Impact Bending Strength as a Function of Selected Factors: 2 – Layered Materials from Densified Lamellas

Milan Gaff,[a,]* Daniel Ruman,[a] Tomáš Svoboda,[a] Adam Sikora,[a] Vladimír Záborský,[a] and Carlos Rodriguez Vallejo [b]

This article examines the effect of selected factors (wood species, lamella combination, type of adhesive, number of loading cycles) on the impact bending strength (IBS) of laminated wood. The IBS was tested on specimens made from beech (*Fagus sylvatica* L.) and aspen lamellas (*Populus tremula* L.). The laminated wood was densified by 10% and 20% of the original thickness. For bonding the wood, polyvinyl acetate (PVA) adhesive was used, and the product was compared with laminated wood bonded with polyurethane adhesive (PUR). The wood species and lamella combination had significant effects on IBS. The highest values of IBS were found for beech wood lamellas.

Keywords: Impact bending strength; Cyclic loading; Laminated wood; Densification

Contact information: a: Department of Wood Processing, Czech University of Life Sciences in Prague, Kamýcká 1176, Prague 6 – Suchdol, 16521 Czech Republic; b: Department of Forestry Engineering, Campus de Rabanales s/n, University of Cordoba, 14071 Cordoba, Spain;
** Corresponding author: gaffmilan@gmail.com*

INTRODUCTION

Beech is a medium weight and hardness wood (Wagenführ 2000). Beech wood is often used in Europe for the manufacture of furniture, toys, sporting goods, plywood, particle boards, stairs, and floor elements (Ohnesorge *et al.* 2010). Beech wood is used also for the production of laminated veneer beams (Guntekin *et al.* 2014; Hassan and Eisele 2015). Aspen (*Populus tremula* L.) wood is soft, with low rigidity and flexibility, and is not used very often commercially. Aspen wood may occasionally also be used for furniture production for invisible parts, such as veneer for the back of furniture, veneer for the underside of desks, *etc.* (Kärki 2001). Aspen wood is often found in packaging products; in the match industry, it can be used for the production of structural plywood, as well as for the production of biomass, paper, and pulp (Heräjärvi and Junkkonen 2006). However, compared with beech wood, it is cheaper and has a much shorter rotation period (Candan *et al.* 2013; Bal 2014).

Wood can be intentionally modified to increase its mechanical properties. One modification is wood densification (Ellis and Steiner 2002; Wang and Cooper 2005). Densifying the wood provides it a higher resistance to permanent stress, greater strength, flexibility, durability, and possibly hardness compared with solid wood (Gong *et al.* 2006; Makovínyi and Zemiar 2012). This expands the area of its application and increases its price (Blomberg *et al.* 2005). Densification of wood is most often performed by compression; a less common method is rolling (Makovínyi and Zemiar 2012).

The bonding technology is an integral component of the lumber industry, which contributes to the improvement of the quality of products and is the basis for the creation of new progressive materials (Sedliačik and Sedliačik 2000; Pizzi and Mittal 2003). The composition of lamellas in laminated wood affects its mechanical properties. Gaff *et al.* (2016) examined the effect of the composition of laminated beech wood and aspen wood on the bonding strength by combining densified and non-densified wood. They found that the effect of the composition on the bonding strength is highly significant. Svoboda *et al.* (2015) examined the effect of the composition of laminated beech wood and aspen wood on the modulus of elasticity in bending and flexural strength. The densified and non-densified layers were combined. They found that the composition had a very significant effect on the monitored characteristic. The type of adhesive also has a significant effect on the properties of such components.

Currently, PVA (polyvinylacetate) and PUR (polyurethane) adhesives that are safe for the environment and human health are promoted in the furniture industry (Mitani and Barboutis 2010). PVA adhesives were first introduced to the market in 1950, replacing adhesives made from animals and urea-formaldehyde glue (UF) (Tout 2000). They are classified as thermoplastic adhesives, which are prepared with acetylene, acetic acid, and mercuric salts, resulting in a vinyl acetate monomer that is used to create polyvinyl acetate by dispersion (PVA) (Sedliačik and Sedliačik 2000; Kim and Kim 2006).

PVA adhesives are cured physically, creating a continuous colorless link; they have good adhesion to wood and provide a flexible and strong bond that is non-flammable and resistant to microorganisms. PUR adhesives are often used in the furniture industry, and they are formed by addition polymerization of polyisocyanates with polyhydric alcohols or polyesters that have sufficient free hydroxyl groups (Sedliačik and Sedliačik 2000; Adams 2005; Uysal and Özçifçi 2006).

Polyurethane adhesives are flexible, resistant to dynamic stress, cure at a wide range of temperatures, and are resistant to cold and boiling water. Humidity from the air or the moisture content of the bonded wood is sufficient to cure polyurethane adhesives (Sedliačik and Sedliačik 2000; Uysal and Özçifçi 2006). Their disadvantage, however, is a higher price compared to PVA adhesives.

Parts manufactured for use in furniture are often subjected to higher stress due to the effect of cyclic loading. This negatively impacts their durability. It represents repeated strain on elements by external force for a certain period of time, which can lead to fatigue failure of the product. Svoboda *et al*. (2015) showed the negative effect of cyclic loading on the bending characteristics of laminated beech and aspen wood. The effect of cyclic loading on the monitored characteristics was highly statistically significant. Gaff and Gašparík (2015) examined the effect of cyclic loading on the modulus of elasticity in bending (MOE) of laminated aspen wood. They found the effect of cyclic loading on MOE values to be highly statistically significant. Increasing the number of loading cycles reduced the MOE values of laminated aspen wood. It was assumed that the given number of cycles led to the breaking of hydrogen bonds, as a result of which the values of the monitored characteristics changed.

Cyclic loading causes frequent failure of furniture components. Dynamic loading includes dynamic durability (Dubovský *et al.* 2003). The dynamic durability of wood is the ability to absorb impact bending (Požgaj *et al.* 1993). Impact is defined as the sudden collision of two bodies, the results of which depend on the strength of the impact force (Bodig and Jayne 1982). IBS tests were the historically first impact tests (Leijten 2004). IBS tests are most often conducted using a Charpy impact test or Izod test (Gambhir and Jamwal 2014). Depending on the type and shape of the fracture of wood after the impact test, the quality of wood can be classified. Tough wood has a fibrous, spiky fracture, while brittle wood creates blunt, non-fibrous stepped fracture (Gašparík *et al.* 2016). Wood with average IBS values creates a shorter fibrous fracture on the tensile side (Požgaj *et al.* 1993). With the use of an impact hammer, IBS values are mostly affected by the size of the body and the support span (Bal 2016). In addition to factors arising from the measurement technology, other factors such as the density of the wood, the microfibril angle, moisture content of the wood, temperature, and the radial or tangential force must be considered (Kollmann 1951; Bučar and Merhar 2015). Wood toughness is important in technological processes such as pressing and bending.

This research focuses on the effect of selected factors, *i.e.*, wood species, lamella combination, and type of adhesive on the IBS of laminated beech and aspen wood, which was subjected to cyclic loading prior to testing.

EXPERIMENTAL

Materials

The two wood species used for the experiment were beech (*Fagus sylvatica* L.) and aspen (*Populus tremula* L.) from Central Slovakia, Poľana. Logs were cut to planks. Planks were formatted into lamellas with the dimensions (3, 5, 9 radial) × 35 (tangential) × 300 (longitudinal) mm (Fig.1), which were conditioned in a chamber APT Line II (Binder, Tuttingen, Germany) to an equilibrium moisture content of 8% at a temperature of 20 °C and relative humidity (RH) of 42%. Eight percent moisture content is the standard moisture content for furniture elements in interiors according to EN 942 (2007) and ČSN 91 0001 (2007). The lamellas were divided into two groups: lamellas prepared for densification and non-densified lamellas. For each group, 20 test samples were used.

Methods

Densification of test specimens

The test specimens intended for densification were pressed in a UPS 1000 hydraulic press (RK MFL Prüfsysteme, Tuttingen, Germany). Table 1 states press values measured when changing the dimensions of the individual sets of test specimens by 10% and 20%. The densified lamellas were rested for 5 min and prepared for lamination.

Table 1. Forces Applied in Individual Sets of Test Specimens

Material Thickness (mm)	Degree of Densification 10%		Degree of Densification 20%	
	Beech (MPa)	Aspen (MPa)	Beech (MPa)	Aspen (MPa)
4	338	103	376	143
6	200	176	371	200
10	357	205	429	238
18	348	164	350	171

The values of spring-back deformation were measured and will be evaluated separately in the part devoted to rheology.

Lamination of wood

Table 2 shows the monitored combinations of laminated wood for both wood species, where the wood lamellas were bonded in various combinations of densified (10% and 20%) and non-densified wood. Figure 1 shows the orthotropic direction of samples.

The wood lamellas were bonded with a single-component waterproof polyvinyl acetate adhesive (PVA) type AG-COLL 8761/L D3 (EOC, Oudenaarde, Belgium) or a single-component polyurethane adhesive (PUR) type NEOPUR 2238R (NEOFLEX, Madrid, Spain) with the parameters listed in Table 3. The adhesive was applied with an adhesive roller in the recommended one-side application 150 to 180 g/m^2 for PVA, and 180 to 250 g/m^2 for PUR adhesive. The specimens were cold-pressed in an industrial press (JU 60, PAUL OTT, Lambach, Austria) for 60 min. After pressing, the test specimens were acclimatized in the climatic chamber APT Line II (Binder, Tuttingen, Germany) at 20 °C and 42% RH. After the bonding, the test specimens were prepared for cyclic loading.

Table 2. Sample Parameters

Sample	Description
3DD10	Includes a pair of lamellas, after densification by 10%, with thickness 2.7 mm
3DD20	Includes a pair of lamellas, after densification by 20%, with thickness 2.4 mm
5DD10	Includes a pair of lamellas, after densification by 10%, with thickness 4.5 mm
5DD20	Includes a pair of lamellas, after densification by 20%, with thickness 4 mm
9DD10	Includes a pair of lamellas, after densification by 10%, with thickness 8.1 mm
9DD20	Includes a pair of lamellas, after densification by 20%, with thickness 7.2 mm
3ND10	Includes a non-densified (3 mm) lamella and lamella densified by 10% (2.7 mm)
3ND20	Includes a non-densified (3 mm) lamella and lamella densified by 20% (2.4 mm)
5ND10	Includes a non-densified (5 mm) lamella and lamella densified by 10% (4.5 mm)
5ND20	Includes a non-densified (5 mm) lamella and lamella densified by 20% (4 mm)
9ND10	Includes a non-densified (9 mm) lamella and lamella densified by 10% (8.1 mm)
9ND20	Includes a non-densified (9 mm) lamella and lamella densified by 20% (7.2 mm)

Note: 3, 5, and 9 are the original thicknesses of the lamellas in millimeters; N, non-densified lamellas, D, densified lamellas

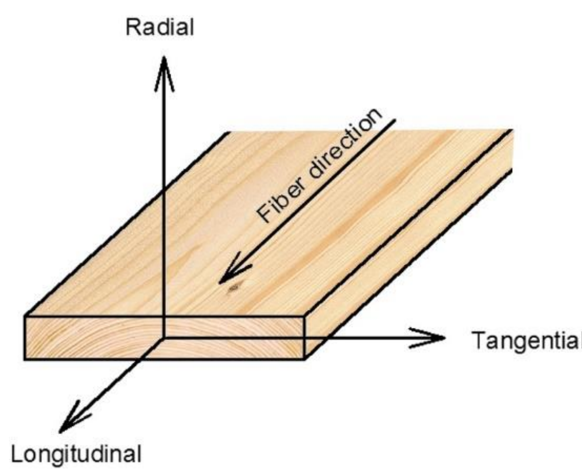

Fig. 1. The orthotropic direction of samples

Table 3. Adhesives Properties

Technical data	AG-COLL 8761/L D3	NEOPUR 2238R
Viscosity (mPas)	5000-7000 at 23 °C	2000-4500 at 25 °C
Dry matter content (%)	49-51	100
Density (g/cm^3)	0.9-1.1 at 23 °C	ca. 1.13
pH	3.8-4.5	-
Color	white, milk	brown
Open time (min)	15	ca. 20-25
NCO content (%)	-	ca. 15.5-16.5
Working time (min)	15-20	60

Cyclic bending stress

Half of the test specimens were subjected to 10,000 cycles of cyclic loading. The cyclical loading was performed on a machine (CULS; Prague, Czech Republic) with the cyclical bending of the specimens using single-axis loading. During preliminary experimental testing, the test specimens were loaded by static bending to determine the modulus of rupture and proportionality limit because the test specimens had to be loaded up to 90% of the proportionality limit. The center of the test specimens was loaded with a frequency of 20 cycles/min.

Calculation and evaluation

The wood density was determined before and after testing according to ISO 13061-2 (2014) and Eq. 1,

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{1}$$

where ρ_w is the density of the sample at moisture content w (kg·m^{-3}), m_w is the mass of the sample (kg), 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. 2,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{2}$$

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).

For the conversion between ρ_w and ρ_{12} a formula listed in standard ISO 13061-2 (2014) applicable to moisture content in the range of 7 to 17% was used, listed as Eq. 3,

$$\rho_{12} = \rho_w \left[1 - \frac{(1-K).(w-12)}{100} \right] \tag{3}$$

where K is the coefficient of volumetric shrinkage in a 1% change in humidity. For approximate calculations, the formula $K = 0.85 \times 10^{-3} \times \rho_w$ was used, where the density is expressed in (kg·m^{-3}).

The deflection at the proportional limit by static bending was tested according to EN 310 (1993). First, the limit of proportionality was determined from the stress-strain graph. The limit of proportionality was on the boundary between the linear and nonlinear relation.

The IBS was determined by the Charpy impact test (CULS, Czech Republic) with a hammer weighing 20 kg. The impact of the hammer on test specimens was in the radial direction. Ten repetitions were performed for each test group. The support span on the Charpy hammer was 240 mm. The IBS was calculated according to ISO 3348 (1975) and Eq. 4,

$$A_w = \frac{Q}{b * h} \tag{4}$$

where A_W is the IBS of wood (J·cm^{-2}), Q is the work needed to break the test specimen (J), b is the width of the sample (cm), and h is the height (thickness) of the sample (cm).

The IBS values were converted to the moisture content of 12% according to ISO 3348 (1975) and Eq. 5,

$$A_{12} = A_w\left[1 + \alpha\left(w - 12\right)\right] \tag{5}$$

where A_w is the IBS at the moisture during the testing (MPa), A_{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 0.02 for all wood species.

To determine the influence of the individual factors on the IBS, the multifactorial analysis ANOVA and the Fischer F-test were applied using STATISTICA 12 (Statsoft Inc., USA) software. Based on the P-level value, it was determined whether the monitored factor affected the values of IBS. The results were processed as diagrams showing a 95% confidence interval.

RESULTS AND DISCUSSION

Table 4 shows the average values of the monitored characteristic and the corresponding coefficient of variation. All IBS values, including the density, were calculated at 12% moisture content.

The highest IBS (27.7 J·cm^{-2}) values were achieved in laminated beech woods with a lamella combination of 9ND20, which were glued with polyurethane adhesive without cyclic loading. The lowest IBS values were measured in laminated aspen wood (3.4 J·cm^{-2}) with a lamella combination of 3ND10. The lamellas were bonded with polyurethane glue and were not subjected to cyclic loading. Aspen combinations had a 117% higher variability in IBS values than beech combinations. The variability of the density of aspen specimens was 266% higher than the variability of the density of beech specimens.

The average IBS value in the combination of beech lamellas 5ND10 bonded with PUR adhesive, not subjected to cyclic loading, was 12.3 J·cm^{-2}. This value is comparable to previously published results. Wagenführ (2000) found the average IBS for European beech (*Fagus sylvatica* L.) was 10.0 J·cm^{-2}. Similarly, Barcík and Gašparík (2014) found an average IBS value for European beech (*F. sylvatica*) of 10.8 J·cm^{-2}. Požgaj *et al*. (1993) reported an average value of 8.1 J·cm^{-2} for European beech (*F. sylvatica*). Lokaj and Vavrušová (2010) reported the average value of 6.9 J·cm^{-2} for European beech (*F. sylvatica*). Gašparík *et al.* (2016) reported the average value of 7.6 J·cm^{-2} for non-densified European beech (*F. sylvatica*) with a thickness of 10 mm.

Table 4. Average Values of IBS, Density, and Coefficient Co variance

Wood species	Glue	Combination	Number of cycles	IBS (J·cm^{-2})	Density (kg/m^3)	Wood species	Glue	Combination	Number of cycles	IBS (J·cm^{-2})	Density (kg/m^3)
Beech	**PVAC**	**3ND10**	**0**	6.8 (27.8)	785 (24.0)	**Aspen**	**PVAC**	**3ND10**	**0**	4.5 (22.2)	720 (2.1)
Beech	**PVAC**	**3ND10**	**10000**	6.4 (15.0)	701 (1.0)	**Aspen**	**PVAC**	**3ND10**	**10000**	5.9 (26.4)	727 (1.2)
Beech	**PVAC**	**3ND20**	**0**	5.9 (16.3)	707 (2.1)	**Aspen**	**PVAC**	**3ND20**	**0**	5.3 (25.5)	730 (1.8)
Beech	**PVAC**	**3ND20**	**10000**	6.6 (27.0)	731 (1.3)	**Aspen**	**PVAC**	**3ND20**	**10000**	5.1 (17.5)	714 (3.6)
Beech	**PUR**	**3ND10**	**0**	6.8 (13.4)	715 (1.3)	**Aspen**	**PUR**	**3ND10**	**0**	3.4 (39.5)	670 (16.6)
Beech	**PUR**	**3ND10**	**10000**	5.7 (28.8)	703 (2.5)	**Aspen**	**PUR**	**3ND10**	**10000**	5.3 (23.7)	562 (11.1)
Beech	**PUR**	**3ND20**	**0**	6.2 (24.6)	706 (3.3)	**Aspen**	**PUR**	**3ND20**	**0**	4.2 (13.6)	638 (4.4)
Beech	**PUR**	**3ND20**	**10000**	6.5 (21.1)	718 (3.0)	**Aspen**	**PUR**	**3ND20**	**10000**	4.7 (23.3)	648 (2.7)
Beech	**PVAC**	**5ND10**	**0**	13.6 (11.5)	723 (3.2)	**Aspen**	**PVAC**	**5ND10**	**0**	8.3 (23.9)	642 (2.9)
Beech	**PVAC**	**5ND10**	**10000**	15.1 (10.0)	716 (2.9)	**Aspen**	**PVAC**	**5ND10**	**10000**	7.6 (28.1)	484 (23.8)
Beech	**PVAC**	**5ND20**	**0**	13.5 (18.0)	735 (1.9)	**Aspen**	**PVAC**	**5ND20**	**0**	10.5 (33.3)	576 (4.9)
Beech	**PVAC**	**5ND20**	**10000**	10.9 (24.8)	733 (1.4)	**Aspen**	**PVAC**	**5ND20**	**10000**	9.1 (18.4)	620 (8.8)
Beech	**PUR**	**5ND10**	**0**	12.3 (21.8)	730 (2.5)	**Aspen**	**PUR**	**5ND10**	**0**	7.8 (31.6)	554 (11.7)
Beech	**PUR**	**5ND10**	**10000**	13.4 (19.6)	749 (2.6)	**Aspen**	**PUR**	**5ND10**	**10000**	9.0 (32.4)	541 (15.0)
Beech	**PUR**	**5ND20**	**0**	12.5 (6.3)	718 (5.1)	**Aspen**	**PUR**	**5ND20**	**0**	7.2 (38.5)	480 (13.1)
Beech	**PUR**	**5ND20**	**10000**	13.2 (12.2)	764 (2.5)	**Aspen**	**PUR**	**5ND20**	**10000**	6.4 (26.7)	499 (10.3)
Beech	**PVAC**	**9ND10**	**0**	25.1 (7.8)	726 (2.6)	**Aspen**	**PVAC**	**9ND10**	**0**	14.4 (34.0)	484 (13.7)
Beech	**PVAC**	**9ND10**	**10000**	18.2 (19.5)	722 (2.1)	**Aspen**	**PVAC**	**9ND10**	**10000**	14.0 (72.8)	489 (11.3)
Beech	**PVAC**	**9ND20**	**0**	23.7 (15.8)	721 (2.0)	**Aspen**	**PVAC**	**9ND20**	**0**	19.2 (61.1)	453 (7.9)
Beech	**PVAC**	**9ND20**	**10000**	27.4 (8.5)	704 (4.0)	**Aspen**	**PVAC**	**9ND20**	**10000**	15.0 (33.1)	432 (8.5)
Beech	**PUR**	**9ND10**	**0**	27.3 (17.9)	692 (3.1)	**Aspen**	**PUR**	**9ND10**	**0**	17.8 (37.1)	493 (13.4)
Beech	**PUR**	**9ND10**	**10000**	23.5 (8.8)	689 (2.9)	**Aspen**	**PUR**	**9ND10**	**10000**	14.9 (29.3)	419 (12.0)
Beech	**PUR**	**9ND20**	**0**	27.7 (17.2)	732 (1.9)	**Aspen**	**PUR**	**9ND20**	**0**	14.8 (37.4)	460 (5.0)
Beech	**PUR**	**9ND20**	**10000**	22.4 (31.2)	733 (2.6)	**Aspen**	**PUR**	**9ND20**	**10000**	16.0 (32.2)	435 (14.3)

**Values in parentheses are coefficients of variation (CV) in %, PUR = polyurethane glue, PVAc = polyvinylacetate glue*

Wood species	Glue	Combination	Number of cycles	IBS (J·cm^{-2})	Density (kg/m^3)	Wood species	Glue	Combination	Number of cycles	IBS (J·cm^{-2})	Density (kg/m^3)
Beech	**PVAC**	**3DD10**	**0**	7.8 (14.2)	710 (2.3)	**Aspen**	**PVAC**	**3DD10**	**0**	5.5 (11.1)	703 (3.8)
Beech	**PVAC**	**3DD10**	**10000**	6.1 (7.4)	709 (2.1)	**Aspen**	**PVAC**	**3DD10**	**10000**	5.2 (49.8)	632 (19.8)
Beech	**PVAC**	**3DD20**	**0**	6.1 (12.5)	742 (2.7)	**Aspen**	**PVAC**	**3DD20**	**0**	4.3 (41.6)	755 (4.6)
Beech	**PVAC**	**3DD20**	**10000**	6.7 (11.8)	729 (1.3)	**Aspen**	**PVAC**	**3DD20**	**10000**	4.7 (29.3)	758 (2.4)
Beech	**PUR**	**3DD10**	**0**	6.5 (9.3)	728 (3.0)	**Aspen**	**PUR**	**3DD10**	**0**	3.6 (24.4)	707 (10.7)
Beech	**PUR**	**3DD10**	**10000**	7.2 (12.5)	740 (5.5)	**Aspen**	**PUR**	**3DD10**	**10000**	6.3 (27.4)	570 (10.0)
Beech	**PUR**	**3DD20**	**0**	6.9 (14.5)	772 (0.8)	**Aspen**	**PUR**	**3DD20**	**0**	4.9 (43.8)	512 (13.8)
Beech	**PUR**	**3DD20**	**10000**	6.6 (29.5)	720 (5.3)	**Aspen**	**PUR**	**3DD20**	**10000**	4.6 (37.2)	537 (22.2)
Beech	**PVAC**	**5DD10**	**0**	13.5 (16.1)	737 (2.5)	**Aspen**	**PVAC**	**5DD10**	**0**	9.2 (36.8)	521 (20.1)
Beech	**PVAC**	**5DD10**	**10000**	13.2 (10.9)	729 (3.7)	**Aspen**	**PVAC**	**5DD10**	**10000**	11.6 (56.0)	430 (7.6)
Beech	**PVAC**	**5DD20**	**0**	12.5 (9.4)	707 (2.0)	**Aspen**	**PVAC**	**5DD20**	**0**	11.4 (46.4)	523 (19.0)
Beech	**PVAC**	**5DD20**	**10000**	14.2 (18.2)	720 (2.1)	**Aspen**	**PVAC**	**5DD20**	**10000**	8.3 (39.6)	657 (12.3)
Beech	**PUR**	**5DD10**	**0**	13.9 (11.8)	760 (2.3)	**Aspen**	**PUR**	**5DD10**	**0**	10.0 (36.1)	578 (15.9)
Beech	**PUR**	**5DD10**	**10000**	11.2 (16.3)	726 (2.3)	**Aspen**	**PUR**	**5DD10**	**10000**	11.7 (26.1)	530 (20.7)
Beech	**PUR**	**5DD20**	**0**	11.2 (14.3)	714 (1.2)	**Aspen**	**PUR**	**5DD20**	**0**	6.6 (25.4)	533 (23.7)
Beech	**PUR**	**5DD20**	**10000**	12.9 (14.6)	722 (0.9)	**Aspen**	**PUR**	**5DD20**	**10000**	6.5 (29.8)	452 (8.8)
Beech	**PVAC**	**9DD10**	**0**	22.0 (8.4)	714 (1.5)	**Aspen**	**PVAC**	**9DD10**	**0**	15.3 (35.9)	524 (16.6)
Beech	**PVAC**	**9DD10**	**10000**	23.2 (14.3)	738 (3.1)	**Aspen**	**PVAC**	**9DD10**	**10000**	14.2 (19.5)	504 (19.4)
Beech	**PVAC**	**9DD20**	**0**	25.1 (16.8)	734 (3.1)	**Aspen**	**PVAC**	**9DD20**	**0**	14.3 (28.6)	487 (10.4)
Beech	**PVAC**	**9DD20**	**10000**	25.5 (22.4)	714 (4.3)	**Aspen**	**PVAC**	**9DD20**	**10000**	12.5 (45.1)	525 (5.5)
Beech	**PUR**	**9DD10**	**0**	24.3 (7.9)	702 (4.8)	**Aspen**	**PUR**	**9DD10**	**0**	12.8 (62.8)	501 (21.1)
Beech	**PUR**	**9DD10**	**10000**	24.8 (3.9)	725 (3.6)	**Aspen**	**PUR**	**9DD10**	**10000**	16.4 (65.0)	488 (9.1)
Beech	**PUR**	**9DD20**	**0**	22.5 (29.5)	762 (2.1)	**Aspen**	**PUR**	**9DD20**	**0**	15.7 (26.9)	430 (3.5)
Beech	**PUR**	**9DD20**	**10000**	23.5 (12.9)	756 (1.1)	**Aspen**	**PUR**	**9DD20**	**10000**	16.1 (50.2)	426 (10.8)

**Values in parentheses are coefficients of variation (CV) in %, PUR = polyurethane glue, PVAc = polyvinylacetate glue*

These values are lower than the values in the current study; it is likely that the IBS laminates, as opposed to solid wood, had a positive effect on the results. The average value of the combination of laminated aspen wood 5ND10 bonded by a PUR adhesive and not subjected to cyclic loading was 7.8 J·cm^{-2}. Wagenführ (2000) reports the value of 4.0 J·cm^{-2} for aspen wood (*Populus tremula* L.), and Barcík *et al.* (2008) reports the average value of 3.2 J·cm^{-2} for aspen wood (*P. tremula*). Gašparík *et al.* (2016) report the average value of 4.6 J·cm^{-2} for non-densified aspen wood (*P. tremula*) with a thickness of 10 mm. These values are all lower than the IBS values measured here; thus, there is a positive effect of laminated wood in comparison to solid wood.

Table 5 shows the results of a multiple factor variance analysis. Based on the results of Fisher's "F" test and the significance level "P", only the wood species and lamellas combination had a statistically significant effect. The other monitored factors and their interaction were not statistically significant.

Table 5. Statistical Evaluation of Factors and their Interaction on IBS

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	70056.15	1	70056.15	5141.650	0.000001
1) Wood species	2896.53	1	2896.53	212.586	0.000001
2) Glue	4.06	1	4.06	0.298	0.585642
3) Combinations	16128.87	11	1466.26	107.614	0.000001
4) Number of cycles	4.43	1	4.43	0.325	0.568772
1*2*3*4	158.25	11	14.39	1.056	0.396380
Error	5232.09	384	13.63		

Aspen wood (9.5 J·cm^{-2}) exhibited 34.5% lower values in comparison to beech wood (14.5 J·cm^{-2}) (Fig. 2). The average density of all the beech test specimens was 726 kg·m^{-3}, and the average density of aspen specimens was 557 kg·m^{-3}. The aspen specimens had a 23.3% lower density, which is probably related to the decrease in IBS values compared with beech specimens. Beech wood has higher values than aspen wood because thicker wood also has more bonds to be broken.

Based on a multiple factor variance analysis (Table 5) and Fig. 3, the type of adhesive had no significant effect on the monitored characteristic. Test specimens bonding with a PVA adhesive had approximately 1.1% higher values than specimens bonding with a PUR adhesive, but this difference was not statistically significant.

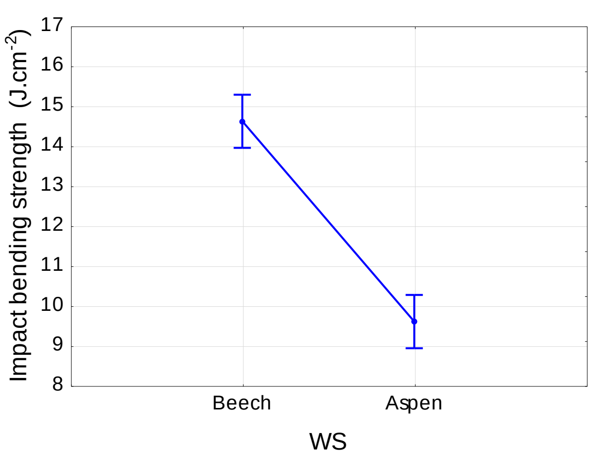

Fig. 2. The effect of the wood species "WS" on the IBS

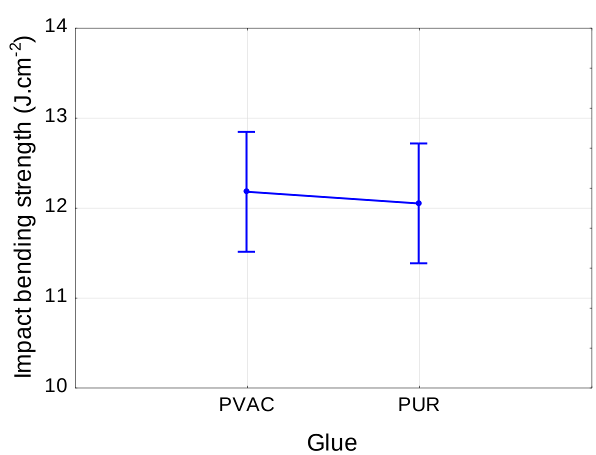

Fig. 3. The effect of the glue on the IBS

The effect of the combinations of the laminated wood on IBS values is shown in Fig. 4. There was a significant increase in the monitored characteristic with the increasing thickness of the laminated wood. The degree of densification of individual lamellas in the layered combination had no significant effect on the monitored characteristic. The highest average values of the monitored characteristic (20.8 J·cm^{-2}) were measured in the combination 9ND20; the lowest values (5.57 J·cm^{-2}) were measured in combinations 3DD20 and 3ND20. There was no significant difference between the values of test specimens consisting of lamellas with 10% and 20% densification. An insignificant difference between test specimens consisting of non-densified lamellas and lamellas with 10% and 20% densification was observed. The results were the same for the IBS values between test specimens consisting of densified lamellas and test specimens consisting of non-densified and densified lamellas. It is also worth noting that both relationships have an almost identical shape, so the combination factor can be reduced to the thickness factor.

There was a 1.6% decline in the monitored characteristic due to cyclic loading; however, this decline was not statistically significant (Fig. 5). In general, cyclic loading negatively affected the IBS values.

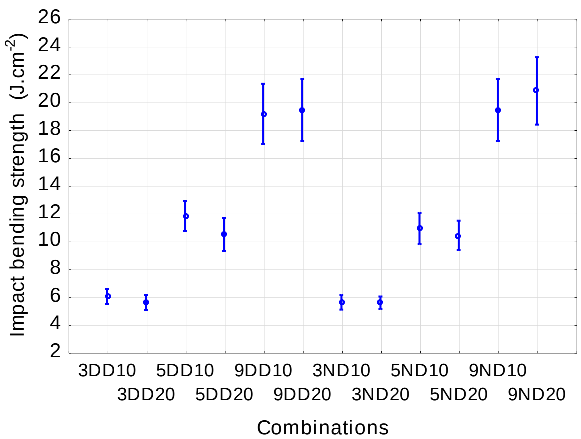

Fig. 4. The effect of combinations on the IBS

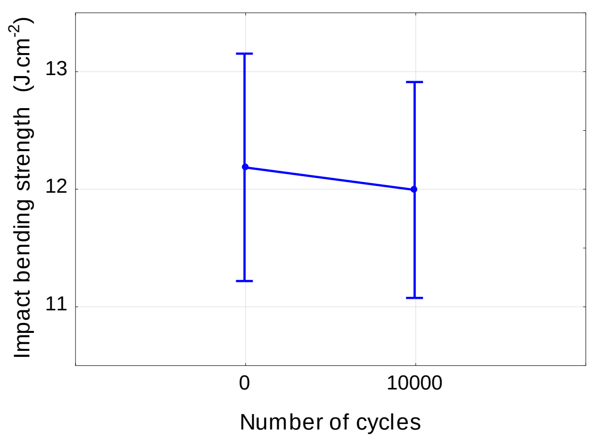

Fig. 5. The effect of the number of cycles on the IBS

Synergistic effects of the monitored factors on IBS values are shown in Figs. 6 and 7.

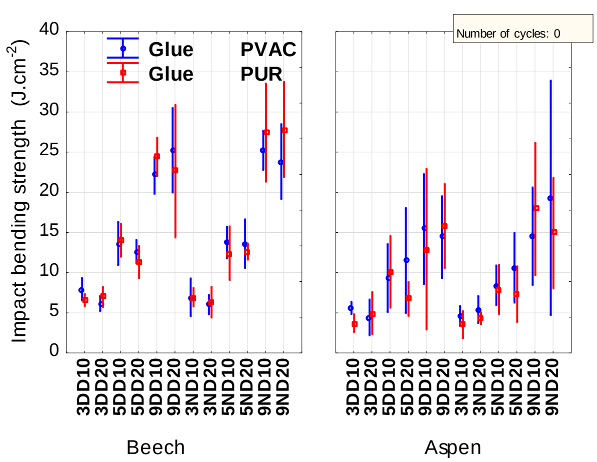

Fig. 6. Synergistic effect of the studied factors on the IBS

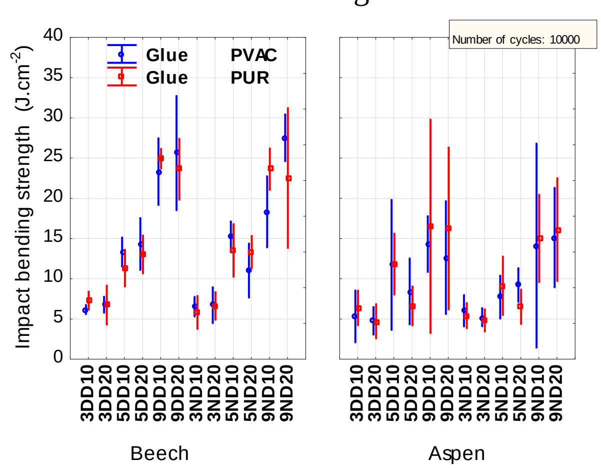

Fig. 7. Synergistic effect of the studied factors on the IBS

The wood species and combination had the greatest effect on changes in the monitored characteristic. The aspen test specimens exhibited approximately 34% lower values than beech test specimens. The values of the monitored characteristic increased with increasing material thickness. The effect of the densification of lamellas placed in the combinations did not show a significant effect, which is evident from Fig. 5. The effect of cyclic loading also showed no significant effect on IBS values.

CONCLUSIONS

1. This article contributes to expanding the knowledge of the synergistic effect of multiple factors (wood species, type of adhesive, lamellas combination, "degree of densification and material thickness," and cyclic loading) on IBS values. These results form a basic knowledge set that is indispensable for the further development of laminated wood-based materials with specific properties for their intended use.
2. The effect of the densification of individual components of laminated wood, the type of adhesive, and cyclic loading, had no significant effect on the monitored characteristic within the range of measurement. For further research, there is a need to focus on determining the effect of a higher number of cycles as well as a higher degree of densification. The effect of the above-mentioned factors is also influenced by other characteristics such as the modulus of elasticity, the limit of proportionality, and the modulus of plasticity, which can change on a larger scale due to the above changes (monitored factors). It is necessary to assess the monitored characteristic and effect of the selected factors with these other characteristics that are just as essential.
3. The wood species and lamellas combination (thickness in interaction with densification) had a highly significant effect on the values of the monitored characteristic of the laminated wood. These results indicate a positive effect of laminated wood in comparison to solid wood.

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