Adhesive as a Factor Affecting the Properties of Laminated Wood

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This study focuses on changing wood's bending properties using several types of adhesives. The strength, flexibility, and durability (service life) of laminated wood, glued with four types of adhesives, were examined. The results were compared with solid beech wood, conditioned to 9% moisture content. Depending on the adhesive used, the results indicate that laminated (layered) wood improved the strength and bending characteristics in comparison to the intact wood. Gained knowledge about materials properties have practical applications in the area of dynamic stress (*e.g.*, as components of vibrating machinery mechanisms or in constructing beds, chairs, and sports equipment).

Keywords: Beech; Solid wood; Laminated wood; Lamination; MOR; Cyclic bending; Bendability coefficient; Minimum bend radius

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INTRODUCTION

People have long favored wood on account of its technical and aesthetic properties. Wood has many beneficial mechanical properties, which are utilized in a broad range of products. In certain cases, its properties need to be modified to better suit a product's specific requirements. One modification possibility is the production of layered (laminated) wood with better strength or bending properties. Laminating is a technique that substantially improves the value of the wood material while enabling changes in the wood's properties. The characteristics of laminated wood can be altered in various ways.

From an environmental perspective, wood is a clean and renewable material held in high regard for its usefulness to society. Wood has had a place in people's lives since ancient times, and it continues to be a widely utilized material. Wood is a strong, elastic, and light material that can bear heavy burdens. Additonally, it is easy to process and can be joined, allowing for added versatility. Untreated wood's low flexibility and the related problems regarding shaping (especially in larger dimensions) are factors motivating the development and application of lamination (Aydin *et al.* 2004). Laminated wood comprises multiple layers of wood, most frequently in the form of veneers (thin slices), glued and pressed together, as shown in Fig. 1. A material's stratification is very important in industrial practice, both in civil engineering and the wood processing industry (Dubovský *et al.* 1998; Glos *et al.* 2004; Frese and Blaß 2006).

In the wood processing industry, material stratification provides greater homogenity, thereby reducing the portion of critical areas that cause damage to the material when under stress. This process also allows for the utilization of lower-rated wood species in the middle layers of the material, with more valued wood species (or those with better mechanical properties) in the outer layers (Gáborík and Dudas 2008; Gaff and Zemiar 2008). Laminated wood can be modified by altering the properties of the individual layers of the structure according to the required purpose (Gaff and Gašparík 2013). This results in a product that can maintain untreated wood's positive properties while suppressing its negative properties (Zemiar *et al.* 2000).

Lamination should be viewed as a technique that substantially improves the value of wood material (Zemiar and Gáborík 1997). Laminated wood is especially utilized in manufacturing chairs and beds. Laminated wood's properties are affected primarily by the type of wood and its subsequent physical and mechanical properties (Gaff and Gáborík 2014). The material is also affected by the type of adhesive and technology used (Sviták *et al*. 2014). The present study focused on the adhesive's effect on selected properties of laminated wood while comparing laminated wood's bending properties with those of solid wood. Almost all types of adhesives are used to produce laminated wood. Gluing mixtures (adhesives) used to produce laminated wood must form strong and elastic bonds between the individual layers (Konnerth *et al*. 2006).

EXPERIMENTAL

Materials and Characterization

Based on the study's defined objective, one batch of samples was prepared from solid wood and four batches were prepared from laminated wood, consisting of five layers or slats. Layers of veneers were glued together with the parallel orientation for each layer. The tests utilized beech wood (*Fagus sylvatica* L.) and veneers by peeling. Each individual layer was composed of beech veneer, each 2 mm thick (Fig. 1). The experiment used four types of adhesive. Diakol F, (Diakol Strážske, Ltd., Slovakia) was selected to represent urea–formaldehyde adhesives and Duvilax LS-50 (Diakol Strážske, Ltd., Slovakia) represented polyvinyl acetate adhesives. A mixture of the two adhesives was also employed, to combine their favorable properties. The ratio of these adhesives (Diakol F:Duvilax LS-50) in the mixture was 4:1. The ratio was determined on the basis of our preliminary experimental works. The fourth batch was composed of laminated wood glued with JOWAPUR 687.40 (Diakol Strážske, Ltd., Slovakia) polyurethane adhesive. The adhesive was layered on one side at 180 g/m^2. There were five veneer layers per laminated batch. In our concept we investigated laminated venner lumber LVL, which are layered in parallel orientation (Fig. 1).

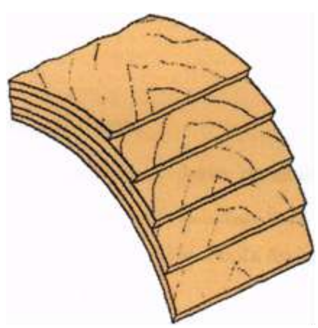

Fig. 1. Laminated sample preparation

Wood was pressed cold at a pressure of 1.2 MPa for a duration of 40 min. Adhesive was applied at 150 to 200 g/m^2. After the wood was removed from the press, it was stabilized for 24 h in a compressed state using a manual press (0.8 MPa). After stabilization, the wood was divided into samples for individual tests according to the diagram in Fig. 2. Samples for static bending measured 45 × 250 x 10 mm (width × length x thickness) (10 pieces), samples for the durability test of dynamic bending measured 45 × 600 x 10 mm (width × length x thickness), (10 pieces), and samples for determining adhesiveness had dimensions of 20 × 150 x 10 mm (width × length x thickness) (10 pieces).

The samples were conditioned to 12% moisture. To achieve the required moisture level, the test samples were placed in a heating chamber APT Line II (Binder, Germany), at the following conditions: relative humidity (ϕ) = 65 ± 3% and temperature (t) = 20 ± 2 °C. Moisture content verification was carried out in accordance with ISO 13061-1 (2014).

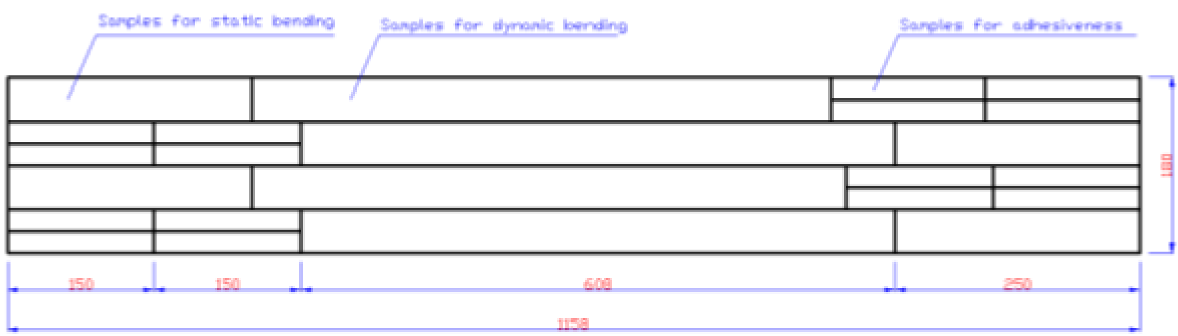

Fig. 2. Distribution of samples from pressed wood

Methods

The samples were bent by the three-point bending principle. Bending was carried out in a FPZ 100/1 testing loading machine (HECKERT, Germany) according to EN 310 (1993); the machine contained a special jig for flexural tests and an ALMEMO 2690-8 data logger (AHLBORN, Germany) for recording the loading forces and maximum deflection.

The adhesiveness test measured the quality of the gluing process. The testing of adhesives' effects on laminated wood's properties focused on the bending properties during static bending as well as cyclic (dynamic) stress. Bending strength (MOR) and modulus of elasticty (MOE) characteristics of layered beech wood were determined through testing at a bend using a single axis of stress (Fig. 3).

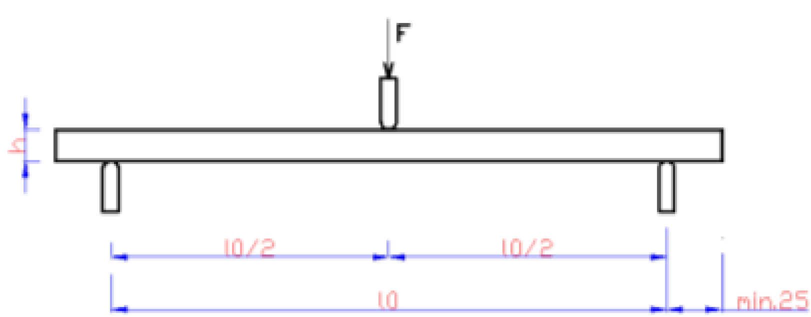

Fig. 3. Stress method for static bending; l_0 is distance between supports ($l_0 = 20 \times h$) (mm), l is sample length (mm), and h is sample thickness (mm)

Measured values were used to calculate bending strength (σ_{bend}) according to Eq. 1, modulus of elasticity (E_m) according to Eq. 2, minimum bend radius (R_{min}) according to Eq. 3, and bendability coefficient (k_{bend}) according to Eq. 4.

Bending Strength (MOR)

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

$$\sigma_{bend} = \frac{3 \times F_{max} \times l_0}{2 \times b \times h^2} \quad \text{(MPa)} \tag{1}$$

where σ_{bend} 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).

Modulus of Elasticity (MOE)

The modulus of elasticity was calculated in accordance with EN 310 (1993) and Eq. 2,

$$E_m = \frac{l_1^3 (F_2 - F_1)}{4bh^3 (a_2 - a_1)} \quad \text{(MPa)} \tag{2}$$

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 ($F_2 - F_1$).

Minimum Bend Radius

The value of the minimum bend radius is given by,

$$R_{min} = \frac{l_0^2}{8 \times y_{max}} + \frac{y_{max}}{2} \quad \text{(mm),} \tag{3}$$

where y_{max} is the maximum bend (mm).

Bendability Coefficient

$$k_{bend} = \frac{h}{R_{min}} \tag{4}$$

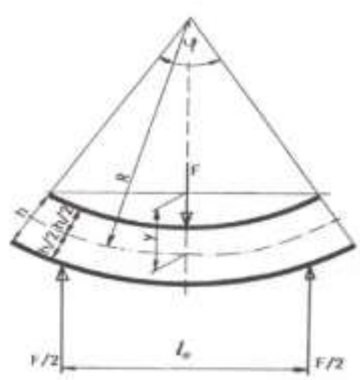

Fig. 4. Measuring the monitored variables in bend tests

The cyclic bend stress test also characterizes the examined materials' elasticity. Laminated wood was placed under repeated cyclical bending stress, increasing from zero to the selected maximum (Fig. 5). The cycle frequency was 22 cycles per min. For testing purposes and based on expected safety, it was decided to stress the laminated wood only up to 50% of the maximum bend, calculated according to Eq. 5,

$$y_{\mathrm{d}} = \frac{l_d^{\,2}}{8 \times R_{\mathrm{min}}} \tag{5}$$

where y_{d} is cyclic bend stress and l_d is the distance between supports in the cyclic test (490 mm).

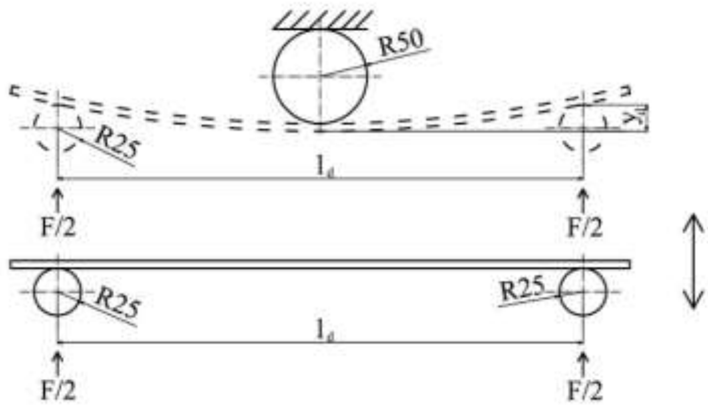

Fig. 5. Cyclic bending of slats

RESULTS AND DISCUSSION

The acquired results indicate that laminated (layered) wood had better bending characteristics than (solid) wood. The results indicate that the choice of adhesive substantially affected the laminated wood's overall strength properties (Table 1). Urea – (UF) adhesives are the most widely used in producing laminated wood for furniture because of their good strength properties and acceptable price.

MOR is a property monitored primarily for sizing cross-sections of materials used to construct products. Materials glued with UF and polyurethane (PUR) adhesives recorded higher strength values than solid wood. With the application of UF adhesive, the MOR was 4.6% higher than that of solid wood. For the PUR adhesive, the figure was 12% higher with σ_{bend} = 148.5 MPa (Table 1). The strength of beech wood varies depending on the origin of the wood, as well as the method of its determination. Požgaj *et al.* (1993) reported MOR of beech wood σ_{bend} = 124 MPa and MOE 12,966 MPa, similar to the MOR results of 117 MPa found by Gašparík and Barcík (2014). Dubovský (1998) reported σ_{bend} = 94 ± 18 MPa and Gáborík (1995) stated σ_{bend} = 77.6 MPa.

The results show that the greatest difference was in durability, where wood glued with UF adhesive recorded only one-quarter the durability of laminated wood glued with PUR adhesive.

Table 1. Bending Properties of Solid and Laminated Beech Wood

Properties		Solid beech wood (9% moisture)	Laminated wood (9% moisture)			
			Adhesive			
			UF	PVAc	Mixture (UF + PVAc)	PUR
MOR	σ_{bend} **(MPa)**	130.2 (9.8)	136.2 (8.7)	101.7 (6.4)	111.2 (7.1)	148.5 (4.8)
MOE	E_m **(MPa)**	11,654 (7.6)	13,060 (9.4)	10,102 (8.5)	11,709 (7.3)	14,268 (4.2)
Durability	**(number of cycles)**	-	9,923 (10.7)	16,882 (10.8)	13,394 (8.0)	40,136 (9.3)
Loading force	F_{max} **(N)**	1,284.2 (8.2)	1,721 (7.5)	1,351 (4.3)	1,446 (7.7)	2,035 (3.3)
Maximal deflection	y_{max} **(mm)**	13.3 (8.4)	9.9 (4.6)	10.7 (9.6)	8.75 (9.7)	13.0 (7.3)
Minimum bend radius	R_{min} **(mm)**	594 (9.2)	467.7 (5.7)	374.6 (4.3)	436.5 (10.9)	491.4 (9.8)
Bendability coefficient	k_{bend}	0.01684 (10.5)	0.0191 (6.3)	0.0240 (6.7)	0.0200 (7.2)	0.0203 (5.4)

Values in parentheses are coefficients of variation (CV) in %

Using a polyvinyl acetate (PVAc) dispersion adhesive or a mixed adhesive (UF + PVAC) when gluing laminated wood can increase the wood's flexibility and durability (service life), while decreasing its MOR and MOE. The MOR was 23% lower for the PVAc adhesive and 14.6% lower for the mixed adhesive than it was for solid wood. In comparison to PUR adhesive, the MOR was 31% and 25% lower, respectively (Fig. 6).

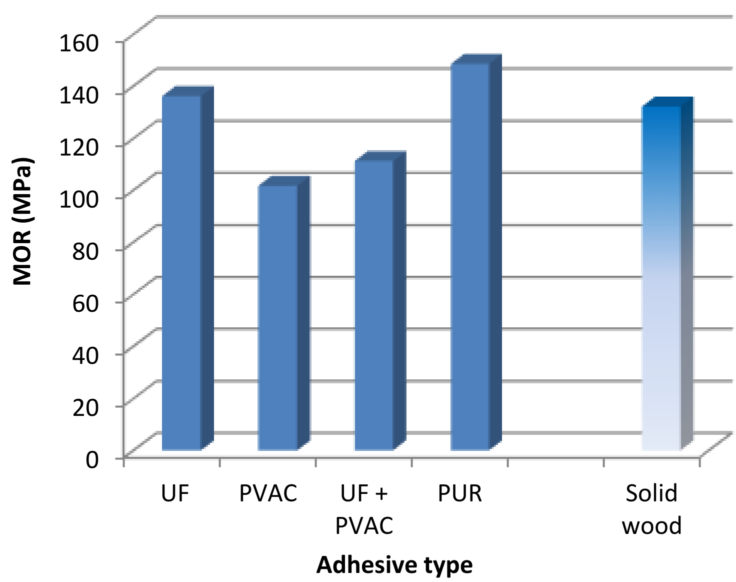

Fig. 6. MOR of solid and laminated beech wood

One may explain these findings based on the fact that PVAc glues hardened physically by evaporation of water. Such evaporative curing can be expeted to create “micro-dowell” connections. UF glues make hard but brittle joints. A suitable combination of UF and PVAc adhesives enables the modification of laminated wood’s properties. Specifically, increasing the proportion of UF adhesive increases the laminated wood’s MOR and MOE while decreasing flexibility and durability. In contrast, increasing the proportion of PVAc adhesive in a mixture produces the opposite changes for these properties.

Even changing the type of UF adhesive can produce a change in properties, as confirmed by the findings of Olekšák (1996), who used a different type of UF adhesive for a similar laminated wood composition and recorded higher MOR (σ_{bend} = 153 MPa) and modulus (E_m = 14,373 MPa) than the present study. The MOE expresses the material’s internal resistance to elastic deformation. As the modulus increases, increasing amounts of stress are required to induce deformation (Požgaj *et al*. 1993). The highest value was recorded by laminated wood glued with PUR adhesive, at E_m = 14,268 MPa, which was 22% higher than the solid wood. Similar results have also been obtained by Farkašovský (2010), with E_m = 14,560 MPa, and Pavlík (2009), with E_m = 15,494 MPa.

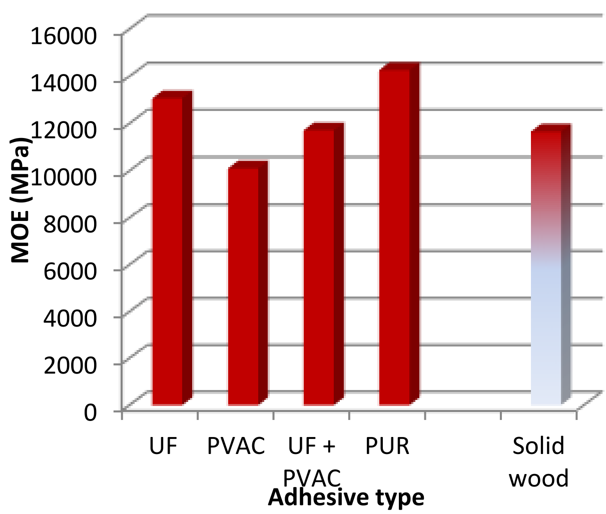

Fig. 7. MOE of solid and laminated beech wood

The bendability coefficient characterizes material in terms of how it is shaped by bending. As exhibited by the irregular shape of bentwood chairs, solid beech wood has high malleability. Laminated wood can be sufficiently shaped after it is glued. The present study recorded durability 13% to 43% higher than that for solid wood. The best malleability was demonstrated by laminated wood glued with PVAc adhesive. Dudas and Gáborík (2006) also recorded improved flexibility for laminated wood.

Durability was evaluated within this study *via* cyclic bend stress. The results showed laminated wood glued with PUR adhesive to have the highest values. Durability with PUR adhesive was four times higher than UF adhesive and 2.4× higher than PVAc adhesive (Table 1, Fig. 8). PUR glues were cured chemically by connection on the free OH groups of the wood, and create the best elastic joints, but UF glues make hard but brittle joints. Dynamic loading is not suitable for UF glues, because at the vibrations disrupt the brittle joints.

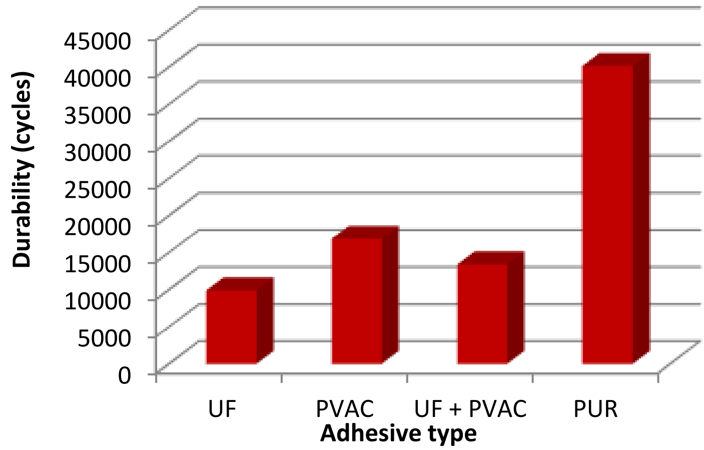

Fig. 8. Durability of laminated beech wood

CONCLUSIONS

1. Laminated wood's properties can be influenced through various means. By combining layers, for example, it is possible to create laminated wood with properties different than those of solid wood. This study focused on examining the effect of altering adhesives on the bending properties of laminated wood. Urea–formaldehyde adhesives create stronger but more brittle bonds, as was confirmed by the results. In this study, the MOR was 4.6% higher for wood glued with such an adhesive than it was for solid wood. In contrast, wood glued with a PVAc adhesive was more flexible than solid wood, as demonstrated by its higher bendability coefficients (43% higher) and high durability/service life (*i.e.*, cyclical bending of up to 16,882 cycles).
2. Suitable selection of adhesive or a combination of adhesives can enable changes to laminated wood's properties, thus creating a material (laminated wood) with specific required properties. The PUR adhesive substantially improved the monitored properties in comparison to both solid wood and laminated wood glued with UF and PVAc adhesives. In comparison to solid wood, the given compositions demonstrated improved strength (by 12% to 31%) and flexibility (by 18% to 43%). The specific adhesive type also affected the final properties as well.

ACKNOWLEDGMENTS

The authors are grateful for support of the University-Wide Internal Grant Agency (CIGA) of the Faculty of Forestry and Wood Science at Czech University of Life Sciences Prague, Project 4311-2016.

REFERENCES CITED

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

Dubovský, J., Babiak, M., and Čunderlík, I. (1998). *Textúra, Štruktúra a Úžitkové Vlastnosti Dreva* (*Texture, Structure and Utility Properties of Wood*), 3rd Ed., Technical University in Zvolen, Zvolen, Slovakia, pp. 106. (in Slovak)

Dudas, J., and Gáborík, J. (2006). "Ohybové charakteristiky lamelového dreva osiky [Bending characteristics of laminated aspen wood]," Zborník Prednášok z MVK – Technológie Spracovania Dreva, Technical University in Zvolen, pp. 63-68 (in Slovak).

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

Farkašovský, M. (2010). *Vybrané Vlastnosti Lamelového Dreva Buka a Breezy [Selected properties of laminated wood of beech and birch]*, M.S. thesis, Technical University in Zvolen, Slovakia (in Slovak).

Frese, M., and Blaß, H. J. (2006). "Characteristic bending strength of beech glulam," *Materials and Structures* 40(1), 3-13. DOI: 10.1617/s11527-006-9117-9

Gáborík, J. (1995). Skúmanie Vlastností Plastifikovaného a Komprimovaného Dreva z Hľadiska Možností Jeho Tvarovania [Examining the Properties of Plasticized and Compressed Wood in Terms of Shaping Possibilities], Ph.D. dissertation, Technical University in Zvolen, Slovakia (in Slovak).

Gáborík, J., and Dudas, J. (2008). "The bending properties of aspen wood (Ohybové vlastnosti osikového dreva)," Annals of Warsaw Agricultural University, Forestry and Wood Technology 65, 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. DOI10.15376/biores.9.3.4288-4296

Gaff, M., and Gašparík, M. (2013). "Shrinkage and stability of thermo-mechanically modified aspen wood," *BioResources* 8(1), 1136-1146. DOI: 10.15376/biores.8.1.1136-1146

Gaff, M., and Zemiar, J. (2008). "Vplyv vlhkosti dreva a ohrevu lisovacieho nástroja na tvarovú stabilitu a kvalitu nerovnomerne zlisovanej plochy osikového dreva," in: Trieskové a Beztrieskové Obrábanie Dreva 2008, Ladislav Dzurenda. Zvolen,

Gašparík, M. and Barcík, Š. (2014). "Effect of microwave heating on bending characteristics of beech wood," *BioResources* 9(3), 4808-4820. DOI: 10.15376/biores.9.3.4808-4820

Glos, P., Denzler, J. K., and Linsenmann, P. (2004). "Strength and stiffness behaviour of beech laminations for high strength glulam," Proceedings Meeting 37 CIB Working Commission W18-Timber Structures, paper CIB-W18/37-6-3.

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.

Konnerth, J., Wolfgang, G., Harm, M., and Muller, U. (2006). "Comparison dry strength of spruce and beech wood glued with different adhesives by means of scarf- and lap joints testing method," *Holz als Roh- und Werkstoff* 64, 269-271, Austria.

Olekšák, M. (1996). Mechanické Vlastnosti Lôžkových Lamiel [Mechanical Properties of Bed Slats], M.S. thesis, Technical University in Zvolen, Slovakia (in Slovak).

Pavlík, M. (2009). *Vybrané Vlastnosti Lamelového Bukového Dreva Lepeného Polyuretanovým Lepidlom [Selected properties of laminated beechwood bonded polyurethane adhesive]*, M.S. thesis, Technical University in Zvolen, Slovakia (in Slovak).

Požgaj, A., Chovanec, D., Kuriatko, S., and Babiak, M. (1993). Štruktúra a Vlastnosti Dreva. [Structure and Properties of Wood], Príroda, Bratislava (in Slovak).

Sviták, M., Gašparík, M. and Penc, J. (2014). "Heat resistance of glued finger joints in spruce wood constructions," *BioResources* 9(4), 7529-7541. DOI: 10.15376/biores.9.4.7529-7541

Zemiar, J., and Gáborík, J. (1997). "Generating of wood properties by the use of high frequency heating for the purpose of its shaping," in: Drewno material ekologiczny : ll. Konferencja naukowa Wydzialu Technologii Drewna SGGW. Warszawa: Wydzial Technologii Drewna SGGW, 1997, s. 309--314. ISBN 83-86980-88-5.

Zemiar, J., Gáborík, J., and Solár, M. (2000). "Vplyv vlhkostno-tepelných parametrov bukového dreva na jeho tvárniteľnosť pri ohýbaní [The influence of moisture and thermal parameters of beech wood upon its molding at bending]," *Vybrané Procesy pri Spracovaní Dreva*, Technical University in Zvolen, Slovakia, pp. 43-47 (in Slovak).

Article submitted: June 2, 2015; Peer review completed: August 30, 2016; Revised version received and accepted: October 26, 2016; Published: November 1, 2016.
DOI: 10.15376/biores.11.4.10565-10574