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TENSILE-SHEAR STRENGTH OF LAYERED WOOD REINFORCED BY CARBON MATERIALS

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ABSTRACT

This article deals with the influence of selected factors (wood species, used adhesive type, carbon reinforcement) on tensile-shear strength of glued layered wood. Tensile-shear strength was investigated on samples of European beech (*Fagus sylvatica* L.) and European spruce (*Picea abies* L.). The laminated wood was modified with carbon polymer or carbon fabric, and the tensile-shear strength values were compared with non-reinforced wood. Polyurethane and epoxide adhesives were used for the experiment. The highest tensile-shear strength values were found on non-reinforced beech wood glued by epoxide adhesive. As far as the tensile-shear strength concerns, each monitored factor as well as their mutual interactions were proven to be statistically significant.

KEYWORDS: Tensile-shear strength, beech wood, spruce wood, CFF, CFRP.

INTRODUCTION

Currently, great attention is paid to the issue of modification of wooden materials properties (Miftieva et al. 2015, Gaff and Gašparík 2015). These improved properties can be achieved in combination of various materials, where the individual layers composition and their thickness can be changed as well as the use of various non-wooden materials is possible (Gaff et al. 2015a). Wood has a very wide range of uses, primarily in construction and furniture industry (Gaff et al. 2015b).

The gluing process plays an important role in wood-processing industry. Its importance is increasing due to the development of new polymeric materials. The polyurethane adhesives belong to the group of synthetic polymers. The synthesis of polyurethane adhesives is based on the reaction of isocyanates, polyols, amines and water. Flexibility is the great advantage of polyurethane adhesives. Various such authors as the following ones were dealing with the wood shear strength while using the polyurethane adhesives: Uysal and Ozcifci (2006), Ozcifci and Yapici (2008), Kläusler et al. (2014), Král et al. (2015). However, the epoxide adhesives are considered today as better since they exhibit very good adhesion to various types of material and their cohesion strength is often greater than that of the glued materials. According to the manufacturer, epoxide adhesives are suitable also for the gluing of carbon-based reinforcements. Various such authors as the following ones were dealing with the wood shear strength while using the epoxide adhesives: Raftery et al. (2009), Arriaga et al. (2011), Mirzaei et al. (2012). Also the glued joint shear strength can be included among the reference parameters while evaluating the glued joint quality (Pizzo et al. 2003, Gaff et al. 2016). For the gluing, the achievement of the required glued joint strength during the entire lifetime of the final product is the most important requirement. Many factors influence the glued joint strength, such as the glue viscosity, pressing pressure, application thickness, open processing time, temperature and the glued wood moisture. Also the process recommended by the manufacturer shall be observed during the gluing (Svoboda et al. 2015).

Both carbon fabrics and carbon polymer belong among the most basic types for wooden composite materials reinforcement. The carbon fabrics are significantly anisotropic, having fibrillary structure. These fabrics consist of graphite crystals in mutual contact (Mochida et al. 2000). The lamellae are manufactured of drawn carbon fibers (CFRP) reinforced with polymers. Typically, they have high tensile strength and they are designed for the reinforcement of wooden, concrete, brick and steel structures. They are also used for repairs of historic objects, changes of structure loading, etc. Many authors were dealing with the research of wooden and non-wooden material combinations (carbon or glass fibers, plastic foils), for example, Richter and Steiger (2005), Raftery et al. (2009). Richter and Steiger (2005) were investigating the thermal stability of wood-based composite materials reinforced with carbon laminate of types T 700 and T 300. The results were compared with non-reinforced wood samples glued with polyurethane and epoxide adhesives. Two wood species were used in the research: beech and spruce. Raftery et al. (2009) used two types of reinforcing polymers: Fulcrum and GFRP delivered by Rotafix UK Ltd. These polymers were used for the reinforcement of the spruce wood in their research. Three types of epoxide adhesives were used. They compared the reinforcing composite materials with non-reinforced wood samples. Johnsson et al. (2006) had reinforced the glued spruce wood by the mean of carbon bars glued into grooves using the epoxide adhesive. Borri et al. (2004) had reinforced old wooden cross beams using carbon fibers and carbon bars glued by the mean of epoxide adhesive. They investigated their most efficient placement in the cross beam cross-section. Wei et al. (2013) had reinforced the aspen wood by the mean of carbon fabrics. In order to glue the individual veneers, they used phenol formaldehyde adhesive and to glue the carbon polymer to the veneers, they used epoxide adhesive. They investigated the bending parameters of the reinforced LVL wood in comparison with those of non-reinforced LVL wood.

The research was aimed to investigate the tensile-shear strength of the glued beech and spruce layered wood. The wood was reinforced with carbon fabric or carbon polymer. The resulting shear strength was compared with values of non-reinforced glued wood. For the gluing, polyurethane and epoxide adhesives were used. The main goal consisted in experimental verification of the influence of the wood species, glue type and reinforcement on the tensile-shear strength in beech and spruce wood.

MATERIAL AND METHODS

Material

European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L.), harvested near Kostelec nad Černými lesy, east of Prague, were used for the experiments. The logs were split into boards. Subsequently, samples with clear dimensions of 150 × 20 × 5 mm were sawn and conditioned in the conditioning chamber Climacell 707 (BMT Medical Technology LtD, Czech Republic) to the moisture content of 12 %. The beech wood density in dry state was 704 $kg \cdot m^{-3}$, and spruce wood had 412 $kg \cdot m^{-3}$.

Then, the samples were divided to three alternatives: glued without reinforcement, reinforced with carbon fabric (CFF) SikaWrap®-300 CZ/60 (Sika AG; Switzerland) and reinforced with carbon polymer (CFRP) Sika® CarboDur® H514 (Sika AG; Switzerland). Tabs. 1 and 2 shows the properties of carbon fabric and carbon polymer.

Epoxide adhesive Sikadur® -330 (Sika AG; Switzerland) and single-component polyurethane adhesive PUR ICEMA® R 145 Professional (H. B. Fuller GmbH; Austria) were used for the gluing of all alternatives. The epoxide adhesive was mixed with the hardener Sikadur-330 Comp B at the ratio of 4:1. See Tabs. 3 and 4 for the adhesives properties.

Manual application roller was used for the adhesives application at thickness as recommended by the manufacturer. The samples were cold-pressed during 90 minutes in an industrial press GS 6/90 (SCM GROUP; Italy). After the press release, the samples were conditioned at 23 °C during 5 days. This is the time specified by the manufacturer to harden the adhesive.

Tab. 1: Properties of CFF.

Fiber density ($g \cdot cm^{-3}$)	Fabric thickness (mm)	Areal weight ($g \cdot m^{-2}$)	Tensile strength of fibers (MPa)	Tensile E-Modulus of fibers (MPa)
1.80	0.17	300	3,900	230,000

Tab. 2: Properties of CFRP.

Fiber density ($g \cdot cm^{-3}$)	Fabric thickness (mm)	Width (mm)	Cross-section areas (mm^2)	Tensile E-Modulus (MPa)
1.60	1.4	50	70	300,000

Tab. 3: Properties of epoxide adhesive.

Density at 23 °C ($g \cdot cm^{-3}$)	Viscosity at 20 °C (m Pa.s)	Working temperature (°C)	Working time (min)	Glue spread ($g \cdot m^{-2}$)
1.3	6,000	40 - 45 °C	45	700 -1,500

Tab. 4: Properties of polyurethane adhesive.

Density at 20°C ($g \cdot cm^{-3}$)	Viscosity at 20 °C (m Pa.s)	Min. film-forming temper. (°C)	Working time with water (min)	Working time without water (min)	Glue spread ($g \cdot m^{-2}$)
1.12	7,000	10	16	40	100-200

Fig. 1 shows the samples classification, with 15 measured samples for each alternative.

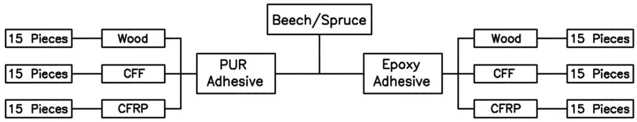

Fig. 1: Classification of samples groups.

Tensile-shear strength

After the gluing, the pieces were cut to 150 × 20 × 10 mm (being changed the sample thickness in function of the wood composition). Thereafter, two opposite grooves were cut, 10 mm distant from each other according to EN 302-1. Fig. 2 shows the testing principle for the tensile-shear strength by the mean of the universal testing machine UTS 50 (TIRA, Germany). The load speed was set up in a manner not allowing the test duration to exceed 90 seconds. The maximum strength at the sample breaking was recoded.

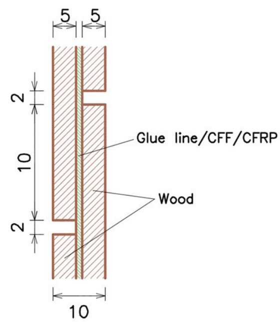

Fig. 2: Testing principle for tensile-shear strength according to EN 302-1 (2013).

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 302-1 (2013) and Eq. 1,

$$f_V = \frac{F_{\max}}{A} \tag{1}$$

where: f_v - the shear strength in (MPa),
F_{max} - the maximum shear strength of samples recorded at the failure (N),
A - the bonded test surface (mm^2).

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

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \tag{2}$$

where ρ_w - the sample density at a certain moisture content w (kg·m^{-3}),
m_w - the sample mass at a certain moisture content w (kg),

a_w, b_w, l_w - the sample dimensions at a certain moisture content w (m),
V_w - 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,

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

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

RESULTS AND DISCUSSION

Tab. 5 shows the resulting effects of the individual factors and their three-factor interactions. Based on the significance level $P < 0.05$ (limit of statistical significance based on 95% confidence interval), statistically very significant effect of the individual factors was proven. The synergetic effect of the three monitored factors was also statistically significant.

Tab. 5: Effect of individual factors on tensile-shear strength.

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	6867.816	1	6867.816	8008.412	0.000001
Wood species	371.098	1	371.098	432.730	0.000001
Adhesive	5.210	1	5.210	6.076	0.014712
Reinforcement	488.039	2	244.019	284.546	0.000001
Wood species* Adhesive * Reinforcement	8.115	2	4.058	4.731	0.010022
Error	144.073	168	0.858		

The greatest values of shear strength, 7.6 MPa, were achieved for beech. This value exceeds by 65% approximately that one for spruce (Fig. 3). Higher values for beech wood are likely caused by its higher density. The wood species factor has proven to be statistically very significant (Tab. 5 and Fig. 3).

Fig. 4 shows the effect of the selected adhesive on the shear strength. While using the epoxide adhesive, shear strength values by approximately 7 % greater as for polyurethane adhesives. Also this factor has proven to be statistically significant for the monitored feature (Tab. 5 and Fig. 4).

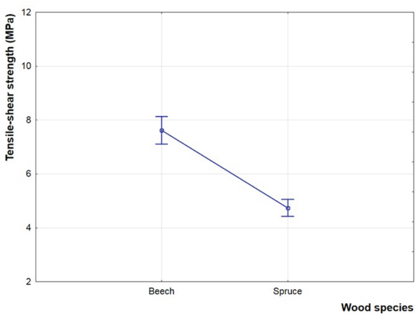

Fig. 3: Wood species influence on tensile-shear strength.

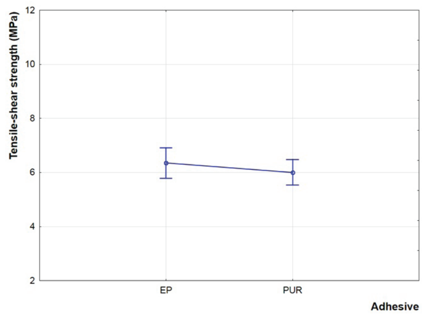

Fig. 4: Influence of the adhesive type on tensile-shear strength.

Fig. 5 shows the influence of the reinforcement type on the shear strength. Also this factor proved to be statistically very significant for the shear strength (Tab. 5 and Fig. 5). The greatest values were achieved for non-reinforced wood: greater by 3% approximately than those for carbon fabric. The smallest values of shear strength were found for carbon polymer reinforcement. The shear strength is by 90% approximately smaller than for carbon fiber fabric. This can be likely caused by worsened adhesion of the adhesive to the carbon polymer.

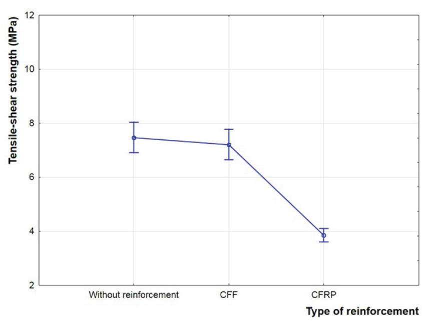

Fig. 5: Influence of the reinforcement type on tensile-shear strength.

In the Fig. 6, the simultaneous influence of the three factors is shown. The greatest values of shear strength at beech samples were achieved with epoxide adhesives. The smallest values were achieved with polyurethane adhesives, where the similarly decreasing character of the shear strength was reported for each type of reinforcement. However, unambiguous courses were found for spruce samples, where the polyurethane adhesives achieved greater values for both reinforcement types, but on the contrary, the value decreased for non-reinforced spruce wood. The carbon polymer reinforcement of the glued joint achieved the smallest values of the monitored feature for both wood species.

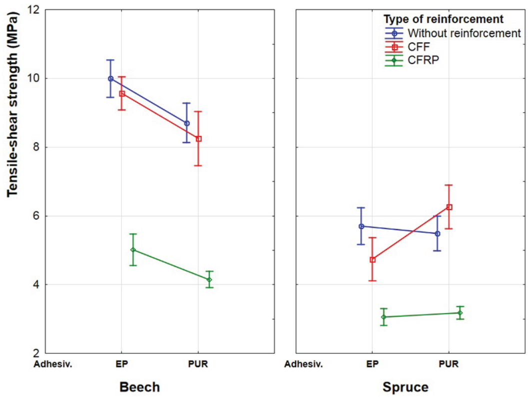

Fig. 6: Influence of the wood species, adhesive type and reinforcement type on tensile-shear strength.

The greatest average value of shear strength for the beech with polyurethane adhesive and without reinforcement achieved 8.7 MPa. Král et al. (2015) tested the shear strength of beech at equal dimensions in different environments. At 12-% moisture, they report the shear strength value of 11.63 MPa achieved with the use of polyurethane adhesive. Kläusler et al. (2014) researched in their paper the influence of the surface treatment on the glued joint shear strength while using polyurethane adhesives and beech samples with equal dimensions. They reported the shear strength value of 12.2 MPa in their paper. Both authors obtained greater values; this might be caused by different type of polyurethane adhesive. In their paper, Ozcifci and Yapici (2008) tested the influence of the wood orientation and surface treatment type on the glued joint shear strength while using various types of adhesives. They report, at the comparison, the shear strength of 12.06 MPa for the beech with the use of polyurethane adhesive DESMODUR-VTKA. However, the authors used another type of adhesive. For the fir samples with surface treated by planning, they mention the shear stress value of 5.03 MPa. This is comparable with our measured value for spruce without reinforcement. Uysal and Ozcifci (2006) used the polyurethane adhesive DESMODUR-VTKA on beech samples. They report the shear stress of 9.353 MPa at equal glued area. This is comparable with our results.

The greatest shear stress value for beech tree without reinforcement and with epoxide adhesive we achieved, was 10 MPa, and for the spruce, 5.8 MPa. Mirzaei et al. (2012) tested the influence of various adhesives on the beech wood shear strength. While using the epoxide adhesives, they report the beech wood shear stress equal to 11.3 MPa. Raftery et al. (2009) tested three types of epoxide adhesives on the spruce (*Picea sitchensis* Carr.). While using the adhesive Sikadur 31 Normal, the authors report the shear strength of 8.5 MPa. This value is greater than our measured strength; this is likely caused by different type of used adhesive.

CONCLUSIONS

1. The highest tensile-shear strength was found at non-reinforced beech wood with epoxy adhesive.
2. The carbon polymer reinforcement of the glued joint achieved the smallest tensile-shear strength for both wood species. However, the beech wood had slight higher values as spruce wood.

3. Beech wood glued with epoxy adhesive reached in all cases the highest tensile-shear values as at polyurethane adhesive. Only spruce wood without reinforcement glued by epoxy adhesive had the highest values.

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