Deflection of Densified Beech and Aspen Woods as a Function of Selected Factors

Adam Sikora,[a] Zuzana Gaffová,[b] Rastislav Rajnoha,[c] Anna Šatanová,[d] and Richard Kminiak [a,]*

Effects of selected factors (wood species (Beech, Aspen), degree of densification (10%, 20%), material thickness (4 mm, 6 mm, 10 mm, and 18 mm), and number of loading cycles (0, 10,000)) were analyzed relative to the bendability of densified wood. The monitored characteristics were the deflection at proportional limit (Y_E), deflection at maximum limit (Y_P), and their ratio (Y_E:Y_P). One of the main causes of unfavorable wood bending is its low deflection under tensile stress parallel to the fiber in comparison to compressive stress in the same direction. From the results it is clear that the deflection at the proportionality limit depended on all monitored factors. The deflection at the yield point was not influenced by cyclic loading, and the ratio of deflection was influenced by material thickness only. Based on this ratio, the moulding properties of material can be identified. There was a strong correlation between the two deflection limits. The results are an important foundation for progress in the production of laminated materials with specific properties for intended use.

Keywords: Cyclic loading; Laminated wood; Bending strength; Modulus of elasticity; Elasticity deflection at proportional limit; Deflection at maximum limit; Ratio of elastic and maximum deflection

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 Forest and Wood Products Economics, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6- Suchdol, 16521 Czech Republic; c: Faculty of Economics and Business, Pan-European University, Tomášikova 20, Bratislava, 821 02 Slovak Republic; d: College of International Business Slovakia in Prešov, Prešov, Slovakia;
** Corresponding author: risko.kminiak@gmail.com*

INTRODUCTION

Wood is a flexible, strong, and yet lightweight material that has good thermal insulation properties, can bear heavy loads, absorb vibrations, and is easily machined with cutting tools (Efe *et al*. 2007). When evaluating the technical characteristics of furniture, the strength, stability, functionality, durability, and quality of each piece of furniture is primarily assessed (Gaff *et al*. 2017).

This article considers selected indicators of the bending strength of wood, the knowledge of which is essential to expand the possibilities of its use in bentwood furniture. For this reason, it is necessary to obtain theoretical knowledge of the positive and negative factors that affect the bending of densified wood.

There has been minimal in-depth research on the bending strength of densified wood conducted in the past, as well as a lack of knowledge of the behavior of the components in the process. The respective knowledge could bring additional technical, technological, and economical benefits. The efficiency of bentwood furniture production is improved with the use of low-grade wood compared to the currently used species, and by the omission of certain technological steps (steaming) in the bending process (Wagenführ 2000; Blomberg *et al.* 2005; Kamke 2006; Boonstra and Blomberg 2007).

Wood properties can be altered chemically, physically, and mechanically, as well as a combination of those methods (Gaff *et al.* 2015a). This article investigates a densification of wood in the radial direction and subsequent bending. Bending is a non-cutting method of shaping wood based on its ability to deform plastically (Sandberg and Navi 2007). The shape is changed by external forces, causing deformation in materials (Schellberg 2012). These deformations are very small in wood with standard processing for furniture that has a moisture content of 8% ± 4% and a temperature of 20 °C. Wood deformability can be significantly increased by plasticizing the wood (Glos *et al*. 2004) *via* higher humidity and temperature to achieve plasticity of the material for the time necessary for bending. Chemical treatments to promote bending have not found a wider application due to ecological and economic reasons (Wagenfuhrer *et al.* 2006; Gaff *et al.* 2015b; Gaff *et al.* 2015c; Gaff *et al.* 2016). There are two primary bending methods typically used. Shaping that uses the moulding form (free bending) is used for shaping parts with a slight bend. Bending is based on the principle patented in 1841 by M. Thonet, on changing the wood properties by plasticizing it and the effect of frontal pressure, using a bending strap that improves the formability of the wood and enables bending with smaller bend radii (Frese and Blaß 2006). Previous authors (Sandberg and Navi 2007; Fortino *et al.* 2013; Laine *et al.* 2014) have indicated that densification improves the mechanical properties of wood. However, the effect of densification on the bendability of wood is unknown. In bending, the neutral layer is moved to the side with higher stiffness (modulus of elasticity MOE) (Fortino *et al.* 2013). However, densification is not uniform across the cross-section. The density of the densified wood typically decreases from the surface layers to the central ones. Increasing the density of the surface layers and therefore increasing the stiffness could theoretically lead to increased flexibility. The main advantage of bending, in comparison with injection molding of parts, is primarily the substantially higher stiffness and strength of bent parts. The parallel course of fibers is maintained in bending, and it does not result in a complicated grain pattern as it does in molding. Wood bending is also associated with a higher yield from the wood, classifying this technology as waste-free (Gaff *et al.* 2017).

Wood bendability is a feature that characterizes its bending potential. It can be expressed by various characteristics, such as the size of elastic deflection (deflection at the proportional limit- Y_E), the level of maximum deflection (deflection at the maximum limit- Y_P), the coefficient of bendability (ratio of the thickness of the bent material h to the minimum bending radius r- has a more practical nature), or the ratio of elastic and maximum deflection and stress (Y_E:Y_P). Each of these characteristics has its advantages and highlights a specific purpose of the future use of the material.

Knowledge on the bendability of densified wood is modest. Thus, this study focused on the analysis of its essential characteristics, such as the size of elastic deflection and the size of maximum deflection.

Elastic deflection shows the material's ability to deform under external mechanical forces and return to its original state after their removal (Požgaj *et al.* 1997). Maximum deflection is the deflection at the modulus of rupture. Part of this deflection remains after the removal of the mechanical force and the material takes a new shape (Yamashita *et al.* 2009). In practical terms, the maximum limit during bending shows the deflection size that the material can be exposed to without causing permanent deflection.

With the ratio of the characteristics described above, namely the deflection at the proportional limit and deflection at the maximum limit, the material can be assessed. When the beam (panel) is loaded by bending, the bending moment causes deformation and the shape of the bent beam is changed (Fig. 1). The resulting deformation is the result of stresses over the cross-section of the beam.

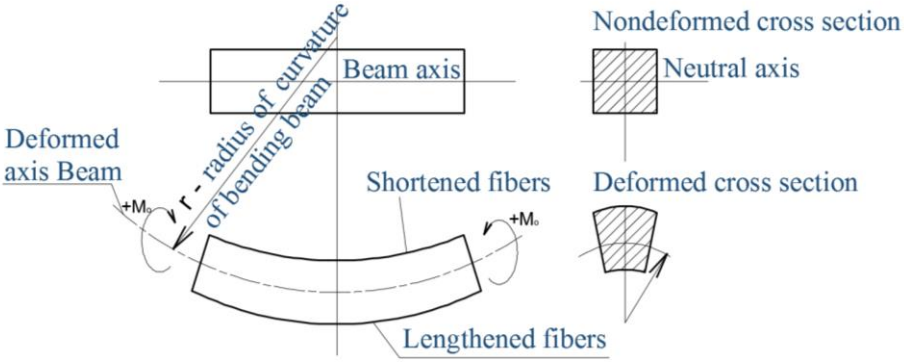


Fig. 1. Deformation of beam loaded by bending moment

However, the size of the deformation achieved through the loading of the beam may not be the same in different materials (M1, M2), or in materials with various treatments (*e.g.*, plasticized and nonplasticized wood, densified and non-densified, *etc*.). In this case, identical load-stress (σx) can result in different deformation of the materials (Y_{E1}, Y_{E2}, Y_{P1}, Y_{P2}), and varying degrees of deformation in materials with different treatments may result in an equal stress. The difference in deformation (bending) caused by stress in these materials is reflected in their linear (elastic), and non-linear (plastic) region (Fig. 2). In material molding the objective is to achieve the highest proportion of plastic deformation, which is why materials with a high proportion of plastic deformation (bending), or ductile materials, are suitable from this point of view (Fig. 2). With an increase of plastic bending in relation to elastic bending, the resulting ratio decreases. The lower the achieved percentage ratio, the greater the proportion of plastic deformation. The ratio increases with a decrease in plastic deformation in relation to elastic deformation. Such materials are characterized by a higher capacity to resist elastic deformation, elastic material, and are also characterized by a low ductile capacity in the plastic region, making them unsuitable for molding, or so-called fragile materials.

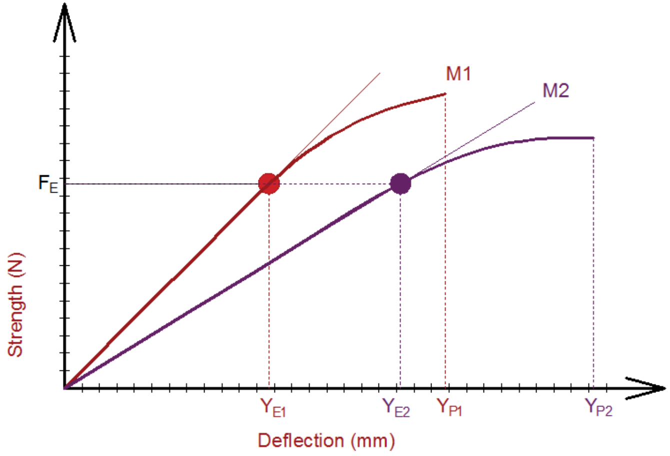


Fig. 2. Deformation of beam under bending moment

Another good example is the stress-strain diagram of the beam subjected to bending (Fig. 3) in an unmodified state (M1) and after plasticization (M2). The figure shows that the proportion of plastic deformation (D) increased several fold due to the effect of plasticization in relation to wood that was not plasticized (C). The increase in the proportion of plastic deformation implies that the material is suitable for molding.

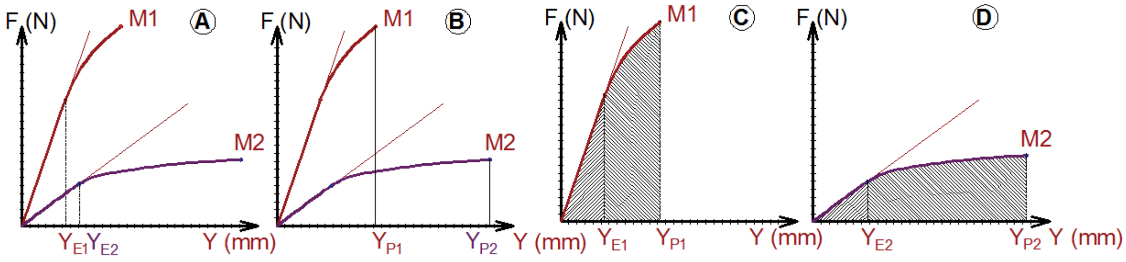


Fig. 3. Deformation of beam under bending moment

Based on the ratio of deformations, the properties of the material can be determined for its further use. Materials with a low deformation ratio are suitable for the purposes of molding. Materials with a high proportion of elastic deformation have the capacity to withstand high levels of stress in the elastic region.

The objective of this study was to assess the properties of these materials based on the knowledge given above, with regard to their future application in the production of wood-based materials and non-wood components. These innovations in increasing process efficiency guarantee knowledgeable decisions represented by innovative wood products. These research results can improve the innovative potential of wood processing companies and increase their performance and competitiveness in the market.

EXPERIMENTAL

Materials

European beech (*Fagus sylvatica* L.) and aspen (*Populus tremula* L.) wood from the Polana region in Slovakia was used as the test specimens.

Wood species with the dimensions of 4 mm, 6 mm, 10 mm, and 18 mm thickness, 35 mm width and 600 mm length were prepared from the selected wood species. The samples were conditioned to the moisture content of 8% in a climate chamber Binder (ED, APT Line II; Binder, Tuttlingen, Germany) with 40% relative humidity and temperature of 20 °C. For these test specimens, the impact of selected factors (wood species, degree of densification, material thickness, and number of loading cycles) on the monitored characteristics was analyzed before cyclic loading (number of cycles = 0) and after cyclic loading (number of loading cycles = 10,000). For the study, Y_E is the deflection at the proportional limit, Y_P is the maximum deflection, and Y_E:Y_P is the ratio of deflections.

The results were compared with results measured on test specimens that were subjected to 10% to 20% densification. Ten test samples were used for each set of test specimens.

Methods

Densification of test specimens

The test specimens that were intended for densification were pressed in a hydraulic press (RK Prüfsysteme MFL 1000, Keyx, Leipzig, Germany). The temperature during densification was 20°C, and the time after pressing was 48 hours.

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

The densification process of each set of test specimens is shown in Table 1.

Table 1. Compressive Load on Each Set of Test Specimens

Specimen Thickness (mm)	Densification 10%		Densification 20%	
	Beech (kN)	Aspen (kN)	Beech (kN)	Aspen (kN)
4	3550	1080	3950	1500
6	2100	1850	3900	2100
10	3750	2150	4500	2500
18	3650	1720	3680	1800

Determination of values of bending characteristics

After the cyclic loading, the support span was adjusted to L1 = 20 × h ; the support span was changed in relation to the thickness of specimens. The samples were bent using 3-point bending with a universal testing machine FPZ 100 (TIRA, Schalkau, Germany) in accordance with EN 310 (1993). The bending characteristics were measured perpendicular to the fibers in radial direction; the tests were carried out according to the standard 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 data logger ALMEMO 2690-8 (Ahlborn GmbH, Braunschweig, Germany).

Evaluation and calculation

To determine the effect of the individual factors on the bending characteristics, an analysis of variance (ANOVA) and the Fischer F-test were performed using Statistica 12 (Statsoft Inc., Tulsa, USA) software. The wood density was determined before and after testing according to ISO 13061-2 (2014) and Eq. 1,

$$\rho_w = \frac{m_w}{V_w} \tag{1}$$

where ρ_w is the density (kg*m^{-3}) of the sample at moisture content w (%), m_w is the mass of the sample (kg) at moisture content w (%), and V_w is the volume of the sample (m^{-3}) at moisture content w (%).

The moisture content of the samples was determined and verified before and after testing. These calculations were performed 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, mw is the mass of the sample (g) at moisture content w (%), and m_0 is the mass of the oven-dry sample (g). Drying to an oven-dry state was also performed according to ISO 13061-1 (2014).

Next, the deflection at the proportional limit in static bending was determined in accordance with EN 310 (1993). First, limit of proportionality from the force-deflection diagram was determined. The limit of proportionality was on the end of the linear part of the curve. The deflection at the maximum limit corresponds to the deflection at the modulus of rupture. Deflection at the maximum limit and deflection at the proportionality limit was determined from the stress-strain diagram recorded in the bending of test specimens.

Cyclic bend loading

The cyclic loading was performed on a cycler machine with cyclic bending of the test pieces using single-axis loading. The following numbers of cycles were selected for testing: 0 and 10,000. During the preliminary experimental testing, the specimens were loaded with static bending to determine the breaking strength and proportionality limit because the test pieces had to be loaded up to 90% of the proportionality limit.

RESULTS AND DISCUSSION

Deflection at the Limit of Proportionality and at the Maximum Limit

Based on the values of the level of significance *P* and the results of Fisher's F-test, the authors can conclude that each of the monitored factors and their mutual interaction were shown to have a statistically significant effect (Table 2). The respective model explains approximately 92% of the total sum of squares. Table 3 shows the average values of the monitored characteristics, average density values measured for each set of test specimens, and the corresponding coefficient of variation.

Table 2. Statistical Evaluation of the Effect of Factors and their Interaction on Deflection at the Limit of Proportionality

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F- Test	Significance Level *P*
Intercept	3962.363	1	3962.363	15373.74	***
1) Wood species “WS”	22.605	1	22.605	87.71	***
2) Material thickness “MT”	460.795	3	153.598	595.95	***
3) Degree of densification “DOD”	1.686	2	0.843	3.27	***
4) Number of cycles “NC”	2.216	1	2.216	8.60	***
WS * MT	9.951	3	3.317	12.87	***
WS * DOD	7.306	2	3.653	14.17	***
MT * DOD	6.651	6	1.108	4.30	***
WS * NC	1.443	1	1.443	5.60	***
MT * NC	9.982	3	3.327	12.91	***
DOD * NC	2.573	2	1.286	4.99	***
WS * MT * DOD	7.418	6	1.236	4.80	***
WS * MT * NC	3.550	3	1.183	4.59	***
WS * DOD * NC	0.460	2	0.230	0.89	NS
MT * DOD * NC	7.526	6	1.254	4.87	***
1*2*3*4	4.382	6	0.730	2.83	***
Error	49.485	192	0.258		

NS- not significant, *** - significant P < 0.01

Table 3. Average Values of Bending Characteristics, Density, and Coefficient of Variance

Wood Species	Material Thickness (mm)	Degree of Densification (%)	Number of Cycles	Y_E (mm)	Y_P (mm)	Y_E:Y_P (%)	Density (Kg/m^3)
Beech	**4**	**0**	**0**	2.8 (3.4)	4.8 (10.2)	58 (11.5)	693 (4.6)
Beech	**4**	**0**	**10,000**	3.0 (18.2)	4.6 (5.2)	65 (16.6)	680 (9.5)
Beech	**4**	**10**	**0**	2.6 (9.7)	4.8 (3.8)	46 (11.2)	725 (8.6)
Beech	**4**	**10**	**10,000**	2.2 (8.0)	3.7 (7.4)	45 (25.6)	739 (6.6)
Beech	**4**	**20**	**0**	2.7 (3.7)	4.8 (3.3)	38 (26.3)	784 (4.0)
Beech	**4**	**20**	**10,000**	2,0 (16.1)	3.8 (8.8)	54 (10.7)	766 (4.7)
Beech	**6**	**0**	**0**	3.5 (6.8)	7.6 (11.2)	36 (16.3)	665 (3.4)
Beech	**6**	**0**	**10,000**	3.1 (19.1)	7.0 (7.0)	37 (17.0)	692 (4.4)
Beech	**6**	**10**	**0**	3.2 (15.3)	7.2 (12.9)	55 (10.0)	703 (4.8)
Beech	**6**	**10**	**10,000**	3.6 (6.9)	7.3 (12.3)	60 (9.7)	749 (5.0)
Beech	**6**	**20**	**0**	2.5 (17.6)	6.7 (16.6)	45 (17.8)	751 (5.6)
Beech	**6**	**20**	**10,000**	3.7 (5.2)	7.6 (10.8)	49 (13.0)	750 (5.3)
Beech	**10**	**0**	**0**	4.4 (14.4)	12.0 (15.7)	42 (25.0)	694 (4.7)
Beech	**10**	**0**	**10,000**	5.1 (3.4)	9.6 (9.0)	49 (10.0)	690 (5.8)
Beech	**10**	**10**	**0**	4.8 (4.1)	11.9 (18.6)	38 (17.4)	733 (3.7)
Beech	**10**	**10**	**10,000**	7.4 (25.7)	14.9 (17.3)	33 (18.8)	719 (5.6)
Beech	**10**	**20**	**0**	4.6 (6.7)	11.7 (13.2)	55 (4.2)	788 (3.5)
Beech	**10**	**20**	**10,000**	5.1 (4.0)	10.5 (2.1)	53 (9.3)	726 (2.5)
Beech	**18**	**0**	**0**	6.6 (17.9)	18.3 (16.6)	38 (17.0)	735 (8.1)
Beech	**18**	**0**	**10,000**	6.3 (9.3)	17.2 (7.6)	49 (13.6)	698 (8.2)
Beech	**18**	**10**	**0**	6.4 (6.3)	17.5 (17.4)	40 (14.9)	744 (3.9)
Beech	**18**	**10**	**10,000**	6.4 (3.9)	19.6 (17.2)	48 (4.4)	749 (4.6)
Beech	**18**	**20**	**0**	6.2 (3.5)	18.9 (15.7)	34 (18.4)	747 (6.8)
Beech	**18**	**20**	**10,000**	6.7 (5.0)	25.4 (12.3)	27 (15.9)	757 (8.6)

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

Wood Species	**Material Thickness (mm)**	**Degree of Densification (%)**	**Number of Cycles**	**Y_E (mm)**	**Y_P (mm)**	**Y_E:Y_P (%)**	**Density (Kg/m^3)**
Aspen	**4**	**0**	**0**	2.4 (8.2)	4.7 (15.6)	53 (9.9)	400 (4.1)
Aspen	**4**	**0**	**10,000**	1.5 (19.4)	3.3 (13.5)	45 (12.8)	416 (8.4)
Aspen	**4**	**10**	**0**	2.2 (6.2)	5.0 (17.9)	53 (19.3)	421 (9.3)
Aspen	**4**	**10**	**10,000**	1.7 (47.0)	3.6 (21.1)	51 (16.8)	404 (3.6)
Aspen	**4**	**20**	**0**	2.7 (8.4)	5.7 (7.7)	48 (27.1)	488 (5.7)
Aspen	**4**	**20**	**10,000**	2.9 (27.7)	4.0 (13.1)	48 (36.2)	476 (14.1)
Aspen	**6**	**0**	**0**	3.1 (13.5)	6.0 (13.9)	42 (20.6)	533 (8.7)
Aspen	**6**	**0**	**10,000**	3.1 (13.8)	6.1 (4.7)	32 (14.3)	539 (4.4)
Aspen	**6**	**10**	**0**	2.9 (16.3)	6.1 (6.8)	46 (22.8)	557 (6.6)
Aspen	**6**	**10**	**10,000**	3.4 (9.4)	6.6 (6.8)	47 (48.7)	584 (7.9)
Aspen	**6**	**20**	**0**	2.7 (14.2)	6.8 (14.9)	47 (11.2)	620 (9.6)
Aspen	**6**	**20**	**10,000**	3.5 (2.6)	6.8 (6.7)	52 (12.0)	580 (6.5)
Aspen	**10**	**0**	**0**	3.8 (6.7)	8.2 (21.6)	38 (6.0)	528 (4.2)
Aspen	**10**	**0**	**10,000**	4.0 (13.7)	8.7 (22.2)	45 (23.7)	536 (8.4)
Aspen	**10**	**10**	**0**	3.7 (4.4)	9.8 (6.3)	39 (28.5)	564 (1.3)
Aspen	**10**	**10**	**10,000**	4.2 (6.9)	9.6 (18.5)	35 (20.6)	560 (5.8)
Aspen	**10**	**20**	**0**	4.5 (12.7)	11.2 (15.0)	48 (6.9)	604 (1.8)
Aspen	**10**	**20**	**10,000**	4.3 (9.7)	10.8 (11.7)	74 (27.1)	628 (13.9)
Aspen	**18**	**0**	**0**	5.3 (8.3)	13.1 (25.4)	40 (19.8)	529 (2.1)
Aspen	**18**	**0**	**10,000**	5.0 (9.4)	16.1 (21.9)	52 (5.3)	519 (12.7)
Aspen	**18**	**10**	**0**	5.7 (12.6)	15.5 (29.6)	40 (8.9)	568 (4.8)
Aspen	**18**	**10**	**10,000**	5.6 (5.6)	16.6 (16.5)	40 (17.4)	581 (4.0)
Aspen	**18**	**20**	**0**	5.8 (6.5)	18.4 (8.5)	32 (4.7)	589 (7.0)
Aspen	**18**	**20**	**10,000**	6.1 (4.1)	15.6 (21.2)	40 (19.6)	594 (6.2)

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

Based on the results of Duncan’s test (Table 4), the factor species was significant at the level *P* = 0.0001. Densification of 10% showed the effect at the level *P* = 0.29 in comparison with not densified specimens. Densification of 20% in comparison with 10% was not determined to be significant (*P* = 0.863). The increase of material thickness showed in all cases statistical significance at the level *P* = 0.0001. The number of loading cycles was not a significant factor.

Table 4. Comparison of the Effects of Individual Factors using Duncan Test on the Values of the Deflection at the Limit of Proportionality

Wood Species		(1) 4.371	(2) 3.7563
1	Beech		0.000
2	Aspen	0.000	

Degree of Densification (%)		(1) 0.021	(2) 0.021	(3) 0.020
1	0		0.029	0.034
2	10	0.029		0.863
3	20	0.034	0.863	

Material Thickness (mm)		(1) 2.3974	(2) 3.1897	(3) 4.6556	(4) 6.0102
1	4		0.000		0.000
2	6	0.000		0.000	
3	10		0.000		0.000
4	18	0.000		0.000	

Number of Cycles		(1) 3.9671	(2) 4.1593
1	0		0.029
2	10000	0.029	

The deflection values at the maximum limit were significantly affected by all of the monitored factors with the exception of cyclic loading, which has shown to be an insignificant factor based on the level of significance *P* (Table 5). Based on these results, the interaction of all the monitored factors can be considered a combination of statistically significant values affecting deflection at the maximum limit. The nonsignificant interactions were WS * DOD, WS * NC, DOD * NC, WS * MT * NC, and MT * DOD * NC. The respective model explained approximately 92% of the total sum of squares.

The results of Duncan’s test of the influence of all factors on the deflection values at the maximum limit are displayed in Table 6. The results show a statistically significant influence of species at the level P = 0.0001. A significant influence was confirmed for a densification of 10% (P = 0.007) and 20% (P = 0.0001). The thickness showed in all cases statistical significance at the level P = 0.0001. The statistical significance of cyclic loading was not proven (P = 0.665).

Table 5. Statistical Evaluation of Factors and their Interaction on Deflection at the Maximum Limit

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F- Test	Significance Level *P*
Intercept	23583.82	1	23583.82	7121.682	***
1) Wood species	160.10	1	160.10	48.346	***
2) Material thickness	6057.26	3	2019.09	609.710	***
3) Degree of densification	71.32	2	35.66	10.769	***
4) Number of cycles	0.62	1	0.62	0.187	NS
WS * MT	108.03	3	36.01	10.874	***
WS * DOD	4.05	2	2.03	0.612	NS
MT * DOD	89.89	6	14.98	4.524	***
WS * NC	6.57	1	6.57	1.985	NS
MT * NC	50.94	3	16.98	5.128	***
DOD * NC	5.86	2	2.93	0.885	NS
WS * MT * DOD	54.53	6	9.09	2.744	**
WS * MT * NC	11.67	3	3.89	1.175	NS
WS * DOD * NC	44.25	2	22.13	6.682	***
MT * DOD * NC	15.07	6	2.51	0.758	NS
1*2*3*4	95.29	6	15.88	4.796	***
Error	635.82	192	3.31		

NS- not significant, *** - significant P < 0.01

Table 6. Comparison of the Effects of Individual Factors using Duncan Test on the Values of the Deflection at the Maximum Limit

Wood Species		(1) 10.730	(2) 9.0962
1	Beech		0.000
2	Aspen	0.000	

Degree of Densification (%)		(1) 9.2104	(2) 9.9892	(3) 10.539
1	0		0.007	0.000
2	10	0.007		0.056
3	20	0.000	0.056	

Material Thickness (mm)		(1) 4.4055	(2) 6.8227	(3) 10.739	(4) 17.684
1	4		0.000	0.000	0.000
2	6	0.000		0.000	0.000
3	10	0.000	0.000		0.000
4	18	0.000	0.000	0.000	

Number of cycles		(1) 9.8621	(2) 9.9637
1	0		0.665
2	10000	0.665	

The average deflection values at the limit of proportionality in aspen wood (3.75 mm) were lower compared to beech wood (4.8 mm) by 21.87% (Fig. 4). This was confirmed by the results shown in Table 3, which revealed a statistically significant effect of the wood species on the monitored characteristic. Beech is a typical example of bendable wood; it has long fibers and a uniform width of annual growth rings that predisposes it to achieve higher values of bending at the proportional limit (Higashihara *et al.* 2000). Although aspen is also a porous wood, its fibers are much shorter, which is why it achieved a 22% lower value of bending at the proportional limit.

The average deflection values at the maximum limit (Fig. 4) measured in aspen wood (9.1 mm) were 15.47% lower than the values measured in beech wood (10.8 mm). Again, the higher values measured in beech wood could be attributed to its longer fibers in comparison to the fibers in aspen wood. These results confirmed the results of multiple authors work (Požgaj *et al.* 1997; Wagenführ 2000; Schellberg 2012; Fortino *et al.* 2013).

It can be generally concluded that elastic deflection increased with the increasing material thickness (Fig. 5). The average elastic deflection in material with a 4 mm thickness was 2.4 mm; in material with a thickness of 6 mm an average value of 3.2 mm was recorded, which was 33.33% higher. The average bending value in material with a thickness of 10 mm (4.6 mm) was 91.67% higher than in lamellas with a thickness of 4 mm, and 43.75% higher than in lamellas with a thickness of 6 mm. The highest values of elastic deflection was measured in materials with a thickness of 18 mm. In the above case, the values were 150% higher than in lamellas with a thickness of 4 mm, 87.5% higher than in lamellas with a 6 mm thickness, and 30.43% higher than in lamellas with a 10 mm thickness.

As in the deflection at the proportional limit, the material thickness could also be considered to be a factor that significantly affected the values of deflection at the maximum limit (Fig. 5). It was evident from the above results that deflection at the maximum limit increased with an increase in the material thickness. In material with a thickness of 6 mm 68.29% higher values of deflection at the maximum limit were measured than in materials with a thickness of 4 mm. In material with a thickness of 10 mm the measured values of deflection at the maximum limit (10.8 mm) were 163.41% higher, and in material with an 18 mm thickness (17.9) they were 336.59% higher than in material with a 4 mm thickness.

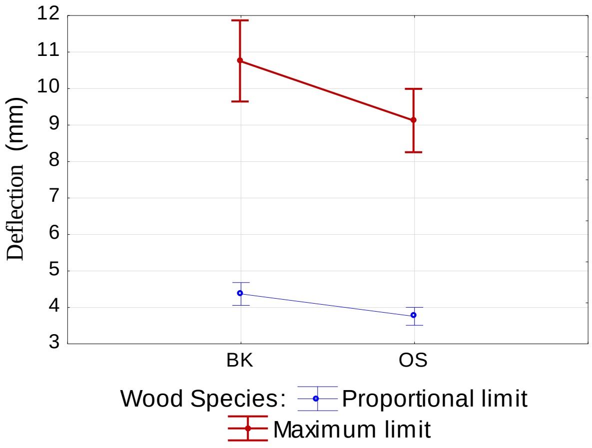


Fig. 4. Effect of the wood species on deflection at the proportional limit and at the maximum limit

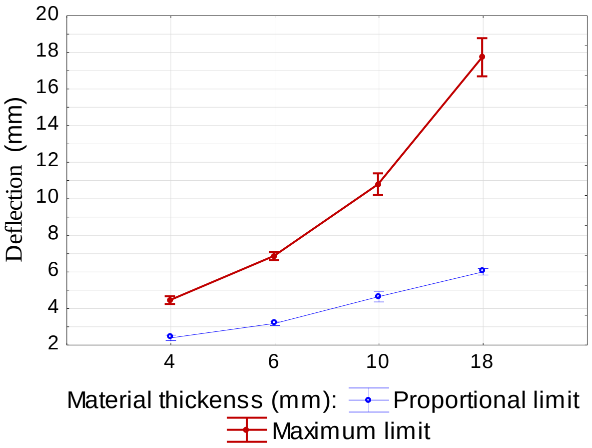


Fig. 5. Effect of the material thickness on deflection at the proportional limit and at the maximum limit

Based on the results, the degree of densification could be considered a moderately significant factor that affected the deflection at the proportional limit (Fig. 6). With 10% and 20% densification, a 9.21% increase in the monitored characteristic was measured in comparison to non-densified wood. There was no statistically significant difference between the average values of the densified wood (10% and 20%). In bending, the neutral layer shifts to the side with the higher stiffness (modulus of elasticity, *E*) (Fortino *et al.* 2013). Increasing the density of surface layers of the wood and therefore increasing the stiffness could theoretically lead to an increase in its bendability.

With the densification of wood, the values of deflection at the maximum limit increased with medium significance (Fig. 6). In comparison with deflection values at the proportional limit (where there was no significant difference between 10% and 20% densification), the monitoring of deflection at the maximum limit showed a medium significant difference between 10% and 20% densification. By a 10% densification a 5.6% to 5.7% increase in density was achieved in both wood species, and the values of the maximum limit increased 7.53% as a result of the densification. By 20% densification of beech wood a 3.6% increase in density was achieved, and in aspen wood an 8.6% increase in density was achieved; the average increase in maximum limit values was 5%.

Due to the effect of cycling loading, the average value of deflection at the proportional limit increased 6.41% in comparison to test specimens that were not subjected to cyclic loading. The authors believe that hydrogen bonds were weakened in the monitored number of loading cycles and the wood became more flexible. As a result the elastic deflection reached higher average values. It is believed that cyclic loading led to the development of plastic deformations, which resulted in a reduction in the nonlinear region. In the results of previous work (Gaff and Gašparík 2015), the cyclic loading (3,000, 6,000, and 7,000 cycles) had no significant effect. The authors expect that with a higher number of loading cycles the difference should be reflected more strongly. The results of previous work indicated that the effect of the monitored number of cycles (10,000) caused an increase in the limit of proportionality and a significant increase in elastic potential, which confirms the current hypothesis about the effect of the monitored number of cyclic loads.

While the assessment of the effect of cyclic loading on deflection at the proportional limit showed that cyclic loading can be considered to be a factor of medium significance (Fig. 7), the assessment of the effect of cyclic loading on deflection at the maximum limit illustrated that this was a factor of low significance (Fig. 7).

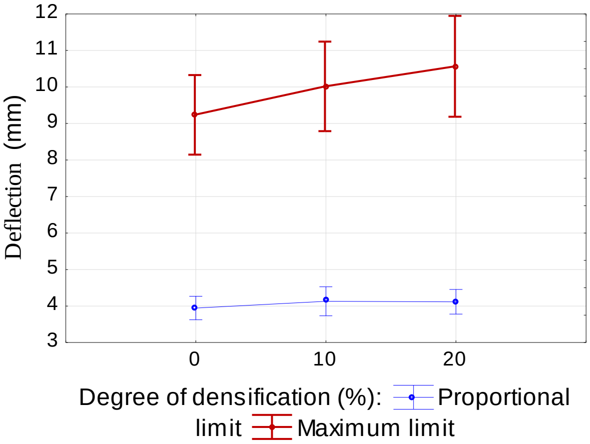


Fig. 6. Effect of the degree of densification on deflection at the proportional limit and at the maximum limit

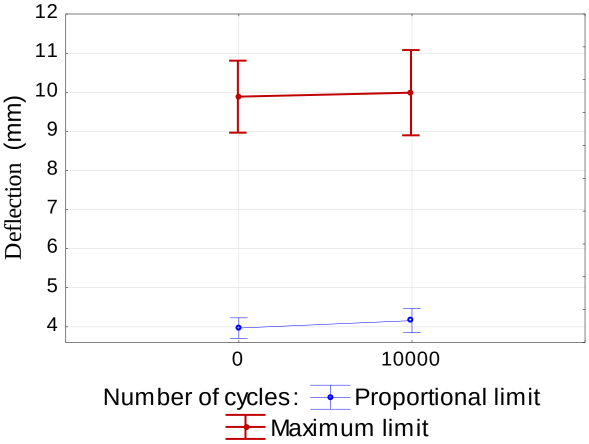
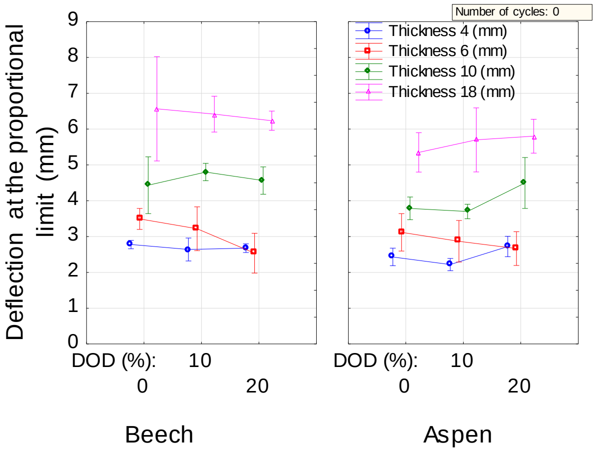


Fig. 7. Effect of the number of cycles on deflection at the proportional limit and at the maximum limit

The results illustrating the synergistic effect of all of the monitored factors suggest that the wood species and material thickness had the most significant impact on the deflection at the proportional limit (Figs. 8 and 9).



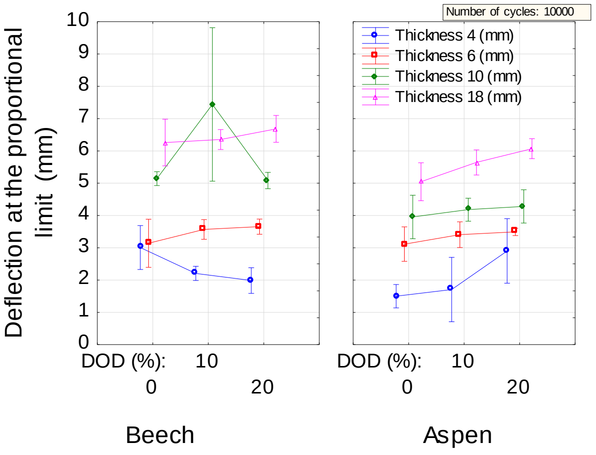
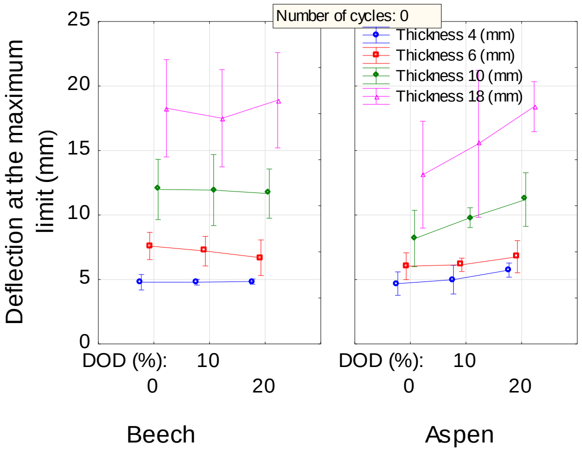


Fig. 8. Synergistic effect of the studied factors on the deflection at the proportional limit

Fig. 9. Synergistic effect of the studied factors on the deflection at the proportional limit

The synergistic effect of all the monitored factors on values of deflection at the maximum limit is shown in Figs. 10 and 11. The values point to the fact that the material thickness, wood species and degree of densification have the most significant effect on the monitored characteristic.



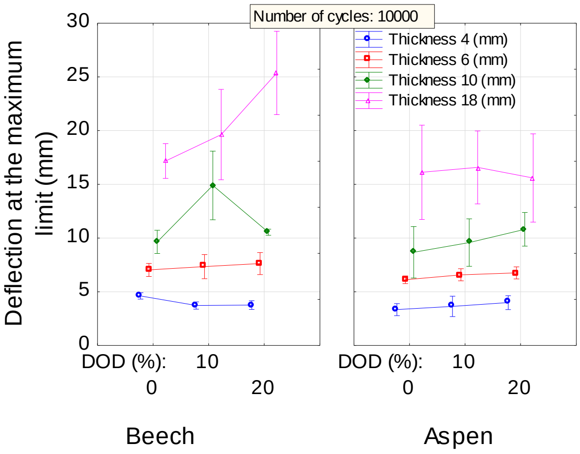


Fig. 10. Synergistic effect of the studied factors on the deflection at the maximum limit

Fig. 11. Synergistic effect of the studied factors on the deflection at the maximum limit

The Ratio of Deflection at the Proportional Limit and at the Maximum Limit

The results of a multi-factor variance analysis evaluating the effect of individual factors and their mutual interaction on the values of the ratio of deflection are shown in Table 7. Based on the results of Fisher's F-test and the level of significance *P*, it can be concluded that only material thickness and number of cycles had a significant effect on the ratio of deflection. The effect of other factors and their interaction was shown to be insignificant.

The interactions WS * DOD, MT * DOD, WS * NC, DOD * NC, WS * MT * NC, and MT * DOD * NC, as well as the interaction of all factors are not significant. The respective model explains roughly 58% of the total sum of squares.

Table 7. Statistical Evaluation of Factors and their Interaction on Ratio of Deflection

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F- Test	Significance Level *P*
Intercept	495717.4	1	495717.4	6695.953	***
1) Wood species	5.6	1	5.6	0.076	NS
2) Material thickness	11604.6	3	3868.2	52.250	***
3) Degree of densification	328.1	2	164.1	2.216	NS
4) Number of cycles	647.5	1	647.5	8.746	***
WS * MT	822.8	3	274.3	3.704	***
WS * DOD	315.2	2	157.6	2.129	NS
MT * DOD	593.3	6	98.9	1.336	NS
WS * NC	3.3	1	3.3	0.045	NS
MT * NC	777.6	3	259.2	3.501	***
DOD * NC	449.6	2	224.8	3.037	NS
WS * MT * DOD	1091.3	6	181.9	2.457	***
WS * MT * NC	320.1	3	106.7	1.441	NS
WS * DOD * NC	963.2	2	481.6	6.505	***
MT * DOD * NC	459.1	6	76.5	1.034	NS
1*2*3*4	865.8	6	144.3	1.949	NS
Error	14214.2	192	74.0		

NS - not significant, *** - significant P < 0.01

The results of Duncan's test (Table 8), confirmed the results shown in Table 7. The species had no influence on the ratio of deflection (*P* = 0.783). A densification of 10% was not statistically significant (*P* = 0.130) and a densification of 20% was close to being insignificant (*P* = 0.055). Cyclic loading significantly influenced the tested property at the level *P* = 0.003.

Table 8. Comparison of the Effects of Individual Factors using Duncan Test on the Values of the Deflection at the Maximum Limit

Wood Species		(1) 45.601	(2) 45.294
1	Beech		0.783
2	Aspen	0.783	

Degree of Densification (%)		(1) 47.052	(2) 44.992	(3) 44.299
1	0		0.130	0.055
2	10	0.130		0.610
3	20	0.055	0.610	

Material Thickness (mm)		(1) 54.833	(2) 47.245	(3) 44.304	(4) 35.408
1	4		0.000	0.000	0.000
2	6	0.000		0.061	0.000
3	10	0.000	0.061		0.000
4	18	0.000	0.000	0.000	

Number of Cycles		(1) 43.805	(2) 47.090
1	0		0.003
2	10000	0.003	

The results evaluating the effect of the wood species on the monitored characteristic are shown in Fig. 12. They confirm the results in Table 5, based on which it can be concluded that the wood species had no significant effect on the monitored characteristic, and the ratio of deflection did not change by the effect of the wood species.

As the material thickness increased, the ratio of deformation significantly decreased (Fig. 13). The results show that the proportion of plastic deformation increased along with the material thickness. Thicker materials were capable of achieving a larger proportion of plastic deformation and were more suitable for shaping by bending. In the bending method, 3-point bending was applied and the shear stress was not taken into account. Greater material thickness with the same width resulted in higher shear stress. Shear stress leads to higher bending values compared to bending measured in pure bending (Esendemir 2009).

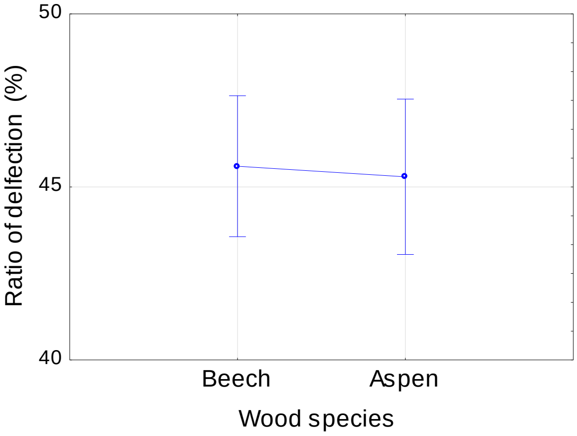


Fig. 12. Effect of the wood species on the ratio of deflection

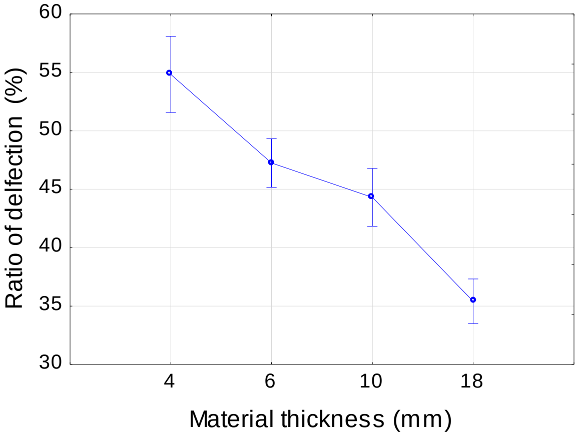


Fig. 13. Effect of the material thickness on the ratio of deflection

The ratio of deformation increased with material thickness. The deformation at the proportional limit increased far more intensively than the deformation at the maximum limit, due to increased material thickness. A thicker material was capable of achieving a large proportion of plastic deformation and was more suitable for shaping with bending. In the 3-point bending that was applied, the shear stress was not taken into account. Greater material thickness with the same width resulted in higher shear stress. Shear stress led to higher deflection values compared to bending measured in pure bending.

Based on the level of significance *P* given in Table 5, the effect of densification could be considered as a factor that significantly affected the ratio of deflection. Figure 14 clearly shows that the ratio of deflection increased with an increase in the degree of densification.

With cyclic loading, a significant increase of the values of elastic deformation in relation to plastic deformation was achieved (Fig. 15), which resulted in an increase in the ratio of deformation. It was most likely possible to achieve higher elastic deformation of material within the monitored range of cyclic loading. In the sets of test specimens not subjected to cyclic loading, the average deflection ratio was 43.6%, whereas in specimens subjected to cyclic loading it was 47%. It was likely that the cyclic loading caused the development of plastic and viscoelastic deformation. For this reason, the plastic deformations in the bending test after cyclic loading were smaller, *i.e.* the deflection ratio increased. Cyclic loading could affect the deflection at the proportional limit and result in an increased proportion of elastic deflection, due to the loosening of hydrogen bonds. The ratio of deformation decreased under cyclic loading, in which plastic and viscoelastic deformations developed. For this reason, the plastic deformations in the bending test after cyclic loading were smaller, *i.e.* the deflection ratio increased. The level of dependence between the deflection at the proportional limit and the deflection at the maximum limit was 90%. The ratio of deflection was 70% at the proportional limit and at the maximum limit only 38%.

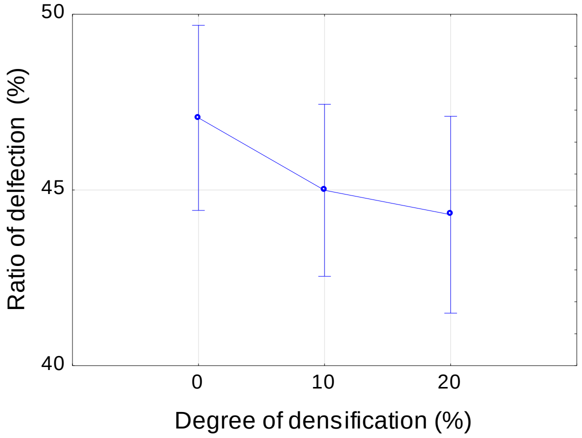


Fig. 14. Effect of the degree of densification on the ratio of deflection

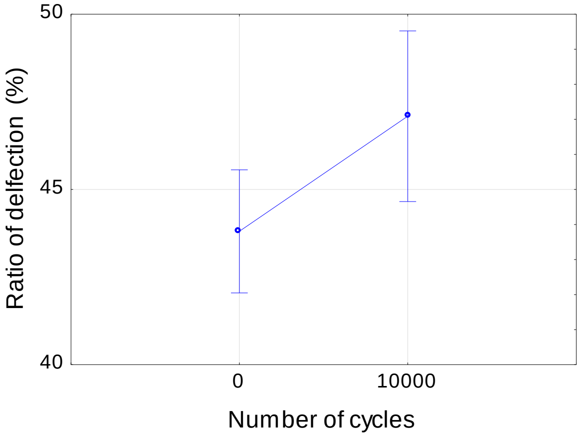


Fig. 15. Effect of the number of cycles on the ratio of deflection

The interaction of the effect of all monitored factors is shown in Figs. 16 and 17. It was apparent that the material thickness had the most significant effect on the monitored characteristic, resulting in an increased deflection ratio.

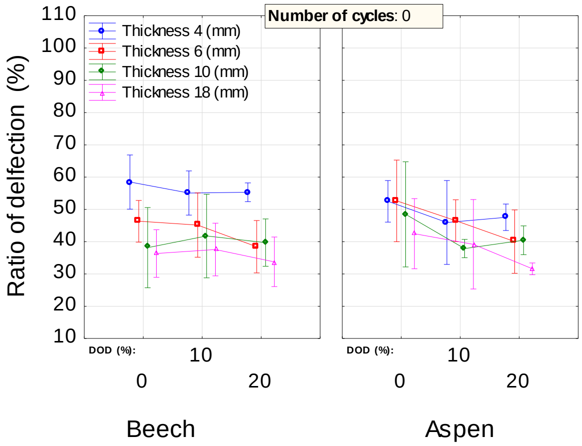


Fig. 16. Synergistic effect of the studied factors on the ratio of deflection

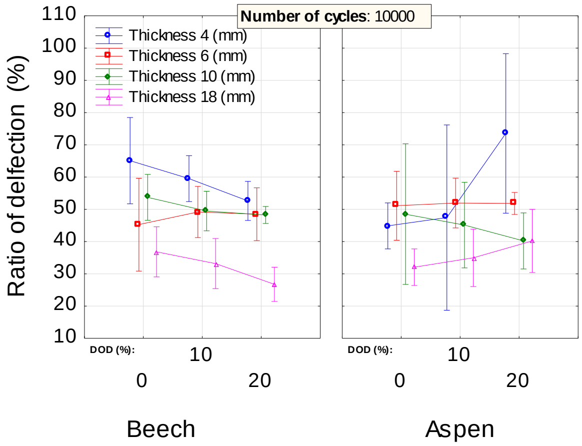


Fig. 17. Synergistic effect of the studied factors on the ratio of deflection

Correlation Analysis

The level of dependence between the deflection at the proportional limit and the deflection at the maximum limit was 91% (Table 9), which indicated a close level of dependence between the monitored characteristics.

The level of significance of the ratio of deflection and deflection at the proportional limit was only 69.5%, which indicated a close level of dependence between the monitored characteristics. The level of dependence between the ratio of deflection and deflection at the maximum limit was 37.7%. It was apparent that the limit of proportionality had a significant effect on this characteristic on the ratio of deflection, whereas the maximum limit had an insignificant effect on this characteristic.

Table 9. Spearman's Correlation

Variable	**Y_E (mm)**	**Y_P (mm)**	**Y_E:Y_P (mm)**
Y_E (mm)	1.000	0.908	-0.694
Y_P (mm)	0.908	1.000	-0.377
Y_E:Y_P (%)	-0.694	-0.377	1.000

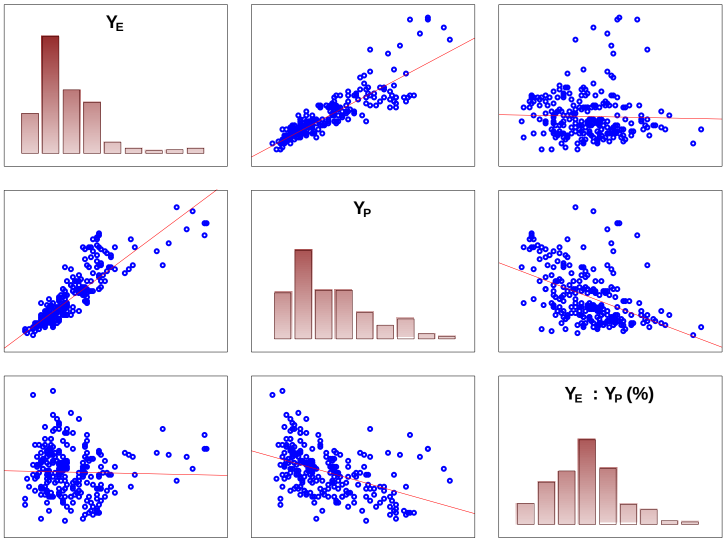


Fig. 18. Correlation matrix of the level of dependence of monitored characteristics

CONCLUSIONS

1. Each of the monitored factors (wood species, material thickness, degree of densification, and number of loading cycles), as well as their synergistic effect significantly affected the deflection at the proportional limit. In wood species with longer fibers, a higher deflection at the proportional limit during bending was achieved. A significant effect of the degree of densification within the monitored parameters was not observed.

2. The effect of the monitored factors on deflection at the proportional limit substantially coincided with the effect of the monitored factors on the deflection at the maximum limit. Only cyclic loading was shown to be insignificant, which had no effect on the deflection at the proportional limit.

3. The ratio of deflection was not affected by the type of material; there was no significant difference between the values measured in beech wood and aspen wood. The ratio of deformation increased with material thickness.
4. The degree of densification also had a significant effect on the monitored characteristic, and in turn the ratio increased significantly.

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REFERENCES CITED

Blomberg, J., Persson, B., and Blomberg, A. (2005). "Effects of semi-isostatic densification of wood on the variation in strength properties in density," *Wood Science and Technology* 39(5), 339-350. DOI: 10.1007/s00226-005-0290-8

Boonstra, M. J., and Blomberg, J. (2007). "Semi-isostatic densification of heat-treated radiate pine," *Wood Science and Technology* 41(7), 607-617. DOI: 10.1007/s00226-007-0140-y

Efe, H., Gürleyen, L., and Budakçi, M. (2007). "Effect of the cutting direction and number of knives on surface smoothness and bonding strength for *Acacia*," *Journal of Forestry Faculty* 7(1), 13-23.

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

Esendemir, U. (2009). "Derivation of equations for flexture and shear deflections of simply supported beams," *Journal of Engineering Sciences* 15(2), 187-193.

Fortino, S., Genoese, A., Genoese, A., and Rautkari, L. (2013). "FEM simulation of the hygro-thermal behavior of wood under surface densification at high temperature," *Journal of Materials Science* 48(21), 7603-7612. DOI: 10.1007/s10853-013-7577-1

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

Gaff, M., and Gašparík, M. (2015). "Effect of cyclic loading on modulus of elasticity of aspen wood," *BioResources* 10(1), 290-298. DOI: 10.15376/biores.10.1.290-298

Gaff, M., Gašparík, M., Babiak, M., and Vokatý, V. (2017). "Bendability characteristics of wood lamellae in plastic region," *Composite Structures* 163, 410-422. DOI: http://dx.doi.org/10.1016/j.compstruct.2016.12.052

Gaff, M., Gašparík, M., Borůvka, V., and Haviarová, E. (2015a). "Stress simulation in layered wood-based materials under mechanical loading," *Materials and Design* 87, 1065-1071. DOI: 10.1016/j.matdes.2015.08.128

Gaff, M., Vokatý, V., Babiak, M., and Bal, B. C. (2016). "Coefficient of wood bendability as a function of selected factors," *Construction and Building Materials* 126, 632-640. DOI: http://dx.doi.org/10.1016/j.conbuildmat.2016.09.085

Gašparík, M., and Gaff, M. (2015b). "The influence of cyclic stress on the attenuation rate of deflection of solid wood and laminated wood," *Wood Research* 60(3), 351-358.

Gašparík, M., and Gaff, M. (2015c). "Influence of densification on bending strength of beech wood," *Wood Research* 60(2), 211-218.

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

Higashihara, T., Morooka, T., and Norimoto, M. (2000). “Permanent fixation of transversely compressed wood by heating and its mechanism,” *Mokuzai Gakkaishi* 52(4), 291-297.

ISO 13061-1 (2014). “Wood-determination of moisture content for physical and mechanical tests,” International Organization for Standardization, Geneva, Switzerland.

ISO 13061-2 (2014). “Wood-determination of density for physical and mechanical tests,” International Organization for Standardization, Geneva, Switzerland.

ISO 3348 (1975). “Wood-determination of impact bending strength,” International Organization for Standardization, Geneva, Switzerland.

Kamke, F. A. (2006). “Densified radiate pine for structural composites,” *Maderas Ciencia y Tecnología* 8(2), 83-92. DOI: 10.4067/S0718-221X2006000200002

Laine, K., Segerholm, K., Wålinder, M., Rautkari, L., Ormondroyd, G., Hughes, M., and Jones, D. (2014). “Micromorphological studies of surface densified wood,” *Journal of Materials Science* 49(5), 2027-2034. DOI: 10.1007/s10853-013-7890-8

Požgaj, A., Chovanec, D., Kurjatko, S., and Babiak, M. (1997). *Štruktúra a Vlastnosti Dreva* [*Structure and Properties of Wood*], A. S. Príroda, Bratislava, Slovakia.

Sandberg, D., and Navi, P. (2007). “Introduction to thermo-hydro-mechanical (THM) wood processing,” *Växjö: School of Technology and Design*, Växjö, Sweden.

Schellberg, D. (2012). *Innovativer Möbelbau - Aktuelle Materialien und Techniken*, Gebundenes Buch mit Schutzumschlag, Germany.

Wagenführ, R. (2000). *Holzatlas* [*Atlas of Wood*] (5th Ed., in German), Fachbuchverlag, Leipzig, Germany.

Wagenfuhrer, A., Buchelt, B., and Pfriem, A. (2006). “Material behaviour of veneer during multidimensional molding,” *Holz als Roh-und Werkstoff* 64, 83-89. DOI: 10.1007/s00107-005-0008-5

Yamashita, O., Yokochi, M., Miki, T., and Kanayama, K. (2009). “The pliability of wood and its application to molding,” *Journal of Materials Processing Technology* 209(12-13), 5239-5244. DOI: 10.1016/j.jmatprotec.2008.12.011

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