Identifying the Characteristics of Laminated Wood Based on the Values of Deflection Measured during its Bending

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This article is aimed at verifying the influence of selected factors (wood species, lamella combination, type of adhesive, number of loading cycles) on the deflection at the proportionality limit Y_E, deflection at the point of rupture Y_{MOR}, and the ratio between the deflection at the proportionality limit and the deflection at the point of rupture $Y_E:Y_{MOR}$. All of the monitored characteristics were evaluated on test specimens made from lamellas of beechwood (*Fagus sylvatica* L.) and aspen wood (*Populus tremula* L.). The laminated wood consisted of a combination of lamellas that were non-densified and densified to 10% and 20% of their original thickness. Two types of adhesives were used for the research: polyvinyl acetate (PVA) glue and polyurethane (PUR) glue. The results create a database of information that can be used in developing materials with specified properties for its intended use.

Keywords: Cyclic loading; Laminated wood; Bending strength; Deflection

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INTRODUCTION

Wood's characteristics make it a unique material (Bodig and Jayne 1982). Since ancient times up until today, it has been one of the most commonly used and most versatile materials. Intensive research is being conducted throughout the world on the internal structure of wood, chemical structure, physics, mechanical properties, processing technologies, and the modification of its properties and wood components (Požgaj *et al.* 1993).

The properties of wood can be improved by deliberately modifying it. Such modifications include lamination, which can be described as a technology of layering and bonding thin veneers cut parallel to the grain in order to obtain the desired shapes and properties of the material (Bodig and Jayne 1982; Zemiar *et al.* 1999; Gašparík and Gaff 2015b). Such materials are characterized by higher strength, higher dimensional stability, higher aesthetic value, and a high degree of prefabrication (Nelson 1997). In addition to commercial formaldehyde adhesives used in the manufacture of laminated wood, the application of environmentally friendly adhesives such as polyvinyl acetate and polyurethane adhesives is becoming more widespread. Their greatest advantage over formaldehyde-based adhesives is the fact that they aren't toxic (Kim and Kim 2006; Gaff *et al.* 2016).

Densification of wood is another way to change its properties (Blomberg *et al.* 2005; Wang and Cooper 2005; Gaff *et al.* 2017). Densification increases the amount of wood substance in the volume, *i.e.* it increases the wood's density. Almost all of the mechanical properties of wood densification increases (Regináč *et al.* 1980). It is most often performed by compression (Tumuluru *et al.* 2010).

A frequent cause of the failure of furniture parts is repetitive deformation stress, which adversely affects the overall durability of the finished products (Bezazi and Scarpa 2007; Smardzewski 2013). If a part is exposed to cyclic loading, the amount of which changes over time, the part may be damaged during its use; we call this fatigue failure (Gašparík and Gaff 2015a). A material's resistance to this type of loading is expressed by the fatigue strength. The authors' research also verified the effect of cyclic loading on lamellas with 10,000 loading cycles.

Probably the most common method of bend loading of beams is loading with a single force at the center of the beam, or outside the center. This is simple bending, where in addition to tensile and compressive stress, shear stress is created in the cross section of the loaded part (Kollmann *et al.* 1975; Bodig and Jayne 1982; Požgaj *et al.* 1993; Zemiar *et al.* 1999). Within the proportionality limit, the tensile and compressive stress on the cross-section is equal, and the neutral layer is in the center and the wood is only deformed elastically. When the stress exceeds the limit of proportionality, the neutral layer is moved to the side that is experiencing tension. In this moment delayed elastic deformation and permanent plastic deformation occurs.

The beam is deformed under the influence of the bending moment. The size of the resulting deflection in the beam caused by stress may not be the same in two different wood species (M1 and M2). To achieve deflection at the proportionality limit in wood species M1, a much larger force was required than in wood species M2 (Fig. 1). Figure 2 shows a force-deflection diagram for wood species M1, which indicates a small percentage of plastic deformation at a large load force. It is the same for deformation (deflection) at the proportionality limit, for which a significant load force is required.

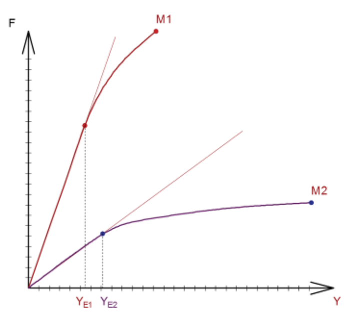


Fig. 1. The effect of the wood species on deflection at the proportional limit

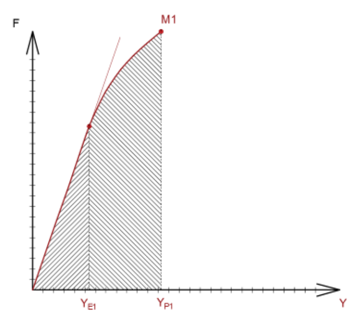


Fig. 2. Deflection at the proportional limit and at the point of rupture of wood species M1 with small plastic deformation

To achieve deformation or deflection at the point of rupture of wood species M1 and M2, a different maximum load force must be applied (Fig. 3). Wood species M1 required a several times higher maximum force than wood species M2 in order to achieve plastic deformation. However, the size of plastic deformation is significantly higher in wood species M2 than in wood species M1. Figure 4 shows a force-deformation diagram for wood species M2, which exhibited a large percentage of plastic deformation at a small load force.

In terms of technological properties of the wood, such as wood bending, the aim is to achieve a high percentage of plastic deformation in the material. It can therefore be concluded that wood species M2 with a greater percentage of plastic deformation are more suitable for technological using *e.g*. pressing, bending, *etc*. (Požgaj *et al*. 1993; Zemiar *et al*. 1999).

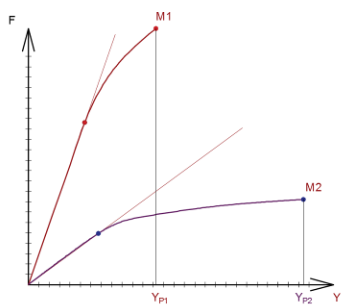


Fig. 3. The effect of the wood species on deflection at the point of rupture

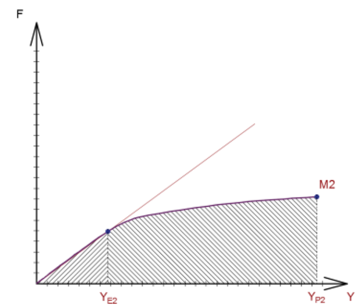


Fig. 4. Deflection at the proportional limit and at the point of rupture of wood species M2 with large plastic deformation

Determining the bending characteristics of wood is of great importance for its qualitative and quantitative assessment. Based on these assessments, the use of the wood and wood composites will be directed in the market to be as effective as possible. Bending characteristics are also important in terms of the comparison of various wood species, or in terms of the comparison of the same wood species from different habitats (Dubovský *et al*. 2003).

The research focuses on monitoring the effect of selected factors, *i.e*. wood species, lamellar combination, type of adhesive, and cyclic loading, on the deflection at the proportionality limit, or strength, as well as the ratio of deflection of glued laminated beech and aspen wood.

EXPERIMENTAL

Materials

Beech wood (*Fagus sylvatica* L.) and aspen wood (*Populus tremula* L.) from the Poľana region in Slovakia were used for the test specimens. The selected wood species were used to produce lamellas consisting of a combination of non-densified wood and wood with different degrees of densification (10% and 20%). The test specimens intended for densification were pressed in a hydraulic press (RK Prüfsysteme MFL 1000, Germany). The values of springback deformation were measured and will be evaluated separately in the part devoted to rheology.

The lamellas were acclimatized to an equilibrium moisture content of 8% in a climatic chamber, where the following parameters were set up: relative humidity of 40% and temperature of 20°C. The moisture content of 8% corresponds to the equilibrium moisture content of interior elements pursuant to ČSN 91 0001 (2007) and EN 942 (2007).

Table 1 shows the lamellar combinations used in research. The same combinations were used for beech and aspen wood.

Table 1. Marking and Parameters of Samples

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

Gluing laminated wood

The lamellas were glued together using a single-component polymer dispersion adhesive with excellent water resistance AG-COLL 8761/L D3 (EOC Belgium; Oudenaarde, Belgium). The measured results were compared with results measured using the polyurethane glue NEOPUR 2238R (NEOFLEX; Alicante, Spain). A specification of the adhesives used is given in Table 2.

Table 2. Adhesives and their Properties

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

Cyclic bend loading

Half of the test specimens were subjected to 10,000 loading cycles. The loading was carried out on a special cyclic loading machine (CULS; Czech Republic). The size of the deflection was experimentally determined under static bending at 90% of the limit of proportionality, so that the stress was only within the elastic limit pursuant to EN 310 (1993). The test specimens were loaded at a rate of 20 cycles/min. in the center of their length.

We used these prepared test specimens to analyze the effect of selected factors on the monitored characteristics:

- $\boldsymbol{Y}_{\mathbf{E}}$ – deflection and the proportionality limit
- $\boldsymbol{Y}_{\mathbf{MOR}}$ – deflection at the point of rupture
- $\boldsymbol{Y}_{\mathbf{E}}$ **:** $\boldsymbol{Y}_{\mathbf{MOR}}$ – ratio of deflection at the proportionality limit and at the point of rupture,

For each set of test specimens, 10 test samples were used. The samples were selected without defects such as knots on the tensile side, cracks and breaks, which could negatively affect the results of the mechanical tests (Požgaj *et al.* 1993).

Bending

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

Evaluation and Calculation

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

The moisture content of samples was determined and verified before and after testing according to ISO 13061-1 (2014). Drying to oven-dry state was also carried out according to ISO 13061-1 (2014).

To convert ρ_W to ρ_{12} experiments with moisture content ranging from 7% to 17% were carried out according to ISO 13061-2 (2014).

Bending was determined according to EN 310 (1993).

The deflection ratio was calculated according to Eq. 1,

$$\mathrm{P}_{EP} = (Y_E / Y_{MOR}) * 100 \qquad (1)$$

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

RESULTS AND DISCUSSION

Table 3 shows the average values of the monitored characteristics, as well as the corresponding coefficient of variation. The highest average values of the deflection at the proportionality limit Y_E 7.0 mm was achieved in a combination of beech lamellas 9ND10 glued with PVA glue, which were subjected to cyclic loading. The combination of glued aspen wood achieved a similar value (6.7 mm). The lowest average values of Y_E (2.0 mm) found in beech test specimens were achieved in a combination of lamellas 3DD20 glued with PVA glue, which were not subjected to cyclic loading. In aspen wood a similar lowest value of Y_E (2.0 mm) was found in two combinations of lamellas glued with PVA glue 5DD10 a 5DD20, which were not subjected to cyclic loading. The beech specimens had an 8.1% higher deflection Y_E than aspen specimens, which had a 9.1% greater variability of Y_E values.

The highest average deflection at the point of rupture Y_{MOR} (19.3 mm) in glued beech wood was found in the combination 9ND10 glued with PVA glue after cyclic loading. In aspen specimens, the lamella combination 9DD20 achieved the highest deflection value Y_{MOR} (18.8 mm). This combination was glued with PUR glue and was not subjected to cyclic loading. The lowest average value of Y_{MOR} in beech specimens (6.3 mm) was measured in the combination 3DD10, which was glued with PVA glue and subjected to 10,000 loading cycles. A similar lowest deflection value with was measured in the aspen wood combination 3ND10 glued with PUR glue and subjected to cyclic loading. The aspen specimens had a 1% higher deflection at the point of rupture Y_{MOR} than beech specimens, but they also had a 39.5% higher variability of Y_{MOR} values.

The highest values of the deflection ratio Y_E: Y_{MOR} (49.1%) in beech wood was found for the combination 3ND20 glued with PVA glue, which was subjected to 10,000 loading cycles. In aspen wood, it was the combination 3ND10 glued with PUR glue and subjected to cyclic loading that achieved the highest ratio value (44.8%). The lowest value of the ratio Y_E: Y_{MOR} in beech wood 25.7% was achieved in the combination 5DD20, which was glued with PVA glue and was not subjected to cyclic loading. This value is similar to the lowest value of the ratio Y_E: Y_{MOR} (20.6 %), which was measured for the aspen combination 5DD10 glued with PVA glue, not subjected to cyclic loading. Beech specimens had 11.8% higher values of the monitored characteristic than aspen specimens; however, the aspen specimens also had a 40% higher variability of values.

The average value of all the beech specimens was 726 kg/m^3 (3.0), and 557 kg/m^3 (11.1) kg/m^3 in aspen wood. Wagenführ (2000) reports a density of 720 kg/m^3 in beech wood (*Fagus sylvatica* L.) at a 12% moisture content, and a density of 490 kg/m^3 in aspen wood. These data are similar to the present results.

Gáborík (2014b) examined the deflection of laminated wood with the dimensions of 10x50x300 mm, consisting of five beech veneers. The beech veneers were bonded with polyurethane glue. A maximum deflection was reported at the point of rupture of 16 mm. This value is higher than the 10.2 mm measured deflection at the point of rupture with the combination 5ND20, which was glued with PUR glue. The reason for this difference is presumably the different sizes of the test specimens. In the cited research, the deflection at the point of rupture for solid wood was reported as 13 mm. This value is closer to the present results.

Table 3. Average Values of Monitored Characteristics and the Relevant Coefficient of Variation

WS	GL	LC	NC	Y_E (mm)	Y_{MOR} (mm)	$Y_E : Y_{MOR}$ (%)	Density (Kg/m^3)	WS	GL	LC	NC	Y_E (mm)	Y_{MOR} (mm)	$Y_E : Y_{MOR}$ (%)	Density (Kg/m^3)
B	PVAC	3ND10	0	2.8 (44.9)	6.7 (5.7)	41.9 (44.0)	785 (24.0)	A	PVAC	3ND10	0	2.5 (8.8)	6.6 (9.2)	37.5 (7.7)	720 (2.1)
B	PVAC	3ND10	10,000	2.3 (57.6)	7.4 (13.7)	41.1 (19.3)	701 (1.0)	A	PVAC	3ND10	10,000	2.8 (26.8)	6.3 (11.7)	44.7 (29.3)	727 (1.2)
B	PVAC	3ND20	0	2.8 (12.9)	6.5 (10.6)	42.9 (16.6	707 (2.1)	A	PVAC	3ND20	0	2.2 (10.6)	6.6 (14.4)	33.9 (21.3)	730 (1.8)
B	PVAC	3ND20	10,000	3.4 (10.7)	6.9 (11.6)	49.1 (12.3)	731 (1.3)	A	PVAC	3ND20	10,000	2.7 (7.7)	6.2 (14.3)	44.7 (24.7)	714 (3.6)
B	PUR	3ND10	0	3.1 (9.7)	6.5 (4.9)	48.0 (7.3)	715 (1.3)	A	PUR	3ND10	0	3.4 (7.6)	7.9 (22.2)	44.2 (19.5)	670 (16.6)
B	PUR	3ND10	10,000	3.0 (3.9)	6.5 (4.7)	45.7 (5.2)	703 (2.5)	A	PUR	3ND10	10,000	2.7 (26.8)	6.1 (12.5)	44.8 (21.5)	562 (11.1)
B	PUR	3ND20	0	3.1 (3.5)	6.8 (6.4)	46.1 (7.1)	706 (3.3)	A	PUR	3ND20	0	3.5 (7.4)	8.3 (8.5)	42.8 (15.1)	638 (4.4)
B	PUR	3ND20	10,000	2.9 (17.0)	6.8 (6.9)	42.3 (17.8)	718 (3.0)	A	PUR	3ND20	10,000	2.5 (27.3)	7.0 (7.3)	35.3 (24.3)	648 (2.7)
B	PVAC	5ND10	0	4.5 (6.9)	11.0 (14.1)	41.6 (18.6)	723 (3.2)	A	PVAC	5ND10	0	3.0 (21.6)	9.6 (10.0)	31.6 (32.2)	642 (2.9)
B	PVAC	5ND10	10,000	4.2 (12.6)	9.6 (3.2)	43.7 (15.2)	716 (2.9)	A	PVAC	5ND10	10,000	4.4 (21.4)	10.2 (16.3)	43.5 (18.5)	484 (23.8)
B	PVAC	5ND20	0	4.5 (4.9)	11.4 (8.2)	39.7 (10.7)	735 (1.9)	A	PVAC	5ND20	0	3.8 (22.4)	10.0 (23.2)	38.2 (10.2)	576 (4.9)
B	PVAC	5ND20	10,000	3.8 (11.9)	9.6 (16.5)	40.2 (24.7)	733 (1.4)	A	PVAC	5ND20	10,000	3.8 (3.6)	10.2 (19.9)	38.8 (16.2)	620 (8.8)
B	PUR	5ND10	0	4.1 (5.6)	9.8 (21.8)	43.5 (25.2)	730 (2.5)	A	PUR	5ND10	0	3.2 (10.5)	9.8 (12.7)	32.6 (14.9)	554 (11.7)
B	PUR	5ND10	10,000	4.0 (3.4)	9.3 (8.8)	43.1 (7.4)	749 (2.6)	A	PUR	5ND10	10,000	3.8 (3.6)	9.4 (14.8)	41.1 (16.0)	541 (15.0)
B	PUR	5ND20	0	3.7 (56.6)	10.2 (6.4)	45.7 (7.5)	718 (5.1)	A	PUR	5ND20	0	3.4 (12.4)	9.9 (23.4)	36.3 (26.6)	480 (13.1)
B	PUR	5ND20	10,000	4.2 (8.5)	9.8 (22.8)	45.1 (27.8)	764 (2.5)	A	PUR	5ND20	10,000	4.1 (32.3)	10.6 (28.8)	38.8 (16.2)	499 (10.3)
B	PVAC	9ND10	0	5.9 (9.8)	15.7 (17.1)	37.7 (9.3)	726 (2.6)	A	PVAC	9ND10	0	5.3 (12.0)	17.8 (16.7)	30.2 (7.5)	484 (13.7)
B	PVAC	9ND10	10,000	7.0 (10.1)	19.3 (12.2)	36.5 (13.5)	722 (2.1)	A	PVAC	9ND10	10,000	6.7 (14.2)	17.5 (18.8)	31.9 (60.7)	489 (11.3)
B	PVAC	9ND20	0	5.6 (26.1)	13.4 (35.9)	43.4 (18.3)	721 (2.0)	A	PVAC	9ND20	0	5.2 (13.0)	13.2 (26.0)	41.1 (15.2)	453 (7.9)
B	PVAC	9ND20	10,000	6.3 (11.7)	16.1 (11.0)	39.2 (7.6)	704 (4.0)	A	PVAC	9ND20	10,000	5.9 (8.2)	15.7 (12.5	38.3 (16.0)	432 (8.5)
B	PUR	9ND10	0	6.3 (7.0)	16.3 (11.0)	38.7 (7.8)	692 (3.1)	A	PUR	9ND10	0	5.4 (5.9)	16.6 (15.5)	32.9 (14.8)	493 (13.4)
B	PUR	9ND10	10,000	6.5 (9.7)	15.9 (18.8)	42.1 (21.7)	689 (2.9)	A	PUR	9ND10	10,000	5.9 (5.9)	14.6 (10.4)	40.7 (7.0)	419 (12.0)
B	PUR	9ND20	0	5.8 (11.8)	14.7 (17.2)	40.0 (10.6)	732 (1.9)	A	PUR	9ND20	0	5.7 (5.1)	18.5 (16.0)	24.5 (59.5)	460 (5.0)
B	PUR	9ND20	10,000	6.2 (7.8)	15.9 (13.6)	39.6 (15.0)	733 (2.6)	A	PUR	9ND20	10,000	5.9 (4.6)	14.8 (15.3)	40.8 (15.4)	435 (14.3)
B	PVAC	3DD10	0	2.1 (5.3)	6.5 (9.8)	32.2 (11.0)	710 (2.3)	A	PVAC	3DD10	0	2.2 (23.4)	7.4 (23.3)	29.6 (7.9)	703 (3.8)
B	PVAC	3DD10	10,000	2.9 (9.5)	6.3 (8.6)	45.9 (12.5)	709 (2.1)	A	PVAC	3DD10	10,000	2.1 (10.6)	7.2 (35.5)	31.5 (28.5)	632 (19.8)
B	PVAC	3DD20	0	2.0 (14.6)	8.0 (21.3)	25.9 (27.9)	742 (2.7)	A	PVAC	3DD20	0	2.4 (11.1)	8.6 (27.6)	29.5 (27.1)	755 (4.6)
B	PVAC	3DD20	10,000	2.8 (5.1)	7.3 (9.0)	38.3 (7.4)	729 (1.3)	A	PVAC	3DD20	10,000	2.1 (5.2)	6.5 (7.4)	32.7 (10.7)	758 (2.4)
B	PUR	3DD10	0	2.9 (14.2)	7.0 (8.9)	42.1 (16.1)	728 (3.0)	A	PUR	3DD10	0	2.4 (20.2)	6.9 (7.2)	34.4 (16.3)	707 (10.7)
B	PUR	3DD10	10,000	2.9 (15.5)	6.8 (4.8)	42.8 (15.3)	740 (5.5)	A	PUR	3DD10	10,000	2.3 (14.4)	7.5 (14.7)	31.8 (23.6)	570 (10.0)
B	PUR	3DD20	0	2.6 (11.1)	7.0 (13.4)	37.3 (7.6)	772 (0.8)	A	PUR	3DD20	0	2.5 (17.7)	7.8 (30.2)	33.4 (21.3)	512 (13.8)
B	PUR	3DD20	10,000	2.6 (3.8)	6.8 (8.3)	38.2 (11.8)	720 (5.3)	A	PUR	3DD20	10,000	2.4 (10.7)	6.8 (7.7)	35.7 (14.6)	537 (22.2)
B	PVAC	5DD10	0	2.8 (9.0)	9.1 (11.9)	31.2 (18.6)	737 (2.5)	A	PVAC	5DD10	0	2.0 (14.1)	10.3 (23.9)	20.6 (22.3)	521 (20.1)
B	PVAC	5DD10	10,000	3.3 (16.6)	9.8 (14.7)	33.2 (4.9)	729 (3.7)	A	PVAC	5DD10	10,000	2.7 (18.1)	9.6 (14.0)	29.2 (30.5)	430 (7.6)
B	PVAC	5DD20	0	3.0 (13.3)	11.9 (15.9)	25.7 (23.7)	707 (2.0)	A	PVAC	5DD20	0	2.0 (16.9)	10.3 (33.3)	20.9 (32.2)	523 (19.0)
B	PVAC	5DD20	10,000	3.0 (7.9)	9.0 (8.6)	34.0 (6.6)	720 (2.1)	A	PVAC	5DD20	10,000	2.7 (16.3)	9.0 (15.5)	30.5 (21.3)	657 (12.3)
B	PUR	5DD10	0	2.9 (8.0)	9.3 (8.4)	30.9 (6.7)	760 (2.3)	A	PUR	5DD10	0	3.1 (5.2)	9.5 (10.9)	32.7 (10.7)	578 (15.9)

WS	GL	LC	NC	Y_E (mm)	Y_{MOR} (mm)	$Y_E : Y_{MOR}$ (%)	Density (Kg/m^3)	WS	GL	LC	NC	Y_E (mm)	Y_{MOR} (mm)	$Y_E : Y_{MOR}$ (%)	Density (Kg/m^3)
B	**PUR**	**5DD10**	**10,000**	2.9 (7.2)	9.6 (6.9)	30.3 (7.5)	726 (2.3)	**A**	**PUR**	**5DD10**	**10,000**	3.1 (14.8)	9.8 (17.2)	32.4 (17.0)	530 (20.7)
B	**PUR**	**5DD20**	**0**	3.1 (9.2)	8.8 (10.4)	35.8 (8.5)	714 (1.2)	**A**	**PUR**	**5DD20**	**0**	2.7 (11.3)	8.3 (22.0)	33.5 (16.2)	533 (23.7)
B	**PUR**	**5DD20**	**10,000**	3.0 (12.1)	9.3 (13.7)	32.4 (19.5)	722 (0.9)	**A**	**PUR**	**5DD20**	**10,000**	3.1 (7.7)	10.1 (25.9)	32.5 (27.3)	452 (8.8)
B	**PVAC**	**9DD10**	**0**	4.9 (5.2)	15.3 (4.2)	31.9 (6.6)	714 (1.5)	**A**	**PVAC**	**9DD10**	**0**	4.4 (6.7)	15.3 (13.7)	28.9 (12.3)	524 (16.6)
B	**PVAC**	**9DD10**	**10,000**	5.0 (5.0)	15.9 (6.3)	31.5 (6.4)	738 (3.1)	**A**	**PVAC**	**9DD10**	**10,000**	4.8 (8.8)	17.4 (9.7)	27.8 (11.5)	504 (19.4)
B	**PVAC**	**9DD20**	**0**	5.2 (5.0)	17.0 (10.1)	31.0 (10.2)	734 (3.1)	**A**	**PVAC**	**9DD20**	**0**	4.3 (9.3)	17.3 (11.7)	24.7 (6.5)	487 (10.4)
B	**PVAC**	**9DD20**	**10,000**	5.2 (6.0)	18.0 (12.9)	29.4 (11.6)	714 (4.3)	**A**	**PVAC**	**9DD20**	**10,000**	5.3 (13.6)	17.6 (19.7)	30.5 (10.3)	525 (5.5)
B	**PUR**	**9DD10**	**0**	5.2 (7.8)	15.9 (17.7)	33.4 (16.7)	702 (4.8)	**A**	**PUR**	**9DD10**	**0**	4.7 (12.8)	17.3 (19.7)	28.0 (25.0)	501 (21.1)
B	**PUR**	**9DD10**	**10,000**	4.9 (5.7)	15.6 (12.3)	31.4 (12.4)	725 (3.6)	**A**	**PUR**	**9DD10**	**10,000**	4.7 (10.6)	15.8 (12.5)	30.0 (3.5)	488 (9.1)
B	**PUR**	**9DD20**	**0**	5.6 (2.1)	18.5 (11.8)	30.4 (11.5)	762 (2.1)	**A**	**PUR**	**9DD20**	**0**	4.9 (14.9)	18.8 (3.3)	26.2 (13.4)	430 (3.5)
B	**PUR**	**9DD20**	**10,000**	5.5 (7.3)	19.1 (17.3)	28.9 (10.6)	756 (1.1)	**A**	**PUR**	**9DD20**	**10,000**	4.8 (7.9)	16.2 (11.1)	29.7 (5.7)	426 (10.8)

Where: WS is wood species; GL is type of adhesive; LC is lamella combination; NC is number of cyclic loading; A is aspen wood; B is beech wood. Values in parentheses are coefficients of variation (CV) in %

In his second study, Gáborík (2014a) also examined the effect of the thickness of aspen wood on the bendability in three-point bending in the radial direction. He reports a maximum deflection at the point of rupture of 4.9 mm at a 5 mm thickness. This value is lower than the deflection values we achieved in our combinations with similar thicknesses. In aspen wood with a 10 mm thickness, he reports a deflection at the point of rupture of 10.3 mm. This value is similar to the results achieved in the present work with similar thicknesses. He reports a 13.8 mm maximum deflection value of aspen wood with a thickness of 15 mm. The closest to this value was achieved in the present work with the combination 9ND20 glued with PVA glue.

In their research, authors Gaff *et al.* (2015) reported average deflection values of beech and aspen wood with a thickness of 18 mm in three-point radial direction bending. For beech wood, they reported 14 mm, which is similar to values found in the present work for combinations of non-densified + densified lamellas with a similar thickness.

For aspen wood they reported a deflection value of 20 mm, which is similar to values found in this work for combinations of non-densified + densified lamellas with a similar thickness.

Deflection at the Limit of Proportionality and at the Point of Rupture

In Table 4 it can be seen that there was a statistically highly significant effect of the wood species, lamella combination, and number of loading cycles on the deflection at the proportionality limit Y_E. The type of adhesive was not statistically significant. The interaction of all the factors had a statistically insignificant effect on the monitored characteristic.

Table 4. Statistical Evaluation of the Effect of Factors and their Interaction on Deflection at the Limit of Proportionality Y_E

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	7061.692	1	7061.692	27563.60	0.000001
1) Wood species	15.333	1	15.333	59.85	0.000001
2) Glue	2.792	1	2.792	10.90	0.001052
3) Lamella combination	780.361	11	70.942	276.90	0.000001
4) Number of cycles	4.935	1	4.935	19.26	0.000015
1*2*3*4	3.734	11	0.339	1.33	0.207942
Error	98.379	384	0.256		

The values shown in Table 5 indicate that only the lamella combination had a statistically significant effect on the deflection at the point of rupture Y_{MOR}. The rest of the factors did not exhibit statistically significant effects on the monitored characteristic, and their interactions were also not statistically significant.

Table 5. Statistical Evaluation of Factors and their Interaction on Deflection at the point of Rupture Y_{MOR}

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	59048.37	1	59048.37	17027.14	0.000001
1) Wood species	1.21	1	1.21	0.35	0.554826
2) Glue	0.89	1	0.89	0.26	0.612279
3) Lamella combination	7732.01	11	702.91	202.69	0.000001
4) Number of cycles	2.80	1	2.80	0.81	0.369133
1*2*3*4	25.60	11	2.33	0.67	0.766043
Error	1331.67	384	3.47		

Figure 5a shows a statistically significant effect of the wood species on the deflection at the proportionality limit Y_E and a statistically insignificant effect of the wood species on the deflection at the point of rupture Y_{MOR}. Beech specimens had 9.7% higher Y_E values than aspen specimens. The average deflection at the point of rupture in beech specimens was 1% lower than in aspen specimens. A statistically very significant effect on the Y_E and Y_{MOR} can be seen in Figure 5b. There was no statistically significant difference between Y_E values of specimens consisting of lamellas densified to 10% and 20%. The results were similar between Y_{MOR} values, with the exception of 9 mm compositions assembled from lamellas densified to 10% and 20%, where there was a statistically significant difference between values. When Y_E values of compositions assembled from non-densified lamellas and lamellas densified to 10% and 20% of similar thicknesses were compared, a statistically significant difference was evident. A similar trend was observed when comparing Y_{MOR} values. It is worth mentioning the fact that both dependencies (Y_E and Y_{MOR}) had practically the same shape. Y_{MOR} deformations had greater variability of values.

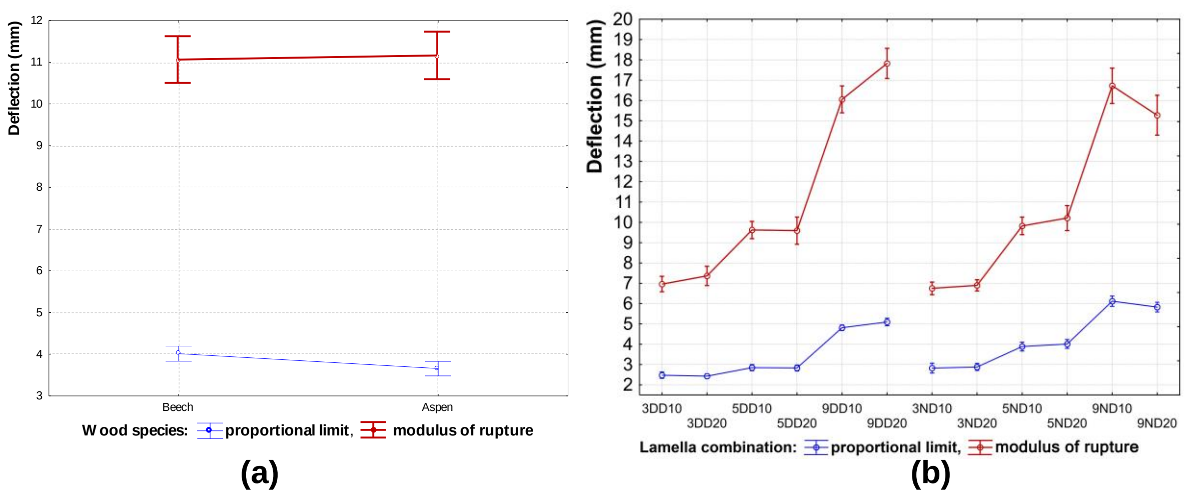


Fig. 5. The effect of the (a) wood species and (b) lamella combination on deflection at the proportional limit and at the point of rupture

Figure 6a and Table 5 show the statistically insignificant effect of the type of adhesive on Y_{MOR} deflection values. PVA adhesives had 0.7% higher Y_{MOR} deformation values than PUR adhesives. The effect of the type of adhesive on the Y_E deformation was on the borderline of statistical significance (Fig. 6a; Table 4). With PUR adhesives, 4% higher Y_E values were achieved in comparison with PVA adhesives.

The effect of the number of cycles on Y_E deformation was statistically significant (Fig. 6b; Table 4). Its effect on the deflection at the point of rupture Y_{MOR} was not statistically significant (Fig. 6b; Table 5). Specimens subjected to cyclic loading had 5.5% higher Y_E deflection values compared to specimens not subjected to cyclic loading. However, in Y_{MOR} deflections the cyclic loading resulted in reduced values in comparison to samples not subjected to cyclic loading (decrease 1.4%).

Figures 7a and 7b and Table 4 show no statistically significant effects for any of the factors on the deflection at the proportionality limit Y_E. Cyclic loading of aspen specimens increased the value of the monitored characteristic by 8.7%. The results were similar for beech specimens, where samples subjected to cyclic loading had 2.8% higher values of deflection at the proportionality limit Y_E than samples not subjected to cyclic loading. The type of adhesive had an unclear effect on the monitored characteristic.

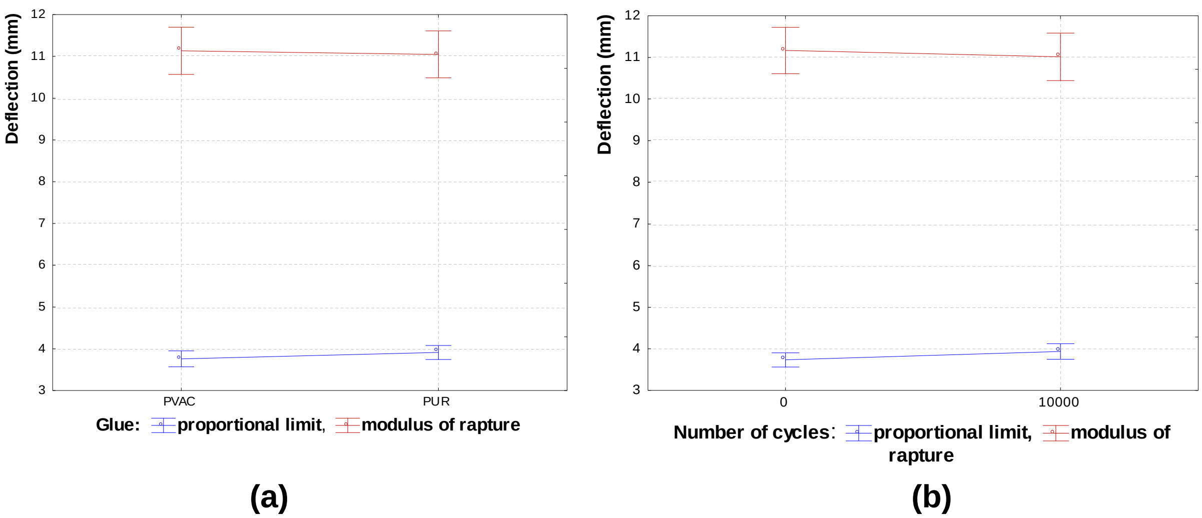


Fig. 6. The effect of the (a) glue and (b) number of cycles on deflection at the proportional limit and at the point of rupture

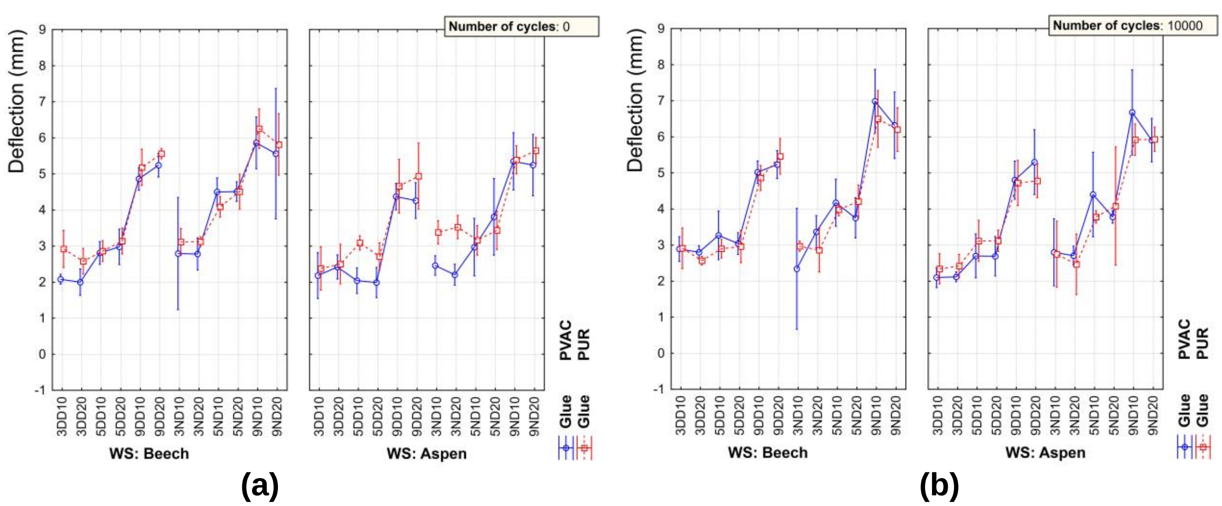


Fig. 7. Synergistic effect of the studied factors on the deflection at the proportional limit (a – Number of cycles 0, b – Number of cycles 10000)

Figures 8a and 8b show the synergistic effect of the selected factors on the deflection at the point of rupture Y_{MOR}, which was not statistically significant, as indicated in Table 5. The thickness of the wood composition, which was very statistically significant, had the greatest effect on the monitored characteristic. The wood species, type of adhesive and cyclic loading did not have a statistically significant effect on the monitored characteristic (Figs. 5a, 6a and 6b ; Table 5). The type of adhesive and cyclic loading did not have a definite effect on the deflection at the point of rupture Y_{MOR}. Beech specimens subjected to cyclic loading had 1.3% higher values of Y_{MOR} than specimens not subjected to cyclic loading. In aspen specimens, the samples not subjected to cyclic loading had 4% higher values of Y_{MOR} than specimens subjected to cyclic loading.

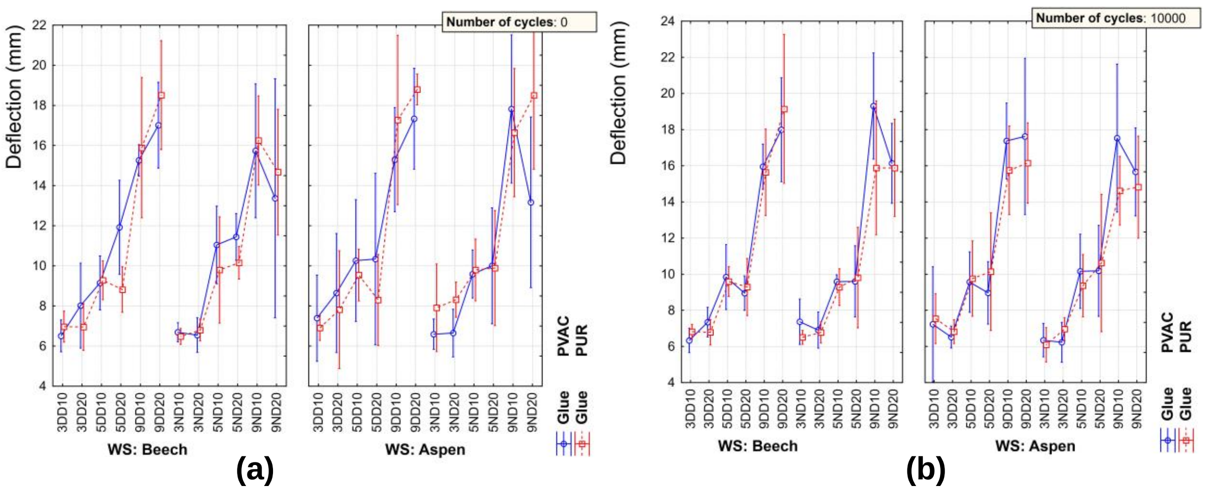


Fig. 8. Synergistic effect of the studied factors on the deflection at the point of rupture (a – Number of cycles 0, b – Number of cycles 10000)

Ratio of Deflection at the Proportional Limit and at the Point of Rupture

Table 6 shows that the wood species, lamella combination, and number of cycles all exhibited a significant effect on the deflection ratio $Y_E : Y_{MOR}$.

Table 6. Statistical Evaluation of Factors and their Interaction on the Ratio of Deflection $Y_E : Y_{MOR}$

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	618842.6	1	618842.6	13584.69	0.000001
1) Wood species	1982.8	1	1982.8	43.52	0.000001
2) Glue	425.9	1	425.9	9.35	0.002386
3) Lamella combination	11454.7	11	1041.3	22.86	0.000001
4) Number of cycles	711.8	1	711.8	15.63	0.000092
1*2*3*4	345.3	11	31.4	0.69	0.749144
Error	17492.9	384	45.6		

The effect of the type of adhesive on the monitored characteristic was on the borderline of statistical significance. The effect of the interaction of all the factors on the deflection ratio $Y_E : Y_{MOR}$ was not significant.

Figure 9a shows that wood species had a significant effect on the monitored characteristic. Beech specimens exhibited 12% higher values of the monitored characteristic than aspen specimens. This is probably related to the higher density of the beech specimens. Figure 9b shows a significant effect of the thickness of the composition, which is also confirmed by data from Table 6. The highest average value of the monitored characteristic 43.5% was achieved in the combination 3ND10, whereas the lowest value 28.8% was achieved in the combination 9DD20. One can conclude from the graph that as the thickness of the composition increased, the deformation ratio $Y_E : Y_{MOR}$ decreased. Thicker material can achieve a higher proportion of plastic deformation, and is more suitable for molding by bending. In the bending method we applied (3-point bending), the shear stress was not included. A greater material thickness at the same width results in greater strength and a higher shear stress. Shear stress results in higher deflection values compared with deflection measured in pure bending Esendemir (2009).

Densification of individual lamellas did not have a significant effect on the monitored characteristic.

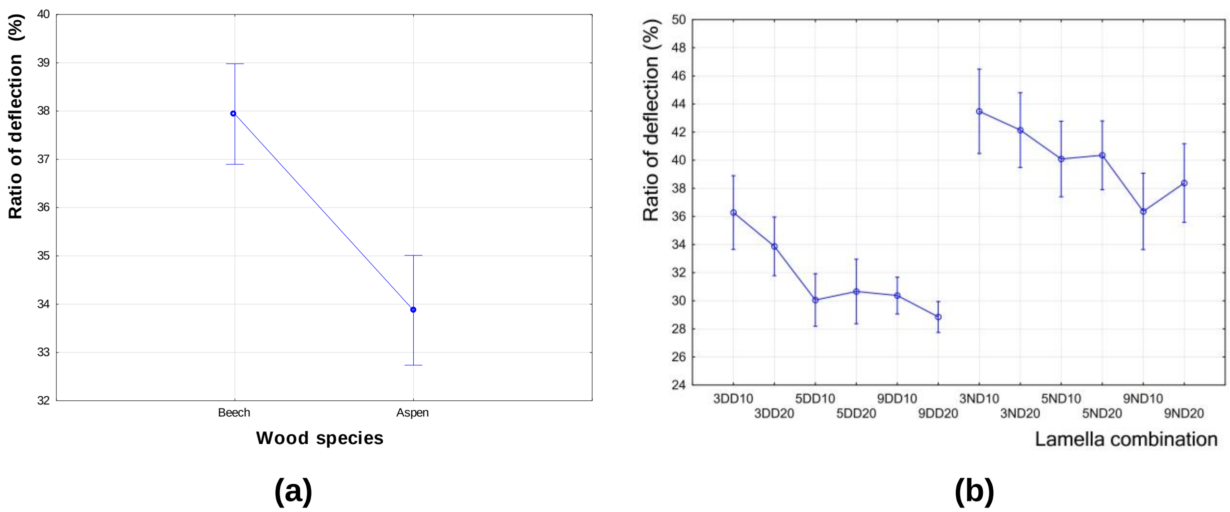


Fig. 9. The effect of the (a) wood species and (b) lamella combination on the ratio of deflection

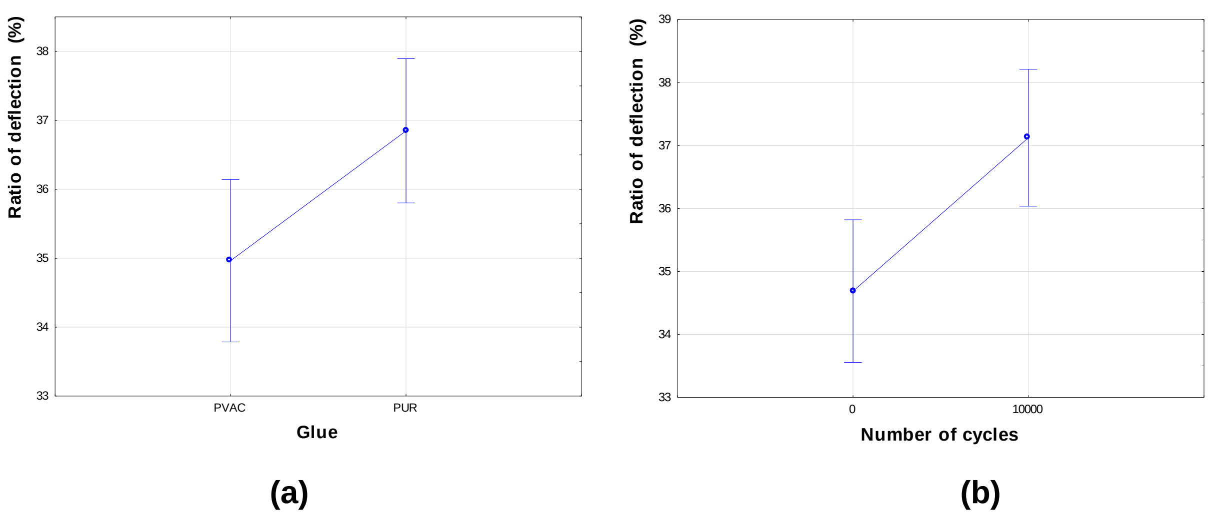
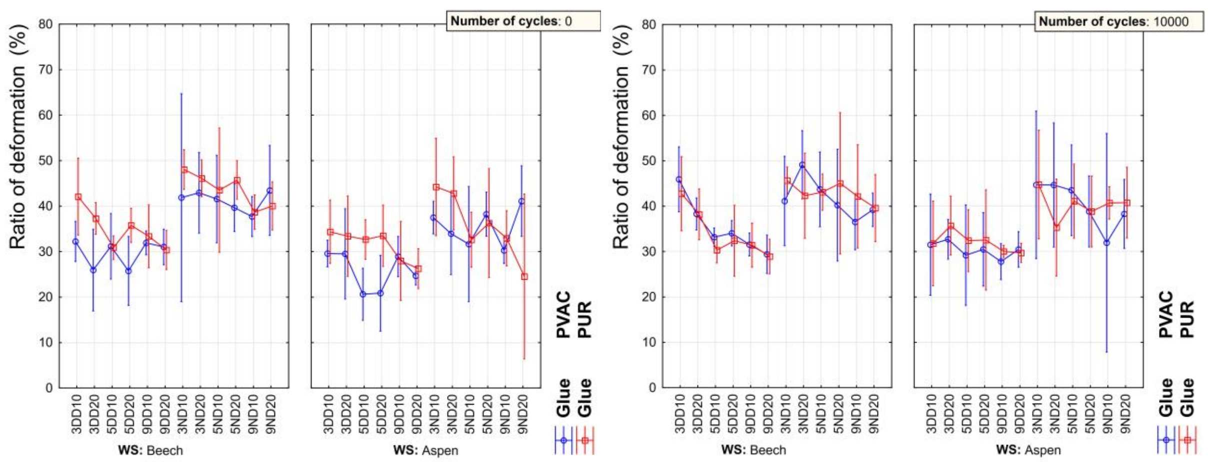


Fig. 10. The effect of the (a) glue and (b) degree of densification on the ratio of deflection

The effect of the type of adhesive used on the monitored characteristic was on the borderline of statistical significance (Fig. 10a; Table 6).

Polyurethane adhesives had 5.4% higher deflection ratio values $Y_E : Y_{MOR}$ than polyvinyl acetate adhesives. The number of cycles had a significant effect on the monitored values (Fig. 10b; Table 6). Increasing the number of loading cycles increased the values of the ratio of deformation $Y_E : Y_{MOR}$ (increase of 7%) compared to samples that were not subjected to cyclic loading. These results correspond with the article by Gaff *et al.* (2016), which reports that cyclic loading resulted in the development of plastic and viscoelastic deformations. For this reason, the plastic deformations during a bending test after cyclic loading were smaller, *i.e.* the ratio of deflection increased.

The synergistic effect of all the factors on the ratio of deflection $Y_E : Y_{MOR}$ was not significant (Fig. 11a and 11b; Table 6). Beech specimens have 3% higher values of the ratio of deflection $Y_E : Y_{MOR}$ than beech specimens that were not subjected to cyclic loading. A similar upward trend can be seen in aspen specimens, where aspen wood subjected to cyclic loading had 11.7% higher values of the ratio of deflection $Y_E : Y_{MOR}$ than aspen wood not subjected to cyclic loading. The highest ratio of deflection (49.1%) was achieved in the beech combination 3ND20 glued with PVA glue, which was subjected to cyclic loading. The lowest values of the monitored characteristic (20.62%) was achieved by the aspen combination 5DD10 glued with PVA glue, which was not subjected to cyclic loading. The lower the value of the ratio of deflection, the most plastic the wood becomes.



(a) (b)

Fig. 11. Synergistic effect of the studied factors on the ratio of deflection (a – Number of cycles 0, b – Number of cycles 10,000)

Correlation Analysis

Table 7 and Fig. 12 show the results of the correlation analysis. After comparing the variables Y_E and Y_{MOR} (0.785), one can conclude that the variables were highly dependent on each other. Their dependence has a growing character, which means it is a positive correlation. The comparison of Y_E with the ratio of deflection $Y_E : Y_{MOR}$ (0.163) showed that these variables had a low dependence on each other. The dependence is shown as a slightly rising straight line, which indicated also a positive correlation between the assessed variables. In the comparison of Y_{MOR} with Y_E : Y_{MOR}, a negative correlation (-0.437) was observed, where an increase in Y_{MOR} values caused the ratio of deflection to decline.

Table 7. Spearman's Correlation

Variable	Y_E (mm)	Y_{MOR} (mm)	Y_E : Y_{MOR}
Y_E (mm)	1.000000	0.784978	0.163422
Y_{MOR} (mm)	0.784978	1.000000	-0.436960
Y_E : Y_{MOR}	0.163422	-0.436960	1.000000

From Figure 12 one can still conclude that the classic Gaussian distribution was most similar to the ratio of deflection Y_E : Y_{MOR} values. The values most deviated from the average were those of the deflection at the point of rupture Y_{MOR}.

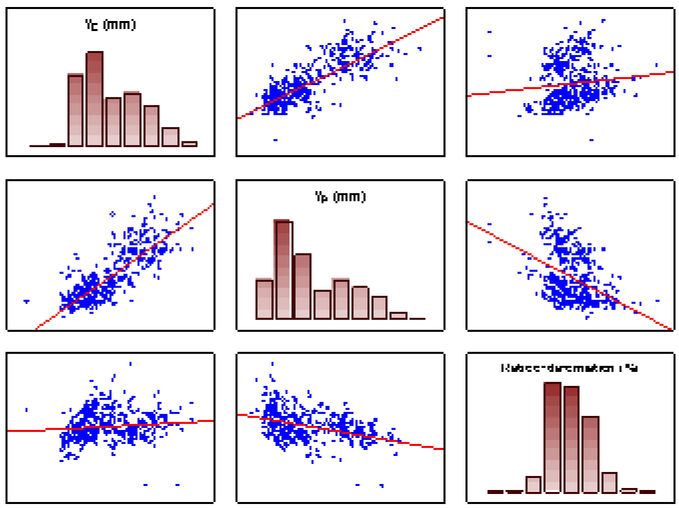


Fig. 12. Correlation matrix of the level of dependence of monitored characteristics

CONCLUSIONS

1. The wood species and lamella combination showed the most significant effects on the deflection at the proportionality limit Y_E. Thicker material can achieve a higher proportion of plastic deformation, and is more suitable for molding by bending. In the bending method we applied (3-point bending), we did not include the shear stress. A greater material thickness at the same width results in greater strength and a higher shear stress. Shear stress results in higher deflection values compared with deflection measured in pure bending.

2. The ratio of deformation decreases under cyclic loading and plastic and viscoelastic deformations formed due to cyclic loading. For this reason, the plastic deformations during a bending test after cyclic loading were smaller, *i.e.* the deflection ratio increases.

3. The values of the correlation analysis show that the deflection at the proportionality limit affects the ratio of deflection positively, but the level of significance is only 16%. A significantly higher level of significance was observed in the deflection at the

proportionality limit in its interaction with the deflection at the point of rupture; in this case, the level of significance was 78%. The effect of the deflection at the point of rupture had a 44% level of significance on the ratio of deflection. Figure 12 shows that as these deformations increase, a decline in relative values can be expected.

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