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Laminated Veneer Lumber with Non-Wood Components and the Effects of Selected Factors on Its Bendability

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Abstract: Knowledge of the coefficients of wood bendability (K_{bendC} and K_{bendB}) and of the effects of selected factors on the listed characteristics in bending stress has both scientific and practical significance. It forms a foundation for designing tools for bending and determines the stress that products and their parts can be exposed to during use. This study analyzes the effects of selected factors on the selected characteristics, such as the coefficients of wood bendability (K_{bendC} and K_{bendB}). The selected factors of this study were wood species (WS) (*Fagus sylvatica* L. and *Populus tremula* L.), non-wood component (carbon fiber and glass fiber), position of the non-wood component in the laminated material (top and bottom), material thickness (T) (6 mm, 10 mm, and 18 mm), and adhesive (polyvinyl acetate and polyurethane), as well as their combined interaction on the monitored characteristics described above. The results contribute to the advancement of knowledge necessary for the study and development of new materials with specific properties for their intended use. The measured values of laminated structures can be compared with the values measured on the samples from the wood. The results can improve the innovative potential of wood processing companies and increase their performance and competitiveness in the market.

Keywords: coefficient of wood bendability; laminated wood; technological and product innovations; minimal curve radius

1. Introduction

The effective use of wood and its by-products has gained increased attention in recent years due to limited natural resources [1,2]. It is in society's general interest to efficiently utilize our limited forest resources and improve recycling [2].

Because composite material production uses materials of varying characteristics, it is necessary to verify their quality to ensure good product performance and market competitiveness. Composite production is a complex process [3]; it requires immediate consideration of various parameters (cutting geometry, production volume, matrix types, machine requirements, market economy, etc.). One of the main aspects limiting the structural use of high-strength composites is their weak interlaminar resistance [4]. Several strategies for enhancing the resistance of composites have been proposed [4–6], such as using a harder resin for hybrid composites, harder adhesive layers, and others.

Material stratification is very important in industrial practice, both in construction and in the manufacturing industry [7,8]. In the woodworking industry, homogeneity leads to better performance, thereby reducing the possible negative properties of wood that could lead to material failures. In environmental modification of wood, a number of studies have focused on thermal modification [9–15]. Densification of wood is also one of the ways to modify the basic properties of wood. It is a process whereby wood is pressed, for example, by rolling or by the action of various presses, thereby reducing its volume and increasing density. Such wood is then harder, firmer, and darker to look at. Densification of wood reduces the porosity and moisture content of the wood [16]. Gaff et al. [17] examined the effect of densification on bond strength. They found that the effect of the densification on bond strength is statistically very significant.

Another way to modify the properties of wood elements is through the use of non-wood reinforcing materials to form wood-based composite materials [18]. Such reinforcing materials include carbon, aramid, basalt, and glass fibers [19–21]. The application of non-wood components in a wood-based laminated veneer lumber material is usually intended to strengthen the material, increase its resistance to stress, and reduce bending values [22,23]. Such materials are characterized by different specific properties for their intended uses [24–27]. The intended use is a determining factor of the desired characteristics in a given material [22,28–30]. In some cases, emphasis is placed on materials with high strength values, while other cases see the creation of materials with high elasticity values [23] or high bendability values [22].

Bendability is a characteristic that has recently attracted great interest. The effect of the placement of a non-wood component in such a material has not yet been given much attention, and the interactions of different types of materials with other factors influencing this characteristic have also not been studied. A mathematical interpretation of the bending coefficient [17] was only recently established for the correct description of bendability.

The bending coefficient (K_{bend}) is a quantitative characteristic that is defined as the ratio of the thickness (h) of the bent material to the minimum bend radius (R) (Figure 1). For most types of wood, the limit ratio is h:R = 1:35 to 1:45. The critical area for bending wood is the tensile zone. The maximum tensile deformation of wood in its original unmodified state is 0.75% to 1%. This can be increased with plasticization to 1.5% to 2%. By contrast, the compressibility of wood is greater at optimum humidity and temperature; if its porosity allows it, it reaches up to 40% [31].

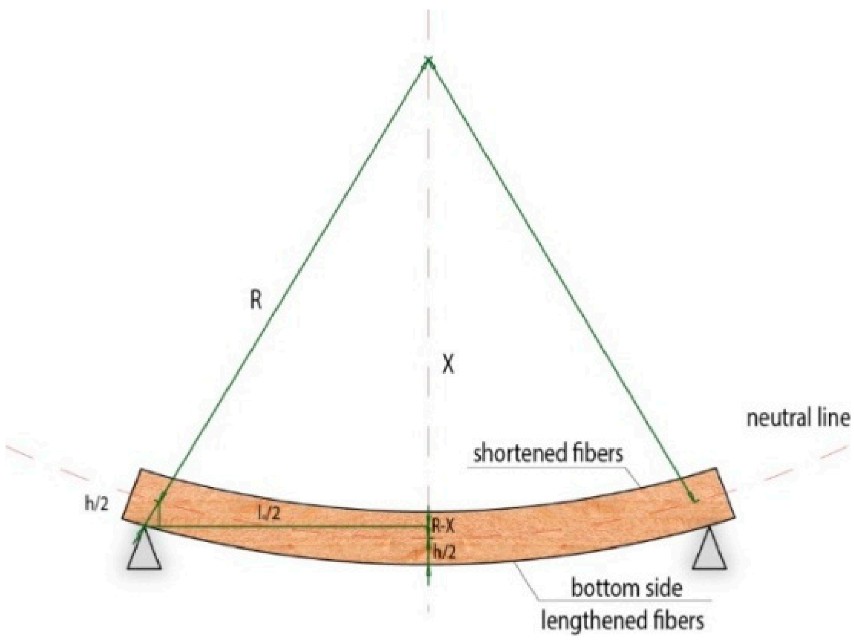

Figure 1. Bending geometry.

There is very little scientific knowledge about the minimum bend radius and bending coefficient. The aim of our work is therefore to deepen the knowledge of the bending coefficient of wood (K_{bendC} and K_{bendB}), namely beech and aspen, under three-point bending. Gaff et al. [32] showed that as the material thickness increases, the value of the bending coefficient decreases, and the force needed for bending increases. Gaff et al. [17] created a model for analyzing bendability, with which it is possible to define the correct relations for determining the minimum bend radius (R_{min}), which can then be used to calculate the bending coefficient (K_{bend}).

2. Materials and Methods

2.1. Material

The wooden lamellas used in this experiment were made of beech wood (*Fagus sylvatica* L.) and aspen wood (*Populus tremula* L.) with thicknesses of 3 mm, 5 mm, and 9 mm, widths of 35 mm, and lengths of 600 mm. The beech and aspen wood came from Polana, Slovakia. Polyvinyl acetate (PVAc) and polyurethane (PUR) adhesives were used to produce laminated wood using the above lamellas. Carbon fibers (SikaWrap-150 C/30, 155 g/m^2 ± 5 g/m^2) and glass fibers (Kittfort, 355 g/m^2) were used as the reinforcing materials, which were first glued on the convex sides and then on the concave sides with respect to the direction of loading. Categorization of the test specimens is shown in Figure 2.

Figure 2. Categorization of test specimens.

After all test specimens were created, they were climatized in a climatic chamber (ED, APT Line II, Binder, Tuttlingen, Germany) to 12% moisture content at 65% relative humidity and 20 °C.

2.2. Methods

2.2.1. Determining Selected Characteristics

Testing was performed with three-point bending (Figure 3), with the bottom support span set to 20 times the total thickness of the test specimen. The top support crossbeam was set in a center position relative to the distance of the bottom support crossbeam. Testing was performed according to EN 310 (1993) [33] using a universal testing machine (FPZ 100, TIRA, Schalkau, Germany). Testing took place in the tangential direction relative to the fiber direction. The feed rate of the top support was set to 3 mm/min due to the duration of the test. An ALMEMO 2690-8 datalogger (AhlbornGmbH, Braunschweig, Germany) was used to record all the forces during the test.

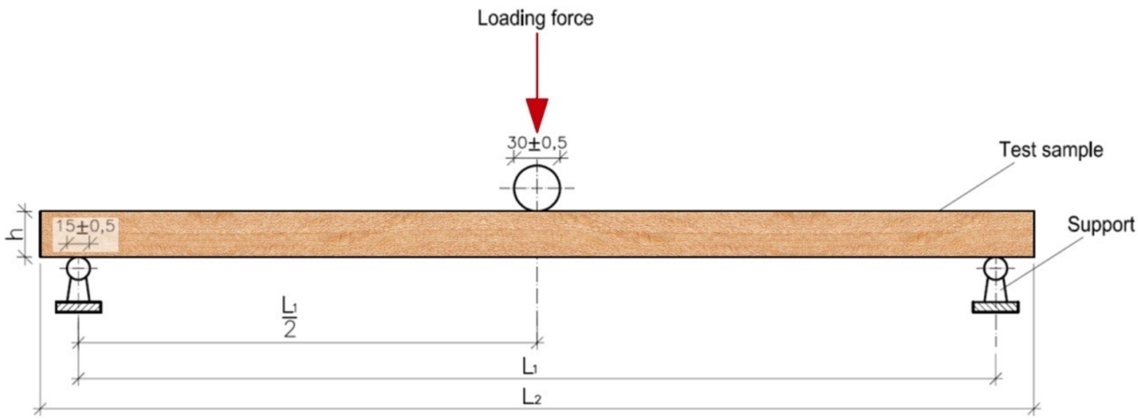

Figure 3. Principle of the three-point bending test [33].

Before the measurement was performed, the densities and humidities of the used wooden components were measured according to ISO 13061-1 (2014) [34] and ISO 13061-2 (2014) [35]. After the tests were completed, all test specimens were dried to 0% moisture content, as necessary to calculate the moisture content at the time of the test.

2.2.2. Evaluation and Calculation of K_{bend} and R_{min}

Based on data obtained from the stress–strain diagram, exact identification of the boundary points between the linear and non-linear parts of the diagram was used to determine forces at the limit of proportionality (F_E) and at the yield point (F_P), along with the deflections at the limit of proportionality (Y_E) and at the yield point (Y_P). These characteristics were identified using the MATESS program, which is currently being developed by the Czech University of Life Sciences in Prague.

In the next step, the bendability of the tested material was evaluated based on the minimum bend radius (R_{minB} and R_{minC}) and the bending coefficient (K_{bendB} and K_{bendC}). Two approaches were used to evaluate the bendability. The first approach was based on bending geometry (Equations (1) and (2)), while the second approach was based on the simple bending equations (Equations (3) and (4)), which were used in the work of Gaff et al. [17]:

$$R_{minB} = \frac{l_0^2}{8\,Y_P} + \frac{Y_P}{2} - \frac{h}{2} \tag{1}$$

$$K_{bendB} = \frac{h}{R_{minB}} = \frac{h}{\frac{l_0^2}{8\,Y_P} + \frac{Y_P}{2} - \frac{h}{2}} \tag{2}$$

$$R_{minC} = \frac{l_0^2}{12\,Y_P} \tag{3}$$

$$K_{bendC} = \frac{h}{R_{minC}} = \frac{h}{\frac{l_0^2}{12\,Y_P}} \tag{4}$$

where R_{minB} is the minimum bend radius based on bending geometry (mm), R_{minC} is the minimum bend radius based on the simple bending equations (mm), K_{bendB} is the bending coefficient based on bending geometry, K_{bendC} is the bending coefficient based on the simple bending equations, Y_P is the deflection at the yield point (mm), l_0 is the bottom support span (mm), and h is the total material thickness (mm).

The results were statistically evaluated with an analysis of variance (ANOVA), specifically Fisher's F-test, with STATISTICA 12 software (Statsoft Inc., Tulsa, OK, USA). The results were evaluated using a 95% confidence interval, which represents a significance level of 0.05 ($p < 0.05$). Duncan's test was also used for deeper analysis to compare all sets of test specimens.

3. Results and Discussion

Tables 1 and 2 show the average values and coefficients of variation (in parentheses) of the monitored characteristics, the average density values measured in individual sets of test specimens, and the corresponding coefficients of variation. Table 1 shows the average values of K_{bendC}, K_{bendB}, R_{minC}, and R_{minB} measured in the aspen test specimens.

Table 1. Values of bending characteristics and the coefficients of variance of layered aspen material.

WS	NWC	Location	Glue	T (mm)	Code of Test Sample	K_{bendC}	K_{bendB}	R_{minC} (mm)	R_{minB} (mm)
A	CA	U	PUR	6	A-CA-U-PUR-6	0.014 (17.0)	0.012 (13.5)	519.28 (9.4)	717.76 (11.9)
A	CA	U	PUR	10	A-CA-U-PUR-10	0.024 (13.3)	0.015 (16.8)	526.38 (14.9)	693.13 (20.4)
A	CA	U	PUR	18	A-CA-U-PUR-18	0.012 (8.4)	0.007 (7.8)	1616.03 (14.7)	2448.28 (13.5)
A	CA	U	PVAc	6	A-CA-U-PVAc-6	0.039 (4.1)	0.026 (4.1)	150.72 (3.3)	227.08 (3.3)
A	CA	U	PVAc	10	A-CA-U-PVAc-10	0.034 (5.0)	0.023 (5.1)	280.19 (12.0)	406.81 (17.0)
A	CA	U	PVAc	18	A-CA-U-PVAc-18	0.013 (14.0)	0.008 (13.6)	1279.40 (15.5)	1651.62 (11.4)
A	LA	U	PUR	6	A-LA-U-PUR-6	0.031 (11.3)	0.021 (17.5)	159.95 (14.3)	238.00 (18.0)
A	LA	U	PUR	10	A-LA-U-PUR-10	0.024 (16.0)	0.015 (14.4)	511.83 (18.5)	671.01 (16.6)
A	LA	U	PUR	18	A-LA-U-PUR-18	0.015 (17.2)	0.010 (17.2)	1233.71 (14.0)	1848.16 (14.0)
A	LA	U	PVAc	6	A-LA-U-PVAc-6	0.043 (14.7)	0.028 (14.1)	134.11 (11.4)	202.81 (11.0)
A	LA	U	PVAc	10	A-LA-U-PVAc-10	0.022 (11.3)	0.015 (17.6)	401.48 (10.8)	628.74 (9.6)
A	LA	U	PVAc	18	A-LA-U-PVAc-18	0.016 (10.3)	0.011 (8.9)	1220.28 (10.8)	1688.32 (13.4)
A	CA	D	PUR	6	A-CA-D-PUR-6	0.026 (19.4)	0.019 (17.9)	248.51 (19.1)	355.31 (16.0)
A	CA	D	PUR	10	A-CA-D-PUR-10	0.022 (17.9)	0.014 (15.4)	379.73 (18.4)	570.20 (18.3)
A	CA	D	PUR	18	A-CA-D-PUR-18	0.020 (19.6)	0.013 (20.4)	878.98 (13.2)	1365.45 (18.2)
A	CA	D	PVAc	6	A-CA-D-PVAc-6	0.036 (19.2)	0.026 (21.0)	165.21 (11.8)	253.26 (7.4)
A	CA	D	PVAc	10	A-CA-D-PVAc-10	0.037 (15.7)	0.024 (15.3)	280.82 (16.4)	427.67 (15.8)
A	CA	D	PVAc	18	A-CA-D-PVAc-18	0.024 (17.2)	0.014 (18.3)	884.80 (12.0)	1454.81 (11.9)
A	LA	D	PUR	6	A-LA-D-PUR-6	0.031 (15.6)	0.024 (20.4)	144.14 (15.0)	218.42 (14.7)
A	LA	D	PUR	10	A-LA-D-PUR-10	0.032 (16.5)	0.021 (16.3)	330.58 (16.3)	495.74 (16.2)
A	LA	D	PUR	18	A-LA-D-PUR-18	0.028 (18.7)	0.019 (18.5)	670.60 (21.4)	1004.97 (21.3)
A	LA	D	PVAc	6	A-LA-D-PVAc-6	0.036 (7.2)	0.027 (12.1)	143.00 (14.7)	225.48 (15.4)
A	LA	D	PVAc	10	A-LA-D-PVAc-10	0.027 (16.6)	0.018 (16.5)	402.30 (18.6)	602.38 (18.5)
A	LA	D	PVAc	18	A-LA-D-PVAc-18	0.023 (19.2)	0.014 (19.9)	886.44 (17.9)	1322.03 (18.0)

WS—wood species; NWC—non-wood component; T—thickness; K_{bendC}—bending coefficient based on simple bending equations; K_{bendB}—bending coefficient based on bending geometry; R_{minC}—minimum bend radius based on simple bending equations; R_{minB}—minimum bend radius based on bending geometry; A—aspen; CA—carbon; LA—glass fiber; U—top; D—bottom.

Table 2. Average values of bending characteristics and the coefficients of variance of layered beech material.

WS	NWC	Location	Glue	T (mm)	Code of Test Sample	K_{bendC}	K_{bendB}	R_{minC} (mm)	R_{minB} (mm)
B	CA	U	PUR	6	B-CA-U-PUR-6	0.024 (17.6)	0.016 (17.6)	231.20 (12.9)	340.25 (8.4)
B	CA	U	PUR	10	B-CA-U-PUR-10	0.026 (15.4)	0.017 (18.6)	459.30 (20.7)	663.96 (17.4)
B	CA	U	PUR	18	B-CA-U-PUR-18	0.011 (6.0)	0.006 (19.4)	2262.89 (18.2)	3288.95 (16.4)
B	CA	U	PVAc	6	B-CA-U-PVAc-6	0.037 (9.1)	0.024 (8.8)	153.98 (8.9)	232.03 (8.7)
B	CA	U	PVAc	10	B-CA-U-PVAc-10	0.031 (9.6)	0.021 (9.6)	354.65 (9.5)	531.16 (9.5)
B	CA	U	PVAc	18	B-CA-U-PVAc-18	0.014 (16.9)	0.009 (9.7)	1416.71 (12.4)	1804.00 (21.0)
B	LA	U	PUR	6	B-LA-U-PUR-6	0.044 (5.1)	0.030 (0.8)	134.43 (11.2)	169.19 (8.5)
B	LA	U	PUR	10	B-LA-U-PUR-10	0.025 (16.4)	0.016 (16.3)	439.62 (18.5)	657.95 (18.4)
B	LA	U	PUR	18	B-LA-U-PUR-18	0.008 (19.3)	0.005 (17.2)	2442.86 (20.3)	3391.53 (14.3)
B	LA	U	PVAc	6	B-LA-U-PVAc-6	0.033 (5.6)	0.022 (5.5)	168.33 (4.7)	253.25 (4.6)
B	LA	U	PVAc	10	B-LA-U-PVAc-10	0.032 (11.8)	0.022 (10.8)	317.76 (16.7)	476.68 (16.4)
B	LA	U	PVAc	18	B-LA-U-PVAc-18	0.013 (19.2)	0.008 (19.2)	1451.32 (18.4)	2171.66 (18.4)
B	CA	D	PUR	6	B-CA-D-PUR-6	0.034 (7.7)	0.023 (7.6)	166.27 (8.6)	250.18 (8.4)
B	CA	D	PUR	10	B-CA-D-PUR-10	0.025 (17.9)	0.015 (17.9)	427.22 (18.8)	644.19 (18.5)
B	CA	D	PUR	18	B-CA-D-PUR-18	0.015 (12.3)	0.015 (18.5)	1232.78 (15.1)	1488.03 (17.2)
B	CA	D	PVAc	6	B-CA-D-PVAc-6	0.042 (14.0)	0.028 (13.6)	135.40 (12.5)	204.75 (12.2)
B	CA	D	PVAc	10	B-CA-D-PVAc-10	0.030 (14.9)	0.021 (19.5)	296.37 (16.9)	489.47 (19.4)
B	CA	D	PVAc	18	B-CA-D-PVAc-18	0.021 (18.9)	0.014 (18.8)	793.45 (18.4)	1248.23 (11.0)
B	LA	D	PUR	6	B-LA-D-PUR-6	0.046 (7.4)	0.030 (7.0)	105.94 (7.5)	162.18 (7.0)
B	LA	D	PUR	10	B-LA-D-PUR-10	0.024 (13.0)	0.015 (17.9)	426.66 (13.0)	683.36 (19.0)
B	LA	D	PUR	18	B-LA-D-PUR-18	0.026 (18.4)	0.016 (16.7)	663.54 (18.5)	1209.10 (14.0)
B	LA	D	PVAc	6	B-LA-D-PVAc-6	0.035 (8.5)	0.023 (8.3)	160.41 (7.9)	241.58 (7.7)
B	LA	D	PVAc	10	B-LA-D-PVAc-10	0.034 (19.3)	0.024 (13.5)	296.34 (19.6)	459.85 (13.9)
B	LA	D	PVAc	18	B-LA-D-PVAc-18	0.033 (17.3)	0.022 (17.0)	526.61 (16.3)	795.58 (16.4)

WS—wood species; NWC—non-wood component; T—thickness; K_{bendC}—bending coefficient based on simple bending equations; K_{bendB}—bending coefficient based on bending geometry; R_{minC}—minimum bend radius based on simple bending equations; R_{minB}—minimum bend radius based on bending geometry; B—beech; CA—carbon; LA—glass fiber; U—top; D—bottom.

The highest average values of R_{minC} (1616 mm) and R_{minB} (2448 mm) were measured in the material with a thickness of 18 mm glued with PUR adhesive and reinforced with carbon fibers placed on the top side with respect to the direction of loading. The lowest average values of R_{minC} (134 mm) and R_{minB} (202 mm) were measured in the material with a thickness of 6 mm glued with PVAc adhesive and reinforced with glass fibers placed on the top side with respect to the direction of loading.

Higher average values for the bending coefficient were obtained in calculations based on the simple bending equation K_{bendC} (0.01 to 0.04) than in calculations based on bending geometry K_{bendB} (0.01 to 0.03), which corresponds with the results reported in the work of Gaff et al. [17], who also studied the bending coefficient of unmodified aspen wood.

Table 2 shows the average values of K_{bendC}, K_{bendB}, R_{minC}, and R_{minB} calculated in beech test specimens. The layered beech materials showed the same tendency of the bending coefficient as the laminated aspen materials. In the laminated beech materials, K_{bendC} values (0.01 to 0.05) were greater than K_{bendB} values (0.01 to 0.03). Comparing these results with those of Gaff et al. [17] confirms the trend of greater K_{bendC} values.

The greatest average value of R_{minB} (3391 mm) was measured in the material with a thickness of 18 mm glued with PUR adhesive and reinforced with glass fibers on the top side with respect to the direction of loading. The lowest value of R_{minB} (162 mm) was measured in the material with a total thickness of 6 mm bonded with PUR adhesive and reinforced with glass fiber on the bottom side of the test specimen relative to the direction of loading. The greatest (2442 mm) and lowest (105 mm) average values of R_{minC} were measured in the same materials as the greatest and lowest values of R_{minB}.

All the measured data were statistically evaluated using a single-factor analysis in which the test specimen type was chosen as the default factor. The evaluation was based on the significance level p, which was less than 0.005. Tables 3–6 show the statistical evaluation of the effect of the test specimen type on the bending coefficient based on the simple bending equations (K_{bendC}) in laminated aspen and beech materials with the non-wood component placed on the top or bottom side with respect to the direction of loading.

Table 3. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendC}) for aspen and non-wood component (NWC) on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.101015	1	0.101015	4182.484	***
1) Type of Sample	0.003778	11	0.000343	14.220	***
Error	0.002608	108	0.000024		

NS—not significant, ***—significant at $p < 0.005$.

Table 4. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendC}) for aspen and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.058817	1	0.058817	5814.366	***
1) Type of Sample	0.010364	11	0.000942	93.141	***
Error	0.001022	101	0.000010		

NS—not significant, ***—significant at $p < 0.005$.

Table 5. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendC}) for beech and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.114036	1	0.114036	5587.265	***
1) Type of Sample	0.008469	11	0.000770	37.724	***
Error	0.002204	108	0.000020		

NS—not significant, ***—significant at $p < 0.005$.

Table 6. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendC}) for beech and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.055837	1	0.055837	5566.564	***
1) Type of Sample	0.011935	11	0.001085	108.163	***
Error	0.001144	114	0.000010		

NS—not significant, ***—significant at $p < 0.005$.

Tables 7–10 show the statistical evaluation of the effect of the test specimen type on the bending coefficient based on bending geometry (K_{bendB}) in laminated aspen and beech materials with the non-wood component placed on the top or bottom with respect to the direction of loading.

Table 7. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendB}) for aspen and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.046953	1	0.046953	3654.379	***
1) Type of Sample	0.002775	11	0.000252	19.633	***
Error	0.001388	108	0.000013		

NS—not significant, ***—significant at $p < 0.005$.

Table 8. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendB}) for aspen and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.026766	1	0.026766	5122.907	***
1) Type of Sample	0.004369	11	0.000397	76.012	***
Error	0.000528	101	0.000005		

NS—not significant, ***—significant at $p < 0.005$.

Table 9. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendB}) for beech and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.052061	1	0.052061	5814.871	***
1) Type of Sample	0.003206	11	0.000291	32.553	***
Error	0.000967	108	0.000009		

NS—not significant, ***—significant at $p < 0.005$.

Table 10. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendB}) for beech and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.024553	1	0.024553	5158.266	***
1) Type of Sample	0.005388	11	0.000490	102.915	***
Error	0.000543	114	0.000005		

NS—not significant, ***—significant at $p < 0.005$.

Tables 11–14 show the statistical evaluation of the effect of the test specimen type on the minimum bend radius based on the simple bending equations (R_{minC}) in laminated aspen and beech materials with the non-wood component placed on the top or bottom with respect to the direction of loading.

Table 11. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minC}) for aspen and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	24436158	1	24436158	3264.754	***
1) Type of Sample	9717956	11	883451	118.032	***
Error	808363	108	7485		

NS—not significant, ***—significant at $p < 0.005$.

Table 12. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minC}) for aspen and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	44421882	1	44421882	2710.337	***
1) Type of Sample	28160468	11	2560043	156.197	***
Error	1655370	101	16390		

NS—not significant, ***—significant at $p < 0.005$.

Table 13. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minC}) for beech and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	22802737	1	22802737	2892.018	***
1) Type of Sample	12097814	11	1099801	139.485	***
Error	851549	108	7885		

NS—not significant, ***—significant at $p < 0.005$.

Table 14. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minC}) for beech and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	58491893	1	58491893	1178.097	***
1) Type of Sample	81191097	11	7381009	148.662	***
Error	5660040	114	49649		

NS—not significant, ***—significant at $p < 0.005$.

Tables 15–18 show the statistical evaluation of the effect of the test specimen type on the minimum bend radius based on bending geometry (R_{minB}) in laminated aspen and beech materials with the non-wood component placed on the top or bottom with respect to the direction of loading.

Table 15. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minB}) for aspen and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	57349324	1	57349324	2933.356	***
1) Type of Sample	24093243	11	2190295	112.031	***
Error	2111481	108	19551		

NS—not significant, ***—significant at $p < 0.005$.

Table 16. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minB}) for aspen and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	89797468	1	89797468	2744.915	***
1) Type of Sample	61286334	11	5571485	170.308	***
Error	3304126	101	32714		

NS—not significant, ***—significant at $p < 0.005$.

Table 17. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minB}) for beech and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	51699287	1	51699287	2759.401	***
1) Type of Sample	22194201	11	2017655	107.690	***
Error	2023455	108	18736		

NS—not significant, ***—significant at $p < 0.005$.

Table 18. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minB}) for beech and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	118241938	1	118241938	1681.398	***
1) Type of Sample	159214450	11	14474041	205.821	***
Error	8016889	114	70324		

NS—not significant, ***—significant at $p < 0.005$.

Duncan's test was performed for a detailed comparison of the differences in the bending coefficients (K_{bendC} and K_{bendB}) among individual types of laminated aspen and beech materials, and the results are shown in Tables 19–26.

Table 19. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendC}) for aspen and NWC on the bottom.

No.	Type of Sample	(1) 0.026	(2) 0.022	(3) 0.020	(4) 0.036	(5) 0.037	(6) 0.024	(7) 0.031	(8) 00.32	(9) 0.028	(10) 0.036	(11) 0.027	(12) 0.023
1.	A-CA-D-PUR-6												
2.	A-CA-D-PUR-10	0.048											
3.	A-CA-D-PUR-18	0.007	0.414										
4.	A-CA-D-PVAc-6	0.000	0.000	0.000									
5.	A-CA-D-PVAc-10	0.000	0.000	0.000	0.973								
6.	A-CA-D-PVAc-18	0.261	0.331	0.092	0.000	0.000							
7.	A-LA-D-PUR-6	0.049	0.000	0.000	0.032	0.035	0.003						
8.	A-LA-D-PUR-10	0.016	0.000	0.000	0.085	0.096	0.001	0.595					
9.	A-LA-D-PUR-18	0.445	0.008	0.001	0.001	0.001	0.077	0.182	0.078				
10.	A-LA-D-PVAc-6	0.000	0.000	0.000	0.943	0.965	0.000	0.036	0.100	0.001			
11.	A-LA-D-PVAc-10	0.895	0.040	0.005	0.000	0.000	0.238	0.057	0.019	0.494	0.000		
12.	A-LA-D-PVAc-18	0.213	0.403	0.120	0.000	0.000	0.840	0.002	0.000	0.056	0.000	0.187	

Table 20. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendC}) for aspen and NWC on top.

No.	Type of Sample	(1) 0.014	(2) 0.024	(3) 0.012	(4) 0.039	(5) 0.034	(6) 0.013	(7) 0.031	(8) 0.024	(9) 0.015	(10) 0.043	(11) 0.022	(12) 0.016
1.	A-CA-U-PUR-6												
2.	A-CA-U-PUR-10	0.000											
3.	A-CA-U-PUR-18	0.198	0.000										
4.	A-CA-U-PVAc-6	0.000	0.000	0.000									
5.	A-CA-U-PVAc-10	0.000	0.000	0.000	0.002								
6.	A-CA-U-PVAc-18	0.886	0.000	0.221	0.000	0.000							
7.	A-LA-U-PUR-6	0.000	0.000	0.000	0.000	0.075	0.000						
8.	A-LA-U-PUR-10	0.000	0.935	0.000	0.000	0.000	0.000	0.000					
9.	A-LA-U-PUR-18	0.603	0.000	0.086	0.000	0.000	0.535	0.000	0.000				
10.	A-LA-U-PVAc-6	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.000			
11.	A-LA-U-PVAc-10	0.000	0.242	0.000	0.000	0.000	0.000	0.000	0.240	0.000	0.000		
12.	A-LA-U-PVAc-18	0.264	0.000	0.022	0.000	0.000	0.228	0.000	0.000	0.502	0.000	0.000	

Table 21. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendC}) for beech and NWC on the bottom.

No.	Type of Sample	(1) 0.034	(2) 0.025	(3) 0.015	(4) 0.042	(5) 0.030	(6) 0.021	(7) 0.046	(8) 0.024	(9) 0.026	(10) 0.035	(11) 0.034	(12) 0.033
1.	B-CA-D-PUR-6												
2.	B-CA-D-PUR-10	0.000											
3.	B-CA-D-PUR-18	0.000	0.000										
4.	B-CA-D-PVAc-6	0.000	0.000	0.000									
5.	B-CA-D-PVAc-10	0.029	0.032	0.000	0.000								
6.	B-CA-D-PVAc-18	0.000	0.042	0.009	0.000	0.000							
7.	B-LA-D-PUR-6	0.000	0.000	0.000	0.107	0.000	0.000						
8.	B-LA-D-PUR-10	0.000	0.655	0.000	0.000	0.012	0.089	0.000					
9.	B-LA-D-PUR-18	0.000	0.702	0.000	0.000	0.061	0.020	0.000	0.438				
10.	B-LA-D-PVAc-6	0.861	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000			
11.	B-LA-D-PVAc-10	0.910	0.000	0.000	0.000	0.027	0.000	0.000	0.000	0.000	0.941		
12.	B-LA-D-PVAc-18	0.592	0.000	0.000	0.000	0.078	0.000	0.000	0.000	0.001	0.516	0.544	

Table 22. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendC}) for beech and NWC on top.

No.	Type of Sample	(1) 0.024	(2) 0.026	(3) 0.011	(4) 0.037	(5) 0.031	(6) 0.014	(7) 0.044	(8) 0.025	(9) 0.008	(10) 0.033	(11) 0.032	(12) 0.013
1.	B-CA-U-PUR-6												
2.	B-CA-U-PUR-10	0.174											
3.	B-CA-U-PUR-18	0.000	0.000										
4.	B-CA-U-PVAc-6	0.000	0.000	0.000									
5.	B-CA-U-PVAc-10	0.000	0.006	0.000	0.001								
6.	B-CA-U-PVAc-18	0.000	0.000	0.062	0.000	0.000							
7.	B-LA-U-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000						
8.	B-LA-U-PUR-10	0.689	0.296	0.000	0.000	0.000	0.000	0.000					
9.	B-LA-U-PUR-18	0.000	0.000	0.060	0.000	0.000	0.000	0.000	0.000				
10.	B-LA-U-PVAc-6	0.000	0.000	0.000	0.017	0.304	0.000	0.000	0.000	0.000			
11.	B-LA-U-PVAc-10	0.000	0.001	0.000	0.005	0.581	0.000	0.000	0.000	0.000	0.585		
12.	B-LA-U-PVAc-18	0.000	0.000	0.313	0.000	0.000	0.333	0.000	0.000	0.006	0.000	0.000	

Table 23. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendB}) for aspen and NWC on the bottom.

No.	Type of Sample	(1) 0.019	(2) 0.014	(3) 0.013	(4) 0.026	(5) 0.024	(6) 0.014	(7) 0.024	(8) 0.021	(9) 0.019	(10) 0.027	(11) 0.018	(12) 0.014
1.	A-CA-D-PUR-6												
2.	A-CA-D-PUR-10	0.004											
3.	A-CA-D-PUR-18	0.003	0.936										
4.	A-CA-D-PVAc-6	0.000	0.000	0.000									
5.	A-CA-D-PVAc-10	0.004	0.000	0.000	0.124								
6.	A-CA-D-PVAc-18	0.003	0.996	0.937	0.000	0.000							
7.	A-LA-D-PUR-6	0.005	0.000	0.000	0.105	0.859	0.000						
8.	A-LA-D-PUR-10	0.112	0.000	0.000	0.005	0.153	0.000	0.181					
9.	A-LA-D-PUR-18	0.918	0.005	0.004	0.000	0.003	0.004	0.005	0.110				
10.	A-LA-D-PVAc-6	0.000	0.000	0.000	0.808	0.093	0.000	0.074	0.003	0.000			
11.	A-LA-D-PVAc-10	0.503	0.021	0.020	0.000	0.001	0.018	0.001	0.034	0.540	0.000		
12.	A-LA-D-PVAc-18	0.005	0.844	0.795	0.000	0.000	0.837	0.000	0.000	0.006	0.000	0.022	

Table 24. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendB}) for aspen and NWC on top.

No.	Type of Sample	(1) 0.012	(2) 0.015	(3) 0.007	(4) 0.026	(5) 0.023	(6) 0.008	(7) 0.021	(8) 0.015	(9) 0.010	(10) 0.028	(11) 0.015	(12) 0.011
1.	A-CA-U-PUR-6												
2.	A-CA-U-PUR-10	0.002											
3.	A-CA-U-PUR-18	0.000	0.000										
4.	A-CA-U-PVAc-6	0.000	0.000	0.000									
5.	A-CA-U-PVAc-10	0.000	0.000	0.000	0.005								
6.	A-CA-U-PVAc-18	0.004	0.000	0.393	0.000	0.000							
7.	A-LA-U-PUR-6	0.000	0.000	0.000	0.000	0.153	0.000						
8.	A-LA-U-PUR-10	0.003	0.820	0.000	0.000	0.000	0.000	0.000					
9.	A-LA-U-PUR-18	0.071	0.000	0.056	0.000	0.000	0.242	0.000	0.000				
10.	A-LA-U-PVAc-6	0.000	0.000	0.000	0.024	0.000	0.000	0.000	0.000	0.000			
11.	A-LA-U-PVAc-10	0.002	0.997	0.000	0.000	0.000	0.000	0.000	0.810	0.000	0.000		
12.	A-LA-U-PVAc-18	0.480	0.000	0.003	0.000	0.000	0.024	0.000	0.000	0.226	0.000	0.000	

Table 25. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendB}) for beech and NWC on the bottom.

No.	Type of Sample	(1) 0.023	(2) 0.015	(3) 0.015	(4) 0.028	(5) 0.021	(6) 0.014	(7) 0.030	(8) 0.015	(9) 0.016	(10) 0.023	(11) 0.024	(12) 0.022
1.	B-CA-D-PUR-6												
2.	B-CA-D-PUR-10	0.000											
3.	B-CA-D-PUR-18	0.000	0.973										
4.	B-CA-D-PVAc-6	0.000	0.000	0.000									
5.	B-CA-D-PVAc-10	0.455	0.000	0.000	0.000								
6.	B-CA-D-PVAc-18	0.000	0.428	0.416	0.000	0.000							
7.	B-LA-D-PUR-6	0.000	0.000	0.000	0.179	0.000	0.000						
8.	B-LA-D-PUR-10	0.000	0.977	0.954	0.000	0.000	0.431	0.000					
9.	B-LA-D-PUR-18	0.000	0.524	0.521	0.000	0.000	0.178	0.000	0.514				
10.	B-LA-D-PVAc-6	0.863	0.000	0.000	0.001	0.382	0.000	0.000	0.000	0.000			
11.	B-LA-D-PVAc-10	0.291	0.000	0.000	0.007	0.087	0.000	0.000	0.000	0.000	0.340		
12.	B-LA-D-PVAc-18	0.473	0.000	0.000	0.000	0.935	0.000	0.000	0.000	0.000	0.405	0.094	

Table 26. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendB}) for beech and NWC on top.

No.	Type of Sample	(1) 0.016	(2) 0.017	(3) 0.006	(4) 0.024	(5) 0.021	(6) 0.009	(7) 0.030	(8) 0.016	(9) 0.005	(10) 0.022	(11) 0.022	(12) 0.008
1.	B-CA-U-PUR-6												
2.	B-CA-U-PUR-10	0.398											
3.	B-CA-U-PUR-18	0.000	0.000										
4.	B-CA-U-PVAc-6	0.000	0.000	0.000									
5.	B-CA-U-PVAc-10	0.000	0.002	0.000	0.003								
6.	B-CA-U-PVAc-18	0.000	0.000	0.014	0.000	0.000							
7.	B-LA-U-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000						
8.	B-LA-U-PUR-10	0.682	0.621	0.000	0.000	0.000	0.000	0.000					
9.	B-LA-U-PUR-18	0.000	0.000	0.690	0.000	0.000	0.006	0.000	0.000				
10.	B-LA-U-PVAc-6	0.000	0.000	0.000	0.031	0.329	0.000	0.000	0.000	0.000			
11.	B-LA-U-PVAc-10	0.000	0.000	0.000	0.032	0.303	0.000	0.000	0.000	0.000	0.902		
12.	B-LA-U-PVAc-18	0.000	0.000	0.038	0.000	0.000	0.615	0.000	0.000	0.018	0.000	0.000	

As shown in Figure 4, the greatest K_{bendC} values in the aspen samples were found in the samples with thicknesses of 6 mm and 10 mm with a carbon fiber non-wood component placed on the bottom of the laminated material. These lamellas were bonded with PVAc adhesive. By contrast, the lowest K_{bendC} values were found in 18 mm thick lamellas, where the non-wood component was placed on the top of the laminated material. In the samples with a carbon fiber non-wood component, the effect of the adhesive used was also significant. The 6 mm thick and 10 mm thick samples with carbon fibers on the top of the material glued with PUR adhesive had significantly lower values (by more than 50%) than all the other samples.

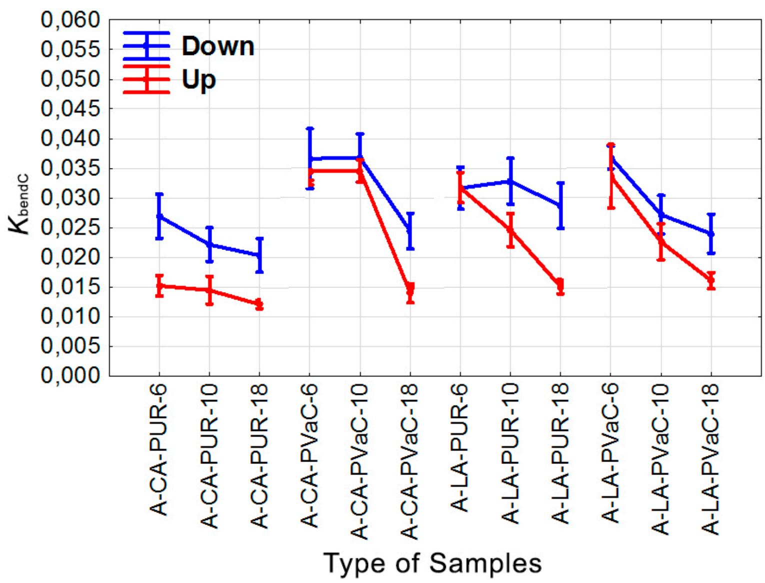

Figure 4. K_{bendC} in case of aspen.

The situation was similar with beech lamellas (Figure 5). The greatest K_{bendC} values were found in the beech samples with a 6 mm thickness, but unlike the aspen lamellas, no significant differences were found when different types of non-wood components were used. As with aspen lamellas, the lowest K_{bendC} values were measured in lamellas with a thickness of 18 mm. The lamella thickness affected the bending coefficient. In beech samples, there was one extreme in the case of lamellas with glass fibers bonded with PVAc adhesive. The values measured on these 6 mm thick and 18 mm thick samples were no different from those measured on the 10 mm thick samples.

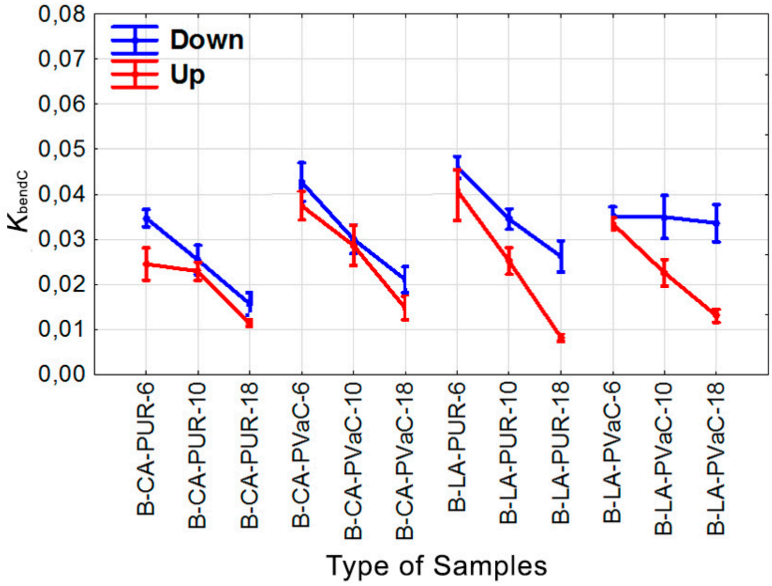

Figure 5. K_{bendC} in case of beech.

Figure 6 shows that the K_{bendB} values were affected most by the material thickness. Materials with lower thicknesses had greater K_{bendB} values. The greatest K_{bendB} values in the aspen lamellas were reached in samples with a non-wood component on the bottom of the laminated material. These lamellas were bonded with PVAc adhesive, and the non-wood component had no influence on these values. By contrast, the lowest values were measured in the aspen lamellas with carbon fibers on the top side of the material and bonded with PUR adhesive. The lowest K_{bendB} values were also found in the samples with a carbon fiber non-wood component placed on the top of the material. In the 6 mm thick and 10 mm thick samples bonded with PUR adhesive with a non-wood carbon fiber component, the values were more than 50% lower than in the samples bonded with PVAc adhesive.

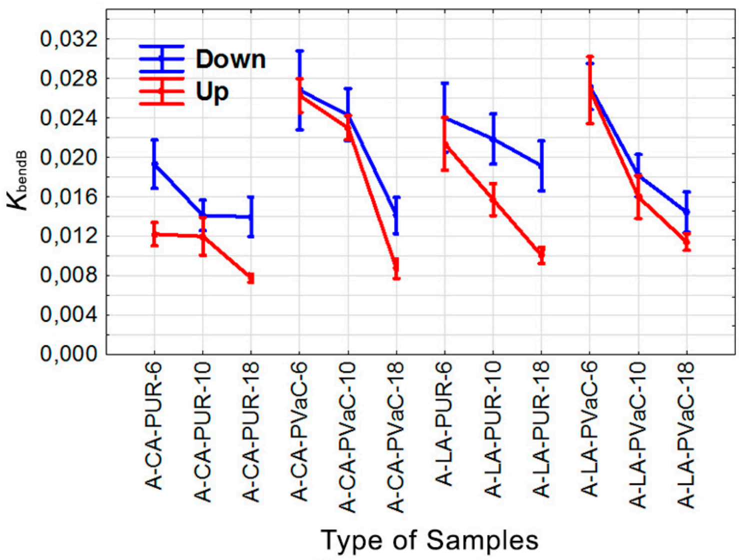

Figure 6. K_{bendB} in case of aspen.

The lowest K_{bendB} values in the beech samples were measured in the 18 mm thick samples bonded with PUR adhesive (Figure 7). In similar samples bonded with PVAc adhesive, the samples reached about 30% greater values. The highest K_{bendB} values were measured in the 6 mm thick beech samples, but unlike aspen lamellas, no significant differences were found with the use of different types of non-wood components and adhesives. As in aspen lamellas, the lowest K_{bendB} values were measured in the 18 mm thick lamellas. The lamella thickness affected the bending coefficient.

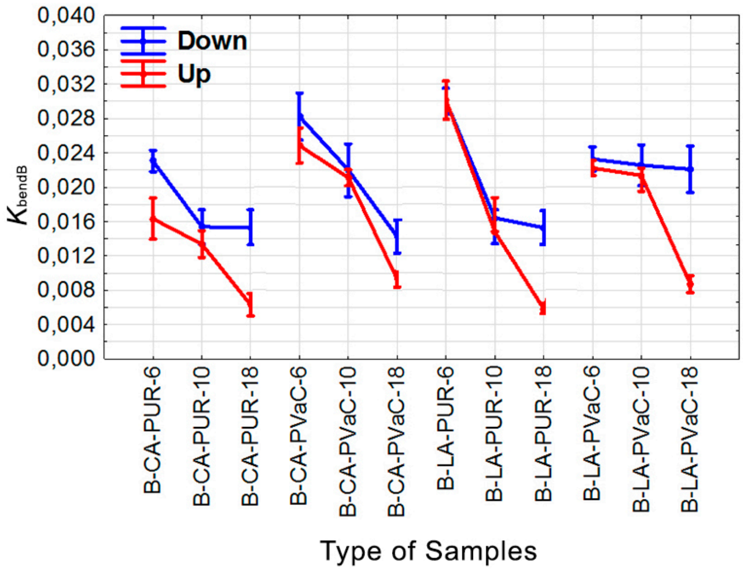

Figure 7. K_{bendB} in case of beech.

4. Conclusions

1. The type and position of the non-wood component used in the laminated materials had a significant effect on all the observed characteristics: K_{bendC}, K_{bendB}, R_{minC}, and R_{minB}.
2. Bending coefficient values based on the simple bending equation (K_{bendC}) tended to be greater than bending coefficient values based on bending geometry (K_{bendB}).
3. The greatest values of the bending coefficient based on the simple bending equation (K_{bendC}) and the bending coefficient based on bending geometry (K_{bendB}) were generally found in materials of lower thickness.
4. No rule was observed for the high or low measured values of the observed characteristics (K_{bendC}, K_{bendB}, R_{minC}, and R_{minB}) in relation to the wood species used.

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References

1. Pokharel, R.; Grala, R.K.; Grebner, D.L. Woody residue utilization for bioenergy by primary forest products manufacturers: An exploratory analysis. *For. Policy Econ.* **2017**, *85*, 161–171. [CrossRef]
2. Long, Z.; Wu, J.; Xu, W.; Lin, W. Study of the coordination mechanism of a wood processing residue-based reverse supply chain. *BioResources* **2018**, *13*, 2562–2577. [CrossRef]
3. Bhoominathan, R.; Divyabarathi, P.; Manimegalai, R.; Nithya, T.; Shanmugapriya, S. Infra-red thermography based inspection of hybrid composite laminates under flexure loading. *IJVSS* **2018**, *10*, 6–9. [CrossRef]
4. Silva, F.G.A.; de Moura, M.F.S.F.; Magalhães, A.G. Lowvelo city impact behaviour of a hybrid carbon-epoxy/corklaminate. *Strain* **2017**, *53*. [CrossRef]
5. Abrate, S. Impact on laminated composite materials. *Appl. Mech. Rev.* **1991**, *44*, 155–190. [CrossRef]

6. Bigg, D.M. The impact behavior of thermoplastic sheet composites. *J Reinf. Plast. Comp.* **1994**, *13*, 339–354. [CrossRef]
7. Glos, P.; Denzler, J.K.; Linsenmann, P. Strength and stiffness behaviour of beech laminations for high strength glulam. In Proceedings of the Meeting 37 CIB Working Commission W18-Timber Structures, Edinburgh, Scotland, UK, August 2004.
8. Frese, M.; Blaß, H.J. Characteristic bending strength of beech glulam. *Mater. Struct.* **2007**, *40*, 3–13. [CrossRef]
9. Hill, C.A.S. *Wood Modification: Chemical, Thermal and Other Processes*; John Wiley & Sons: Chichester, UK, 2006. [CrossRef]
10. Kubovský, I.; Babiak, M. Color changes induced by CO2 laser irradiation of wood surface. *Wood Res.* **2009**, *54*, 61–66.
11. Hrčka, R.; Babiak, M. Some non-traditional factors influencing thermal properties of wood. *Wood Res.* **2012**, *57*, 367–374.
12. Gašparík, M.; Barcík, Š. Impact of plasticization by microwave heating on the total deformation of beech wood. *BioResources* **2013**, *8*, 6297–6308. [CrossRef]
13. Gašparík, M.; Barcík, Š. Effect of plasticizing by microwave heating on bending characteristics of beech wood. *BioResources* **2014**, *9*, 4808–4820. [CrossRef]
14. Svoboda, T.; Ruman, D.; Gaff, M.; Gašparík, M.; Miftieva, E.; Dundek, L. Bending characteristics of multilayered soft and hardwood materials. *BioResources* **2015**, *10*, 8461–8473. [CrossRef]
15. Miftieva, E.; Gaff, M.; Svoboda, T.; Babiak, M.; Gašparík, M.; Ruman, D.; Suchopár, M. Effects of selected factors on bending characteristics of beech wood. *BioResources* **2016**, *11*, 599–611. [CrossRef]
16. Fang, C.-H.; Mariotti, N.; Cloutier, A.; Koubaa, A.; Blanchet, P. Densification of wood veneers by compression combined with heat and steam. *Eur. J. Wood Prod.* **2012**, *70*, 155–163. [CrossRef]
17. Gaff, M.; Vokatý, V.; Babiak, M.; Bal, B.C. Coefficient of wood bendability as a function of selected factors. *Constr. Build Mater.* **2016**, *126*, 632–640. [CrossRef]
18. Blomberg, J.; Persson, B. Swelling pressure of semi-isostaticallydensified wood under different mechanical resraints. *Wood Sci. Technol.* **2007**, *41*, 401–415. [CrossRef]
19. Plevris, N.; Triantafillou, T.C. CreepbehaviorofFRP-reinforcedwoodmembers. *J. Struct. Eng.* **1995**, *121*, 174–186. [CrossRef]
20. Redon, C.; Li, V.C.; Wu, C.; Hoshiro, H.; Saito, T.; Ogawa, A. Measuring and modifying interface propertiesof PVA fibers in ECC matrix. *J Mater. Civil Eng.* **2001**, *13*, 399–406. [CrossRef]
21. Sviták, M.; Ruman, D. Tensile-shear strength of layered wood reinforced by carbon materials. *Wood Res.* **2017**, *62*, 243–252.
22. Gaff, M.; Babiak, M.; Vokatý, V.; Gašparík, M.; Ruman, D. Bending characteristics of hardwood lamellae in the elastic region. *Compos. Part B-Eng.* **2017**, *116*, 61–75. [CrossRef]
23. Babiak, M.; Gaff, M.; Sikora, A.; Hysek, Š. Modulus of elasticity in three- and four-point bending of wood. *Compos. Struct.* **2018**, *204*, 454–465. [CrossRef]
24. Gaff, M.; Gašparík, M.; Babiak, M.; Vokatý, V. Bendability characteristics of wood lamellae in plastic region. *Compos. Struct.* **2017**, *163*, 410–422. [CrossRef]
25. Gaff, M.; Babiak, M. Methods for determining the plastic work in bending and impact of selected factors on its value. *Compos. Struct.* **2018**, *202*, 66–76. [CrossRef]
26. Sikora, A.; Gaff, M.; Hysek, Š.; Babiak, M. The plasticity of composite material based on winter rapeseed as a function of selected factors. *Compos. Struct.* **2018**, *202*, 783–792. [CrossRef]
27. Gaff, M.; Babiak, M. Tangent modulus as a function of selected factors. *Compos. Struct.* **2018**, *202*, 436–446. [CrossRef]
28. Saracoglu, E. Finite-element Simulations of the Influence of Cracks on the Strength of Glulam Beams. Master's Thesis, Blekinge Institute of Technology, Karlskrona, Sweden, 2011.
29. Khorasan, S.R. Finite-element Simulations of Glulam Beams with Natural Cracks. Master's Thesis, Blekinge Institute of Technology, Karlskrona, Sweden, 2012.
30. Hýsek, Š.; Gaff, M.; Sikora, A.; Babiak, M. New composite material based on winter rapeseed and his elasticity properties as a function of selected factors. *Compos. Part B-Eng.* **2018**, *153*, 108–116. [CrossRef]
31. Požgaj, A.; Chovanec, D.; Kurjatko, S.; Babiak, M. Štruktúra a Vlastnosti Dreva. In *Structure and Properties of Wood*; Príroda: Bratislava, Slovakia, 1997.

32. Gaff, M.; Gašparík, M.; Borůvka, V.; Haviarová, E. Stress simulation in layered wood-based materials under mechanical loading. *Mater. Des.* **2015**, *87*, 1065–1071. [CrossRef]
33. European Committee for Standardization, Wood-Based Panels. *EN 310: Determination of Modulus of Elasticity in Bending and of Bending Strength*; European Committee for Standardization: Brussels, Belgium, 1993.
34. International Organization for Standardization. *ISO 13061-1: Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens—Part 1: Determination of Moisture Content for Physical and Mechanical Tests*; International Organization for Standardization: Geneva, Switzerland, 2014.
35. International Organization for Standardization. *ISO 13061-2: Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens—Part 2: Determination of Density for Physical and Mechanical Tests*; International Organization for Standardization: Geneva, Switzerland, 2014.