods for truss structures, concrete casing, scaffolding elements, and pre-fabricated houses. In the furniture industry, LVL is also used for structural carpentry products such as stairs, windows, and doors, as well as for supporting elements of seats and beds (Ozarska 1999).

Wood gluing is one of the most important process steps in the wood-working industry (Sedliačik 2005). The glued joint strength is crucial for all materials glued from several layers of wood. Many factors influence the glued joint strength, such as pressing pressure, glue spread, open processing time, glue viscosity, temperature, and wood moisture.

Polyvinyl acetate glues appeared in 1950, and they began to substitute for glues based on natural raw materials. They can be regarded as being relatively favorable to human health and the natural environment (Mitani and Barboutis 2010). During use, the glued joint can be exposed to moisture changes, high temperature, or cyclic stress (Gašparík and Gaff 2015). PVAc glues are commonly used in the furniture industry for gluing wood-based products (Bomba *et al.* 2014).

This research investigated the selected factor's influence on the bending characteristics (modulus of elasticity and bending strength) of *Fagus sylvatica* (L.) and *Populus tremula* (L.) laminated wood after cyclic loading. Laminated wood was created from densified and non-densified veneers.

EXPERIMENTAL

Materials

Wood

European beech (*Fagus sylvatica* (L.)) and Eurasian aspen (*Populus tremula* (L.)) trees were used for the experiment. Both were grown in the Poľana area in central Slovakia. Rotary peeling of steamed logs was used to manufacture 2-mm-thick veneers, which were conditioned subsequently in the conditioning chamber APT Line II (Binder, Germany) to a moisture content of 8% (ϕ = 42 ± 3% and t = 20 ± 2 °C). The veneers of both wood species were divided into two groups: veneers for densification and non-densified veneers.

Veneer densification

The beech and aspen veneers were not plasticized before densification. The groups of veneers for densification were treated by a rolling machine according to previous work (Gašparík and Gaff 2015). Figure 1 shows the 30% thickness densification whereby 2-mm-thick veneers were reduced to 1.4-mm veneers.

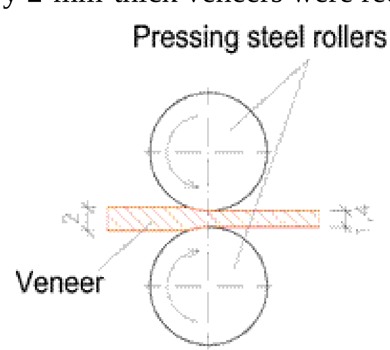

Fig. 1. Densification rolling machine

For both wood species, the densities before and after densification were evaluated (Table 1).

Table 1. Average Density of Wooden Veneers before and after Densification

Wood species	Density before densification (kg/m^3)	Density after densification (kg/m^3)
Eurasian aspen	425.22	649.02
European beech	627.03	867.89

Laminated wood gluing

Figure 2 shows the studied combinations of glued laminated wood for both wood species, with densified and non-densified veneers glued to each other. A waterproof polyvinyl acetate glue (PVAc), Duvilax D3 Rapid (Duslo Šaľa, Slovakia), was used for the laminated wood production. The glue parameters are shown in Table 2.

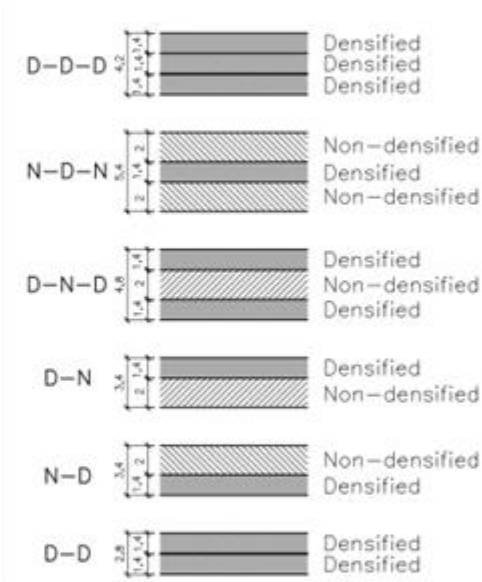

Fig. 2. Investigated combinations of glued laminated wood for European beech and Eurasian aspen

Table 2. Adhesive Properties

Dry matter content (%)	Viscosity (Pa*s)	pH	Working time (min)	Working temperature (°C)	Drying time at 20 °C (min)	Glue spread recommended (g/m^2)
49	4 to 8	3 to 4	10	15 to 100	10 to 30	150 to 200

The average glue spread at the application was 160 g/m^2. The veneers were pressed in an industrial press JU 60 (Paul Ott, Austria) for 40 min at lab temperature. Afterwards, the samples were conditioned in the climate chamber APT Line II (Binder, Germany) to a moisture content of 8%. Clear samples, with dimensions of *h* (final thickness of laminated materials according to combinations shown at Fig. 2) × 30 mm × 620 mm, were prepared for tests.

Cyclic bend loading

First, the maximum loading was set up to 90% of the proportional limit for the glued laminated wood. This value was determined from an average values of samples without cyclic loading. A cycling machine, with support distances of 490 mm, was used for cyclic loading with 0, 1000, 3000, and 7000 cycles. The cyclic bend loading procedure was carried out according to Gašparík and Gaff (2015). Each combination of laminated material contained 12 samples for each cycle type (Fig. 3).

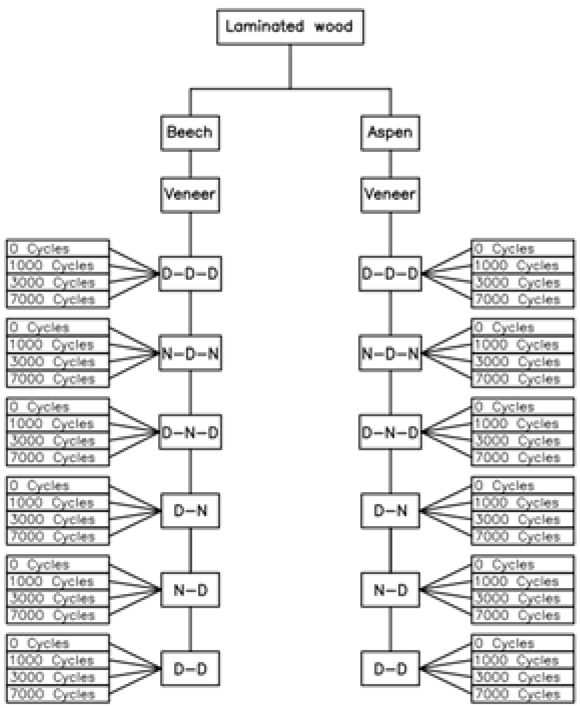

Fig. 3. Classification of sample groups

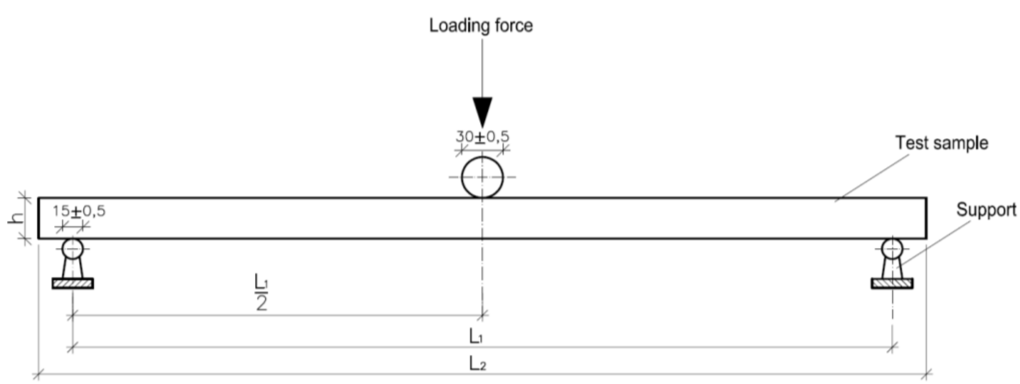

Fig. 4. Principle of the three-point bending test (EN 310)

Determination of bending strength and modulus of elasticity

After the cyclic loading, the support span was adjusted to $L_1 = 20 \times \mathrm{h}$ (support span was changed in relation to thickness of materials combinations). The samples were bent in middle-length distance (Fig. 4) using a universal testing machine FPZ 100 (TIRA, Germany) in accordance with EN 310 (1993). The loading speed was set to 3 mm/min so that the test duration would not exceed 2 min. Maximum breaking forces of samples were measured using the datalogger ALMEMO 2690-8 (Ahlborn GmbH, Germany).

Evaluation and Calculation

To determine the influence of the individual factors on the bending characteristics, analysis of variance (ANOVA) and the Fischer F-test were performed using Statistica 12 (Statsoft Inc., USA) software.

The bending strength was calculated in accordance with EN 310 (1993) and Eq. 1,

$$\sigma_b = \frac{3 * F_{\max} * l_1}{2 * b * h^2} \tag{1}$$

where σ_b is the (ultimate) bending strength of wood (MPa), F_{max} is the maximum (breaking) force (N), l_1 is the distance between supporting pins (mm), b is the width of the sample (mm), and h is the height (thickness) of the sample (mm).

The bending strength values were converted to the moisture content of 12% in accordance with ISO 13061-3 (2014) and Eq. 2,

$$\sigma_{12} = \sigma_w \left[1 + \alpha(w - 12)\right] \tag{2}$$

where σ_w is the wood bending strength at the moisture during the testing (MPa), σ_{12} is the wood bending strength at the moisture of 12% (MPa), w is the sample moisture during the testing (%), and α is the moisture correction coefficient, which was taken to be equal to 0.04 for all wood species.

The modulus of elasticity was calculated in accordance with EN 310 (1993) and Eq. 3,

$$E_m = \frac{l_1^{\,3}(F_2 - F_1)}{4bh^3(a_2 - a_1)} \tag{3}$$

where E_m is the modulus of elasticity perpendicular to fibers in radial direction (MPa), l_1 is the supports distance (mm), b is the width of sample (mm), h is the thickness of sample (mm), $F_2 - F_1$ is the loading increment in the proportional section of the load vs. deflection diagram, where F_1 must represent approximately 10% and F_2 is approximately 40% of the breaking load (N), and $a_2 - a_1$ is the deflection increment in the half of the sample length corresponding to the loading increment ($F_2 - F_1$).

The conversion of modulus of elasticity to the moisture content of 12% was performed according to ISO 13061-4 (2014) and Eq. 4,

$$E_{12} = \frac{E_w}{1 - \alpha(w - 12)} \tag{4}$$

where E_{12} is the modulus of elasticity at the moisture content of 12% (MPa), E_w is the modulus of elasticity at the moisture w (MPa), w is the moisture content of sample (%), and α is the moisture correction coefficient for the modulus of elasticity, 0.01 for all wood species.

The wood density was determined before and after testing according to ISO 13061-2 (2014) and Eq. 5,

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{5}$$

where ρ_w is the density of the sample at moisture content w (kg/m^3); m_w is the mass (weight) of the sample at moisture content w (kg); a_w, b_w, and l_w are dimensions of the sample at moisture content w (m); and V_w is the volume of the 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 13061-1 (2014) and Eq. 6,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{6}$$

where w is the moisture content of the samples (%), m_w is the mass (weight) of the sample at moisture content w (kg), and m_0 is the mass (weight) of the oven-dry sample (kg). Drying to oven-dry state was also carried out according to ISO 13061-1 (2014).

RESULTS AND DISCUSSION

Modulus of Elasticity

Table 3 shows the effects of the individual factors with their two and three factor interactions on the modulus of elasticity. Based on the value of the significance level P < 0.05, it is possible to conclude that the individual and synergetic effects monitored factors were statistically significant.

Table 3. Influence of Factors and their Interaction on Moduli of Elasticity

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	3.973251E+10	1	3.973251E+10	15108.44	0.000001
Combinations	1.347088E+08	5	2.694175E+07	10.24	0.000001
Wood species	1.067094E+09	1	1.067094E+09	405.77	0.000001
Loading Cycles	9.321213E+07	3	3.107071E+07	11.81	0.000001
Combinations * Wood species * Loading Cycles	8.763795E+07	15	5.842530E+06	2.22	0.005979
Error	7.573889E+08	288	2.629823E+06		

As apparent from Fig. 5, the highest values of modulus of elasticity were found out at D-D-D combination while the lowest ones corresponding to the N-D combination. The highest variability of values was found for the D-D combination.

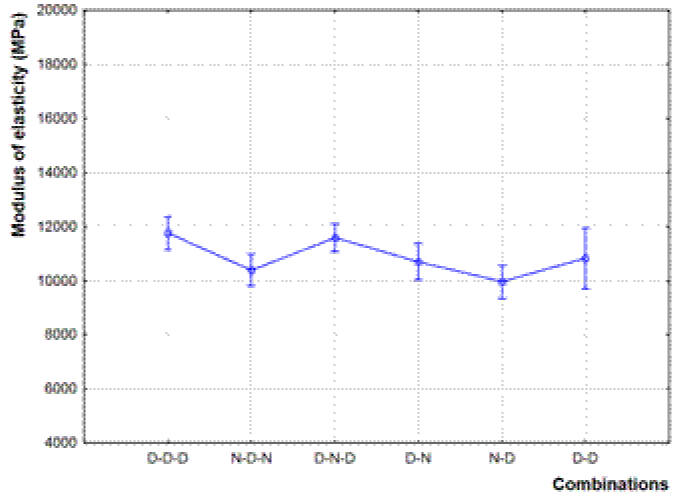

Fig. 5. Influence of veneer combinations on the modulus of elasticity

As shown in Fig. 6, the highest values of modulus of elasticity were found for beech wood. The highest value of modulus of elasticity for beech wood was 12,600 MPa, which is approximately 39% higher than aspen wood. The higher values for beech wood were likely a result of its different density.

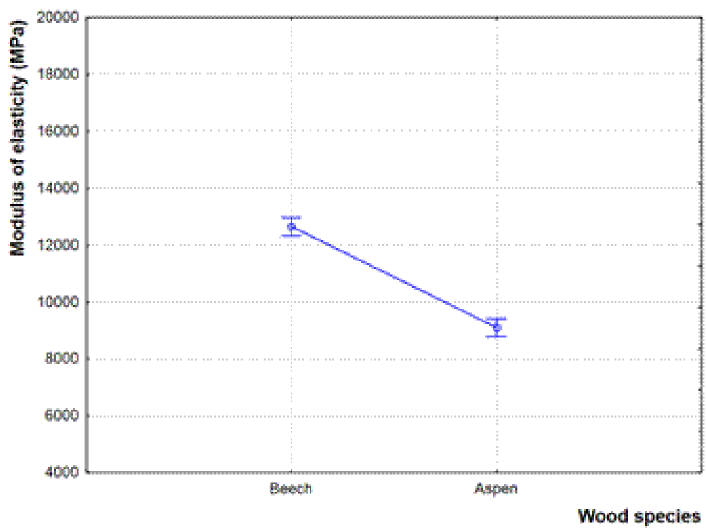

Fig. 6. Influence of wood species on the modulus of elasticity

Figure 7 shows that number of loading cycles had no clear influence on the modulus of elasticity. The highest modulus of elasticity was 11,600 MPa for non-loaded samples. Then, the modulus of elasticity of cyclically loaded samples at 1000 and 3000 cycles was lowered in comparison with non-loaded samples. But a slight increase in the modulus of elasticity occurred at 7000 cycles.

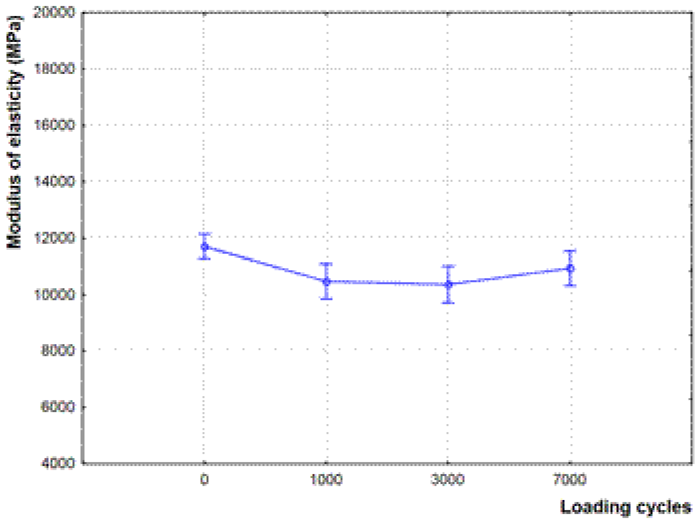

Fig. 7. Influence of number of loading cycles on modulus of elasticity

In Fig. 8, the simultaneous influence of all factors is shown. Generally, the conclusion can be made that the modulus of elasticity values for beech are significantly higher than for aspen. The highest values of the modulus of elasticity were reached for the D-D combination of beech veneers, while the same combination of aspen veneers had the smallest values. The D-D-D combination of aspen veneers reached the highest values of modulus of elasticity.

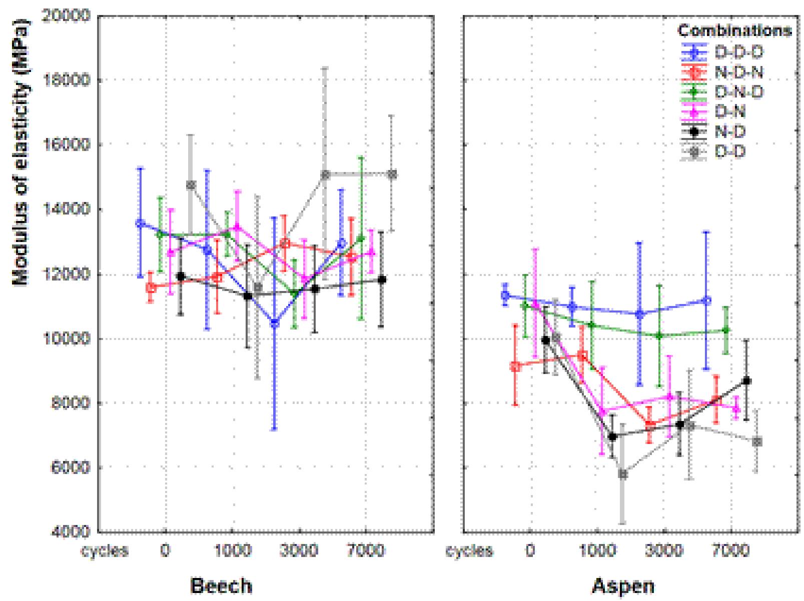

Fig. 8. Influence of the veneer combination, wood species and number of loading cycles on modulus of elasticity

The N-D-N combination of beech veneers reached the highest modulus of elasticity, *i.e.* 11,500 MPa. For three-layer non-densified beech laminated wood, Gaff and Gáborík (2014) found a modulus of elasticity of 11,600 MPa. These authors also found that the modulus of elasticity for two-layer non-densified beech wood was 9,800 MPa.

Erdil *et al*. (2009) investigated 11-layer beech laminated wood glued with PVAc glue. They observed an average value of the modulus of elasticity of 10,647 MPa.

The highest modulus of elasticity (9,200 MPa) was found for the N-D-N combination of aspen veneers. For three-layer aspen laminated wood, Gaff and Gašparík (2015) specify a value of 8,700 MPa. For a two-layer combination, the same authors specify a modulus of elasticity of 9,800 MPa. This value corresponds to our N-D combination. For three-layer non-densified aspen laminated wood, Shukla and Kamden (2008) reported a modulus of elasticity ranging from 7,900 to 8,370 MPa, which is comparable with our N-D-N combination.

Bending Strength

Table 4 shows the effects of the individual factors and their interaction on the bending strength. Based on the significance level P < 0.05, it is possible to conclude that the effect of each of the individual factors was statistically significant. However, the simultaneous effect of all factors was statistically insignificant.

Table 4. Influence of Individual Factors and their Interaction on Bending Strength

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	2163840	1	2163840	14722.49	0.000001
Combinations	7226	5	1445	9.83	0.000001
Wood species	37922	1	37922	258.02	0.000001
Loading Cycles	75526	3	25175	171.29	0.000001
Combinations * Wood species * Loading Cycles	3396	15	226	1.54	0.090278
Error	42329	288	147		

As shown in Fig. 9, the highest bending strength was found for the D-N combination. The lowest bending strength was reached with the N-D-N combination. The increasing of number of densified veneers in the composition did not provide a clear improvement in bending strength.

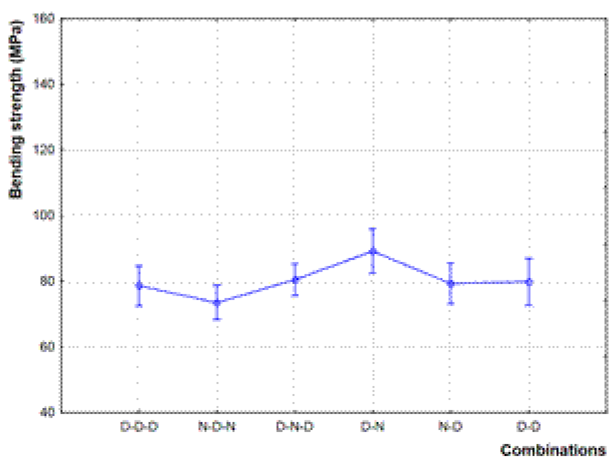

Fig. 9. Influence of veneer combinations on bending strength

Figure 10 shows that the beech wood reached the highest values of the bending strength. The highest value of bending strength for beech wood was 90 MPa, which is approximately 32% higher than aspen wood. Higher values for beech wood were probably caused by its higher density.

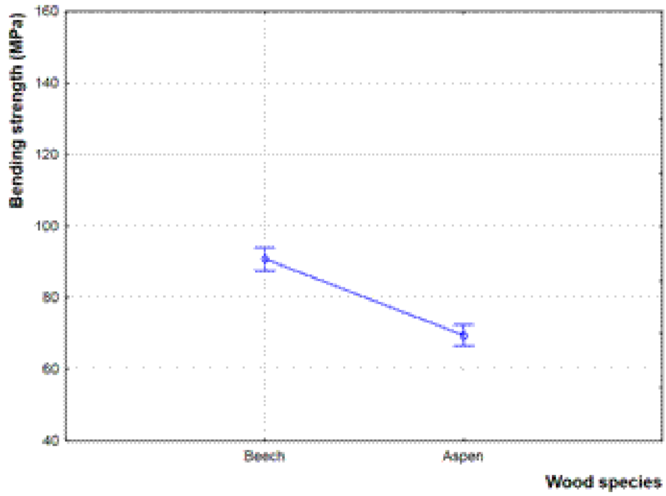

Fig. 10. Influence of wood species on bending strength

Figure 11 shows the effect of number of cycles on the bending strength. The highest bending strength of 106 MPa was found for non-loaded wood. Then, the bending strength dropped to its lowest value at 1000 cycles. Further, a very slight gradually increase occurred from 3000 to 7000 cycles.

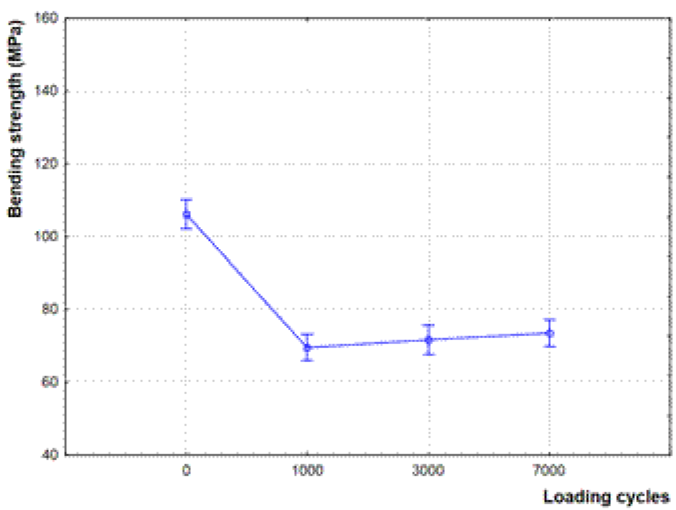

Fig. 11. Influence of number of loading cycles on bending strength

In Fig. 12, the simultaneous influence of all factors is shown. Generally, the bending strength of beech wood was significantly higher than aspen wood. D-N combination had the greatest values of the bending strength for both wood species. The lowest bending strength of beech wood was found for the D-D-D combination, while N-D-N combination reached the lowest bending strength of aspen wood. The highest values of the bending strength for both wood species were found with non-loaded samples.

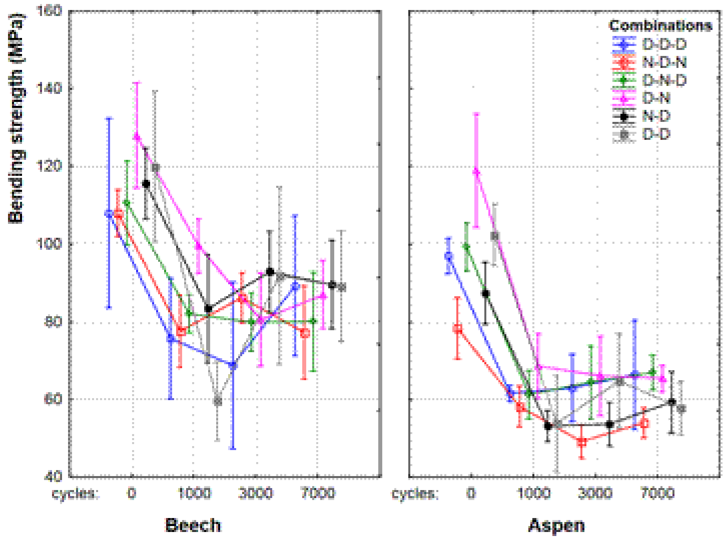

Fig. 12. Influence of combination of wood species and number of load cycles on bending strength values

The highest bending strength, 106 MPa for beech, was reached with the combination N-D-N. Erdil *et al.* (2009) investigated 11-layer beech laminated wood glued with PVaC-based glue. They reported an average bending strength value of 97.59 MPa. For a two-layer non-densified combination of beech laminated wood, Gaff *et al*. (2014) observed a bending strength of 152 MPa. This value was higher than the present result reached with the combination D-N. The lowest bending strength of aspen wood, *i.e*. 78 MPa, was found for the N-D-N combination. Erdil *et al*. (2009) found a bending strength of 72.47 MPa for black poplar (*Populus nigra* L.). No clear effect of densified veneers could be explained by the cold rolling densification method. Cold rolling densification is simple and fast method mostly used for solid wood. However, thin-layer wood material can be affected considerably because of the creation of small cracks on the surface.

CONCLUSIONS

1. The differences between two-layer and three-layer laminated beech wood were not substantial; however, three-layer laminated aspen wood exhibited higher moduli of elasticity than two-layer laminated wood. The difference of modulus of elasticity between cyclically loaded wood and non-loaded samples was not important. The number of loading cycles had not have a clear effect on modulus of elasticity. Significantly higher values of modulus of elasticity were found for beech than aspen.
2. For both wood species, the highest bending strength was observed for the non-loaded samples. The number of loading cycles had a negative influence on the bending strength for all combinations. Two-layer laminated wood exhibited the highest bending strength than three-layer laminated wood. Higher values of bending strength were found for beech wood than aspen wood. Position of densified veneers is more important that number of densified veneers in laminated wood composition. For

further research it may be better to use more suitable densification method for thin-layered laminated material, *e.g.* hot plate plasticizing, infrared radiation, or steaming.

ACKNOWLEDGMENTS

The authors are grateful for the support of Internal Grant Agency of the Faculty of Forestry and Wood Science; project B05/15 and also of the Ministry of Agriculture of the Czech Republic; project No. QJ1330233.

REFERENCES CITED

Aydin, I., Colak, S., Colakoglu, G., and Salih. E. (2004). "A comparative study on some physical and mechanical properties of laminated veneer lumber (LVL) produced from beech (*Fagus orientalis* L.) and eucalyptus (*Eucalyptus camaldulensis* Dehn.) veneers," *Holz als Roh- und Werkstoff* 62(3), 218-220. DOI: 10.1007/s00107-004-0464-3

Blomberg, J., and Persson, B. (2007). "Swelling pressure of semi-isostatically densified wood under different mechanical restraints," *Wood Science and Technology* 41(5), 401-415. DOI: 10.1007/s00226-006-0118-1

Blomberg, J., Persson, B., and Blomberg, A. (2005). "Effects of semi-isostatic densification of wood on the variation in strength properties in density," *Wood Science and Technology* 39(5), 339-350. DOI: 10.1007/s00226-005-0290-8

Bomba, J., Cvach, J., Šedivka, P., and Kvietková, M. (2014). "Strength increase pattern in joints bonded with PVAc adhesives," *BioResources* 9(1), 1027-1037. DOI: 10.15376/biores.9.1.1027-1037.

EN 310 (1993). "Wood-based panels – Determination of modulus of elasticity in bending and of bending strength," *European Committee for Standardization*, Brussels, Belgium.

Erdil, Y. Z. , Kasal, A., Zhang, J. L., Efe, H., and Dizel, T. (2009). "Comparison of mechanical properties of solid wood and laminated veneer lumber fabricated from Turkish beech, Scotch pine, and Lombardy poplar," *Forest Products Journal* 59(6), 55-60.

Gaff, M., and Gáborík, J. (2014). "Effect of cyclic loading on the elasticity of beech solid and laminated wood," *BioResources* 9(3), 4288-4296. DOI: 10.15376/biores.9.3.4288-4296.

Gaff, M., Gašparík, M., and Barcík, Š. (2014). "The influence of cyclic loading on ultimate bending strength of beech solid and laminated wood," *Drvna Industrija* 65(3), 197-203. DOI: 10.5552/drind.2014.1336

Gašparík, M., and Gaff, M. (2015). "The influence of densification on bending strength of beech wood," *Wood Research* 60(2), 211-218.

Gaff, M., and Gašparík, M. (2015). "Effect of cyclic loading on modulus of elasticity of aspen wood," *BioResources* 10(1), 290-298. DOI: 10.15376/biores.10.1.290-298.

ISO 13061-1 (2014). "Wood – Determination of moisture content for physical and mechanical tests," International Organization for Standardization, Geneva, Switzerland.

ISO 13061-2 (2014). “Wood – Determination of density for physical and mechanical tests,” International Organization for Standardization, Geneva, Switzerland.

ISO 13061-3 (2014). “Physical and mechanical properties of wood. Test methods for small clear wood specimens. Part 3: Determination of ultimate strength in static bending,” International Organization for Standardization, Geneva, Switzerland.

ISO 13061-4 (2014). “Physical and mechanical properties of wood -- Test methods for small clear wood specimens -- Part 4: Determination of modulus of elasticity in static bending,” International Organization for Standardization, Geneva, Switzerland.

Kamke, F. A. (2006). “Densified radiate pine for structural composites,” *Maderas. Ciencia y Tecnología* 8(2), 83-92. DOI: 10.4067/S0718-221X2006000200002

Kurjatko, S., Čunderlík, I., Dananajová, J., Dibdiaková, J., Dudas, J., Gáborík, J., Gaff, M., Hrčka, R., Hudec, J., Kačík, F., Kúdela, J., Lagaňa, R., Laurová, M., Mamoň, M., Mišíková, O., Račko, V., Rohanová, A., and Solár, R. (2010). “Parametre kvality dreva určujúce jeho finálne použitie [Wood quality parameters determining its end use],” *Monograph*, Technical University in Zvolen, Slovakia, 352 pp.

Laine, K., Rautkari, L., Hughes, M., and Kutnar, A. (2013). “Reducing the set-recovery of surface densified solid Scots pine wood by hydrothermal post-treatment,” *European Journal of Wood and Wood Products* 71(1), 17-23. DOI: 10.1007/s00107-012-0647-2

Mitani, A., and Barboutis, I. (2010). “Shear strength by compression loading of some hardwoods glued with PVAc and casein adhesives,” *First Serbian Forestry Congress*, Belgrade University, Faculty of Forestry, Serbia, 11-13 November 2010, 1352-1360.

Ozarska, B. (1999). “A review of the utilization of hardwoods for LVL,” *Wood Science and Technology* 33(4), 341-351. DOI: 10.1007/s002260050120.

Sedliačik, J. (2005). *Procesy Lepenia Dreva, Plastov a Kovov [Bonding Processes for Wood, Plastics and Metals]*, Technical University in Zvolen, Slovakia.

Shukla, S. R., and Kamdem, D. P. (2008). “Properties of laminated veneer lumber (LVL) made with low density hardwood species: Effect of the pressure duration,” *Holz als Roh- und Werkstoff* 66(2), 119-127. DOI: 10.1007/s00107-007-0209-1

Uysal, B., and Kurt, S. (2006). “Combustion properties of laminated veneer lumbers bonded with PVAc, PF adhesives and impregnated with some chemicals,” *Doguş Universitesi Dergisi* 7(1), 112-126.

Article submitted: September 3, 2015; Peer review completed: October 10, 2015; Revised version received: October 13, 2015; Accepted: October 14, 2015; Published: November 2, 2015.
DOI: 10.15376/biores.10.4.8461-8473