Tensile-Shear Strength of Glued Line of Laminated Veneer Lumber

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This article presents an investigation of the influence of selected factors (wood species, composition, and number of loading cycles) on the shear strength of laminated veneer lumber previously affected by cyclic loading. The monitored properties were determined on samples of European beech (*Fagus sylvatica* L.) and Eurasian aspen (*Populus tremula* L.). The laminated veneer lumber consisted of a combination of densified and non-densified veneers. Wood densification of up to 30% was carried out by means of rolling. The results show that each monitored factor significantly influenced the shear strength. The results also indicate a significant decrease in glued joint shear strength with increasing number of densified veneers in the laminated veneer lumber.

Keywords: Cyclic loading; Densification; Tensile-shear strength; Multilayered material; Laminated veneer lumber; Beech; Aspen

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INTRODUCTION

Wood is a natural, renewable material with multiple applications. It has both desirable and certain undesirable intrinsic properties. Most of wood's physical and mechanical properties can be improved by means of controlled changes. New processes to reduce wood's undesirable properties and to widen its applications in non-traditional areas are being investigated in the wood processing industry (Kurjatko *et al.* 2010).

The materials and semi-finished products' transformation into finished products under the required functional parameters constitutes the overall goal of the manufacturing process. This transformation process is based on the input energy (Gaff 2011). Wood modification may take place directly during the manufacturing process. Mechanical, thermal, and chemical modifications of the wood or combination thereof may result in materials with properties as required for their subsequent processing and industrial applications (Kurjatko *et al*. 2010; Gaff and Gáborík 2014).

Wood densification is one of the methods of changing the properties of wood by mechanical treatment. Densification is a modification process that forms wood by, *e.g.*, rolling, thus reducing the material volume and increasing its density (Kamke 2006). This process is most frequently utilized in the furniture industry, but it is also utilized in the building industry (Blomberg and Persson 2007; Laine *et al*. 2013; Gaff and Gáborík 2014). With densification, the qualitative modification of wood properties can be achieved, thus obtaining a material with improved properties. In comparison with solid wood, the resulting densified product has better physical and mechanical properties, which increase its possibilities for utilization in the manufacture of finished products for various purposes. After densification, wood species with lower initial moisture contents may replace hardwood. During hardwood's densification, its mechanical properties improve when compared with the original wood material (Blomberg *et al*. 2005). The density of beech ranges from 650 to 730 kg/m^3 before densification; however, after densification, it can increase up to 1,450 kg/m^3 (Blomberg 2006). The densified wood can be used for floor stepping elements, stairs, wall cladding, and furniture parts such as desk tops and boards (Blomberg and Persson 2007; Laine *et al*. 2013).

Laminated veneer lumber (LVL) is fabricated by gluing parallel veneer layers. It has excellent mechanical properties, and its dimensional stability gives an advantage to this material for application in various areas. Glues based on urea formaldehyde (UF) and phenol formaldehyde (PF) are commonly used. LVL is used in the building industry for, *e.g.*, beams and balks, rods for dam structures, concrete casing, scaffolding elements, and pre-fabricated houses. LVL is also used in the furniture industry for the supporting elements of seats and beds, as well as for structural carpentry products such as stairs, windows, and doors (Ozarska 1999).

Konnerth *et al.* (2006) investigated the response and durability of beech wood joints glued with polyvinyl acetate (PVaC)-based glue and made a comparison with other glues. During use, the joint could be exposed to moisture changes, high temperatures, or cyclic loading. Cyclic loading takes place if the material is exposed repeatedly to loads, and the material therefore can be ruptured because of fatigue.

The glued joint strength has a crucial impact on all glued materials consisting of several wood layers. To reach the correct standardized values of the glued joint strength, procedures recommended by the manufacturer should be observed throughout the manufacture (such as forming pressure, film thickness, open working time, wood temperature, and moisture). Provided that these conditions are met, the glued joint should reach the standard strength. The use of thermoplastic PVaC glues is frequent in the furniture industry. PVaC glues appeared in 1950 as substitutes for natural glues because they are not detrimental to human health or the environment (Mitani and Barboutis 2010). The products designed for the furniture industry include, *e.g.*, bed lamellae and armchairs. Therefore, their resistance testing is appropriate, as well as the determination of the conditions in which they might be used, in order to achieve their permanent strength as given by the standard.

The aim of the work was to investigate the glue line of beech and aspen-laminated veneer lumber with combinations of densified and non-densified veneers. Prior to the proper testing of the glued line, the samples underwent cyclic loading. The main goal was experimental verification of the influence of wood species, composition, densification, and cyclic loading on glue line strength in aspen and beech laminated veneer lumber.

EXPERIMENTAL

Materials

Veneer preparation

Two wood species were used in the experiment: European beech (*Fagus sylvatica* L.) and Eurasian aspen (*Populus tremula* L.), grown in the Poľana area of central Slovakia. Rotational peeling of steamed beech and aspen logs was used to manufacture 2-mm-thick veneers, which were subsequently conditioned in the conditioning chamber APT Line II

(Binder, Germany) to a moisture content of 8% at an air relative humidity of 60% and a temperature of 20 °C. The tangential veneers were divided into two groups: 1) veneers ready for densification; and 2) non-densified veneers.

There were 24 samples for each combination of densified and non-densified veneers (Table 3 and Fig. 3) and number of cycles (6 samples for each cycle type) per wood species, so the whole research contained 240 specimens.

Veneer densification

Neither beech nor aspen veneers were plasticized prior to densification. The samples determined for densification were densified using a rolling press machine. Densification pressing roller generated pressure of 3 MPa at speed of 0.03 m/s. The densification process was carried out according to previous work of Gašparík and Gaff (2015).

Figure 1 shows the basic densification principle. Total densification was 30% from initial veneer thickness 2 mm to final thickness 1.4 mm.

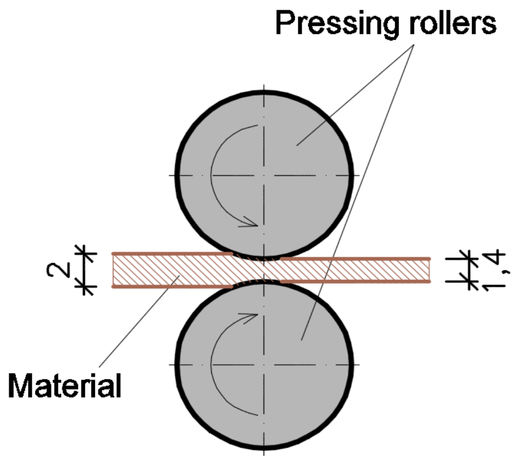

Fig. 1. Basic scheme of densification

For both wood species, the densities before and after densification were evaluated (Table 1).

Table 1. Average Density of Wood Veneers Before and After Densification

Wood Species	Density before Densification (kg/m^3)	Density after Densification (kg/m^3)
Eurasian aspen	425	649
European beech	627	868

LVL creation

Figure 2 shows the investigated combinations of LVL of both wood species. The water-proof PVAc glue Duvilax D3 Rapid (Duslo Šaľa, Slovakia) with parameters shown in Table 2 was used for gluing of LVL.

A gluing roller was used for the glue application, creating the recommended film from 150 to 200 g/m^2. The veneers were cold-pressed in an industrial press JU 60 (Paul Ott, Austria) with pressure 1 MPa for 40 min. Subsequently, the samples were conditioned in the conditioning chamber APT Line II (Binder, Germany) to a moisture content of 8%.

Then the samples were formatted to 600 × 30 × 5.4 mm (changing the sample thickness as a function of the veneer combination) and prepared for cyclic loading.

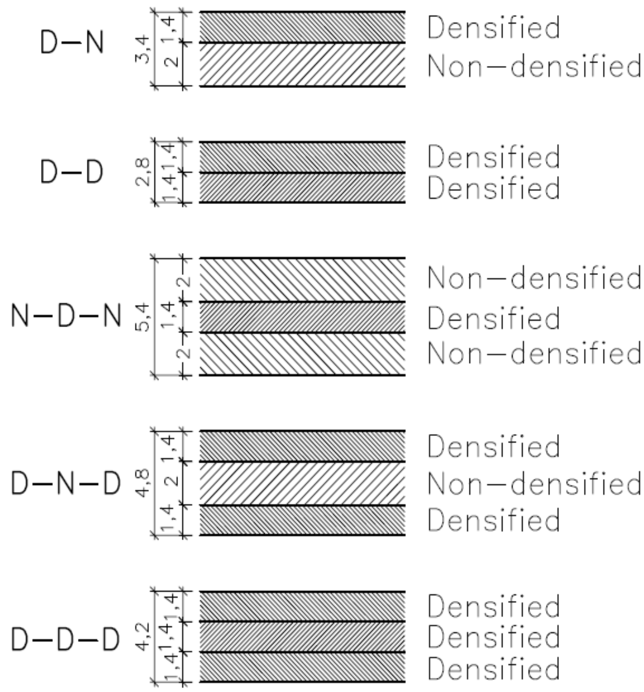

Fig. 2. Combinations of beech and aspen veneers with various thicknesses (*Note*: **D** – densified veneer, **N** – non-densified veneer)

Table 2. Glue Properties

Dry matter content (%)	**Viscosity** (m Pa.s)	**pH**	**Min. film-forming temper.** (°C)	**Working time** (min)	**Working temper.** (°C)	**Drying time at 20 °C** (min.)	**Wood moisture content** (%)
49	4000–8000	3–4	10	10	15–100	10–30	8–12

Cyclic loading

The cyclic loading of LVL samples was carried out on a cycling machine based on uniaxial stress. During preliminary bending tests, the ultimate bending strengths and proportional limits for these combinations were measured. These values were necessary for avoiding the sample overloading during the cyclic loading. First, the loading value for the laminated veneer lumber was set up to 90% of the proportionality limit. Subsequently, the samples for cyclic loading underwent 1,000, 2,000, and 3,000 cycles, and then were compared with samples without cyclic loading (0 cycles) (Fig. 3). The proper cyclic loading took place on a cycling machine with a support distance of 490 mm. The cyclic bend loading process was carried out according to previous research of Gašparík and Gaff (2015).

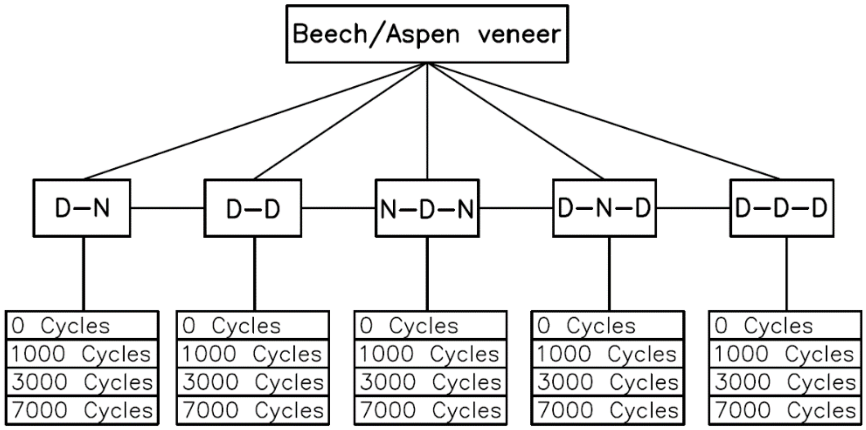

Fig. 3. Classification of sample groups

Glue joint strength

After cyclic loading, the samples were cut to 150 × 25 × 5.4 mm (sample thickness being changed according to veneer combination). Thereafter, two opposite grooves were cut 25 mm from each other in order to allow for the glued surface strength, according to EN 314-1 (2004). Figure 4 shows the testing principle for the glueline shear strength using the universal testing machine UTS 50 (TIRA, Germany). The loading speed was set to 15 mm/min. Maximum force and deformation were measured using the datalogger ALMEMO 2690-8 (Ahlborn GmbH, Germany).

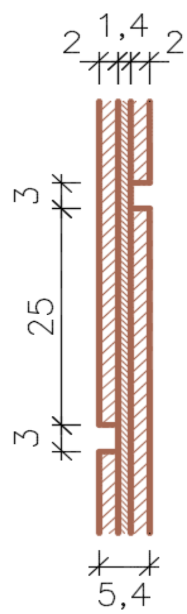

Fig. 4. Testing principle for tensile-shear strength EN 314-1 (2004)

Evaluation and Calculation

To determine the influence of the individual factors on the shear strength of glue line, ANOVA and Fischer's F-test were performed using STATISTICA 12 (Statsoft Inc., USA) software.

The shear strength (f_v) of each sample was calculated according to EN 314-1 (2004) and Eq. 1,

$$f_V = \frac{F_{\max}}{l * b} \quad (1)$$

where f_V is the tensile-shear strength parallel to the fibers (MPa), F_{max} is the maximum shear strength of samples recorded at the breaking point (N), l is the length of the shear area (mm), and b is the width of the shear area (mm).

The wood density was determined according to ISO 13061-2 (2014) before and after densification using Eq. 2,

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w}, \quad (2)$$

where ρ_w is the sample density at a certain moisture content w (kg/m^3); m_w is the sample mass at a certain moisture content w (kg); a_w, b_w, and l_w are the sample dimensions at a certain moisture content w (m); and V_w is the sample volume at a certain moisture content w (m^3).

The moisture content in the samples was determined according to ISO 13061-1 (2014) and Eq. 3,

$$w = \frac{m_w - m_0}{m_0} * 100 \quad (3)$$

where w is the moisture content in the sample (%), m_w is the sample mass at a certain moisture content w (kg), and m_0 is the sample mass in a dry state (kg).

RESULTS AND DISCUSSION

Table 3 shows the resulting effects of the individual factors and their two- and three-factor interactions. Based on the value of the significance level P < 0.05 (limit of statistical significance based on 95% confidence interval), it is possible to conclude that the loading cycles as well as combination of veneers were statistically significant factors. Wood species was a moderate statistically significant factor. The synergetic effect of all factors was also statistically significant.

Table 3. Effect of Individual Factors and their Interaction on Tensile-Shear Strength

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F-Test	Significance level P
Intercept	10485.08	1	10485.08	9223.950	0.000001
Wood species	5.14	1	5.14	4.526	0.033654
Loading cycles	18.98	3	6.33	5.566	0.000872
Combinations	2202.84	4	550.71	484.471	0.000001
Wood species * Loading cycles * Combinations	42.46	12	3.54	3.113	0.000239
Error	1045.79	920	1.14		

As shown in Fig. 5, the highest values of the monitored feature were found for beech. The average value for beech's maximum shear strength was 3.4 MPa, which is greater by 6% greater than that of aspen. The higher values found for beech wood should be caused by its higher density.

Figure 6 shows no consistent effect of number of cycles on maximum shear strength. The maximum shear strength for the wood species was 3.4 MPa at 3,000 loading cycles. A slight decrease of the glued joint shear strength occurred at 1,000 and 7,000 cycles in comparison with those at 0 and 3,000 cycles.

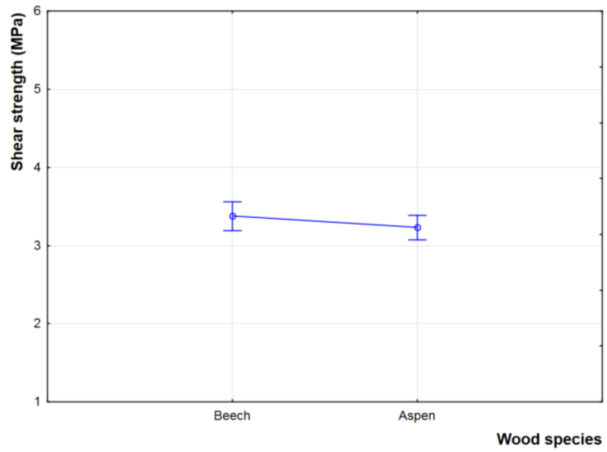

Fig. 5. Influence of wood species on tensile-shear strength

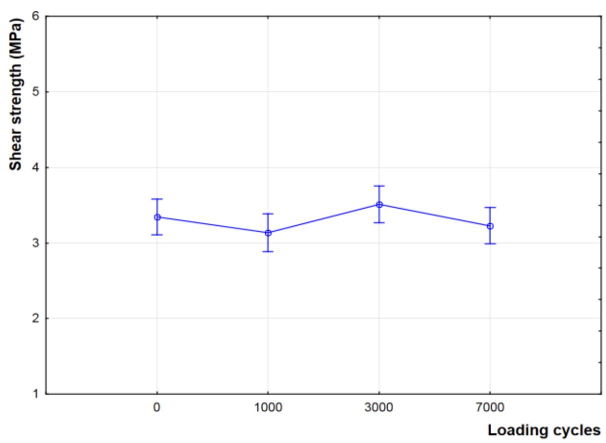

Fig. 6. Influence of loading cycles on tensile-shear strength

Figure 7 leads to the conclusion that, in general terms, two-layer LVL has more than double the value of the shear strength of three-layer laminated veneer lumber. A smaller number of glued lines may cause this fact. The glued joint shear strength decreased gradually with an increasing number of densified veneers in two- and three-layer compositions. The lowest value of shear strength was achieved with LVL solely composed of densified veneers. This may be caused by smooth rolls of the densifier, which over-smoothen (deteriorate) the veneer surface during densification, thereby impairing the adhesion of their surfaces to the glue. Therefore, lower values of tensile-shear strength occurred.

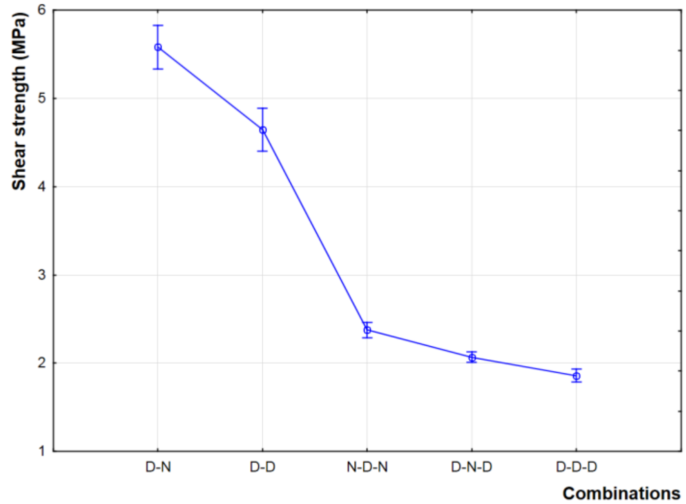

Fig. 7. Influence of veneer combinations on tensile-shear strength

In Fig. 8, the simultaneous influence of all factors is shown. In general terms, two-layer combinations had higher values of glued joint shear strength than three-layer combinations. When comparing beech with aspen, the greatest differences in shear strength were observed between the individual two-layer combinations. D-N combinations of beech veneers achieved values approximately 16.7% higher than D-N combinations of aspen veneers. For D-D combinations, the shear strength differences between the wood species were smaller. For aspen, the differences of shear strength at D-N and D-D combinations were minimal. With the gradual increase of the number of veneers in the combinations, the shear strength differences decreased, *i.e.*, the shear strength of three-layer combinations was almost equal for both wood species.

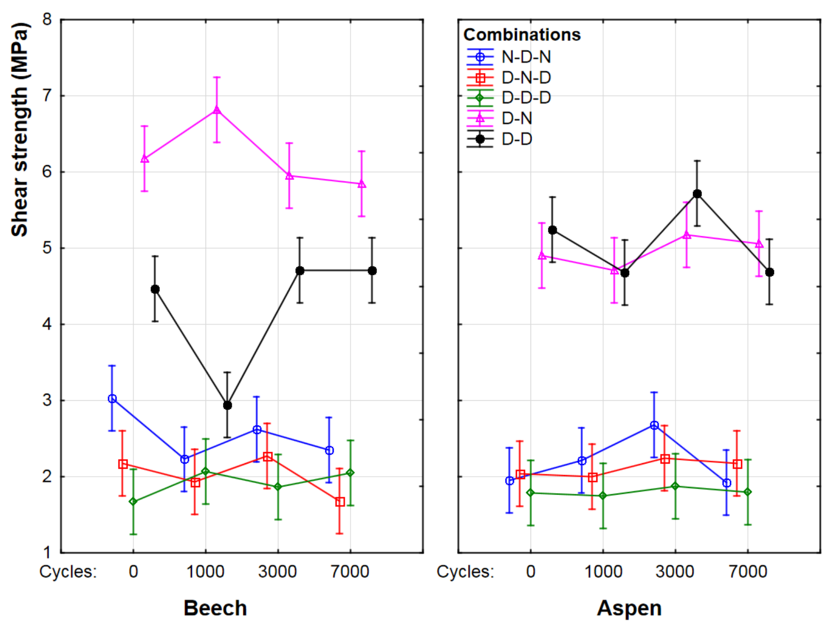

Fig. 8. Influence of combinations, wood species, and number of loading cycles on tensile-shear strength

The maximum average value of shear strength for beech was 6.2 MPa. This result is consistent with those of other authors, *e.g.*, Ozkaya *et al.* (2015), who investigated 7-layer beech laminated veneer lumber glued with PVaC-based glue. They found the glued joint shear strength was equal to 8.07 MPa. Some authors, for example, Ozcifci and Yapici (2008), investigated treated surface quality, and achieved higher values of shear strength of the joint glued with PVaC-based glue for both beech and aspen. This is caused by the use of research samples of surfaces machined with a four-sided cutter. Vick (1999) also drew the attention to this fact.

Shukla and Kamdem (2008) mentioned a glued joint shear strength of 3.04 MPa for three-layer laminated veneer lumber of aspen glued with PVaC-based glue. This value is comparable with the three-layer combinations herein.

Bekhta and Marutzky (2007) and Kurowska *et al.* (2010) affirmed that veneer densification and the creation of their combinations within the group improve their material, physical, and mechanical properties. The present research partially confirmed this premise.

CONCLUSIONS

1. Combinations of densified and non-densified veneers had the most significant effect on maximum shear strength for both wood species.
2. The effect of cyclic loading on the shear strength of aspen- and beech laminated veneer lumber did not have a consistent trend.
3. The increase in the number of densified veneers in the laminated veneer lumber composition decreased the shear strength of the glued wood.

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