Impact of Selected Factors on the Bending Forces at the Proportionality Limit and Yield Point in Laminated Veneer Lumber

Tomáš Svoboda,[a] Adam Sikora,[a,]* Vladimír Záborský,[a] and Zuzana Gaffová [b]

Knowledge of the force required to overcome deformation at the proportionality limit, yield point, as well as knowledge of the effect of selected factors on the characteristics during bending stress, have scientific and practical significance. They are the basis for designing tools for bending and accurately determining the stresses to which products and their parts may be subjected during use. This study analyzed the effect of selected factors on the selected characteristics, including the forces at the proportionality limit (F_E) and yield point (F_P). The chosen factors of this study were the wood species (*Fagus sylvatica* L. and *Populus tremula* L.), non-wood component (carbon and fiberglass), non-wood component position in the composition matrix (up and down), material thickness (6 mm, 10 mm, and 18 mm), and adhesive used (polyvinyl acetate and polyurethane), as well as their combined interaction. The results contributed to the advancement of knowledge necessary for the study and development of new materials with specific properties for their intended use. The results could improve the innovative potential of wood processing companies and increase their performance and competitiveness in the market.

Keywords: Product innovations; Laminated wood; Force at the proportionality limit; Force at the maximum limit

*Contact information: a: Department of Wood Processing and Biomaterials, 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; *Corresponding author: sikoraa@fld.czu.cz*

INTRODUCTION

From an environmental point of view, wood is a renewable material, which makes it important. Wood has always been present in the lives of people, and it is still widely used today. A great advantage of wood is its elasticity in relation to its density. However, it is characterized by a low flexibility and difficulty in molding, especially in bigger material sizes. These negative properties motivate the development and application of lamination (Aydın *et al*. 2004).

Wood-based laminated veneer lumber (LVL) materials consist of several components, but the basic component is wood. The composition design and production of LVL materials is primarily geared to the intended use of the material. Therefore, to create LVL, it is necessary to understand the proposed composition under the influence of various factors. The individual layers of this material can be modified or unmodified. The properties of these materials can be monitored and assessed on the basis of a force-deflection diagram, in which the forces required to achieve deflection at the proportionality limit and yield point can be determined (Fig. 1).

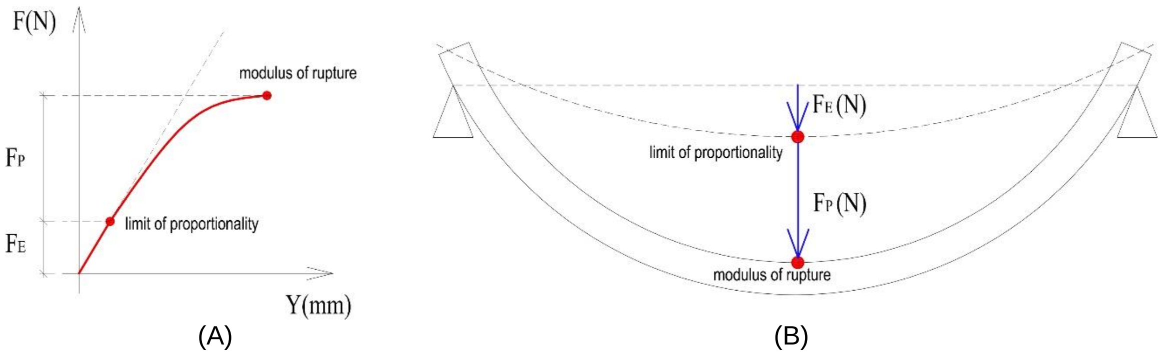


Fig. 1. Force-deflection diagram during bending (A) and determining the proportionality limit and yield point (modulus of rupture) (B) (Svoboda *et al*. 2017)

The force at the proportionality limit F_E can be defined as the force required to achieve deflection at the proportionality limit, and the force at the yield point F_P is characterized as the force required to achieve deflection at the yield point. In a deeper analysis of the force-deflection diagram up to the proportionality limit, it can be found that deflection only causes elastic deformation (Gaff *et al.* 2016; Gaff *et al.* 2017a; Babiak *et al.* 2018; Hýsek *et al.* 2018). Once the proportionality limit has been reached and the external forces are released, the deformation returns to its original state. From this assumption it can be concluded that only elastic deformation occurs and stress is evenly distributed in the wood up to the proportionality limit. Stress above the proportionality limit is no longer even (Požgaj *et al*. 1997) and plastic deformation occurs (Gaff *et al.* 2017b; Gaff and Babiak 2018a,b; Sikora *et al.* 2018).

The strength and stiffness of wood can be increased by combining it with non-wood components based on different materials and also by obtaining adhesive joints (Blomberg and Persson 2007; Corigliano *et al*. 2016). In the 1960s, technologists and manufacturers became interested in improving the mechanical properties of wood, which led to the production of composite fibers. Composite materials include carbon fiber, aramid fiber, basalt fiber, fiberglass, asbestos fiber, polyvinyl alcohol (PVA), and others (Plevris and Triantafillou 1995; Redon *et al.* 2001; Sviták and Ruman 2017). An important factor in the use of these materials, in addition to their mechanical properties, is the location in the laminate material composition (Mosallam 2016). Experimental research has shown that by correctly locating the non-wood component on the stressed tensile zone, it is possible to significantly improve bending properties of layered materials (Raftery and Harte 2013).

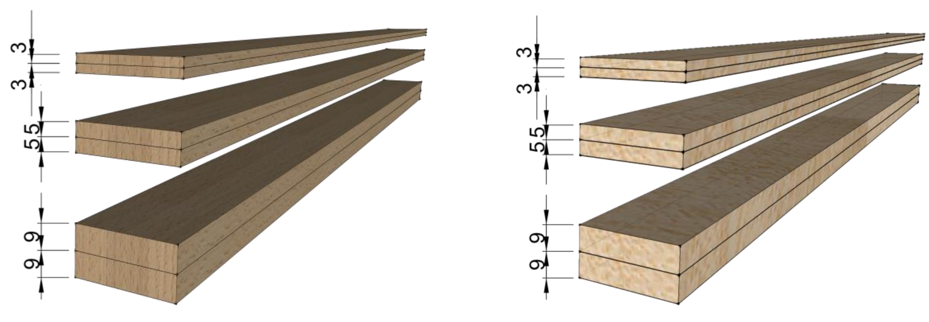
The literature points to increasing requirements for wood quality and methods of joining individual layers (Florek *et al.* 2009; Sandoz 2009; Steiger and Gehri 2010; Stöd and Heräjärvi 2010). Another important factor when gluing laminated wood-based materials or laminated materials based on wood and non-wood components is the type of adhesive used. Glued structural elements are characterized by improved properties compared with solid wood (Lorenzo 2010; Vallée *et al*. 2015). As a result of poor spreading of the adhesive, improper pressing, or an uneven surface of the glued components, the load bearing capacity may decrease because of incorrect bonding. Wood, as a hygroscopic material, continuously absorbs and releases moisture from and into the atmosphere, which results in changes in the moisture stress, and hence dimensional changes. These changes may cause the adhesive to separate from the wooden element. This can be prevented by using a suitable adhesive for the specific purpose of the bonded element (Saracoglu 2011; Khorasan 2012).

The aim of this study was to determine the effect of the laminated wood structure (wood type, non-wood component type, non-wood component position in the structure, material thickness, and adhesive type) on the main strength characteristics of the force-deflection diagram (forces at the proportionality limit and yield point).

EXPERIMENTAL

Materials

The experiments were conducted on lamellas with a thickness of 6 mm, 10 mm, and 18 mm (thickness of non-wood component was 0.15 mm), width of 35 mm, and length of 600 mm (Fig. 2). Lamellas were made from beech wood (*Fagus sylvatica* L.) and aspen wood (*Populus tremula* L.) from the Polana region of Slovakia. Each test group was represented by 20 replicate samples.



(A) (B)

Fig. 2. Test samples: beech (A) and aspen lamellas (B)

The effect of the non-wood component on the monitored characteristics was evaluated by comparing the values measured using carbon or fiberglass cloth. The effect of the non-wood component position within the lamella structure was also studied. The non-wood component was positioned as the top (orange color for carbon and red color for fiberglass in Fig. 3) or bottom layer (dark blue for carbon and light blue for fiberglass in Fig. 3). The effect of the adhesive was evaluated by comparing the test results obtained from the lamellas glued using polyvinyl acetate (PVAc) (green in Fig. 3) and polyurethane (PUR) adhesive (yellow in Fig. 3). The samples were conditioned to a moisture content of 8% in a climate chamber (ED, APT Line II, Binder, Tuttlingen, Germany) at a relative humidity of 40% and temperature of 20 °C.

Methods

Determination of the selected characteristics

During testing, the support span length for three-point bending was set to 20 times the thickness (*i.e.*, the support span length was changed in relation to the thickness of the lamellas). The samples were subjected to flexural testing using an FPZ 100 universal testing machine (TIRA, Schalkau, Germany), according to EN 310 (1993), Eilmann *et al.* (2014), and ISO 13061-2 (2014).

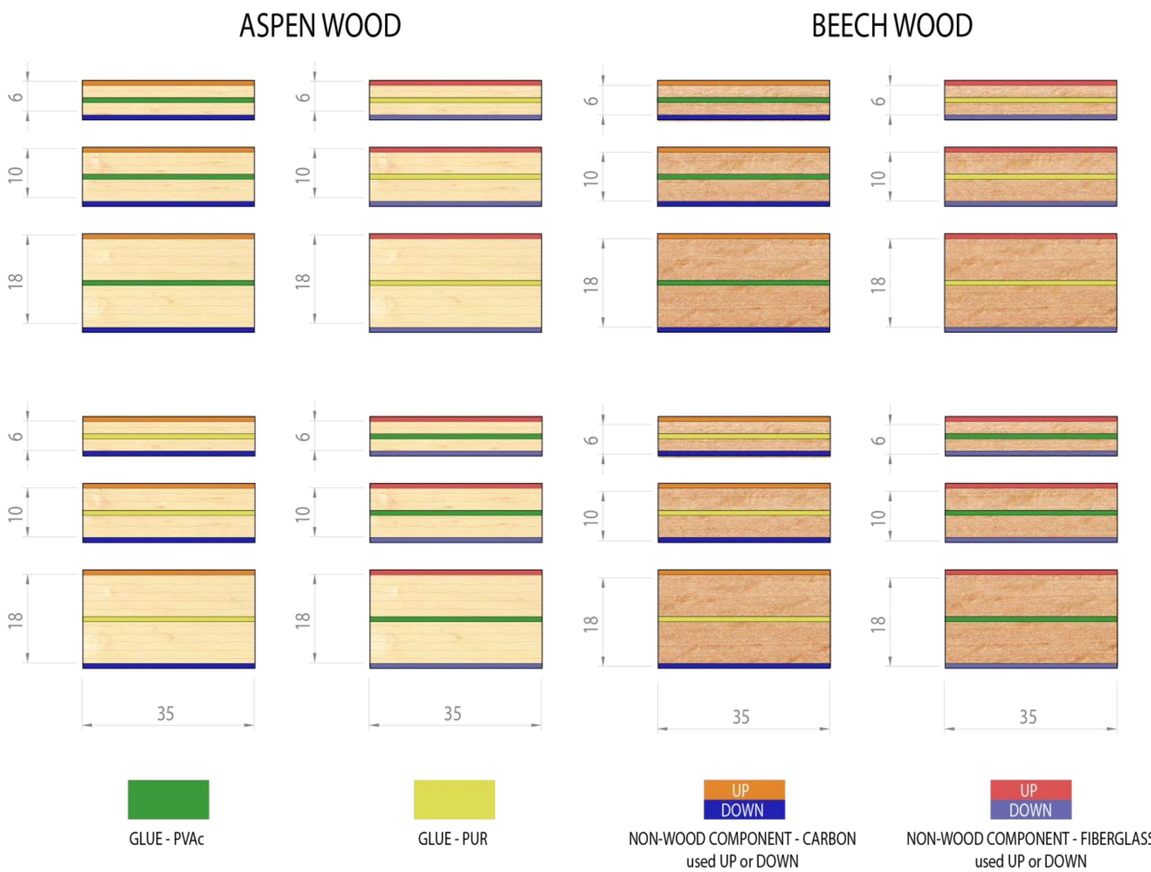


Fig. 3. Arrangement of the test specimens

The cross-head speed was set to 3 mm/min so that the duration of the test did not exceed 2 min. The forces that exceeded the proportionality limit and yield point of the samples were recorded using an ALMEMO 2690-8 datalogger (Ahlborn GmbH, Braunschweig, Germany).

Evaluation and calculation

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

RESULTS AND DISCUSSION

Table 1 shows the average values and variation coefficients (in parentheses) of the forces at the proportionality limit (F_E) and yield point (F_P) of the aspen laminated materials reinforced with non-wood components (carbon fiber and fiberglass) and glued with PVAc and PUR adhesives. The largest force at the proportionality limit (1094 N) was measured with the 18-mm-thick test specimens with fiberglass on the convex side glued with PUR adhesive. The largest force at the yield point (2112 N) was measured with the test specimens that had a total thickness of 18 mm and carbon fibers glued on the convex side with PUR adhesive. The importance of the quality of the bottom layer of laminated wood has been examined in detail in the work (Raftery and Harte 2013). The effect of the non-wood component was verified after comparison with the results of Svoboda *et al*. (2017), who determined the forces at the proportionality limit and yield point for laminated materials without non-wood components.

Table 1. Mean Values of the Forces at the Proportionality Limit and Yield Point, and the Coefficient of Variance of the Aspen Wood

WS	NWC	NWC Location	Glue	*T* (mm)	Code	F_E (N)	F_P (N)
A	CA	U	PUR	6	A-CA-U-PUR-6	419 (18.8)	614 (17.4)
A	CA	U	PUR	10	A-CA-U-PUR-10	650 (19.0)	1078 (18.8)
A	CA	U	PUR	18	A-CA-U-PUR-18	850 (15.4)	2087 (9.4)
A	CA	U	PVAc	6	A-CA-U-PVAc-6	249 (7.5)	622 (8.9)
A	CA	U	PVAc	10	A-CA-U-PVAc-10	339 (17.7)	707 (18.6)
A	CA	U	PVAc	18	A-CA-U-PVAc-18	783 (12.2)	1536 (12.2)
A	LA	U	PUR	6	A-LA-U-PUR-6	219 (17.8)	441 (20.8)
A	LA	U	PUR	10	A-LA-U-PUR-10	531 (15.2)	965 (18.1)
A	LA	U	PUR	18	A-LA-U-PUR-18	958 (7.4)	1454 (7.8)
A	LA	U	PVAc	6	A-LA-U-PVAc-6	183 (18.0)	462 (19.4)
A	LA	U	PVAc	10	A-LA-U-PVAc-10	459 (13.4)	946 (19.5)
A	LA	U	PVAc	18	A-LA-U-PVAc-18	817 (10.2)	1417 (13.1)
A	CA	D	PUR	6	A-CA-D-PUR-6	572 (19.2)	869 (7.7)
A	CA	D	PUR	10	A-CA-D-PUR-10	916 (20.5)	1632 (18.1)
A	CA	D	PUR	18	A-CA-D-PUR-18	987 (11.0)	2112 (19.0)
A	CA	D	PVAc	6	A-CA-D-PVAc-6	557 (15.9)	782 (10.3)
A	CA	D	PVAc	10	A-CA-D-PVAc-10	672 (4.6)	1204 (17.9)
A	CA	D	PVAc	18	A-CA-D-PVAc-18	724 (15.8)	1528 (13.1)
A	LA	D	PUR	6	A-LA-D-PUR-6	340 (15.2)	554 (16.2)
A	LA	D	PUR	10	A-LA-D-PUR-10	617 (20.0)	1090 (15.2)
A	LA	D	PUR	18	A-LA-D-PUR-18	1094 (14.9)	1515 (14.6)
A	LA	D	PVAc	6	A-LA-D-PVAc-6	344 (4.7)	512 (6.2)
A	LA	D	PVAc	10	A-LA-D-PVAc-10	488 (11.5)	1049 (2.6)
A	LA	D	PVAc	18	A-LA-D-PVAc-18	928 (14.0)	1517 (16.1)

WS – wood species; NWC – non-wood component; *T* – thickness; F_E – force at the proportionality limit; F_P – force at the yield point; A – aspen; CA – carbon; LA – fiberglass; U – up; D – down

Table 2 shows the average values and variation coefficients (in parentheses) of the forces at the proportionality limit (F_E) and yield point (F_P) for the laminated beech materials reinforced with non-wood components and glued with PVAc and PUR. The largest force at the proportionality limit (1419 N) was measured in the test specimens with an overall thickness of 18 mm and carbon fibers glued with PVAc on the convex side relative to the load direction. The largest force at the yield point (2405 N) was measured on the 18-mm-thick test specimens with fiberglass glued on the convex side with PVAc adhesive. After comparing the results with those of Svoboda *et al*. (2017), the same conclusions were reached as for the laminated aspen materials. The effectiveness of the type of adhesive is determined by the surface structure of the bonded surface, as has been shown in the research by Vallée *et al.* (2015). The results of this research were used to verify the effects of the adhesive on all the characteristics observed for both beech and poplar layered wood.

Table 2. Mean Values of the Forces at the Proportionality Limit and Yield Point, and Coefficient of Variance of the Beech Wood

WS	NWC	NWC Location	Glue	*T* (mm)	Code	F_E (N)	F_P (N)
B	CA	U	PUR	6	B-CA-U-PUR-6	658 (18.8)	1011 (11.4)
B	CA	U	PUR	10	B-CA-U-PUR-10	687 (16.6)	1447 (18.3)
B	CA	U	PUR	18	B-CA-U-PUR-18	926 (11.7)	1472 (11.9)
B	CA	U	PVAc	6	B-CA-U-PVAc-6	342 (8.3)	815 (9.0)
B	CA	U	PVAc	10	B-CA-U-PVAc-10	841 (12.2)	1858 (6.7)
B	CA	U	PVAc	18	B-CA-U-PVAc-18	1372 (18.3)	1982 (12.6)
B	LA	U	PUR	6	B-LA-U-PUR-6	201 (12.4)	464 (10.5)
B	LA	U	PUR	10	B-LA-U-PUR-10	758 (14.4)	1638 (18.3)
B	LA	U	PUR	18	B-LA-U-PUR-18	1271 (19.1)	2253 (14.4)
B	LA	U	PVAc	6	B-LA-U-PVAc-6	341 (9.2)	841 (9.0)
B	LA	U	PVAc	10	B-LA-U-PVAc-10	763 (11.9)	1724 (18.3)
B	LA	U	PVAc	18	B-LA-U-PVAc-18	1074 (19.1)	2189 (20.6)
B	CA	D	PUR	6	B-CA-D-PUR-6	874 (21.0)	1418 (11.9)
B	CA	D	PUR	10	B-CA-D-PUR-10	968 (12.1)	1546 (15.2)
B	CA	D	PUR	18	B-CA-D-PUR-18	1076 (8.0)	1508 (16.8)
B	CA	D	PVAc	6	B-CA-D-PVAc-6	641 (17.0)	1119 (8.5)
B	CA	D	PVAc	10	B-CA-D-PVAc-10	1316 (20.3)	2320 (7.7)
B	CA	D	PVAc	18	B-CA-D-PVAc-18	1419 (16.3)	2117 (19.1)
B	LA	D	PUR	6	B-LA-D-PUR-6	293 (26.4)	586 (11.0)
B	LA	D	PUR	10	B-LA-D-PUR-10	781 (14.6)	1733 (16.0)
B	LA	D	PUR	18	B-LA-D-PUR-18	1249 (14.1)	2399 (15.9)
B	LA	D	PVAc	6	B-LA-D-PVAc-6	499 (14.8)	860 (10.6)
B	LA	D	PVAc	10	B-LA-D-PVAc-10	781 (14.7)	1668 (15.5)
B	LA	D	PVAc	18	B-LA-D-PVAc-18	1119 (17.9)	2405 (20.8)

WS – wood species; NWC – non-wood component; *T* – thickness; F_E – force at the proportionality limit; F_P – force at the yield point; B – beech; CA – carbon; LA – fiberglass; U – up; D – down

All of the measured data was 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 and 4 show the statistical evaluation of the effect of the test specimen type on the force at the proportionality limit in the aspen laminated materials with the non-wood component placed on the top or bottom side with respect to the direction of the stress. The results clearly showed that the test specimen type had a significant effect on the force at the proportionality limit.

Table 3. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Proportionality Limit for Aspen and NWC Down

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	46153050	1	46153050	4765.727	***
1) Type of Sample	4295507	11	390501	40.323	***
Error	1045912	108	9684		

NS – not significant, *** – significant at $p < 0.005$

Table 4. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Proportionality Limit for Aspen and NWC Up

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	28234194	1	28234194	4206.166	***
1) Type of Sample	8009036	11	728094	108.467	***
Error	677970	101	6713		

NS – not significant, *** – significant $p < 0.005$

Tables 5 and 6 show the statistical evaluation of the effect of the test specimen type on the force at the proportionality limit in the beech laminated materials with the non-wood component placed on the top or bottom side with respect to the direction of the stress. These results showed that the test specimen type had a significant effect on the force at the proportionality limit.

Table 5. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Proportionality Limit for Beech and NWC Down

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	101134235	1	101134235	3397.933	***
1) Type of Sample	12696908	11	1154264	38.781	***
Error	3214453	108	29763		

NS – not significant, *** – significant $p < 0.005$

Table 6. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Proportionality Limit for Beech and NWC Up

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	63365377	1	63365377	2105.246	***
1) Type of Sample	21213860	11	1928533	64.073	***
Error	3431262	114	30099		

NS – not significant, *** – significant $p < 0.005$

The statistical evaluation of the effect of the test specimen type on the force at the yield point in the layered aspen materials with the non-wood component on the top or bottom side in relation to the direction of the stress is shown in Tables 7 and 8. The results clearly showed that the test specimen type had a significant effect on the force at the yield point.

Table 7. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Yield Point for Aspen and NWC Down

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	171984002	1	171984002	4192.093	***
1) Type of Sample	25344583	11	2304053	56.161	***
Error	4430787	108	41026		

NS – not significant, *** – significant $p < 0.005$

Table 8. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Yield Point for Aspen and NWC Up

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	131628796	1	131628796	4477.039	***
1) Type of Sample	62616662	11	5692424	193.614	***
Error	2969487	101	29401		

NS – not significant, *** – significant $p < 0.005$

The results of the statistical evaluation of the effect of the test specimen type on the force at the yield point in the layered beech materials with the non-wood component on the top or bottom side in relation to the direction of the stress are shown in Tables 9 and 10. These results clearly showed that the test specimen type had a significant effect on the force at the yield point.

Table 9. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Yield Point for Beech and NWC Down

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	322747426	1	322747426	4281.145	***
1) Type of Sample	39241711	11	3567428	47.321	***
Error	8141916	108	75388		

NS – not significant, *** – significant $p < 0.005$

Table 10. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Yield Point for Beech and NWC Up

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	282099740	1	282099740	2095.762	***
1) Type of Sample	103786852	11	9435168	70.095	***
Error	15344954	114	134605		

NS – not significant, *** – significant $p < 0.005$

Table 11. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Proportionality Limit for Aspen and NWC Down

No.	Sample Type	(1) 572	(2) 915	(3) 986	(4) 557	(5) 672	(6) 723	(7) 340	(8) 517	(9) 694	(10) 344	(11) 488	(12) 628
1	A-CA-D-PUR-6												
2	A-CA-D-PUR-10	0.000											
3	A-CA-D-PUR-18	0.000	0.108										
4	A-CA-D-PVAc-6	0.740	0.000	0.000									
5	A-CA-D-PVAc-10	0.032	0.000	0.000	0.017								
6	A-CA-D-PVAc-18	0.002	0.000	0.000	0.001	0.275							
7	A-LA-D-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000						
8	A-LA-D-PUR-10	0.244	0.000	0.000	0.363	0.001	0.000	0.000					
9	A-LA-D-PUR-18	0.011	0.000	0.000	0.005	0.615	0.508	0.000	0.000				
10	A-LA-D-PVAc-6	0.000	0.000	0.000	0.000	0.000	0.000	0.926	0.000	0.000			
11	A-LA-D-PVAc-10	0.084	0.000	0.000	0.141	0.000	0.000	0.002	0.512	0.000	0.002		
12	A-LA-D-PVAc-18	0.201	0.000	0.000	0.129	0.323	0.049	0.000	0.021	0.161	0.000	0.004	

Table 12. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Proportionality Limit for Aspen and NWC Up

No.	Sample Type	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	A-CA-D-PUR-6												
2	A-CA-D-PUR-10	0.000											
3	A-CA-D-PUR-18	0.000	0.000										
4	A-CA-D-PVAc-6	0.000	0.000	0.000									
5	A-CA-D-PVAc-10	0.050	0.000	0.000	0.027								
6	A-CA-D-PVAc-18	0.000	0.051	0.005	0.000	0.000							
7	A-LA-D-PUR-6	0.000	0.000	0.000	0.455	0.005	0.000						
8	A-LA-D-PUR-10	0.009	0.004	0.000	0.000	0.000	0.000	0.000					
9	A-LA-D-PUR-18	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.000				
10	A-LA-D-PVAc-6	0.000	0.000	0.000	0.129	0.000	0.000	0.386	0.000	0.000			
11	A-LA-D-PVAc-10	0.330	0.000	0.000	0.000	0.005	0.000	0.000	0.076	0.000	0.000		
12	A-LA-D-PVAc-18	0.000	0.000	0.416	0.000	0.000	0.033	0.000	0.000	0.001	0.000	0.000	

Table 13. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Proportionality Limit for Beech and NWC Down

No.	Sample Type	(1) 874	(2) 967	(3) 1076	(4) 640	(5) 1316	(6) 1419	(7) 293	(8) 781	(9) 1248	(10) 498	(11) 781	(12) 1119
1	B-CA-D-PUR-6												
2	B-CA-D-PUR-10	0.228											
3	B-CA-D-PUR-18	0.014	0.162										
4	B-CA-D-PVAc-6	0.006	0.000	0.000									
5	B-CA-D-PVAc-10	0.000	0.000	0.004	0.000								
6	B-CA-D-PVAc-18	0.000	0.000	0.000	0.000	0.186							
7	B-LA-D-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000						
8	B-LA-D-PUR-10	0.260	0.027	0.001	0.072	0.000	0.000	0.000					
9	B-LA-D-PUR-18	0.000	0.001	0.035	0.000	0.384	0.038	0.000	0.000				
10	B-LA-D-PVAc-6	0.000	0.000	0.000	0.068	0.000	0.000	0.009	0.001	0.000			
11	B-LA-D-PVAc-10	0.232	0.023	0.000	0.088	0.000	0.000	0.000	0.999	0.000	0.001		
12	B-LA-D-PVAc-18	0.003	0.065	0.581	0.000	0.016	0.000	0.000	0.000	0.095	0.000	0.000	

Table 14. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Proportionality Limit for Beech and NWC Up

No.	Sample Type	(1) 658	(2) 687	(3) 1225	(4) 342	(5) 841	(6) 1371	(7) 201	(8) 757	(9) 1470	(10) 341	(11) 763	(12) 1753
1	B-CA-D-PUR-6												
2	B-CA-D-PUR-10	0.749											
3	B-CA-D-PUR-18	0.000	0.000										
4	B-CA-D-PVAc-6	0.001	0.000	0.000									
5	B-CA-D-PVAc-10	0.075	0.127	0.000	0.000								
6	B-CA-D-PVAc-18	0.000	0.000	0.113	0.000	0.000							
7	B-LA-D-PUR-6	0.000	0.000	0.000	0.147	0.000	0.000						
8	B-LA-D-PUR-10	0.307	0.442	0.000	0.000	0.394	0.000	0.000					
9	B-LA-D-PUR-18	0.000	0.000	0.011	0.000	0.000	0.278	0.000	0.000				
10	B-LA-D-PVAc-6	0.001	0.000	0.000	0.992	0.000	0.000	0.127	0.000	0.000			
11	B-LA-D-PVAc-10	0.299	0.437	0.000	0.000	0.396	0.000	0.000	0.951	0.000	0.000		
12	B-LA-D-PVAc-18	0.000	0.000	0.000	0.000	0.000	0.037	0.000	0.000	0.262	0.000	0.000	

Table 15. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Yield Point for Aspen and NWC Down

No.	Sample Type	(1) 869	(2) 1631	(3) 2112	(4) 782	(5) 1203	(6) 1527	(7) 554	(8) 1090	(9) 1514	(10) 512	(11) 1048	(12) 1517
1	A-CA-D-PUR-6												
2	A-CA-D-PUR-10	0.000											
3	A-CA-D-PUR-18	0.000	0.000										
4	A-CA-D-PVAc-6	0.339	0.000	0.000									
5	A-CA-D-PVAc-10	0.001	0.000	0.000	0.000								
6	A-CA-D-PVAc-18	0.000	0.253	0.000	0.000	0.001							
7	A-LA-D-PUR-6	0.001	0.000	0.000	0.013	0.000	0.000						
8	A-LA-D-PUR-10	0.022	0.000	0.000	0.002	0.214	0.000	0.000					
9	A-LA-D-PUR-18	0.000	0.245	0.000	0.000	0.001	0.894	0.000	0.000				
10	A-LA-D-PVAc-6	0.000	0.000	0.000	0.005	0.000	0.000	0.646	0.000	0.000			
11	A-LA-D-PVAc-10	0.050	0.000	0.000	0.006	0.109	0.000	0.000	0.647	0.000	0.000		
12	A-LA-D-PVAc-18	0.000	0.237	0.000	0.000	0.001	0.909	0.000	0.000	0.978	0.000	0.000	

Table 16. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Yield Point for Aspen and NWC Up

No.	Sample Type	(1) 613	(2) 1078	(3) 2286	(4) 621	(5) 707	(6) 1535	(7) 441	(8) 964	(9) 2451	(10) 461	(11) 946	(12) 1715
1	A-CA-D-PUR-6												
2	A-CA-D-PUR-10	0.000											
3	A-CA-D-PUR-18	0.000	0.000										
4	A-CA-D-PVAc-6	0.922	0.000	0.000									
5	A-CA-D-PVAc-10	0.299	0.000	0.000	0.313								
6	A-CA-D-PVAc-18	0.000	0.000	0.000	0.000	0.000							
7	A-LA-D-PUR-6	0.055	0.000	0.000	0.051	0.004	0.000						
8	A-LA-D-PUR-10	0.000	0.183	0.000	0.000	0.004	0.000	0.000					
9	A-LA-D-PUR-18	0.000	0.000	0.049	0.000	0.000	0.000	0.000	0.000				
10	A-LA-D-PVAc-6	0.075	0.000	0.000	0.075	0.008	0.000	0.808	0.000	0.000			
11	A-LA-D-PVAc-10	0.000	0.144	0.000	0.000	0.006	0.000	0.000	0.826	0.000	0.000		
12	A-LA-D-PVAc-18	0.000	0.000	0.000	0.000	0.000	0.035	0.000	0.000	0.000	0.000	0.000	

Table 17. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Yield Point for Beech and NWC Down

No.	Sample Type	(1) 1418	(2) 1545	(3) 1508	(4) 1119	(5) 2320	(6) 2117	(7) 586	(8) 1732	(9) 2398	(10) 860	(11) 1667	(12) 2405
1	B-CA-D-PUR-6		0.332	0.464	0.017	0.000	0.000	0.000	0.022	0.000	0.000	0.065	0.000
2	B-CA-D-PUR-10	0.332		0.761	0.001	0.000	0.000	0.000	0.154	0.000	0.000	0.322	0.000
3	B-CA-D-PUR-18	0.464	0.761		0.003	0.000	0.000	0.000	0.098	0.000	0.000	0.225	0.000
4	B-CA-D-PVAc-6	0.017	0.001	0.003		0.000	0.000	0.000	0.000	0.000	0.037	0.000	0.000
5	B-CA-D-PVAc-10	0.000	0.000	0.000	0.000		0.101	0.000	0.000	0.524	0.000	0.000	0.519
6	B-CA-D-PVAc-18	0.000	0.000	0.000	0.000	0.101		0.000	0.002	0.031	0.000	0.001	0.032
7	B-LA-D-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.028	0.000	0.000
8	B-LA-D-PUR-10	0.022	0.154	0.098	0.000	0.000	0.002	0.000		0.000	0.000	0.599	0.000
9	B-LA-D-PUR-18	0.000	0.000	0.000	0.000	0.524	0.031	0.000	0.000		0.000	0.000	0.958
10	B-LA-D-PVAc-6	0.000	0.000	0.000	0.037	0.000	0.000	0.028	0.000	0.000		0.000	0.000
11	B-LA-D-PVAc-10	0.065	0.322	0.225	0.000	0.000	0.001	0.000	0.599	0.000	0.000		0.000
12	B-LA-D-PVAc-18	0.000	0.000	0.000	0.000	0.519	0.032	0.000	0.000	0.958	0.000	0.000	

Table 18. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Yield Point for Beech and NWC Up

No.	Sample Type	(1) 1011	(2) 1647	(3) 2471	(4) 815	(5) 1857	(6) 2582	(7) 464	(8) 1638	(9) 2552	(10) 840	(11) 1723	(12) 3989
1	B-CA-D-PUR-6												
2	B-CA-D-PUR-10	0.002											
3	B-CA-D-PUR-18	0.000	0.000										
4	B-CA-D-PVAc-6	0.341	0.000	0.000									
5	B-CA-D-PVAc-10	0.000	0.308	0.002	0.000								
6	B-CA-D-PVAc-18	0.000	0.000	0.592	0.000	0.001							
7	B-LA-D-PUR-6	0.009	0.000	0.000	0.071	0.000	0.000						
8	B-LA-D-PUR-10	0.002	0.963	0.000	0.000	0.306	0.000	0.000					
9	B-LA-D-PUR-18	0.000	0.000	0.674	0.000	0.001	0.878	0.000	0.000				
10	B-LA-D-PVAc-6	0.378	0.000	0.000	0.893	0.000	0.000	0.066	0.000	0.000			
11	B-LA-D-PVAc-10	0.001	0.692	0.000	0.000	0.489	0.000	0.000	0.679	0.000	0.000		
12	B-LA-D-PVAc-18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

Duncan's test was performed for a detailed comparison of the differences between the forces at the proportionality limit and yield point for the different types of aspen and beech laminate materials, and the results are shown in Tables 11 to 18.

Figure 4 shows that the largest force required to reach the proportionality limit for the aspen lamellas was found with the 18-mm-thick samples that had the fiberglass cloth component on the bottom of the laminated material. These lamellas were glued with PUR adhesive. In contrast, the smallest force needed to reach the proportionality limit was found with the 6-mm-thick lamellas, especially those with fiberglass on top. Moreover, this material reached only 16.7% of force at the proportionality limit in comparison to the above-mentioned material.

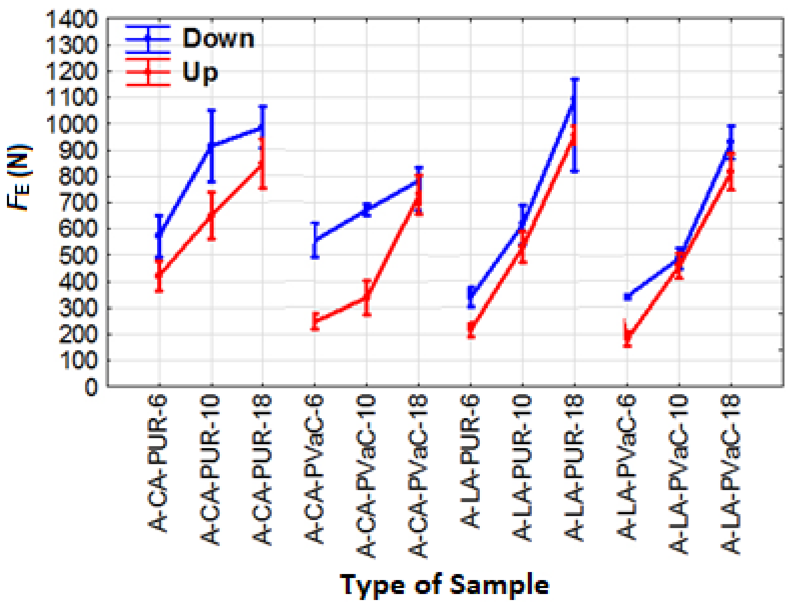


Fig. 4. Effect of aspen on the force at the proportionality limit

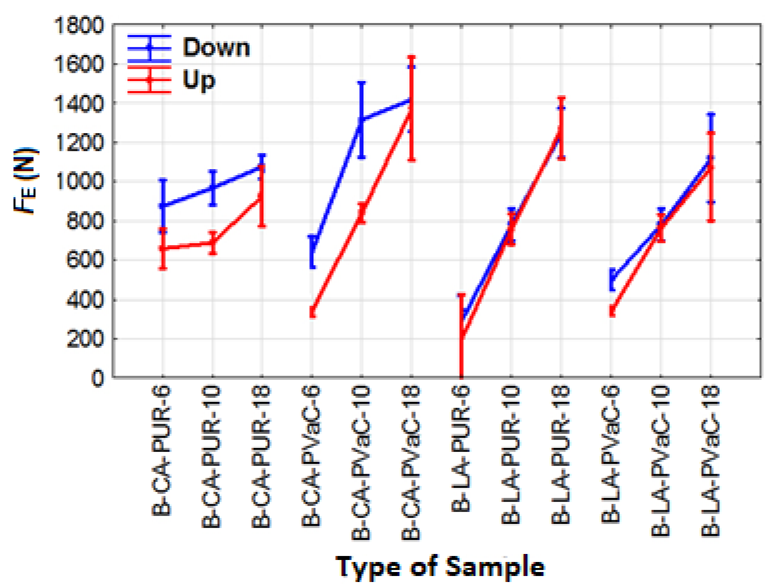


Fig. 5. Effect of beech on the force at the proportionality limit

For the beech lamellas, the results were different (Fig. 5). The largest force needed to reach the proportionality limit for the beech lamellas was found with the 18-mm-thick specimens with carbon on the bottom of the lamella, unlike the aspen lamellas. These lamellas were glued with PVAc adhesive. As with the aspen lamellas, the 6-mm-thick beech lamellas glued with PUR reinforced with carbon fibers located on the top required the smallest force to reach the proportionality limit. This material reached only 14.2% of force at the proportionality limit compared to the above-mentioned material.

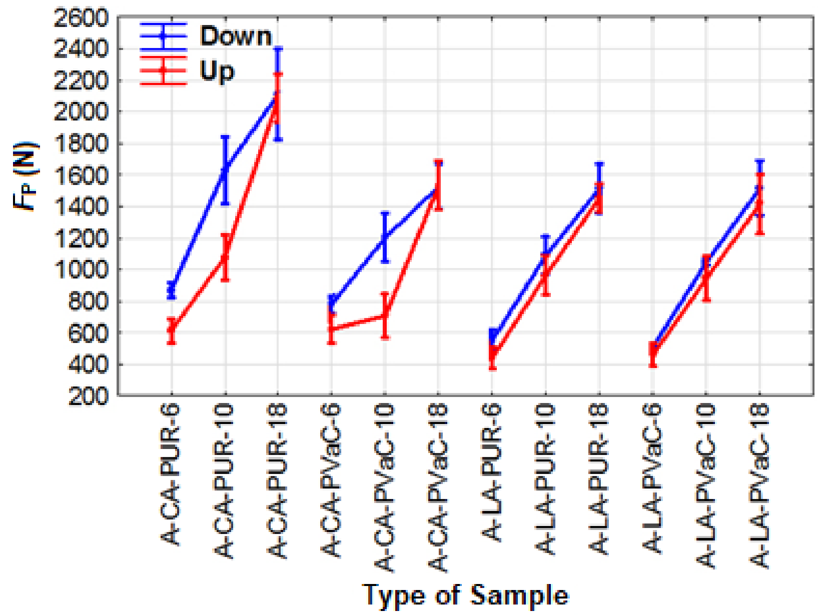


Fig. 6. Effect of aspen on the force at the yield point

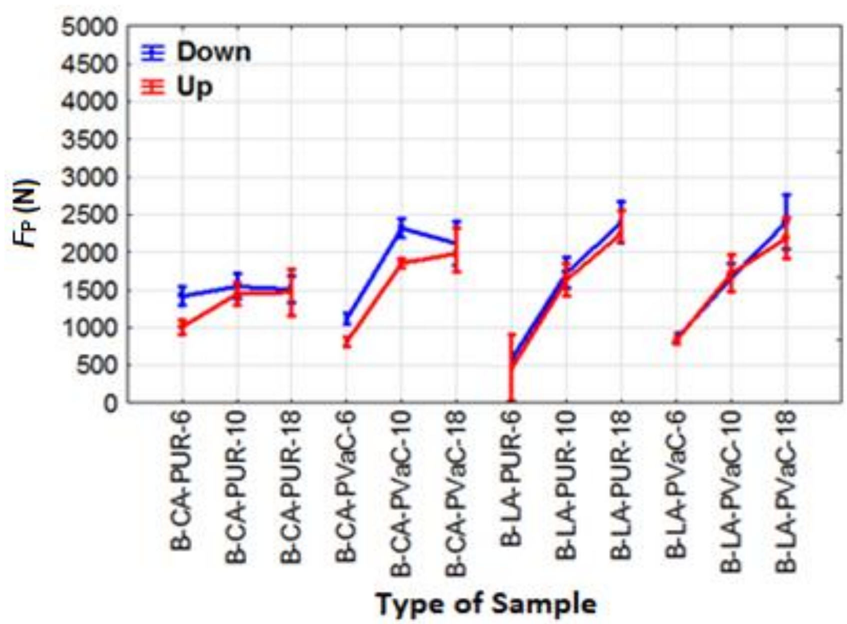


Fig. 7. Effect of beech on the force at the yield point

Figure 6 clearly shows that the largest force required to reach the yield point for the aspen lamellas was found with the 18-mm-thick samples with carbon on the bottom of the lamella. These lamellas were glued with PUR adhesive. The smallest force needed to reach the yield point was found with the 6-mm-thick lamellas with fiberglass on the top, this material reached only 20.9 % of the force at the yield point in comparison to the above-mentioned material. The trend was therefore similar to that of the proportionality limit for the aspen lamellas.

As was the case for the proportionality limit, the results for the yield point for the beech lamellas were different (Fig.). The largest force needed to reach the yield point for the beech lamellas was found with the 18-mm-thick specimens that had fiberglass on the bottom of the lamella, unlike the aspen lamellas. These lamellas were glued with PVAc adhesive. The smallest test values were recorded with the beech lamellas bonded with PVAc adhesive and reinforced with fiberglass on the top. This material reached only 22.7% of force at the yield point relative to the above-mentioned material.

CONCLUSIONS

1. It was generally found that the monitored characteristics, namely the forces at the proportionality limit and yield point, reached higher values in the laminated beech wood modified with a non-wood component than in the laminated aspen wood modified with a non-wood component.
2. For the aspen laminated wood with a non-wood component, it can be safely said that the largest values of the monitored characteristics were measured in the test specimens with a non-wood component glued on the convex side with respect to the stress. These materials showed that the largest forces at the proportionality limit and yield point were achieved when the individual layers were glued with PUR adhesive. The results for the effect of the non-wood component in the aspen laminates on the force at the proportionality limit showed that fiberglass glued to the convex side had the greatest effect. For the force at the yield point, the opposite trend was found, *i.e.*, larger values were achieved using carbon fibers glued to the convex side.
3. In the case of the laminated wood with beech and non-wood components, an opposite trend was found with regards to the effect of the adhesive compared with the aspen specimens. The PVAc glue was shown to be the most effective adhesive for the monitored characteristics. As for the effect of the non-wood component, an opposite trend compared with that of the laminated aspen specimens was also seen. For the force at the proportionality limit, modification with carbon fibers was shown to be the best, and for the force at the yield point, modification with fiberglass was the best.
4. As was expected, the material thickness proved to be a significant factor that affected the forces at the proportionality limit and yield point for all of the materials.

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