Impact Bending Strength as a Function of Selected Factors

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This article examines the influence of selected factors (wood species, densification, thickness, glue type, and number of cycles) on the impact bending strength (IBS) of solid and laminated wood. The evaluated properties were measured on samples of European beech (*Fagus sylvatica* L.) and common aspen (*Populus tremula* L.). Two types of glues were used for laminated wood: polyvinyl acetate (PVAc) and polyurethane (PUR). The highest IBS values were recorded in laminated beech specimens glued with polyvinyl acetate glue that were not subjected to cyclical loading.

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

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INTRODUCTION

Wood is a unique natural material demonstrating both positive and undesirable natural properties (Bodig and Jayne 1982). In the wood processing industry, new possibilities for eliminating its undesirable properties are constantly being sought, as are various modifications to improve its physical and mechanical properties. Such modifications include wood densification (Kurjatko *et al.* 2010). Each wood species is characterized by a specific density influencing its physical and mechanical properties. Higher density woods are firmer, harder, and more resistant than those with lower densities (Požgaj *et al.* 1993). Densification can increase the densities of woods with lower initial densities, thereby expanding the range of their possible uses.

Various densification methods have been used to increase wood density and improve its mechanical properties (Kollmann *et al.* 1975; Higashihara *et al.* 2000; Navi and Heger 2004; Boonstra and Blomberg 2007; Fukuta *et al.* 2008; Gabrielli and Kamke 2008; Fang *et al.* 2011; Fang *et al.* 2012). Wood densification techniques have been applied to wood for various purposes, such as, for example, to increase the adhesion of glue through the mechanical activation of the glued surface (Aydin 2004; Bekhta *et al.* 2009). Densification depends on many factors such as the wood species, density, and anisotropy (the direction of loading in pressure perpendicularly to the grain, radial or tangential) (Easterling *et al.* 1982; Morsing 2000; Nairn 2006), and is most frequently carried out by pressing. Knowledge about the dynamic strength of densified wood is minimal, and for this reason was included in the experimental part of our study.

Wood properties can also be modified by gluing together individual lamellas, resulting in the formation of so-called laminated materials. Phenol-formaldehyde (PF) glues are most frequently used for the industrial production of laminated veneer lumber (LVL) and other components (Adams 2005). PF glues are toxic, however, and thus the use of more environmentally friendly glues, such as polyvinyl acetate (PVAc) and polyurethane (PUR), is beginning to appear in manufactured furniture components. PVAc glues do not present a risk for human health and are environmentally friendly (Mitani and Barboutis 2010). They harden by a physical process wherein wood gradually draws water from the PVAc glue, thereby creating a continuous film on its surface (Sedliačik and Sedliačik 2000; Uysal and Kurt 2006).

The disadvantage of PVAc glues is that their price is higher than PF and UF glues. PUR glues are also used for gluing furniture elements; they harden through polymerization of isocyanates with alcohols or esters, which have many hydroxyl groups (Sedliačik and Sedliačik 2000). Their main advantages include flexibility, high resistance to temperature and water, and firmness (Vick and Okkonen 1998; Clauß *et al.* 2011; Hass *et al.* 2012). The main disadvantage of using PUR glues in gluing furniture components is, again, their higher price than PVAc glues.

During use, furniture can be subject to cyclical loading, represented by the repeated loading of an element by an external force over a certain time period. Repeated and alternating loading of metals was studied by Požgaj *et al.* (1993), which revealed the material’s permanent dynamic firmness and a curve demonstrating the relationship between tension and cyclical loading. After a certain number of cycles, the curve approaches the asymptote defining the limit of strain σ_F. The limit of strain also represents the tension at which wood will last for a theoretically infinite number of loading cycles. This research focused on the cyclical loading of solid and laminated densified wood.

In practice it frequently happens that furniture is damaged by the influence of dynamic loading. Dynamic loading of wood and wooden components also encompasses impact bending strength (IBS). Impact bending strength is the ability of wood to absorb strain energy through impact bending. It is measured mainly by using an impact head, whereby the objective of such loading is to determine the amount of force necessary to break the wood. High-strength wood will suffer a fibrous fracture while brittle wood usually exhibits a blunt fracture (Požgaj *et al.* 1993). Numerous authors have studied the IBS of grown wood and LVL. Barcík *et al.* (2008) presented a comparison of IBS for juvenile wood *versus* mature aspen wood, and demonstrated a higher value of IBS for mature aspen wood than for juvenile aspen wood. Bal and Bektaş (2012) studied the IBS of beech and poplar LVL glued with PF, urea-formaldehyde (UF), and melamine-urea-formaldehyde (MUF) glues. The results were compared with those for solid wood. The results of their research indicated that the influence of wood species on IBS was highly significant. The influence of glue type was found to be insignificant. Their research also presented lower IBS values for beech LVL in comparison with solid wood. The differences between IBS of LVL and solid poplar wood were not significant.

The selection of aspen wood for this research was mainly due to its low market price and quick growth (Bal 2014). Though seldom used in industry, its felling time is considerably shorter than that of beech. The results for aspen wood obtained in the research were compared with the values for beech wood, which is more frequently used for furniture production but is markedly more expensive. The objective of this study was to determine the influence of the aforementioned factors on breaking force, mainly due to the possible replacement of beech wood, and to determine the positive and possibly negative impacts of individual wood treatments (*i.e.*, densification and gluing) as well as the cycling process.

EXPERIMENTAL

Materials

Two wood species were used for the experiment: European beech (*Fagus sylvatica* L.) and common aspen (*Populus tremula* L.). Both woods originated from the Poľana region of central Slovakia. Lamellas were formed from cutouts and were then divided into two groups. The first group comprised lamellas with dimensions of 4, 6, 10 and 18 × 20 × 300 mm. The second group consisted of glued lamellas with the dimensions of 3 + 3, 5 + 5, and 9 + 9 × 20 × 300 mm which were conditioned in an APT Line II air-conditioning chamber (Binder; Tuttlingen, Germany) to an even moisture of 8% at a temperature of 20 °C and relative air humidity of 42%. This moisture level is the standard level for furniture elements.

Densification of solid wood

The first group of test specimens were cold-pressed in a UPS 1000 hydraulic press (RK MFL Prüfsysteme GmbH, Germany). The test specimens were subjected to 10% and 20% densification. The cold pressing was carried out in three phases:

1. First phase was closing the press and gradually densifying the specimens to the required thickness value. This process took 5 min.
2. During the second phase were specimens cold-pressed after 2 min.
3. The third phase was gradually opening the press and unloading the specimens – this process took 3 min. After this were the specimens relaxed (5 min).

The loading pressure was set in the radial direction of the wood fiber. Thickness of specimens was measured after relaxation of specimens. Table 1 presents the pressing parameters for individual lamella thicknesses of beech and aspen wood.

Table 1. Pressure Used for Individual Sets of Test Objects

Thickness of Lamellae (mm)	Degree of Densification 10%		Degree of Densification 20%	
	Beech (kN)	Aspen (kN)	Beech (kN)	Aspen (kN)
4	3,550	1,080	3,950	1,500
6	2,100	1,850	3,900	2,100
10	3,750	2,150	4,500	2,500
18	3,650	1,720	3,680	1,800

Gluing laminated wood

Lamellas with thicknesses of 3 + 3, 5 + 5, and 9 + 9 mm were glued with single-component, water-resistant PVAc glue, type AG-COLL 8761/L D3 (EOC Belgium; Oudenaarde, Belgium), and single-component polyurethane (PUR) glue, type NEOPUR 2238R (NEOFLEX; Alicante, Spain). Glue parameters are presented in Table 2. Glue was spread using a manual cylindrical spreader in the recommended single-side layer of 150 to 180 g/m^2 and 180 to 250 g/m^2 for PVAc and PUR, respectively. The lamellas were cold-pressed in a JU 60 industrial press (PAUL OTT; Austria) for 60 min. After pressing, the test specimens were conditioned in the same APT Line II air-conditioning chamber at a temperature of 20 °C and relative humidity of 42%.

Table 2. Adhesives and their Properties

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

Cyclical loading

Half of all test specimens were subject to cyclical loading of 10,000 cycles. Loading was performed on a special cyclical instrument (CULS; Praha, Czech Republic). Bending magnitude was determined experimentally for static loading at the 90% boundary of the proportionality limit so that the loading was applied only in a flexible area (see Methods). Test specimens were loaded at 20 cycles/min in the center of their length.

Methods

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 (weight) of the sample at moisture content w (kg); a_w, b_w, and l_w are dimensions of the sample at moisture content w (m); and V_w is the volume of the sample at moisture content w (m^3).

The moisture content of samples was determined and verified before and after testing. These calculations were carried out according to ISO 13061-1 (2014) and Eq. 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 (in kg), and m_0 is the mass (weight) of the oven-dry sample (in kg). Drying to oven-dry state was also carried out according to ISO 13061-1 (2014).

To convert ρ_w to ρ_{12}, we used the formula stated in ISO 13061-2 (2014) valid for humidity ranging from 7% to 17%, Eq. 3,

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

where K is the coefficient of volumetric drying for a 1% change of humidity. For approximate calculations it is possible to use $K = 0.85 \cdot 10^{-3} \cdot \rho_w$, where density is expressed in kg/m^3, ρ_{12} is density of the sample at moisture content 12 % (kg/m^3).

For determining three point's bending at the proportionality limit by means of static bending, the EN 310 (1993) standard was followed. First, we determined the proportionality limit from the graph of dependence between tension and deformation. The proportionality limit was at the boundary between straight-line and curved dependence (plastic domain). Bending was determined according to EN 310 (1993) and Eq. 4,

$$\Delta y = \frac{1}{4}\frac{\Delta F . l_0^3}{b . h^3 . E} \tag{4}$$

where Δy is the test sample deflection in the area of pure bending, equal to the difference between the bending values corresponding to maximum and minimum limits (mm), E is the elasticity modulus in MPa, ΔF is the difference between the forces at maximum and minimum load limits in N, l_0 is the distance between the supports (mm), and b and h are the width and height dimensions (mm).

To determine IBS, a Charpy hammer (CULS; Praha, Czech Republic) with a hammer weight of 20 kg was used. The principle in testing IBS is displayed in Fig. 1, wherein the hammer fell from height h_1. If the hammer had no obstacle, it reached height h_0. In case it encountered resistance from the test specimens, it reached position h_2. The energy, or rather work, consumed in damaging the specimens was determined as the difference of positional energies before and after hitting the specimens.

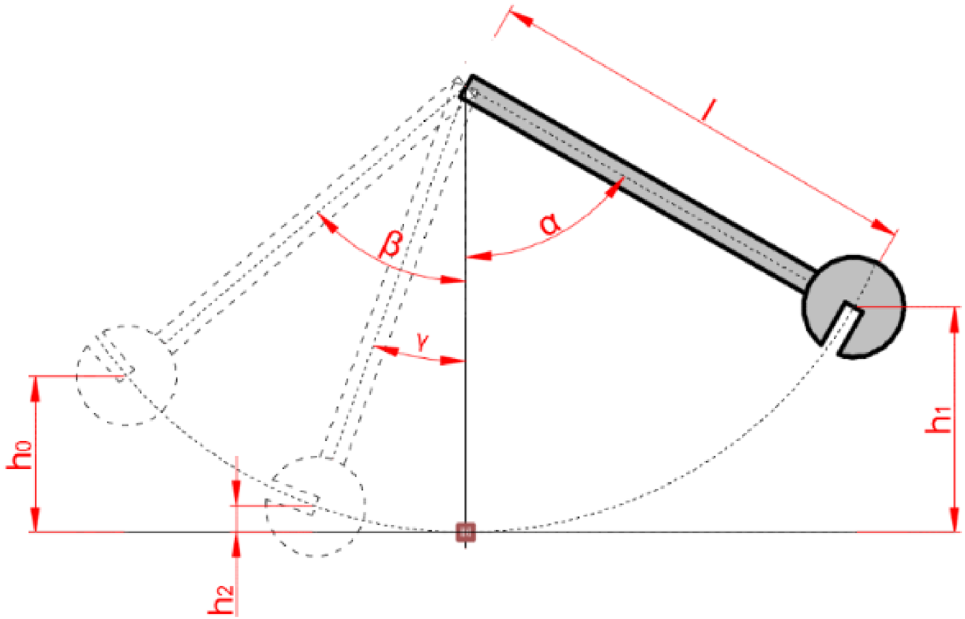

Fig. 1. Test of IBS

The direction of the hammer impact on the test specimens was to the tangential surface. For each test group, 10 test specimens were examined. Totally were prepared 180 specimens. The spread of supports on the Charpy hammer was 240 mm. The IBS test was calculated in accordance with ISO 3348 (1975) and Eq. 5,

$$A_w = \frac{Q}{b * h} \tag{5}$$

where A_W is the IBS of wood (J.cm^{-2}), Q is the energy involved in damaging 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% in accordance with ISO 3348 (1975) and Eq. 6,

$$A_{12} = A_w\left[1+\alpha(w-12)\right] \tag{6}$$

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

In order to determine the influence of the multifactorial analysis and of the individual factors on the IBS, both the ANOVA and, in particular, the Fischer F-test were used in STATISTICA 12 (Statsoft Inc., Tulsa, OK, USA) software.

Based on P-level, it was determined whether the evaluated factor affected the IBS values. The results obtained were processed by means of diagrams showing a 95% confidence interval.

RESULTS AND DISCUSSION

Table 3 shows that the highest average value for IBS of 29.6 J/cm^2 was achieved using PVAc glue with 18 mm laminated glued beech wood that was not densified or cyclically loaded.

The lowest IBS value, at 2.3 J/cm^2, was recorded for solid non-densified aspen wood, with a thickness of 4 mm, that was not subjected to cyclical loading (Table 4). In general, aspen showed higher variability in IBS values than did beech. All values of IBS, as well as density, were converted to 12% humidity equivalents to compare the results with those of other authors.

The average IBS value for non-densified solid beech 10 mm thick and not cyclically loaded was 7.6 J/cm^2 (Table 3). This value is comparable to those of various other authors. Wagenführ (2000) reported 10.0 J/cm^2 as an average value for beech. Požgaj *et al.* (1993) stated an average IBS for beech wood of 8.1 J/cm^2, while Lokaj and Vavrušová (2010) indicated an average value of 6.9 J/cm^2.

For non-densified and not cyclically loaded aspen with a 10 mm thickness, the present study measured an average IBS of 4.6 J/cm^2 (Table 4), which is comparable to the 4.0 J/cm^2 reported by Wagenführ (2000). Barcík *et al.* (2008) indicated an average IBS for aspen of 3.2 J/cm^2. Based on the values presented in Table 3, aspen had greater density variability than did beech.

The average density of non-densified and not cyclically loaded wood was 693 (6.4) kg/m^3 for beech and 500 (12.6) kg/m^3 for aspen. Wagenführ (2000) reported beech density as 720 kg/m^3 and aspen density as 490 kg/m^3 at 12% humidity, which correspond to the values measured here.

Table 3. Basic Statistical Analysis of IBS for Solid and Glued Laminated Beech Wood

Wood Species	Material Thickness (mm)	Degree of Densification (%)	Number of Cycles	Glue	Impact Bending (J/cm^2)	Density (Kg/m^3)
Beech	4	0	0	-	5.9 (19.7)	693 (4.6)
Beech	4	0	10,000	-	6.8 (27.6)	680 (9.5)
Beech	4	10	0	-	5.6 (23.0)	725 (8.6)
Beech	4	10	10,000	-	6.6 (28.9)	739 (6.6)
Beech	4	20	0	-	5.7 (7.3)	784 (4.0)
Beech	4	20	10,000	-	5.1 (9.9)	766 (4.7)
Beech	6	0	0	-	5.8 (31.3)	665 (3.4)
Beech	6	0	10,000	-	5.8 (13.7)	692 (4.4)
Beech	6	10	0	-	4.9 (23.0)	703 (4.8)
Beech	6	10	10,000	-	5.8 (31.3)	749 (5.0)
Beech	6	20	0	-	7.8 (33.4)	751 (5.6)
Beech	6	20	10,000	-	4.9 (3.4)	750 (5.3)
Beech	10	0	0	-	7.6 (13.2)	694 (4.7)
Beech	10	0	10,000	-	6.0 (5.8)	690 (5.8)
Beech	10	10	0	-	6.6 (14.8)	733 (3.7)
Beech	10	10	10,000	-	7.4 (8.2)	719 (5.6)
Beech	10	20	0	-	6.4 (13.7)	788 (3.5)
Beech	10	20	10,000	-	5.8 (25.4)	726 (2.5)
Beech	18	0	0	-	9.9 (17.0)	735 (8.1)
Beech	18	0	10,000	-	8.0 (16.1)	698 (8.2)
Beech	18	10	0	-	8.0 (33.0)	744 (3.9)
Beech	18	10	10,000	-	8.3 (18.5)	749 (4.6)
Beech	18	20	0	-	8.5 (34.4)	747 (6.8)
Beech	18	20	10,000	-	8.0 (33.0)	757 (8.6)
Beech	3+3	0	0	PVAC	6.1 (14.1)	721 (1.3)
Beech	3+3	0	10,000	PVAC	6.2 (10.9)	663 (3.0)
Beech	3+3	0	0	PUR	7.6 (13.4)	643 (2.7)
Beech	3+3	0	10,000	PUR	6.7 (6.0)	685 (2.9)
Beech	5+5	0	0	PVAC	13.6 (8.5)	703 (2.7)
Beech	5+5	0	10,000	PVAC	13.0 (22.3)	691 (7.9)
Beech	5+5	0	0	PUR	12.9 (16.5)	667 (2.9)
Beech	5+5	0	10,000	PUR	14.6 (12.7)	684 (1.5)
Beech	9+9	0	0	PVAC	29.6 (16.5)	699 (4.3)
Beech	9+9	0	10,000	PVAC	28.2 (14.5)	681 (2.1)
Beech	9+9	0	0	PUR	25.3 (7.7)	682 (2.0)
Beech	9+9	0	10,000	PUR	27.8 (14.6)	697 (2.4)

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

Table 4. Basic Statistical Analysis of IBS for Solid and Glued Laminated Aspen Wood

Wood Species	Material Thickness (mm)	Degree of Densification (%)	Number of Cycles	Glue	Impact Bending (J/cm^2)	Density (Kg/m^3)
Aspen	4	0	0	-	2.3 (28.3)	400 (4.1)
Aspen	4	0	10,000	-	3.1 (4.1)	416 (8.4)
Aspen	4	10	0	-	2.4 (10.5)	421 (9.3)
Aspen	4	10	10,000	-	4.6 (47.9)	404 (3.6)
Aspen	4	20	0	-	2.6 (37.3)	488 (5.7)
Aspen	4	20	10,000	-	2.8 (31.7)	476 (14.1)
Aspen	6	0	0	-	4.3 (48.5)	533 (8.7)
Aspen	6	0	10,000	-	3.5 (9.1)	539 (4.4)
Aspen	6	10	0	-	6.0 (28.1)	557 (6.6)
Aspen	6	10	10,000	-	6.9 (29.5)	584 (7.9)
Aspen	6	20	0	-	8.1 (37.8)	620 (9.6)
Aspen	6	20	10,000	-	4.3 (9.6)	580 (6.5)
Aspen	10	0	0	-	4.6 (7.9)	528 (4.2)
Aspen	10	0	10,000	-	4.9 (32.7)	536 (8.4)
Aspen	10	10	0	-	4.0 (17.7)	564 (1.3)
Aspen	10	10	10,000	-	4.3 (0.9)	560 (5.8)
Aspen	10	20	0	-	4.5 (33.7)	604 (1.8)
Aspen	10	20	10,000	-	5.4 (47.5)	628 (13.9)
Aspen	18	0	0	-	6.7 (54.0)	529 (2.1)
Aspen	18	0	10,000	-	6.1 (34.5)	519 (12.7)
Aspen	18	10	0	-	7.6 (26.9)	568 (4.8)
Aspen	18	10	10,000	-	4.3 (56.0)	581 (4.0)
Aspen	18	20	0	-	7.3 (22.4)	589 (7.0)
Aspen	18	20	10,000	-	6.1 (33.8)	594 (6.2)
Aspen	3+3	0	0	PVAC	3.6 (44.3)	490 (14.0)
Aspen	3+3	0	10,000	PVAC	4.1 (34.8)	465 (21.6)
Aspen	3+3	0	0	PUR	6.1 (19.7)	563 (9.8)
Aspen	3+3	0	10,000	PUR	4.0 (48.7)	464 (8.5)
Aspen	5+5	0	0	PVAC	7.9 (36.8)	417 (8.3)
Aspen	5+5	0	10,000	PVAC	10.8 (18.0)	471 (13.6)
Aspen	5+5	0	0	PUR	6.7 (46.1)	378 (2.0)
Aspen	5+5	0	10,000	PUR	10.0 (43.4)	439 (14.0)
Aspen	9+9	0	0	PVAC	16.4 (24.9)	387 (3.9)
Aspen	9+9	0	10,000	PVAC	14.3 (27.6)	413 (10.3)
Aspen	9+9	0	0	PUR	14.4 (41.2)	379 (6.0)
Aspen	9+9	0	10,000	PUR	15.8 (29.3)	375 (3.8)

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

Table 5 presents the results of individual factors' influence as well as their four-factor interaction. Based on the P significance levels, *wood species* and *material thickness* demonstrated a significant effect on the IBS values of solid wood. *Degree of densification* and *number of cycles* did not have significant influence on the values of the evaluated characteristic. The synergistic effect of the evaluated factors was demonstrated to be insignificant.

Table 5. Influence of Factors and their Interaction on IBS for Solid Wood

Evaluated Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level P
Intercept	8,031.393	1	8,031.393	2,281.333	0.000001
1) Wood species	205.379	1	205.379	58.338	0.000001
2) Material thickness	265.659	3	88.553	25.154	0.000001
3) Degree of densification	13.558	2	6.779	1.926	0.148604
4) Number of cycles	2.520	1	2.520	0.716	0.398530
1*2*3*4	24.006	6	4.001	1.136	0.342645
Error	675.933	192	3.520		

Significance was accepted at P < 0.01

The statistical influence of individual factors and their four-factor combination on the IBS of laminated wood is presented in Table 6. The factors *wood species* and *material thickness* were significant, while *glue* and *number of cycles* were shown to be insignificant. The interaction of all factors was insignificant in relation to IBS.

Table 6. Influence of Factors and their Interaction on IBS for Laminated Wood

Evaluated Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level P
Intercept	19,469.27	1	19,469.27	1,700.528	0.000001
1) Wood species	1,251.30	1	1,251.30	109.294	0.000001
2) Glue	0.75	1	0.75	0.066	0.798267
3) Material thickness	5,216.26	2	2,608.13	227.805	0.000001
4) Number of cycles	5.85	1	5.85	0.511	0.476378
1*2*3*4	0.79	2	0.39	0.034	0.966205
Error	1099.10	96	11.45		

Significance was accepted at P < 0.01

Figure 2 displays the significant influence of wood species on the IBS of solid wood and laminated wood. The average IBS value for beech wood was 6.7 J/cm^2, which was 40% higher than that for aspen. The statistical significance of wood species on the IBS of laminated wood can be seen in Fig. 2. Laminated beech achieved 68% higher IBS values than did aspen wood. In comparing solid and laminated wood, laminated wood showed markedly higher values of the evaluated characteristic, with laminated beech having 139% higher values than solid beech. A 98% increase was also observed in laminated aspen as compared to solid wood. Laminated wood's higher values were likely due to the homogenization of laminated wood as compared to solid wood. In comparing solid and laminated wood, another interesting fact was observed: laminated aspen achieved 42% higher IBS values than did solid beech. It could therefore be used as a replacement for the more expensive beech wood.

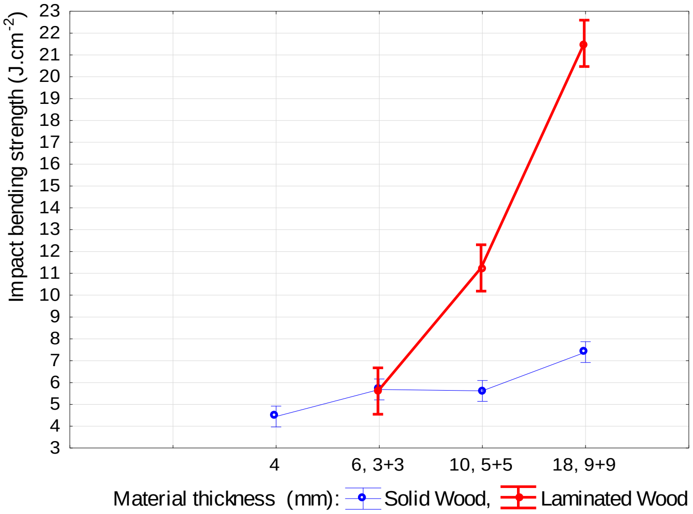

Fig. 2. Effect of wood species on IBS for solid wood and laminated wood

The statistically significant influence of thickness on IBS values for solid wood can be seen in Fig. 3. The values of the evaluated characteristic rose with increasing material thickness. The highest IBS (7.4 J/cm^2) was achieved at 18 mm thickness, representing a 66% increase over the average value detected at 4 mm thickness. There were no significant differences between the values at 6 mm and 10 mm material thickness, while the others were significantly different. Figure 5 also shows the significant effect of material thickness on the evaluated characteristic for laminated wood. The highest average value (21.3 J/cm^2) was achieved by laminated wood with a thickness of 9 + 9 mm and was 284% higher than that for 3 + 3 mm thickness. A positive effect of gluing was demonstrated on the values on IBS, especially at higher thicknesses of lamellas (5 + 5 a 9 + 9 mm) compared to the solid wood of the same thickness. Laminated wood 5 + 5 mm should have IBS values approximately 100% higher than those of solid wood with a thickness of 10 mm. Laminated wood 9 + 9 mm should have values approximately 188% higher than the observed growth characteristics of solid wood with a thickness of 18 mm.

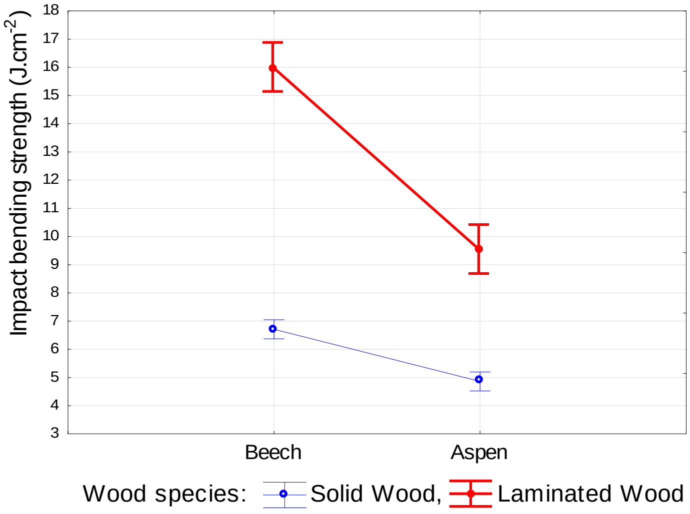

Fig. 3. Effect of material thickness on IBS for solid wood and laminated wood

The statistically insignificant influence of the number of cycles on IBS values for solid and laminated wood can be seen in Fig. 4. In both cases, a 4% increase in IBS was achieved at 10,000 cycles. The increase in proportionality limits could have occurred due to a release of bonds between the components of lignin and cellulose at the submicroscopic level. These bonds constituted the main component providing wood strength. Releasing these bonds increased the values of the flexibility limit (Požgaj *et al.* 1993). This increase, however, was statistically insignificant. Cyclically loaded laminated wood had markedly higher IBS values (120%) than non-cyclically loaded solid wood.

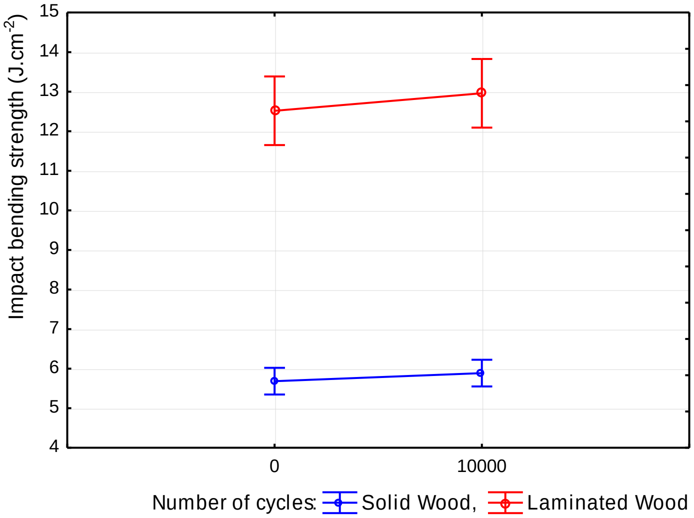

Fig. 4. Effect of number of cycles on IBS for solid wood and laminated wood

Densification showed no significant effect on IBS for solid beech and aspen wood (Fig. 5 and Table 5). The differences in IBS values at 10% densification in comparison with non-densified wood were negligible. A higher decrease in values can be observed at 20% densification (*ca.* 7%), but this is also insignificant in comparison with non-densified wood.

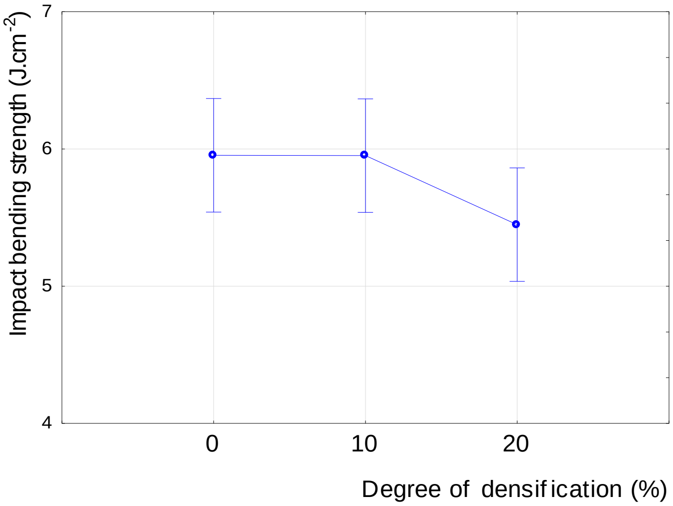

Fig. 5. Effect of the degree of densification on IBS for solid wood

The type of glue used in laminated wood demonstrated a statistically insignificant effect on the evaluated characteristic (Fig. 6 and Table 6). Specimens glued with PVAc had approximately 1% higher values than did specimens glued with PUR. However, the difference between these values was insignificant.

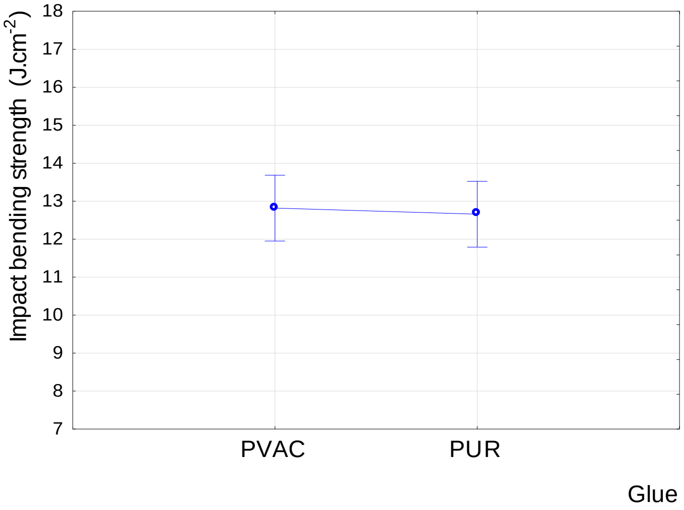

Fig. 6. Effect of the glue type on IBS for laminated wood

The synergistic effect of all factors on IBS of solid wood is presented in Figs. 7 and 8. Figure 7 shows the synergistic effect without cyclical loading, while Fig. 10 represents the synergistic effect of all factors with cyclical loading (10,000 cycles). The highest IBS (9.9 J/cm^2) was exhibited by non-densified beech specimens 18 mm thick that were not subject to cyclical loading (Fig. 7). On the other hand, non-densified aspen wood that was not cyclically loaded had the lowest value (2.3 J/cm^2). The figures also demonstrate the inconclusive influences of densification and cyclical loading.

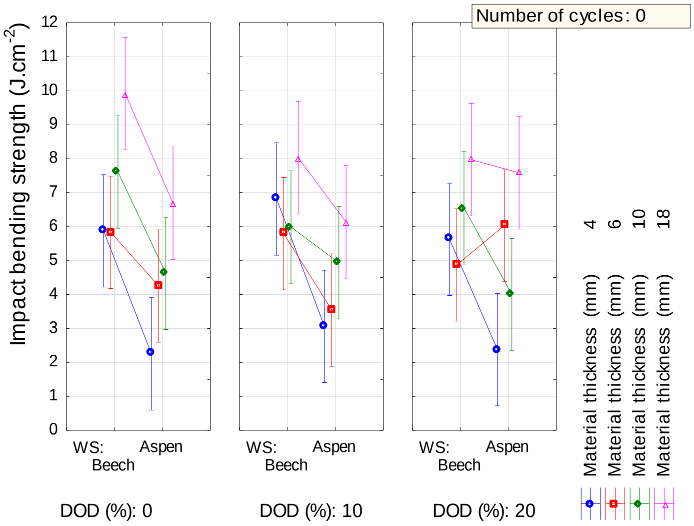

Fig. 7. Synergistic effect of the studied factors on the IBS for solid wood

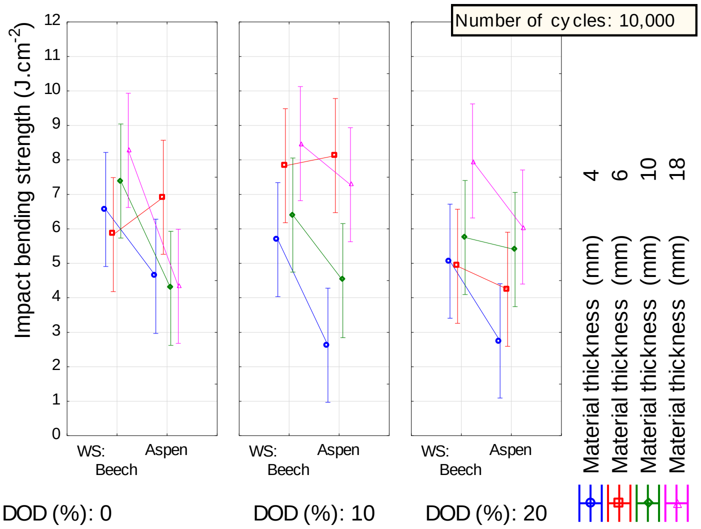

Fig. 8. Synergistic effect of the studied factors on IBS for solid wood

Figures 9 and 10 present the interaction of all factors on the evaluated characteristic of laminated wood. Figure 9 shows the interaction of factors for specimens not cyclically loaded, while Fig. 10 displays the interaction of factors for cyclically loaded specimens (10,000 cycles). Laminated beech wood with a thickness of 9 + 9 mm (29.6 J/cm^2) and was not cyclically loaded exhibited the highest values, while aspen with a thickness of 3 + 3 mm (3.6 J/cm^2) not subject to cyclical loading showed the lowest IBS. Both figures demonstrate the statistically insignificant influence on the evaluated characteristic of glue type used and of the number of loading cycles.

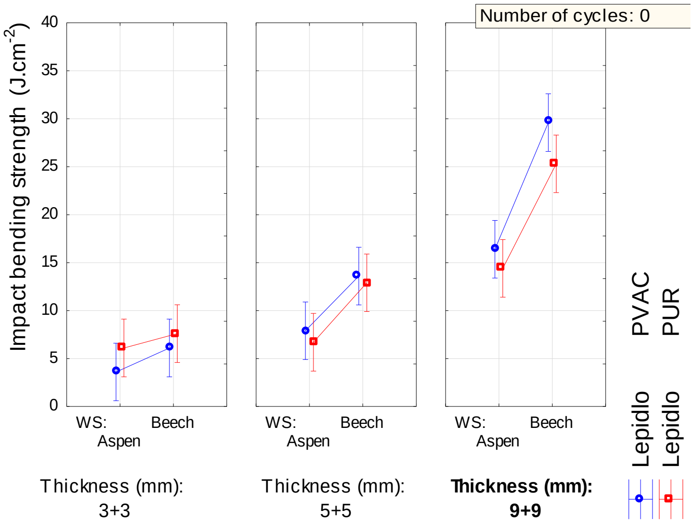

Fig. 9. Synergistic effect of the studied factors on IBS for laminated wood

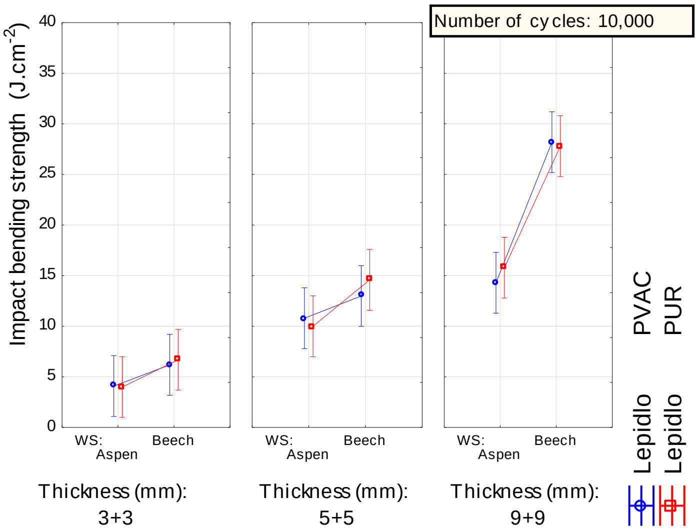

Fig. 10. Synergistic effect of the studied factors on IBS for laminated wood

CONCLUSIONS

1. Densification had no statistically significant influence on IBS values for solid beech or aspen wood. Increasing the densification level negligibly decreased IBS, whereas the decrease in values was not significant at the evaluated significance level.
2. The influence of cyclical loading on IBS for beech and aspen wood was statistically insignificant at 10,000 cycles and frequency 20 cycles per minute. Wood species, thickness, and glue type were shown to be significant. Cyclically loaded specimens had slightly higher values than did specimens that were not cyclically loaded, although this difference was not statistically significant.
3. The largest increase in IBS as compared to solid wood was recorded in laminated wood at 18 mm thickness. This demonstrated the positive effect of gluing lamellas for both beech and aspen.

ACKNOWLEDGMENTS

The authors are grateful for the support of the University-wide Internal Grant Agency (CIGA) of the Faculty of Forestry and Wood Sciences, Project No. 2016 - 4311.

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Article submitted: August 9, 2016; Peer review completed: September 24, 2016; Revised version received: September 26, 2016; Accepted: September 27, 2016; Published: October 3, 2016.
DOI: 10.15376/biores.11.4.9880-9895