Shear Bond Strength of Two-Layered Hardwood Strips Bonded with Polyvinyl Acetate and Polyurethane Adhesives

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This article deals with the effects of various parameters on the shear bond strength (SBS) of glued wood. A four-factor analysis showed that the combination of only non-densified wood pieces achieves higher shear bond strength values than densified ones. In this case, only the piece combination was a significant factor. The other factors (glue type, wood species, and number of loading cycles) had no significant effect. Although the differences were not large, a higher SBS was achieved in beech wood glued with polyvinyl acetate (PVAc) glue. Glued wood consisting of the combination of densified and non-densified pieces had slightly lower SBS values. In this case, all the factors were statistically significant. Beech wood had a more significant impact on the SBS than aspen wood. The effect of the type of glue showed an opposite trend than that in the previous variant, *i.e.*, a higher SBS was achieved with polyurethane (PUR) glue. Wood subjected to cyclic loading had slightly higher SBS values than non-cyclically loaded wood. The degree of densification had no significant effect. Glued wood composed entirely of densified pieces showed greater SBS variation between versions.

Keywords: Shear bond strength; Beech; Aspen; Densification; PVAc; PUR; Cyclic loading

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INTRODUCTION

Although wood is an exceptional material, people are still trying to improve its desirable properties and eliminate its shortcomings. This is why new materials are created either by modifying the properties of the wood, or by combining wood materials of different properties. The mentioned combination of materials creates widespread wood-based composites that are applied in the most common spheres of the timber industry, such as in the production of furniture and wooden buildings (Stoeckel *et al*. 2013).

Wood-based composites are one of the core materials in the woodworking industry. In general, wood-based composites are formed by layering wood materials (plies, strips, veneers, strands, pieces, fibres, *etc*.) (Cai and Ross 2010) and then pressing the material to a final shape with the desired properties. In the construction industry, where these types of composites are most commonly applied, they are divided into two subgroups: structural composite lumber materials (LVL, PSL, LSL, OSL, glulam), and other materials (OSB, fibreboard, plywood, particleboard). Structural composite lumber materials are used for load-bearing elements in buildings and structures, such as rafters, headers, beams, joists, studs, and columns (Stark *et al.* 2010). Other materials are used for non-load bearing applications, such as tiling, floors, formwork, and thermal and sound insulating layers. In the furniture industry, wood-based composites are used a little differently. Structural composite lumber is not used at all, but some principles of its formation are used in other elements (*e.g.*, LVL and bed piece component). Most materials that are intended for non-load bearing use in construction are used to manufacture load-bearing elements in the furniture industry, with the exception of OSB (not used at all) and fiberboards.

Gluing wood is one of the basic methods of bonding wood, known since ancient times. In terms of gluing wood, both the bonding strength and the properties of the glue are important. These characteristics are affected by the gluing conditions (open time, curing method, moisture content of wood, and necessary ambient temperature), as well as the length of the entire production process and the strength of the final product. Today, the most widely used adhesives in the furniture and construction industries are polyvinyl acetate (PVAc) and polyurethane (PUR), which are both defined as elastic polymers (Stoeckel *et al*. 2013). PVAc glues (most often dispersed in the form of an emulsion) are thermoplastics characterized by the need for an absorbent surface, and their glass-transition temperature (T_g) is close to room temperature (Motohashi *et al*. 1984; Minelga *et al*. 2010). Their mechanical properties are closely linked to changes in temperature, which is why even the slightest change in their T_g affects their mechanical properties under specified usage conditions (Motohashi *et al*. 1984). The advantage of PVAc glue is its water solubility, low curing temperature, non-toxic composition, transparent adhesive joints, and its ease of use. PUR glues are thermoplastics most often cured using the wood's moisture content, which reacts with the glue's isocyanate groups (Ren and Frazier 2012). PUR glue for wood creates strong joints with good flexibility, cures at a normal ambient temperature, and is more water resistant than PVAc glue, but it requires a higher moisture content of the glued material or air (Vick and Okkonen 1998).

The bonding quality of glued wood-based composites is affected by various factors. First of all, there are the basic physical and structural properties of the adherent wood, such as moisture content, density, porosity, properties of the cell wall, lumen, and extracellular spaces, which can sometimes change when the wood is modified (impregnation, grinding, and surface treatment). Another group of factors are the properties of the glue in its application (*e.g.*, penetration behavior and surface free energy) and curing (*e.g.*, creep and stiffness) states (Follrich *et al*. 2007; Li *et al*. 2015). Finally, the gluing parameters (adhesive spread, pressing time and temperature, and applied pressure) determine the final properties of the glue and therefore the entire glued wood-based composite (Follrich *et al*. 2007).

The suitability of an adhesive for bonding wood under certain conditions can be determined by various characteristics. The most commonly used reference parameter for the bond strength of the glued wood is its shear bond strength (Serrano 2004; Burdurlu *et al*. 2006; Konnerth *et al*. 2006; Raftery *et al*. 2009; Derikvand *et al*. 2014). The bond strength is the ability of the bonded wood to hold the wood-based composite elements together, ensuring its overall strength. If the bond has a low strength, then the wood-adhesive interface fails; the elements stop sharing the load and the entire composite will have poor characteristics (Le and Nairn 2014).

This research focuses on examining the shear bond strength of beech and aspen wood consisting of pieces bonded with PVAc and PUR adhesives. The main goal was to determine the effects of wood densification, combination of pieces, wood species, and number of cycles on the shear bond strength values.

EXPERIMENTAL

Materials

European beech (*Fagus sylvatica* L.) and European aspen (*Populus tremula* L.) woods were used for testing. Thin wood pieces of three thicknesses (3, 5, and 9 mm), 25 mm in width and 600 mm in length were produced. These pieces were conditioned to an equilibrium moisture content (EMC) of 8% (ϕ = 40 ± 3% and t = 20 ± 2 °C). The EMC represented the final moisture content of furniture and wooden joinery (flooring and cladding) for interior use, according to EN 942 (2007) and ČSN 91 0001 (2007). The pieces of both wood species were divided into two groups: the first group consisted of non-densified pieces, and the second group consisted of pieces designed for densification.

Densification

Pieces intended for densifying were cold-pressed in a UPS 1000 hydraulic press (RK MFL Prüfsysteme GmbH, Germany) without previous plasticizing. The press was closed for 5 min, and gradual densification of the pieces began. The pieces were kept densified for 2 min. In the last stage, which lasted 3 min, the press was opened and the pressure was released. Subsequently, the pieces relaxed for 5 min.

Table 1 shows all the individual densities of the non-densified and densified pieces for each combination.

Table 1. Average Density Values of Pieces at Moisture Content of 12%

			Density (kg/m^3)		
	Pieces Combination	**Wood Species**	Before Densification (original)	After Densification by 10%	After Densification by 20%
I. group	Non-densified + Non densified	Beech N	679	-	-
		Aspen N	451	-	-
II. group	Densified + Densified	Beech D	704	734	766
		Aspen D	471	503	508
	Non-densified + Densified	Beech N	715	-	-
		Aspen N	505	-	-
		Beech 10% D	703	745	-
		Beech 20% D	702	-	769
		Aspen 10% D	474	490	-
		Aspen 20% D	473	-	514

N – non-densified, D – densified pieces

Sample preparation

The one-component dispersion water-proof polyvinyl acetate (PVAc) adhesive AG-Coll 8761/L D3 (Agglu SK Ltd., Slovakia) and moisture-curing one-component polyurethane (PUR) adhesive Neopur 2238R (Neoflex S.L., Spain) were used for the gluing of pieces. According to EN 204 (2001) these PVAc and PUR adhesives belong to durability classes D3 and D4, respectively. The adhesive properties are shown in Table 2.

Table 2. Adhesives Properties

Glue Type	**Dry Matter Content** (%)	**Viscosity** (mPas)	**Density** (g/m^3)	**pH**	**Working Time** (min)	**Pressing Force at 20 °C** (MPa)	**Wood Moisture Content** (%)
PVAc	49-51	7,000-13,000	0.9-1.1	3.8-4.5	15	0.2-0.8	8-12
PUR	-	2,000-4,000	1.13	-	20-25	-	6-12

A toothed spatula was used for the glue application, laying a thin film of glue at the recommended level of 160 g/m^2. The samples were pressed in an industrial press GS 6/90 (SCM GROUP S.p.A., Italy) under 0.6 MPa at a temperature 20 °C during 20 min. Subsequently, the samples were conditioned in the humidity chamber HCP 108 (Memmert, Germany) to a moisture content of 8% (ϕ = 40 ± 3% and t = 20 ± 2 °C). Lastly, the 2-layered samples were cut to final dimensions of 600 × 35 × h mm^3 (thickness was dependent on the combination of pieces).

Table 3 shows samples with various combinations of pieces. One group consisted of 120 glued samples made of non-densified pieces and the second group consisted of 480 glued samples created by various combinations of densified and non-densified pieces. One half of the samples were intended for cyclic loading testing.

Table 3. Marking and Parameters of Samples

Sample Marking	**Description**
3NN	The sample includes a pair of non-densified pieces with thickness 3 mm
5NN	The sample includes a pair of non-densified pieces with thickness 5 mm
9NN	The sample includes a pair of non-densified pieces with thickness 9 mm
3DD10	The sample includes a pair of pieces, after densification by 10%, with thickness 2.7 mm
3DD20	The sample includes a pair of pieces, after densification by 20%, with thickness 2.4 mm
5DD10	The sample includes a pair of pieces, after densification by 10%, with thickness 4.5 mm
5DD20	The sample includes a pair of pieces, after densification by 20%, with thickness 4 mm
9DD10	The sample includes a pair of pieces, after densification by 10%, with thickness 8.1 mm
9DD20	The sample includes a pair of pieces, after densification by 20%, with thickness 7.2 mm
3ND10	The sample includes a non-densified (3 mm) piece and piece densified by 10% (2.7 mm)
3ND20	The sample includes a non-densified (3 mm) piece and piece densified by 20% (2.4 mm)
5ND10	The sample includes a non-densified (5 mm) piece and piece densified by 10% (4.5 mm)
5ND20	The sample includes a non-densified (5 mm) piece and piece densified by 20% (4 mm)
9ND10	The sample includes a non-densified (9 mm) piece and piece densified by 10% (8.1 mm)
9ND20	The sample includes a non-densified (9 mm) piece and piece densified by 20% (7.2 mm)

3, 5, and 9 are the original thicknesses of the pieces in millimeters
N – non-densified pieces, D – densified pieces

Cyclic loading

At least 24 h after bonding, cyclic loading was carried out. Cyclic loading testing, based on uniaxial bending stress, was carried out using a cycling machine (designed by Milan Gaff at the Faculty of Forestry and Wood Sciences, CULS Prague) with a distance between supporting pins of 490 mm. Cyclic loading was based on bending loading with repetitive loading and releasing. The cyclic loading rate was 60 cycles/min. Maximum load was set to 90% of the limit of proportionality. The limit of proportionality was found during the preliminary tests. Its value is important for avoiding the sample overloading during the cyclic loading. Therefore, the loading value was set up to 90% of the proportionality limit. Subsequently, the samples underwent 10,000 cycles and were compared with non-cyclic loaded samples (0 cycles).

Many of glued furniture parts are loaded cyclically during their use (*e.g*. lamellar grid of chairs and bed furniture). Therefore, the impact of cyclic loading should be examined for glued wood designed for such furniture components.

Shear bond strength

After cyclic loading, the clear samples were cut to 110 × 25 × h mm^3 (sample thickness according to Table 3) and were conditioned to an equilibrium moisture content (EMC) of 12% (ϕ = 65 ± 3% and t = 20 ± 2 °C). The shear bond strength (SBS) was represented by tensile-shear strength using a lap joint test according to EN 205 (2003) (Fig. 1). Tensile-shear strength was determined using the universal testing machine UTS 50 (TIRA, Germany). The constant loading speed was set to 5 ± 0.5 mm/min such that the time required to reach failure was between 30 s and 50 s. Maximum loading force was directly recorded into the computer software.

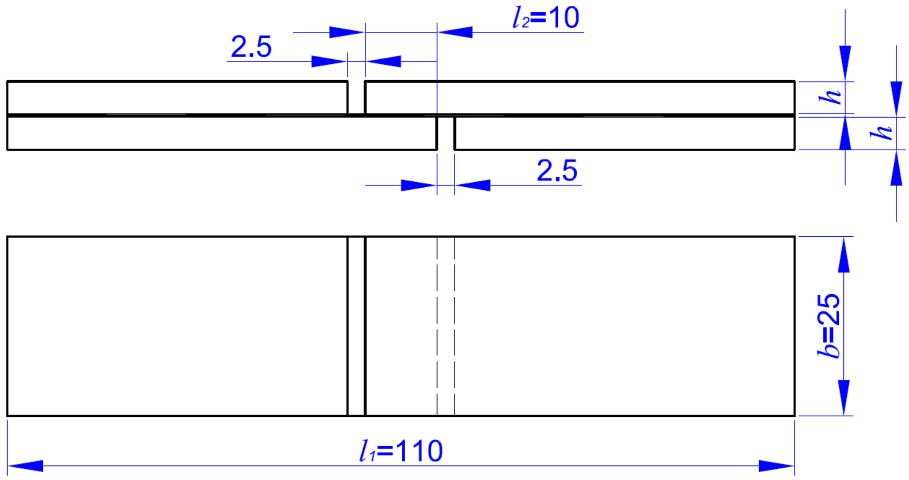

Fig. 1. Testing sample dimensions
Note: l_1 – sample length (mm), l_2 – shear area length (mm), b – sample width/shear area width (mm), h – piece thickness (mm).

Evaluation and Calculation

The shear bond strength values were evaluated using MANOVA, specifically utilizing Fisher's F-test in STATISTICA 13 software (Statsoft Inc., Tulsa, Oklahoma, USA). The results were evaluated using a 95% confidence interval, which reflects a probability of 0.05 (P < 0.05).

The tensile-shear strength was calculated according to EN 205 (2003) and Eq. 1:

$$\tau = \frac{F_{max}}{l_2 . b} \tag{1}$$

where τ is the tensile-shear strength parallel to the fibers (MPa), F_{max} is the maximum loading force recorded at the breaking point (N), l_2 is the length of the shear area (mm), and b is the width of the shear area/sample (mm).

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

$$\rho_w = \frac{m_w}{V_w} \tag{2}$$

where ρ_w is the density of the sample at moisture content w (kg/m^3), m_w is the weight of the sample at moisture content w (kg), and V_w is the volume of the sample at moisture content w (m^3).

The moisture content of the samples was determined according to ISO 13061-1 (2014) and Eq. 3,

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

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

RESULTS AND DISCUSSION

Combination of Non-Densified Pieces

Table 4 presents a statistical evaluation of the influence of factors on the shear bond strength of the samples with non-densified piece combination. Only the piece combination was statistically significant ($P < 0.04$). The wood species, glue type, number of cycles, as well as the interaction of all factors, did not significantly influence the shear bond strength.

Table 4. Statistical Evaluation of the Shear Bond Strength for Combinations of Non-densified Pieces

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F - test	*p*-value
Intercept	15,974.13	1	15,974.13	1,117.206	0.001
Wood species (1)	24.20	1	24.20	1.692	0.196
Glue type (2)	1.04	1	1.04	0.073	0.788
Piece combination (3)	165.70	2	82.85	5.794	0.004
Number of cycles (4)	0.42	1	0.42	0.029	0.865
1*2*3*4	43.23	2	21.61	1.512	0.226
Error	1,372.64	96	14.30		

The mean shear bond strength value for beech wood (12 MPa) was approximately 8.1% higher than that of aspen (11.1 MPa; Fig. 2). The differences in shear bond strength values between the different wood species were probably caused by the different anatomical structures (length of wood fibers, porosity, water absorption, and surface roughness), which affect the adhesion of the glue to the surface of the wood pieces.

Fig. 2. Influence of wood species on tensile-shear strength

Shear bond strength also depends on the type of adhesive used. It is generally believed that PUR adhesives achieve slightly higher strength values. In this research, no significant differences between PUR and PVAc were observed. However, the shear bond strength found using PVAc glue was 1.7% higher than that with PUR glue (Fig. 3), which is the opposite of the general assumption.

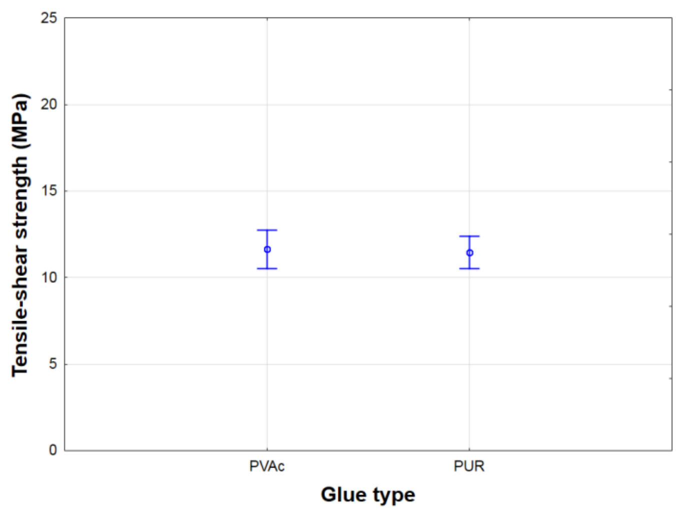

Fig. 3. Influence of glue type on tensile-shear strength

The effect of piece combinations proved to be the only statistically significant factor. Although the area for finding the shear bond strength was the same for all combinations (10 × 25 mm), the thickness of individual pieces changed, which also changed the overall thickness of the samples. The shear bond strength values increased with the increase in sample thickness (Fig. 4).

While the samples composed of 3 mm pieces achieved shear bond strength of 9.9 MPA, the samples composed of 5 mm pieces achieved shear bond strength of 11.9 MPa. The highest value of shear bond strength, 12.6 MPa, was found in the samples composed of 9 mm pieces.

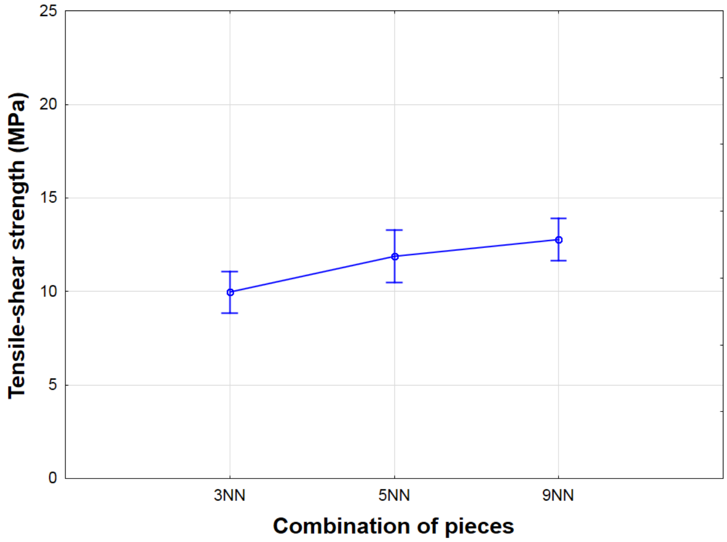

Fig. 4. Influence of pieces combination on tensile-shear strength

Cyclic loading had almost no effect on the shear bond strength. The shear bond strength in the samples without cyclic loading were slightly higher, but only by 1.1%, in comparison to the cyclically-loaded samples (Fig. 5). Both adhesives created a sufficiently flexible bond that could withstand cyclic loading, and the bonded sample therefore remained intact.

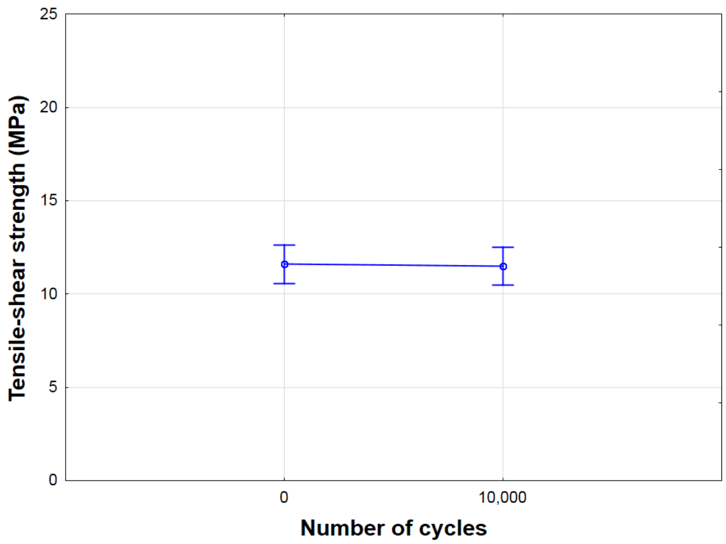

Fig. 5. Influence of number of loading cycles on tensile-shear strength

Figure 6 shows the combined effect of piece combination, glue type, and wood species on the samples without cyclic loading. The shear bond strength is only clear in one case: in beech pieces bonded by PVAc glue. In this case, the shear bond strength increased in proportion to the increase in the thickness of the pieces, or samples. Other cases did not confirm this relationship. It can be concluded that slightly higher shear bond strength values were achieved with PVAc glue.

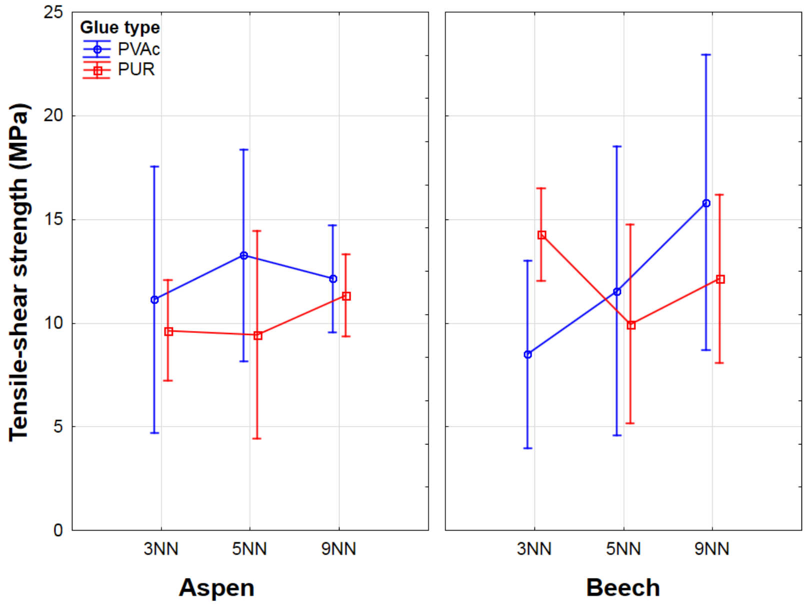

Fig. 6. Influence of piece combination, glue type, and wood species on the tensile-shear strength without cyclic loading

The combined effect of piece combination, glue type, wood species, and cyclic loading had a different character than that in the case of wood without cyclic loading (Fig. 7). This case is characterized by a distinctive trend in the shear bond strength dependency on the piece combination.

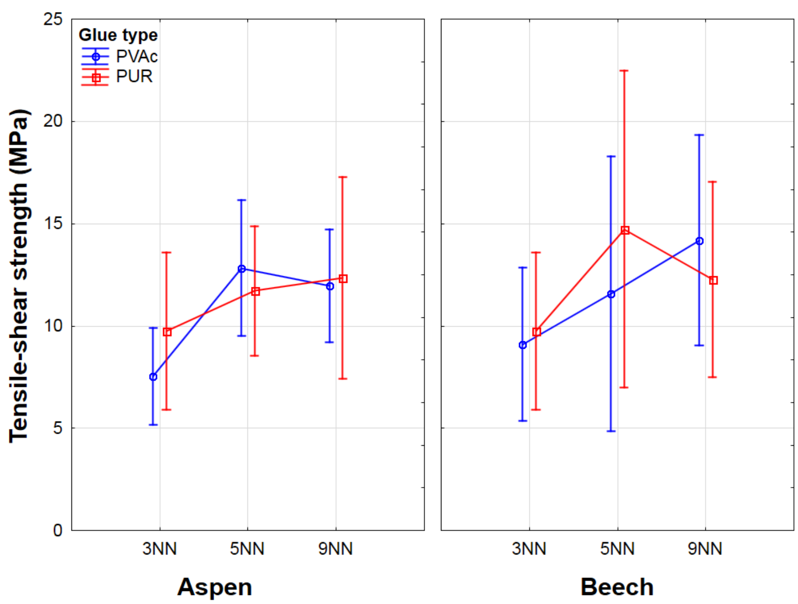

Fig. 7. Influence of piece combination, glue type, and wood species on the tensile-shear strength after cyclic loading by 10,000 cycles

Large differences between different wood species were also found, where higher shear bond strength was measured in beech wood samples. The influence of the glue type exhibited smaller differences than in the previous case.

Comparing these results with other studies, it is clear that the SBS values are similar in most cases (Table 5).

For example, Konnerth *et al*. (2006) reported an SBS value in laminated beech wood of 10.8 MPa using PVAc glue, and 9.7 MPa using PUR glue.

On the other hand, Derikvand and Pangh (2016) found higher SBS values using PUR glue (13.4 MPa) than using PVAc glue (12.3 MPa) to bond Oriental beech (*Fagus orientalis* Lipsky).

Král *et al*. (2015), who investigated plasma surface treatment and subsequent bonding of beech wood with polyvinyl acetate glue, reported a relatively lower SBS value of 8.2 MPa.

Tiryaki *et al*. (2015) reported an even lower SBS value, 6.9 MPa, in the bonding of Oriental beech wood (*Fagus orientalis* Lipsky) using PVAc glue.

Özçifçi and Yapici (2008) reported an even lower SBS value for aspen wood bonded with PUR glue – a value of 4.9 MPa.

The differences in SBS values among various studies are caused by the different physical and mechanical properties of the wood (surface roughness, porosity, density, *etc.*), the variability of the adhesives used (viscosity, open time, fillers and hardeners, water resistance D1 – D4, *etc*.), as well as the gluing conditions (temperature, pressure, and pressing time).

Table 5. Mean Values of the Tensile-shear Strength for Combination of Non-densified Pieces

Combination of Pieces	Glue Type	Number of Cycles	Tensile-Shear Strength (MPa)	
			Beech	Aspen
3NN	PVAc	0	8.9 (3.65)	11.1 (5.18)
3NN	PVAc	10,000	9.1 (3.01)	7.5 (1.90)
3NN	PUR	0	14.3 (1.81)	9.6 (1.95)
3NN	PUR	10,000	9.8 (3.08)	9.7 (3.08)
5NN	PVAc	0	11.5 (5.61)	13.3 (4.11)
5NN	PVAc	10,000	11.6 (5.41)	12.8 (2.67)
5NN	PUR	0	9.9 (3.86)	9.4 (4.03)
5NN	PUR	10,000	14.7 (6.22)	11.7 (2.54)
9NN	PVAc	0	15.8 (5.72)	12.1 (2.09)
9NN	PVAc	10,000	14.2 (4.13)	11.9 (2.22)
9NN	PUR	0	12.1 (3.28)	11.3 (1.60)
9NN	PUR	10,000	12.3 (3.85)	12.3 (3.98)

*Values in parentheses are standard deviations

Combination of Non-Densified and Densified Pieces

Table 6 contains a statistical evaluation of factors that affect the shear bond strength. All individual factors and their combined effect were statistically significant (P <0.05; Table 6).

Table 6. Statistical Evaluation of the Shear Bond Strength for Combinations of Densified and Non-Densified Pieces

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F - test	*p*-value
Intercept	31,136.12	1	31,136.12	3,208.876	0.001
Pieces combination (1)	835.49	11	75.95	7.828	0.001
Wood species (2)	434.14	1	434.14	44.742	0.001
Glue type (3)	59.83	1	59.83	6.166	0.013
Number of cycles (4)	39.54	1	39.54	4.075	0.044
1*2*3*4	296.89	11	26.99	2.782	0.002
Error	3,726.00	384	9.70		

As in the previous case of the combination of non-densified pieces, in the combination of densified and non-densified pieces the shear bond strength was higher in beech wood than in aspen wood (Fig. 8). The average value for the glued wood consisting of beech pieces was 26.8% higher than in aspen pieces.

Fig. 8. Influence of wood species on tensile-shear strength

The type of adhesive used had an opposite effect on the shear bond strength (Fig. 9) than in the combination consisting only of non-densified pieces. The shear bond strength of the wood glued with PUR glue was 9.1% higher than that with PVAc glue. The smoother surface of the pieces, as a result of densification, had a positive effect on the adhesion of the glue. The works of Özçifçi (2006), Özçifçi and Yapici (2008), as well as Frihart and Hunt (2010) confirm that higher surface smoothness increases the shear bond strength of wood.

Figure 10 shows the shear bond strength for different combinations of non-densified and densified pieces. Based on the course of the curves in the graph, it can be concluded that the combination of only densified pieces exhibits the greatest differences in shear bond strength values.

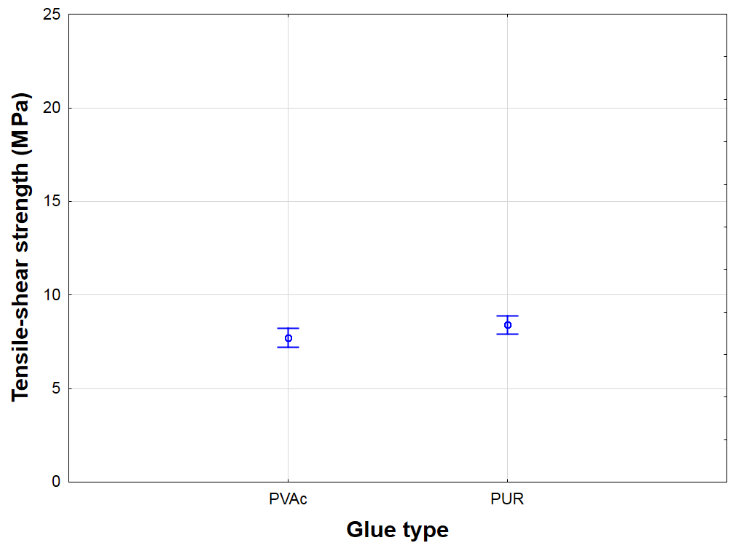

Fig. 9. Influence of glue type on tensile-shear strength

Paradoxically, the glued wood consisting of pieces densified by 20% achieved lower shear bond strength values in all cases, whereas the thickness of the individual pieces had no significance. However, glued wood consisting of densified and non-densified pieces showed smaller differences, and as the thickness of the pieces increased, there was a gradual increase in the shear bond strength.

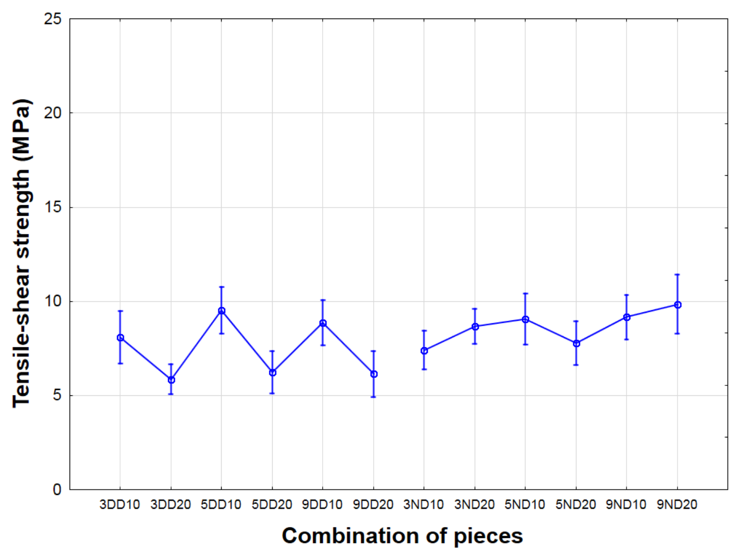

Fig. 10. Influence of piece combination on tensile-shear strength

Although cyclic loading was a statistically significant factor, its probability P <0.04 was close to P <0.05. Based on this result, it can be concluded that the number of cycles had the smallest effect on the shear bond strength of all the factors. The shear bond strength of the glued wood subjected to cyclic loading was 7.4% higher than that of wood without cyclic loading (Fig. 11).

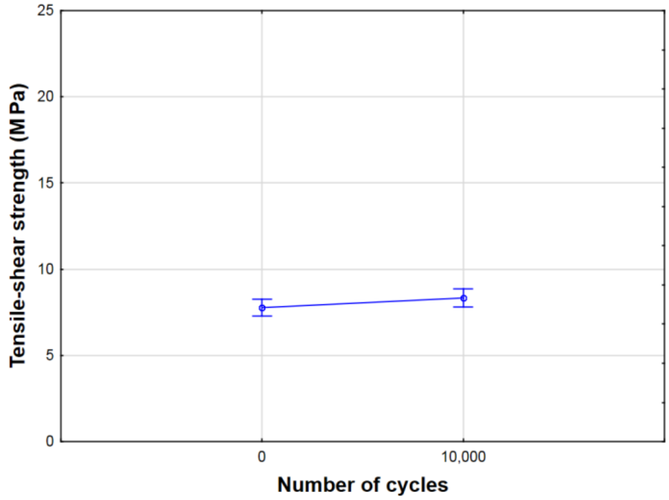

Fig. 11. Influence of number of cycles on tensile-shear strength

The assessment of the effect of all the factors on the SBS of wood not subjected to cyclic loading is shown in Fig. 12. The glued wood consisting of both wood species did not achieve a clear trend in SBS values for any combination of densified and non-densified pieces. A clear dependence on the piece thickness or their combination in terms of densification was not confirmed. The use of PUR glue resulted in greater fluctuations in SBS values in beech wood. These results confirmed the assumption that the glued beech wood achieved higher SBS values than the aspen wood with the use of both types of adhesives.

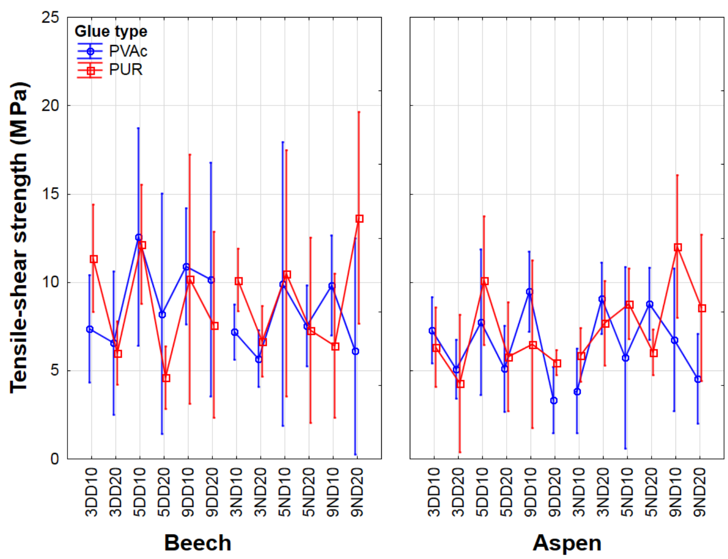

Fig. 12. Influence of piece combination, glue type, and wood species on the tensile-shear strength without cyclic loading

The effect of the combination of all the factors (wood species, glue type, combination of pieces, and cyclic loading) on the SBS is shown in Fig. 13. In this case, there were greater differences between the combinations of densified and non-densified pieces in glued beech wood. Glued wood consisting of both densified and non-densified pieces achieved significantly higher SBS values but a dependence on the piece thickness was not confirmed in compariosn with the combination of densified pieces. Glued beech wood without cyclic loading also achieved higher SBS values than those of aspen wood. The SBS of aspen wood did not have a definite dependence on the combination of pieces or their thickness in any of the cases.

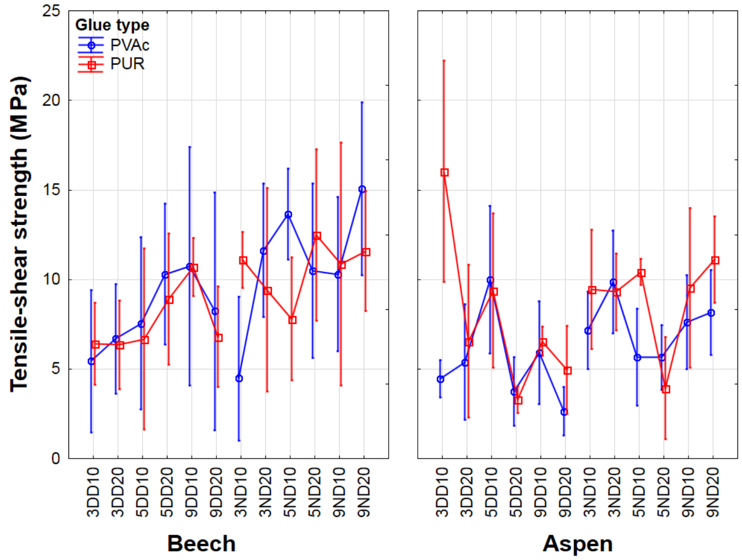

Fig. 13. Influence of piece combination, glue type, and wood species on the tensile-shear strength after cyclic loading by 10,000 cycles

The SBS values obtained have some similarities with other studies (Table 7) as stated previously. Similar values were reported by Özkaya *et al*. (2015), who found the SBS value of 8.1 MPa in beech LVL glued with PVAc glue. Slightly higher values were found by Kläusler *et al*. (2014), who reported an SBS value of 12.5 MPa for beech wood glued with single-component PUR glue. Shukla and Kamden (2008), who studied LVL consisting of thin aspen veneer and PVAc glue, found SBS values in the range of 2.1 to 3 MPa. In this case, the densification of the pieces played a certain role in the results, which was most clearly demonstrated in the gluing of the pieces densified by 20%. The combination of densified and non-densified pieces balanced the SBS values of the glued wood. Similar studies indicate that densification has no significant effect on SBS values. For example, Kurowska *et al*. (2010) found that densification of veneers has no significant effect on the SBS value of plywood glued with UF glue.

Wood, as a natural heterogeneous material, is affected by many factors during gluing. The quality of the adhesive bond depends primarily on the properties of the wood, as well as the gluing parameters. One of the most basic wood properties, that affect the gluing process, is density. Generally speaking, the shear bond strength increases along with the density. However, increasing density requires higher compression pressure, depending on the surface flatness. Hardwood species with higher density require a smoother surface for bonding, while softwood species require a rougher surface. Excessive compression pressure has a negative effect, because it densifies the wood and pushes the glue out of the glue line (Seldiačik and Sedliačik 2000). Densification or pressing of wood can eliminate surface roughness to a certain extent, but it also causes a decrease in the wood's porosity (Schneider and Wagner 1974, Patyakin et al. 2008, Plötze and Niemz 2011), which limits the ability of the adhesive to bind to its surface.

Table 7. Mean Values of the Tensile-shear Strength for Combinations of Densified and Non-Densified Pieces

Combination of Pieces	Tensile-Shear Strength (MPa)		Glue Type	Number of Cycles	Tensile-Shear Strength (MPa)		Combination of Pieces
	Beech	Aspen			Beech	Aspen	
3DD10	7.4 (2.44)	7.4 (1.51)	PVAc	0	7.2 (1.26)	3.8 (1.93)	3ND10
3DD10	5.4 (3.19)	4.5 (0.84)	PVAc	10,000	4.5 (4.44)	7.2 (1.74)	3ND10
3DD10	11.4 (2.43)	6.3 (1.82)	PUR	0	10.1 (1.42)	5.9 (1.22)	3ND10
3DD10	6.4 (1.84)	16.0 (4.97)	PUR	10,000	11.1 (1.26)	9.4 (2.67)	3ND10
3DD20	6.6 (3.27)	5.1 (1.33)	PVAc	0	5.7 (1.30)	9.1 (1.64)	3ND20
3DD20	6.7 (2.45)	5.4 (2.60)	PVAc	10,000	11.6 (2.99)	9.9 (2.31)	3ND20
3DD20	6.0 (1.43)	4.3 (3.13)	PUR	0	6.7 (1.60)	7.7 (1.92)	3ND20
3DD20	6.4 (1.99)	6.6 (3.42)	PUR	10,000	9.4 (4.57)	9.3 (1.73)	3ND20
5DD10	12.6 (4.97)	7.8 (3.31)	PVAc	0	9.9 (6.47)	5.7 (4.15)	5DD10
5DD10	7.6 (3.87)	10.0 (3.32)	PVAc	10,000	13.7 (2.05)	5.7 (2.19)	5DD10
5DD10	12.2 (2.70)	10.1 (2.93)	PUR	0	10.5 (5.61)	8.8 (1.62)	5ND10
5DD10	6.7 (4.07)	9.4 (3.46)	PUR	10,000	7.8 (2.77)	10.4 (0.58)	5ND10
5DD20	8.2 (5.48)	5.1 (1.96)	PVAc	0	7.5 (1.84)	8.8 (1.63)	5ND20
5DD20	10.3 (3.17)	3.7 (1.53)	PVAc	10,000	10.5 (3.91)	5.7 (1.46)	5ND20
5DD20	4.6 (1.42)	5.8 (2.49)	PUR	0	7.3 (4.21)	6.0 (1.05)	5ND20
5DD20	8.9 (2.95)	3.3 (0.60)	PUR	10,000	12.5 (3.85)	3.9 (2.29)	5ND20
9DD10	10.9 (2.65)	9.5 (1.83)	PVAc	0	9.8 (2.27)	6.7 (3.24)	9ND10
9DD10	10.7 (5.36)	5.9 (2.30)	PVAc	10,000	10.3 (3.46)	7.6 (2.11)	9ND10
9DD10	10.2 (5.67)	6.5 (3.82)	PUR	0	6.4 (3.29)	12.0 (3.26)	9ND10
9DD10	10.7 (1.31)	6.5 (0.65)	PUR	10,000	10.8 (5.46)	9.5 (3.59)	9ND10
9DD20	10.2 (5.32)	3.3 (1.51)	PVAc	0	6.1 (6.75)	4.6 (2.05)	9ND20
9DD20	8.2 (5.34)	2.6 (1.08)	PVAc	10,000	15.1 (3.88)	8.2 (1.91)	9ND20
9DD20	7.6 (4.24)	5.5 (0.58)	PUR	0	13.7 (4.82)	8.6 (3.34)	9ND20
9DD20	6.8 (2.26)	4.9 (1.98)	PUR	10,000	11.6 (2.70)	11.1 (1.94)	9ND20

Values in parentheses are standard deviations
3, 5, and 9 are the original thicknesses of the pieces in millimeters

The outer and inner surface of the wood is considered. The outer surface, which consists of the wood's anatomical structure (porosity, differences between spring and summer wood, the width of annual rings, etc.), and the type of machining tool, is measured by the surface roughness and waviness. The surface roughness of the wood is strictly dependent on the method of processing. A milled surface does not require high pressure for gluing in order to achieve higher shear bond strength. In a sanded surface, the higher the compression pressure, the higher the shear strength. The inner surface is the set of all capillary cavities from wood fiber lumens, the spaces between the fibrils and submicroscopic areas between microfibrils and micelles (Sedliačik and Sedliačik 2000). The wood surface affects the penetration of the adhesive into its structure, and therefore the adhesion between the wood and the glue.

Based on these facts, it is important to further examine the various effects on the interaction between wood and glue. It is necessary to examine wood as an adherend with certain anatomical properties (porosity, surface roughness, waviness) and changes to these properties through technological operations (densification, machining, modifications) based on the properties of the adhesive and gluing parameters.

CONCLUSIONS

1. In general, glued wood consisting only of non-densified pieces achieved higher SBS values in both wood species. As expected, higher SBS values were found in glued beech wood. However, statistical probability was only confirmed for the pieces combination ($P > 0.04$), where there was a slight increase in SBS values as the piece thickness increased. The other factors had no significant effect on the SBS. The difference in the SBS between PUR and PVAc glue was only 1.7% in the favor of PVAc. The comparison of SBS values of glued wood subjected to cyclic loading and wood not subjected to cyclic loading showed a difference of only 1.1%.
2. Glued wood consisting of a combination of densified and non-densified pieces had lower SBS values. All the factors were statistically significant. The SBS of glued beech wood was 26.8% higher than that of aspen wood. The combination of non-densified and densified pieces achieved lower SBS values than those of glued wood consisting only of densified pieces. PUR glue ensured 9.1% higher SBS as compared to PVAc glue, which was the opposite of the trend as in the previous variant (combination of NN pieces). Cyclic loading of glued wood increased the SBS by 7.4% compared to wood not subjected to cyclic loading.

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REFERENCES CITED

Burdurlu, E., Kılıç, Y., Elībol, G. C., and Kılıç, M. (2006). "The shear strength of Calabrian pine (*Pinus brutia* Ten.) bonded with polyurethane and polyvinyl acetate adhesives," *Journal of Applied Polymer Science* 99(6), 3050-3061. DOI: 10.1002/app.22905

Cai, Z., and Ross, R. J. (2010). "Mechanical properties of wood-based composite materials," in: *Wood Handbook-Wood as an Engineering Material*, Centennial edition, Forest Product Laboratory, USDA Forest Service, Madison, WI, pp. 12.1-12.12.

ČSN 91 0001 (2007). "Furniture -Technical requirements," Czech Office for Standards, Metrology and Testing, Prague, Czech Republic (in Czech).

Derikvand, M., and Pangh, H. (2016). "A modified method for shear strength measurement of adhesive bonds in solid wood," *BioResources* 11(1), 354-364. DOI: 10.15376/biores.11.1.354-364

Derikvand, M., Ebrahimi, G., and Tajvidi, M. (2014). "A feasibility study of using two-component polyurethane adhesive in construction wooden structures," *Journal of Forestry Research* 25(2), 477-482. DOI: 10.1007/s11676-013-0425-y

EN 204 (2001). "Classification of thermoplastic wood adhesives for non-structural applications," European Committee for Standardization, Brussels, Belgium.

EN 205 (2003). "Adhesive – Wood adhesives for non-structural applications-Determination of tensile shear strength of lap joints," European Committee for Standardization, Brussels, Belgium.

EN 942 (2007). "Timber in Joinery – General requirements," European Committee for Standardization, Brussels, Belgium.

Frihart, C. R., and Hunt, C. G. (2010). "Adhesives with wood materials – Bond formation and performance," in: *Wood Handbook-Wood as an Engineering Material*, Centennial edition, Forest Product Laboratory, USDA Forest Service, Madison, WI, pp. 10.1-10.24.

Follrich, J., Teischinger, A., Gindl, W., and Müller, U. (2007). "Tensile strength of softwood butt end joints. Part 1: Effect of grain angle on adhesive bond strength," *Wood Material Science & Engineering* 2(2), 83-89. DOI: 10.1080/17480270701841043

ISO 13061-1 (2014). "Physical and mechanical properties of wood-Test methods for small clear wood samples. Part 1: Determination of moisture content for physical and mechanical tests," International Organization for Standardization, Geneva, Switzerland.

ISO 13061-2 (2014). "Physical and mechanical properties of wood-Test methods for small clear wood samples. Part 2: Determination of density for physical and mechanical tests," International Organization for Standardization, Geneva, Switzerland.

Kläusler, O., Hass, P., Amen, C., Schlegel, S., and Niemz, P. (2014). "Improvement of tensile shear strength and wood failure percentage of 1C PUR bonded wooden joints at wet stage by means of DMF priming," *European Journal of Wood and Wood Products* 72(3), 343-354. DOI: 10.1007/s00107-014-0786-8

Konnerth, J., Gindl, W., Harm, M., and Müller, U. (2006). "Comparing dry bond strength of spruce and beech wood glued with different adhesives by means of scarf- and lap joint testing method," *Holz als Roh-und Werkstoff* 64(4), 269-271. DOI: 10.1007/s00107-006-0104-1

Král, P., Ráheľ, J., Stupavská, M., Šrajer, J., Klímek, P., Mishra, P. K., and Wimmer, R. (2015). "XPS depth profile of plasma-activated surface of beech wood (*Fagus sylvatica*) and its impact on polyvinyl acetate tensile shear bond strength," *Wood Science and Technology* 49(2), 319-330. DOI: 10.1007/s00226-014-0691-7

Kurowska, A., Borysiuk, P., Mamiński, M., and Zbieć, M. (2010). "Veneer densification as a tool for shortening of plywood pressing time," *Drvna Industrija* 61(3), 193-196.

Le, E. A., and Nairn, J. A. (2014). "Measuring interfacial stiffness of adhesively bonded wood," *Wood Science and Technology* 48(6), 1109-1121. DOI: 10.1007/s00226-014-0661-0

Li, R., Guo, X., Ekevad, M., Marklund, B., and Cao, P. (2015). "Investigation of glueline shear strength of pine wood bonded with PVAc by response surface methodology," *BioResources* 10(3), 3831-3838. DOI: 10.15376/biores.10.3.3831-3838

Minelga, D., Ukvalbergiené, K., Norvydas, V., Buika, G., and Dubininkas, M. (2010). "Impact of aliphatic isocyanates to PVA dispersion gluing properties," *Material Science (Medžiagotyra)* 16(3), 217-220.

Motohashi, K., Tomita, B., Mizumachi, H., and Sakaguchi, H. (1984). "Temperature dependency of bond strength of polyvinyl acetate emulsion adhesives for wood," *Wood and Fiber Science* 16(1), 72-85.

Özçifçi, A. (2006). "Effects of boron compounds on the bonding strength of phenol–formaldehyde and melamine–formaldehyde adhesives to impregnated wood materials," *Journal of Adhesion Science and Technology* 20(10), 1147-1153. DOI: 10.1163/156856106777890590

Özçifçi, A., and Yapici, F. (2008). "Effects of machining method and grain orientation on the bonding strength of some wood species," *Journal of Materials Processing Technology* 202(1-3), 353-358. DOI: 10.1016/j.jmatprotec.2007.08.043

Özkaya, K., Ayrilmis, N., and Özdemir, S. (2015). "Potential use of waste marble powder as adhesive filler in the manufacture of laminated veneer lumber," *BioResources* 10(1), 1686-1695. DOI: 10.15376/biores.10.1.1686-1695

Patyakin, V. I., Sugaipov, U. U., Birman, A. R., Bazarov, S. M., Pilshikov, Y. N., Spitsyn, A. A., and Mettee, H. D. (2008). "Mechanical and chemical modification of wood materials – compressed wood and oxidized charcoal," *BioResources* 3(3), 731-744. DOI: 10.15376/biores.3.3.731-744

Plötze, M., and Niemz, P. (2011). "Porosity and pore size distribution of different wood types as determined by mercury intrusion porosimetry," *European Journal of Wood and Wood Products* 69(4), 649-657. DOI: 10.1007/s00107-010-0504-0

Raftery, G. M., Harte, A. M., and Rodd, P. D. (2009). "Bond quality at the FRP-wood interface using wood-laminating adhesives," *International Journal of Adhesion and Adhesives* 29(2), 101-110. DOI: 10.1016/j.ijadhadh.2008.01.006

Ren, D., and Frazier, C. E. (2012). "Wood/adhesive interactions and the phase morphology of moisture-cure polyurethane wood adhesives," *International Journal of Adhesion and Adhesives* 34(1), 55-61. DOI: 10.1016/j.ijadhadh.2011.12.009

Sedliačik, J., and Sedliačik, M. (2000). *Lepenie dreva* (*Bonding of wood*), *University Textbook*, Technical University in Zvolen, Zvolen, Slovakia, 236 pp.

Serrano, E. (2004). "A numerical study of the shear-strength-predicting capabilities of samples for wood-adhesive bonds," *International Journal of Adhesion and Adhesives* 24(1), 23-35. DOI: 10.1016/S0143-7496(03)00096-4

Schneider, A., and Wagner, L. (1974). "Bestimmung der Porengrößenverteilung in Holz mit dem Quecksilber-Porosimeter (Determination of poresize distribution in wood with a mercury porosimeter)," *Holz als Roh- und Werkstoff* 32(6), 216-224. DOI: 10.1007/BF02607257 (in German)

Shukla, S. R., and Kamden, 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

Stark, N. M., Cai, Z. and Carll, C. (2010). "Wood-based composite materials panel products, glued-laminated timber, structural composite lumber, and wood–nonwood composite materials," in: *Wood Handbook-Wood as an Engineering Material,* Centennial edition, Forest Product Laboratory, USDA Forest Service, Madison, WI, pp. 11.1-11.28.

Stoeckel, F., Konnerth, J., and Gindl-Altmutter, W. (2013). "Mechanical properties of adhesives for bonding wood – A review," *International Journal of Adhesion and Adhesives* 45(1), 32-41. DOI: 10.1016/j.ijadhadh.2013.03.013

Tiryaki, S., Bardak, S., and Bardak, T. (2015). "Experimental investigation and prediction of bonding strength of Oriental beech (*Fagus orientalis* Lipsky) bonded with polyvinyl acetate adhesive," *Journal of Adhesion Science and Technology* 29(23), 32-41. DOI: 10.1080/01694243.2015.1072989

Vick, C. B., and Okkonen, E. A. (1998). "Strength and durability of one-part polyurethane adhesive bonds to wood," *Forest Products Journal* 48(11/12), 71-76.

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