Physical and Bending Properties of Beech Laminated Veneer Lumber Reinforced with Carbon Fiber Fabric

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Nine-layer laminated veneer lumber (LVL) 1300 by 850 mm, in nominal thickness of 20 mm, was produced using beech veneer and reinforced LVL (RLVL), by inserting carbon fiber fabric between the veneer sheets. The research aimed to assess the enhancement of flexural properties, both in edgewise and flatwise bending, of beech LVL reinforced with carbon fiber fabric. Two types of reinforcements were made, using two types of adhesives: phenol-formaldehyde (PF) and polyurethane (PUR), in the industrial conditions. In the first group of samples (K1), the reinforcements were placed further from the neutral axis, and in the second group (K2) closer to the neutral axis. These groups were compared to the unreinforced control sample (K). Some physical properties, bending behavior parallel to the grain, and failure mode were determined and analyzed. Edgewise bending strength of the RLVL was about 11% higher than the control in the case of PF adhesive, while flatwise bending strength was about 40% lower than the control in the case of PUR adhesive. The experimental data were verified using the ANOVA model. The most important results of the study define different behavior and fracture mechanisms for each reinforcement and adhesive, highlighting the potential of RLVL for structural applications.

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INTRODUCTION

Laminated veneer lumber (LVL) is an engineered wood product that uses multiple, graded, veneer sheets with a thickness of 2.5 mm to 4.8 mm, typically 3.2mm, assembled with adhesives. It was first developed in the 1970s as a high-strength, versatile engineered wood product used primarily for structural applications as beams, columns, and panels. Due to its manufacturing method and even distribution of defects, the mechanical properties of the final product are more uniform and can be more precisely predicted. The size of LVL is not limited by log size and its length is restricted only by transportation to site.

The most commonly used raw material for LVL manufacture are species including Douglas fir, southern pine, as well as other softwoods, and yellow poplar. Wood density directly affects the strength of LVL; consequently, hardwoods typically provide a higher strength of the final product than softwoods (Baldwin 1995; Aydin *et al.* 2004).

Despite superior flexural properties of softwoods, which has been shown in practice regarding LVL, due to climate change and the lack of quality wood (Garamvölgyi and Hufnagel 2013), hardwood species are becoming increasingly important. The results of some research (Shukla and Kamdem 2007; Kurt 2010; Fleckenstein *et al.* 2018; Nguyen *et al.* 2019; Purba *et al.* 2019) showed the suitability of using hardwoods in the production of LVL. Ozarska (1999) presented the possibilities of using hardwoods in producing LVL. According to this author, research in North America was focused on the use of poplar and aspen, in Asia on eucalyptus, while in Europe, research has focused on lower quality, small-diameter logs in the production of LVL. In contrast, some research has focused on combined LVL composed of poplar and beech veneers (Zdravković *et al.* 2017).

The possibilities of strengthening with fiber-reinforced polymers (FRP) have been examined to improve the mechanical properties of structural products. The first strengthening of wood using glass fiber reinforced polymer (GFRP) and epoxy resin was in the 1960s by Wangaard and Biblis (Bulleit 1984). More intensive research has been carried out since the 2000s, when the mechanical properties of three-ply and five-ply veneer panels reinforced with GFRP fabric using phenol as an adhesive were examined (Biblis and Carino 2000). Over time, various materials were used for reinforcement such as glass, carbon, aramid fibers, natural fibers, basalt, metal, plastic, *etc.* (Xu *et al.* 1998; Brezović *et al.* 2003; Bal 2014a, 2014b; Kramár and Král 2019; Anoop and Sajan 2021).

The mechanical properties and the behavior of the most commonly used reinforced veneer-based composites depend on the veneer species and quality, adhesive type, type of synthetic fibers, and manufacturing conditions. Adhesive consistency regarding the wetting of the veneer surface, as well as strength and modulus of elasticity after curing, are responsible for the stress transmission. Different types of adhesives, including phenol formaldehyde (PF), epoxy adhesive, isocyanate adhesive, melamine-urea formaldehyde (MUF), urea formaldehyde (UF), *etc.*, have been used in the experimental research of reinforced plywood or LVL (Rowlands *et al.* 1986; Davalos *et al.* 2000; Lopez-Andio *et al.* 2000; Davalos and Qiao 2003; Lyons and Mallik 2005; Bal and Bektaş 2012).

Synthetic fibers are responsible for the strength and behaviour of the veneer-based composites. Structural properties of the reinforced panel are influenced by the type of wood used, the quantity, position, and fiber orientation, as well as its position in sublayers. The quantity of carbon fibers on flatwise bending properties of reinforced plywood influences the reduction of stress and deformations in the composite, which positively affects the flexural properties of the plate under load (Brezović *et al.* 2003).

Experimental research on reinforced veneer or LVL panels often focuses mainly on flexural properties. In the flatwise bending test, the poplar LVL reinforced with carbon fiber reinforced polymer (CFRP) showed a greater modulus of elasticity (MOE) and modulus of rupture (MOR) than the control LVL (Wei *et al.* 2013). Sokolovic *et al.* (2023) studied CFRP reinforced poplar LVL behavior in edgewise bending using epoxy or melamine-urea formaldehyde adhesive. Epoxy adhesive is applicable, and edgewise bending strength and MOE were significantly greater of RLVL, but MUF adhesive is unsuitable for gluing synthetic fibers and wood.

Some studies of plywood or LVL strengthening have focused on examining wood of lower quality, such as poplar (Brezović *et al.* 2002; Bal 2014; Wang *et al.* 2015; Sokolović *et al.* 2023). Lui *et al.* (2019) tested the flexural properties of structural plywood composed of different wood species, poplar and eucalyptus veneer as base material and carbon fabric as reinforced material. Auriga *et al.* (2020) analyzed 5-ply Scots pine plywood panel reinforced with CFRP in parallel orientation glued with MUF adhesive and affected the increased values of MOE and MOR compared to commercial boards. They concluded that carbon fibers decrease the tensile strength perpendicular to the planes.

The improvement of certain physical and mechanical properties of plywood, particularly tensile strength, using carbon fiber fabric reinforcement was analyzed by Wang *et al*. (2024). Bakalarz and Kossakowski (2022) studied bending behavior under static loads of full-size pine and spruce LVL beams strengthened with CFRP sheet in three different configurations, bonded to the external faces with epoxy resin. The same authors studied load-bearing capacity and bending stiffness for commercial LVL reinforced with CFRP sheet placed in the core layer of the beam as a sandwich-type structure (Bakalarz and Kossakowski 2024).

Reinforcement with FRP can significantly enhance the mechanical properties of hardwoods, enabling exceptional performance in veneer-based products for structural applications. Some research has been conducted on the reinforcement of birch LVL. Comparing the flexural properties of LVL, Bal and Bektaş have shown that LVL made from beech veneer exhibits the highest MOE and MOR values compared to eucalyptus or poplar LVL, regardless of the formaldehyde-based adhesive (UF, MUF, or PF) used (Bal and Bektaş 2012). Some studies have reinforced heat-treated beech LVL with carbon or glass fibers to improve its physical and mechanical properties (Percin and Altunok 2017; Çiğdem and Perçin 2023; Perçin and Uzun 2023).

The potential of LVL reinforced with CFRP indicated the possibility of its application in spatial structures – segmented shell or folded structure. Planar elements in spatial structures can be exposed to a transverse load – perpendicular to the plate surface (slab mechanism), or with a load in the plane of the plate (plate mechanism). Transverse load causes flatwise bending moments and torsional moments in the plate, while the plate mechanism has a component load in the panel plane, *i.e.*, the elements are loaded with axial forces and panel shear.

Polygonal segmented shell structures were designed using trivalent polyhedral segments' structural principles (Krieg *et al.* 2015). Each plate in the construction must be designed according to the diaphragm principle to accept the forces in its plane. The plates and their connections must not be designed to accept torsion or bending moments to achieve the structure's stability. The connections between the plates were formed as linear joint connections, and they are possible to transmit only axial and shear forces but not bending moments (Sokolović 2022).

Several examples of folded or segmented shell structures have been realized as temporary pavilions using plywood, cross-laminated timber (CLT), or LVL panels (Stitic and Weinand 2015; Robeller *et al.* 2017; Weinand 2017). However, their main limitation is the construction span and the design of connections between elements. The RLVL has great potential to improve the design and realization of more reliable wooden spatial structures.

The LVL could also be used as beams. This is relevant for reciprocal frame construction, where large spans of spatial structures can be formed by combining short elements. The RLVL might provide sufficient shear strength at the critical points of element connections and sufficient edgewise bending strength at the places of the highest bending stress, thus creating direct connections between wooden elements without additional metal fittings. This could reduce the weight of the structure.

This research is, in a certain sense, an extension of the previous research of the bending properties of poplar LVL reinforced with carbon fibers (Sokolović *et al.* 2023). The cited study was performed under laboratory conditions with adhesives that are not suitable for large-scale industrial application (especially epoxy). This study focuses on the production of LVL under controlled industrial conditions, with beech wood (*Fagus sylvatica* L.), the most dominant wood species in the Western Balkans, and certified adhesives for load-bearing structures in construction: phenol-formaldehyde adhesive (PF) and polyurethane adhesive (PUR). These adhesives are already widely used in EWP production and they are suitable for designing more complex structures, such as load-bearing boxes or shells in construction of residential buildings. Based on previous research on poplar RLVL, the two constructions that showed optimal bending properties in technical, technological, and economic terms were selected.

Some new findings in this research have not yet been widely reported. To bring the results of this research closer to practical application, instead of a laboratory experiment, an experiment in controlled industrial conditions was chosen, together with widely used industrial adhesives. In the industrial circumstances, all three boards per each batch were pressed together in the same press daylight, so the pressing conditions for all three combinations of LVL were the same: control FK, reinforced FK1 and FK2 for PF adhesive, and control PK, reinforced PK1 and PK2 for PUR adhesive (see Fig. 2). This was to minimize experimental error among LVL combinations for the same adhesive.

Based on previous experience (Sokolović *et al.* 2023), the authors introduced the cooling stage under pressure, which is uncommon in LVL production, but it was introduced to prevent steam from forming under high pressure and temperature in the gluelines, near the carbon fiber fabric, which is characteristic of water-based adhesives. This could cause blisters in the gluelines, which usually lead to a weakening of the LVL construction, and in that way, it was avoided.

The objective of this study was to evaluate the effects of the adhesive type and carbon fiber fabric position in LVL construction on some physical and mechanical properties of LVL manufactured from beech (*Fagus sylvatica* L.) veneers and to consider the possibility of its application in load-bearing construction as a beam or plate element. This research is part of an effort to encourage the implementation of hardwoods, especially beech, in load-bearing building structures.

EXPERIMENTAL

Materials

Veneer preparation

In this study LVL and RLVL panels were formed using 2.3-mm-thick constructive beech (*Fagus sylvatica* L.) veneers, produced by peeling (rotary-cut veneers), and at the moisture content of 7±1%, manufactured by "Simpo ŠIK", Kuršumlija, located in the south part of Serbia. The veneer was produced using beech wood sourced from local forests, with an oven-dry density of about 680 kg/m³. All full sheets were free of defects and veneers were cut to dimensions of approximately 1300 x 850 x 2.3 mm.

Adhesives

Two types of adhesives were selected in this study: phenol-formaldehyde adhesive (PF) BOROFEN B-407/L produced by FENOLIT Ltd., Slovenia and one-component polyurethane adhesive (PUR) LOCKTITE® HB S509 Purbond® produced by Henkel & Cie AG, Germany. The both adhesives fulfill the requirements of corresponding standards

EN 301 (2023) and EN 15425 (2023). In adhesive selection, among mechanical strength, other aspects, such as ecological, energy consumption in production process, adhesive price, labor cost, and productivity, should be considered. The reasons to choose these two adhesives for research were because PF glue already has been widely used in the production of commercial LVL, and the application of PUR adhesive in load-bearing constructions has already been proved in products, such as Glue Laminated Timber (Glulam) or Cross-Laminated Timber (CLT), so the idea was to test the possibility of using this glue in LVL and RLVL production. The main characteristics for both types of adhesives used in this study, together with assembly and curing conditions in the production of LVL, are shown in Table 1.

Table 1. Adhesive Characteristics, Assembly and Curing Conditions

	BOROFEN B-407/L FENOLIT Ltd., Slovenia	**LOCKTITE® HB S509 Purbond Henkel & Cie AG, Germany**
Base	Phenolic liquid	Polyurethane
Component	1 component	1 component
Adhesive color	reddish brown	beige
Joint color	reddish brown	transparent
Assembly time	10 min	50 min
Curing time*	18 min + 10 min cooling to 65 °C	125 min
Curing conditions*	135 °C to 140 °C / cooling under pressure to 65 °C	20 °C / 65% relative AH 12% wood moisture
Curing pressure	2 MPa	2 MPa
Storage after bonding	24 h	24 h
Solid content	48.2% (3g / 1 h / 135 °C)	100 %
Density	1.11 to 1.15 g/mL (at 25 °C)	1.1 g/mL
Application weight	180 g/m^2	180 g/m^2
Gel time	34 min	-
Free formaldehyde	0.09%	-
*Pressing regime with cooling stage under pressure was established by authors		

Carbon fiber fabric

The reinforcement utilized in this study was the unidirectional “plain-weave” type of knitting carbon fiber (MapeWrap C UNI-AX 300/40). Main technical properties are presented in Table 2.

Table 2. Carbon Fiber Fabric Technical Properties

Technical Properties Carbon Fiber Fabric	**MapeWrap C UNI-AX 300**
Mass (g/m^2):	300
Density (kg/m^3):	1800
Equivalent thickness of dry fabric (mm):	0.164
Load resistant area per unit of width (mm^2/m):	164.3
Tensile strength (MPa)	≥ 4900
Tensile modulus of elasticity (N/mm^2):	252,000±2%
Elongation at breakage (%):	≥ 2

Methods

LVL and RLVL production

According to the experimental design, six beech nine-layer LVL boards with a nominal thickness of 20 mm and dimension 1300 x 850 mm were produced in industrial conditions. In each set, for each adhesive, two types of reinforced LVL boards and one type of non-reinforced LVL boards were formed (Fig. 1). The panels were reinforced with carbon fabric, produced in 400 mm wide strips. A reinforced layer was formed by placing two strips side by side, with the carbon fibers running parallel to the grain direction of the outer veneer.

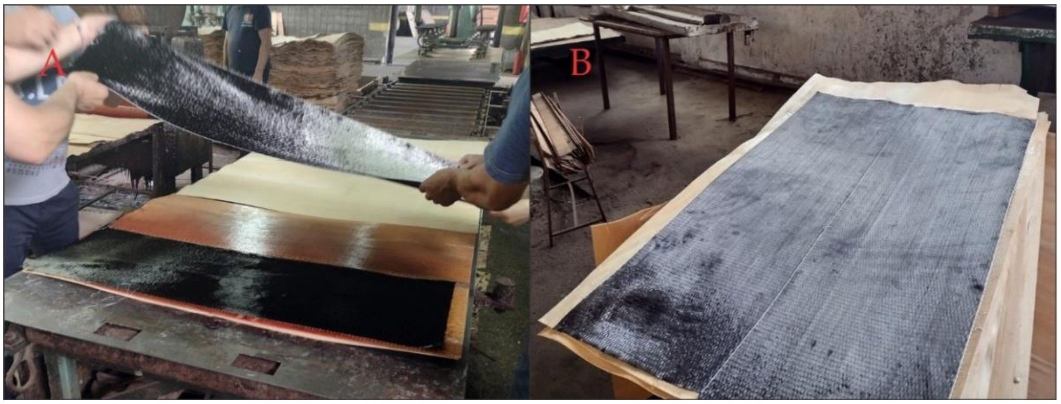

Fig. 1. Veneer and carbon fiber fabric assembly in LVL construction: A - construction assembly of LVL glued with PF adhesive, B- construction assembly of LVL glued with PUR adhesive

All panels were produced as nine-layer panels with veneer sheets, eight oriented in the longitudinal direction, and the central one oriented perpendicular to core layers.

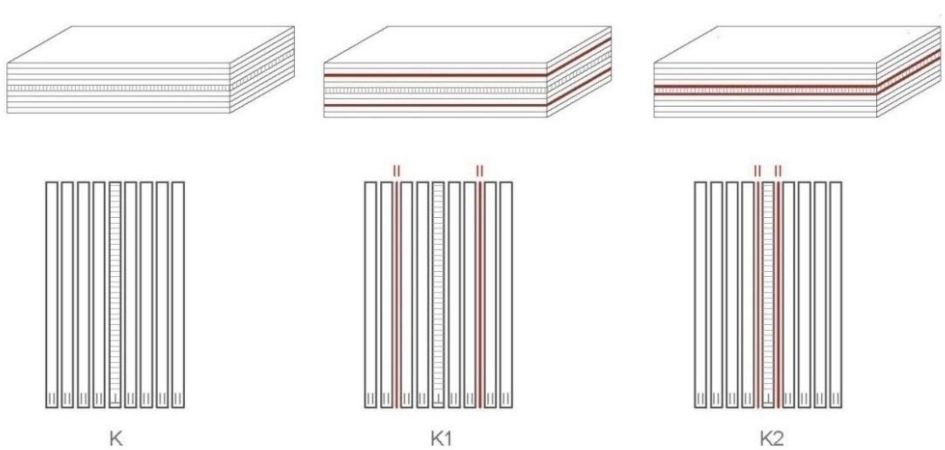

Fig. 2. Schematic representation of control and reinforced LVL panels

Figure 2 shows the construction of panels through cross-section with the position of reinforcement between the veneer layers and its orientation:

- Control (K) – unreinforced panels, *i.e.*, control reference samples;
- Combination 1 (K1) – reinforcement placed in the second and seventh glueline, parallel oriented as outer veneer grain (S2‖7‖);
- Combination 2 (K2) – reinforcement placed in the fourth and fifth glueline, parallel oriented as outer veneer grain (S4‖5‖).

Considering the cross-section's symmetry, the fabrics are placed in both reinforced combinations. Two types of adhesives were used: PF adhesive (FK, FK1, FK2 panels) and PUR adhesive (PK, PK1, PK2 panels).

In the PF adhesive combination, the application weight was 180 g/m^2 per one side of the veneer, applied by an industrial contact roller spreader. The roller spreader applies adhesive on both sides of the veneer sheet simultaneously. Target amount was controlled by doctor rollers, and it was within specifications. Three LVL boards (control FK, reinforced FK1 and FK2) glued with PF adhesive were hot pressed under the two-stage pressing regime, including heating, curing at a high temperature of 135 to 140 °C, and cooling under pressure to approximately 65°C. The specific pressure was 2 MPa, pressing time under temperature of 135 to 140 °C was 18 min, and the water-cooling stage under pressure to 65 °C was 10 min. The cooling stage under pressure is not very common in LVL production, but it was introduced to prevent high-pressure steam from forming in the gluelines near the carbon fiber fabric, which could form blisters in the gluelines.

The other three LVL boards with PUR adhesive were cold-pressed in the industrial multi-daylight press Filli Pagnonni, Monza, Italy, at approximately 25°C (indoor temperature at the time of the experiment). As in the case of the PF adhesive combination, the adhesive application weight was 180 g/m^2 per one side of veneer, applied by hand with a spatula. Therefore, as with PF adhesive, all three boards were pressed together in the same press daylight. The specific pressure was the same as in the case of PF adhesive, 2 MPa, but the curing time was 135 min, as the adhesive manufacturer prescribed.

It was of great importance that all three boards were pressed all together in the same press daylight, so the pressing conditions for all three combinations of LVL (control FK, reinforced FK1 and FK2 for PF adhesive, and control PK, reinforced PK1 and PK2 for PUR adhesive) was the same. It was introduced to minimize experimental error among LVL combinations for the same adhesive.

All LVL boards were conditioned in the laboratory climate of approximately 20±1 °C and 65±5% relative humidity for 45 days before cutting the test sample.

Physical properties of LVL

For the main physical properties testing, including density of LVL, moisture content (MC), thickness swelling, and thickness shrinkage, 30 pcs 5x5 cm^2 samples were cut from each LVL panel. The density (ρ) of LVL panels was determined according to ISO 13061-2 (2014) and MC according to EN 322 (2023). After cutting, 30 samples per each combination were weighed on a 0.01 g scale so that their dimensions were measured with an accuracy of 0.01 mm. After that, samples were oven-dried at 103±2 °C to a constant mass, for density and MC calculations. To simulate the maximum swelling and shrinkage of LVL (from fiber saturation point to absolutely dry condition), the samples were first dried in oven-dry condition (at 103±2 °C). After that, samples were conditioned in sealed containers over water to achieve 100% RH for six weeks until their mass stabilized, and the total Volumetric Swelling (VSw) was calculated. Then, the samples were oven dried again at 103±2 °C until their mass stabilized. Thus, the total Volumetric Shrinking (VS) was calculated.

Flexural properties in edgewise and flatwise bending parallel to the grain testing procedure

Both physical and flexural properties in edgewise and flatwise bending of LVL parallel to the grain were tested at the University of Belgrade, Faculty of Forestry – Wood

Science and Technology Department, Chair of Primary Wood Processing laboratory for veneers and plywood on their equipment.

Bending strength modulus of rupture (MOR) and modulus of elasticity (MOE) in bending assessments were performed in both the edgewise and flatwise orientations parallel to the grain, using a three-point bending configuration, as shown in Fig. 3. Before the testing phase, all sample specimens underwent conditioning in a climatic chamber set at a temperature of 20 ± 1°C and a relative humidity of 65 ± 5% for six weeks. For PF adhesive type, 14 samples measuring 520x30xt mm^3 were prepared for both MOR and MOE tests within each group (in total of 84 prismatic samples). For PUR adhesive type, at least 10 samples measuring 520x30xt mm^3 were prepared for both MOR and MOE tests within each group (in total of 56 prismatic samples). The difference in the number of samples is due to the dimensions of the LVL boards, but in both cases it was more than was prescribed by the standards.

The bending test was performed on a machine "Wood Tester WT-4", to test the mechanical properties of wood and wood-based products. The maximum force capacity of the machine is 40 kN. The edgewise bending tests were carried out in accordance with the requirements of the standards EN 14374 (2012) and EN 408 (2014). The flatwise bending tests were carried out in accordance with the requirements of the standard EN 310 (2016). The testing procedure was modified into a 3-point bending test due to the capabilities of the equipment regarding maximum force that can be achieved.

In accordance with the standards, the samples were tested as beams subjected to a single concentrated force applied at the middle of the span. The test protocol diverged from the standard by applying the load using a three-point static bending test instead of the prescribed four-point static bending test (on thirds of the span), which is shown in Fig. 3. In the edgewise bending test, 84 prismatic samples were evaluated, each having cross-sectional dimensions of approximately 30 mm with a tolerance of ±1 mm, and the span between support points was set at 450 mm. The standard specifies the range between support points as l=18h±3h as illustrated in Fig. 3.

For the flatwise bending (Fig.3) test, a total of 56 prismatic samples with cross-sectional dimensions of 40 mm were tested, and the span between support points was 400 mm. The deflection was measured at the midpoint of the beam utilizing an inductive deflection meter. The modulus of elasticity was determined using a probe designed specifically for testing elasticity modulus. The testing continued until failure, with a controlled displacement speed of 4.0 mm/min, leading to reaching the maximum force within a specified interval of 300 ± 120 s, in accordance with the standard.

This method is much simpler, less demanding than direct measurement, and it is accurate enough to determine relative relationships between treatments (combinations). The MOR and MOE were calculated using the following formulas,

$$f_{\mathrm{m}}=\frac{3F_{\max}l_1}{2bt^2} \tag{1}$$

Where f_m is the bending strength (N/mm^2), F_{max} is the maximum load (N), l_1 is the distance between the centres of the supports (mm), b is the width of the test piece (mm), and t is the thickness of the test piece (mm).

$$E_{\mathrm{m}}=\frac{l_1^3(F_2\text{-}F_1)}{4bt^3(a_2\text{-}a_1)} \tag{2}$$

In Eq. 2, E_m is the modulus of elasticity (N/mm^2), F_2 is approximately 40% of the maximum load (N), F_1 is approximately 10% of the maximum load (N), a_2 is deflection at the mid-length of the test piece corresponding to F_2 (mm), and a_1 is deflection at the mid-length of the test piece corresponding to F_1 (mm).

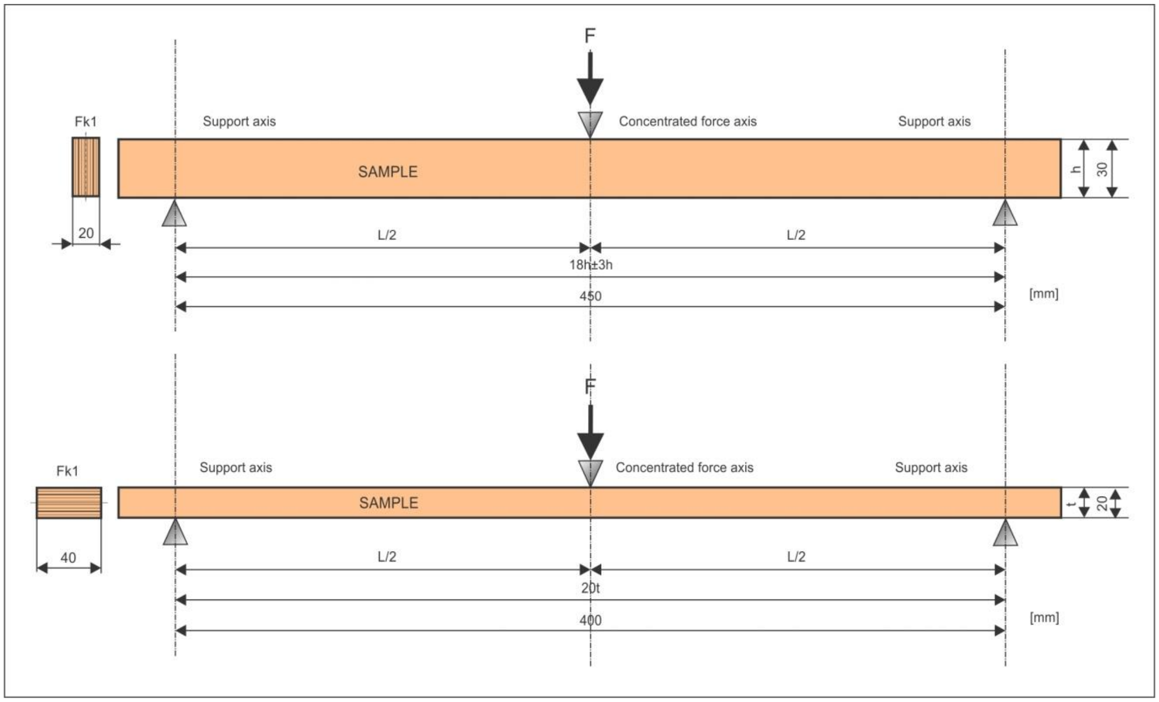

Fig. 3. Schematic of the setup for the edgewise bending test (SRPS EN 4082014) and flatwise bending test (SRPS EN 3101993)-both modified into 3-point bending

Data on the maximum force, modulus of elasticity, and maximum deflection were gathered using the "Console" acquisition system, with a recording frequency of 0.1 s. Subsequently, the failure mode was documented after the completion of tests. Figure 4 illustrates the procedure for conducting tests on one sample in both edgewise and flatwise bending configurations.

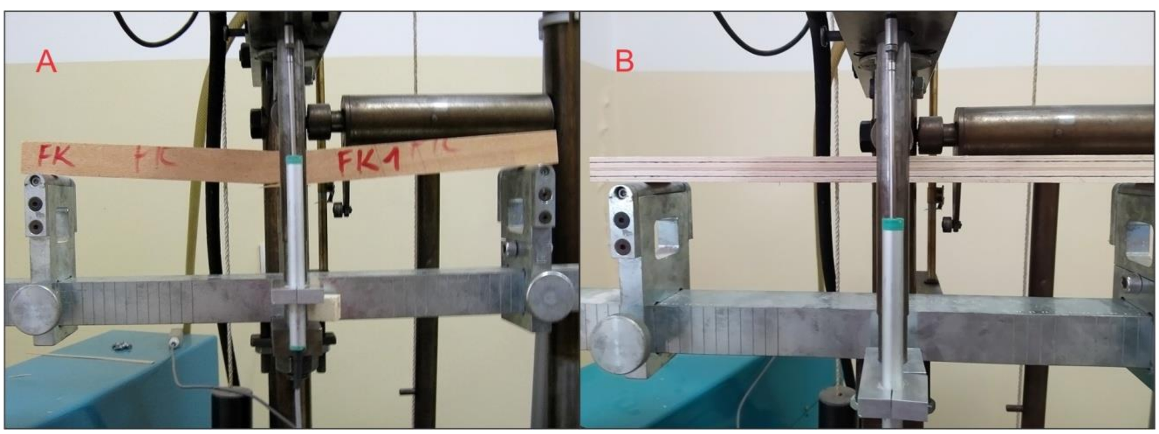

Fig. 4. Testing was conducted for bending strength and modulus of elasticity in both edgewise (A) and flatwise (B) bending configurations

Statistical Analysis

Data obtained from the laboratory experiments were analyzed using the SPSS 20.0 statistical package (IBM Corporation, Armonk, NY, USA). The values of the factor effects of reinforcing material were determined using the analysis of variance (ANOVA) procedure (Fisher's Least Significant Difference (LSD test)), and the differences in the means were accepted at a significance of $p < 0.05$.

RESULTS AND DISCUSSION

Physical Properties of LVL and RLVL

Moisture content and density

Based on the test results, the average MC and ρ values of LVL and RLVL are given in Table 3. An increase in MC and ρ was observed for all RLVL samples compared to the control LVL. The PF adhesive analysis showed an increasing percentage of MC for 9.16% and 12.99% and ρ_0 for 6.96% and 5.05% for FK1 and FK2 relative to FK, respectively. Observing the results obtained from PUR adhesive, MC and ρ_0 of panel PK2 increased 2.31% and 2.75%, respectively, relative to PK, while for panel PK1, MC decreased 3.86% and ρ_0 increased 3.44% relative to PK. According to these findings, MC and density change significantly for each reinforced category relative to the control sample. A greater density increase was expected due to the carbon fibers fabric influence.

The ANOVA analysis showed significance in RLVL density relative to the control samples. However, there was no significance between FK1 and FK2 samples and the PK1 and PK2 samples. The significant difference between MC values for FK and PK samples is a consequence of the adhesive nature. The PF glue is a water-based adhesive that influenced the moisture increase in the FK samples, *i.e.*, because of the additional water inserted into gluelines with adhesive.

Table 3. Panel Moisture Content (MC) and Density (ρ)

Type	MC_c (%)	SD (%)	COV (%)	ρ_c (g/cm^3)	SD (g/cm^3)	COV (%)	ρ_0 (g/cm^3)	SD (g/cm^3)	COV (%)
F_K	9.93^a	0.39	3.9	0.794^a	0.007	0.94	0.732^a	0.009	1.22
F_{K1}	10.84^b	0.39	3.63	0.852^b	0.019	2.2	0.783^b	0.019	2.45
F_{K2}	11.22^c	0.28	2.54	0.849^b	0.02	2.35	0.769^b	0.018	2.34
P_K	7.77^d	0.37	4.82	0.769^c	0.012	1.56	0.725^c	0.013	1.75
P_{K1}	7.47^e	0.27	3.65	0.797^a	0.012	1.55	0.750^a	0.011	1.44
P_{K2}	7.95^f	0.29	3.68	0.792^a	0.020	2.48	0.745^a	0.018	2.47

LEGEND	
F_K - phenol-formaldehyde (PF) adhesive, control F_{K1}- PF adhesive, CFRP in outer layers F_{K2}- PF adhesive, CFRP in the middle layer P_K - polyurethane adhesive (PUR), control P_{K1}- PUR adhesive, CFRP in outer layers P_{K2}- PUR adhesive, CFRP in the middle layer	MC_c – Moisture content (conditioned) MC_o – Moisture content (oven dry) ρ_c – LVL panel density (conditioned) ρ_0 – LVL panel density (oven dry) SD – standard deviation COV – coefficient of variation

*Means in the same column with the same superscripts are not significantly different at p<0.05

Swelling and shrinking

The dimensional changes accompanying the shrinking and swelling of LVL are major sources of visual and structural problems. In volumetric swelling and shrinkage of

LVL and RLVL analysis the mean values, standard deviations (SD), and coefficient of variation (COV) were calculated, as shown in Table 4.

For both adhesives, VSw increased in comparison to control samples of LVL. VSw of RLVL glued with PF resin was 11.25% (FK1) and 9.53% (FK2) greater than VSw of control LVL, and 23.62% (PK1), 17.63% (PK2) for PUR adhesive samples. Similar results were obtained by Wang *et al.* (2024), who concluded that due to the more densified structure of RLVL, and with the same initial panel thickness, an increased expansion of these panels occurs during the swelling process.

RLVL samples exhibited greater volumetric swelling than the control samples, due to the increased permeability of the carbon layers compared to the gluelines. This indicates that, despite the use of waterproof adhesive, RLVL may still be sensitive to direct moisture and water exposure during service. This could be solved with proper surface protection against moisture.

Table 4. Volumetric Swelling and Shrinkage

Volumetric Swelling (from 0% MC to FSP)					Volumetric Shrinkage (from FSP to 0% MC)			
Type	**VSw (%)**	**INC** (%)**	**SD (%)**	**COV (%)**	**VS (%)**	**INC** (%)**	**SD (%)**	**COV (%)**
F_K	6.989[a]	-	0.831	11.886	6.647[a]	-	1.449	21.800
F_{K1}	7.775[b]	↑11.24	1.157	14.884	7.108[a]	↑6.93	1.578	22.200
F_{K2}	7.655[b]	↑9.53	1.172	15.308	5.695[b]	↓14.32	1.272	22.334
P_K	7.899[b]	-	1.191	15.078	6.776[a]	-	1.293	19.087
P_{K1}	9.765[c]	↑23.62	1.278	13.084	6.231[a]	↓6.25	1.194	19.161
P_{K2}	9.292[c]	↑17.63	1.208	13.001	8.644[c]	↑30.04	0.987	11.415

*Means in the same column with the same superscripts are not significantly different at $p<0.05$
** increment and decrement to the control sample

Note that this represents the worst case, which will never realistically happen because neither FSP nor 0% MC will not be reached. The LVL is dried to 0% MC for the same starting point. In reality, swelling and shrinkage will only be a small part of the above-calculated values, especially if the EWP is well protected after installation.

Bending Behavior and Failure Mode

Bending behavior and failure mode edgewise

In Table 5, mean values, SD, and COV, of MOR and MOE for edgewise bending are listed.

Table 5. MOR and MOE in Edgewise Direction

TYPE	MOR (MPa)	INC** (%)	SD (MPa)	COV (%)	MOE (MPa)	INC** (%)	SD (MPa)	COV (%)
F_K	124.80[a]	-	3.53	2.83	12361.78[a]	-	346.76	2.81
F_{K1}	139.08[b]	↑11.44	3.86	2.78	14850.44[b]	↑20.13	673.88	4.54
F_{K2}	138.46[b]	↑10.94	4.45	3.21	14577.42[b]	↑17.92	606.43	4.16
P_K	120.68[c]	-	3.28	2.72	11741.84[c]	-	338.87	2.89
P_{K1}	119.76[c]	↓0.76	6.83	5.70	12045.85[c]	↑2.58	382.46	3.18
P_{K2}	127.84[a]	↑5.93	5.02	3.93	12436.54[a]	↑5.91	390.99	3.14

*Means in the same column with the same superscripts are not significantly different at $p<0.05$
** increment and decrement to the control sample

Samples FK1 exhibited MOR and MOE values considerably greater than the control sample FK by approximately 11.5% and 20%, respectively. The improvement in the MOR and MOE ratios for sample FK2 was similar to the above. Samples where PUR adhesive was applied had a significantly lower percentage of improvement relative to control PK samples, which was near to 6% for PK2 samples. The ANOVA analysis showed significant difference between control samples (FK and PK) in MOR and MOE both between adhesives and reinforced samples. There was no significant difference in ANOVA analysis between the FK1 and FK2 samples. The same was true for the PK and PK1 samples.

All samples bonded with both PF adhesive and PUR adhesive throughout the testing process exhibited good performance during the edgewise bending tests. Within each adhesive group, all reinforced samples demonstrated comparable behavior during the bending tests. Unreinforced samples, regardless of the testing direction, were destroyed due to exceeding the tensile strength in the tensile zone (typified as tension). The typical destruction of samples in an edge configuration was a slow degradation of wood in the compressed zone (typified as compression), combined with the rupture of wooden fibers in the tensile zone (tension) in the final phase of loading. The critical state was signaled visually through the wrinkling surfaces in the compressed zone and acoustically in the form of cracking sounds. In the CFRP layers no delamination was observed for any adhesive or combination. A typical beam fracture for the FK1 combination is shown in Fig. 5.

In the edgewise direction, the failure modes for control samples were almost identical for both adhesives, with no delamination of veneer layers or shear failures. Destruction usually resulted from a single crack encompassing a few layers of veneers in the tension zone. Figure 5 (B) shows load-deflection diagrams for all tested samples in combination FK1. The diagram generally depicts a linear trend followed by plastic behavior, which is ultimately interrupted by failure. The samples of combination FK1 show a certain ductile behavior. The plastic flow of samples, the zone of the non-linear diagram trend, is interrupted by a fracture in the tensioned cross-section zone.

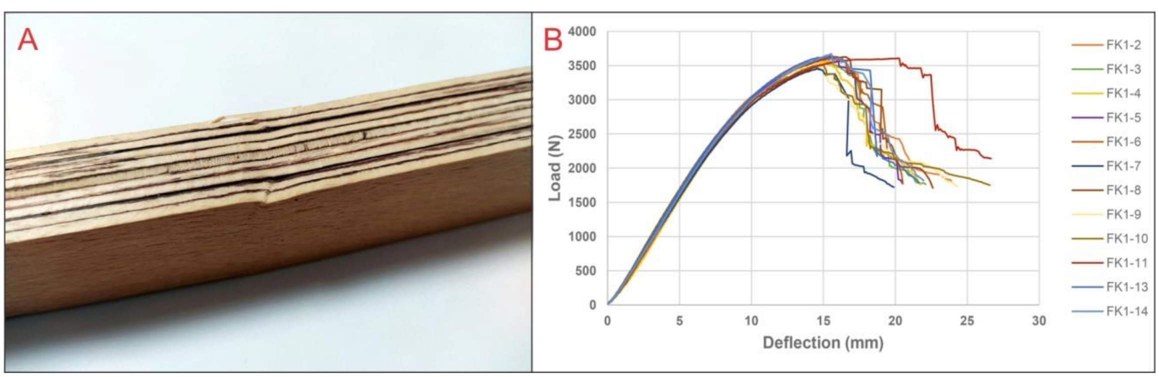

Fig. 5. An example of a failure mode in the edgewise bending of a RLVL bonded by PF adhesive is FK1 – view from above (A) and load-deflection diagrams for edgewise bending of FK1 samples group (B)

Bending behavior and failure mode flatwise

In the case of flatwise bending, RLVL samples of PF adhesives did not express significant difference in MOR values, in contrast to MOE values, where the difference was significant. The MOE values were significantly higher in the RLVL samples, especially at FK1 combination, a 17.5% increase compared to control samples. Reinforcement enhanced the lateral resistance, so MOE was the highest of all combinations and was significant. There was no significant difference in control samples (FK and PK) neither in MOR or in MOE between adhesives, indicating that the manufacturing procedures for both adhesives were performed correctly.

Table 6. MOR and MOE in Flatwise Direction

TYPE	MOR (MPa)	SD	INC** (%)	COV (%)	MOE (MPa)	INC** (%)	SD	COV (%)
F_K	139.56^a	5.65	-	4.05	13808.94^a	-	740.27	5.36
F_{K1}	140.87^a	6.32	↑0.94	4.48	16221.67^b	↑17.47	565.71	3.49
F_{K2}	141.99^a	9.50	↑1.74	6.69	14592.69^c	↑5.67	556.05	3.81
P_K	132.65^a	10.19	-	7.68	13478.10^a	-	604.34	4.48
P_{K1}	79.33^b	5.82	↓40.19	7.33	11102.65^d	↓17.62	893.82	8.05
P_{K2}	78.75^b	5.31	↓40.63	6.74	11171.45^d	↓17.11	966.68	8.65

*Means in the same column with the same superscripts are not significantly different at p<0.05
**increment and decrement to the control sample

In the flatwise direction, Figs. 6 and 7 provide the various failure mechanisms for reinforced samples for PF and PUR adhesives. The failure modes for control samples were almost the same for both adhesives, with no delamination of veneer layers or shear failures and with brittle fracture in the tensioned section zone.

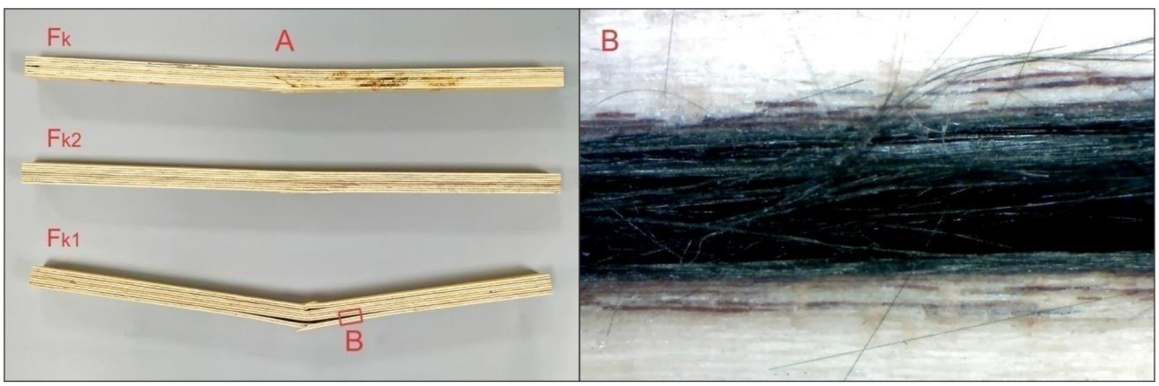

Fig. 6. A-Failure modes of control (Fk) and reinforced samples (Fk1, Fk2) bonded by PF adhesive in flatwise bending; B- breaking up of CFRP material (200 x magnifications)

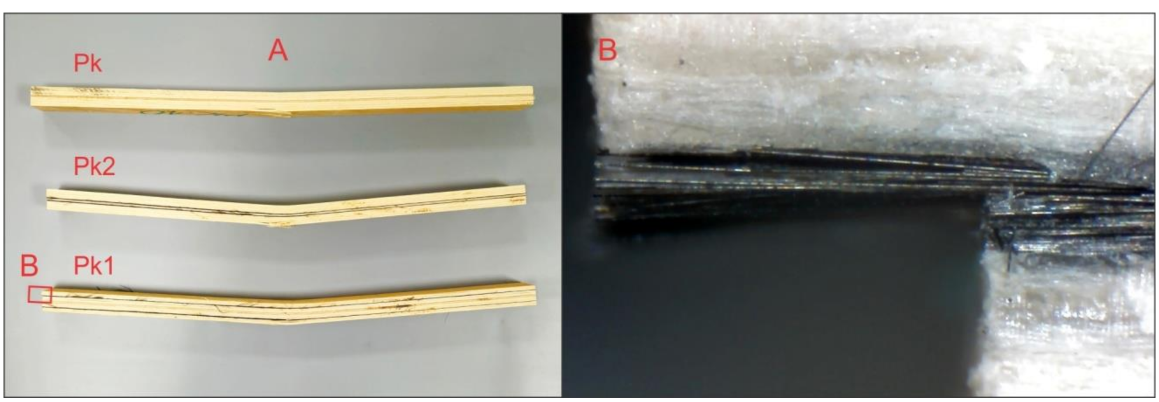

Fig. 7. A-Failure modes of control (Pk) and reinforced samples (Pk1, Pk2) bonded by PUR adhesive in flatwise bending; B- shear failure of CFRP material (200 x magnifications)

A load-deflection diagram for control samples (Fig. 8) shows brittle behavior during flatwise bending, especially for PF adhesive. Unlike PF adhesive, samples with PUR adhesive have noticeable landing zones and plastic behavior. For PUR adhesive, at reinforced samples, the net-tension mode showed little lateral resistance of CFRP (Fig. 7). Shear failure of CFRP material contributed to significantly lower strengths and MOE of PK1 and PK2 combinations, compared to appropriate combinations bonded with PF adhesive (FK1 and FK2). The ANOVA test showed significant differences between PF adhesive control samples (PK) and reinforced samples (PK1 and PK2), while reinforced samples were the same.

The load-deflection diagram of the FK1 samples (Fig. 9 A) shows a distinctly linear elastic behavior until almost maximum force value, followed by plasticization, which is not the expected behavior for a RLVL. Observing all diagrams, it can be concluded that the FK1 combination has the greatest engineering potential, especially for load-bearing structures. In these samples, almost the maximum force value was reached by the linear trend of the diagram, and the yield in force was close to the ultimate force. Samples of the FK2 combination (Fig. 10 A) exhibited high force values and ultimate strength, but unlike FK1, they showed part of the plastic curve, and values of yield force were significantly lower. Reinforced samples bonded with PUR adhesive (Fig. 9 A and Fig. 10 B) showed expressed ductile behavior. After failure and force reduction, these graphics continued to exhibit flow in the plastic behavior zone until complete failure. This means the veneers in the tensioned zone, under the carbon reinforcement, after sheer failure, continued to accept the load until failure happened.

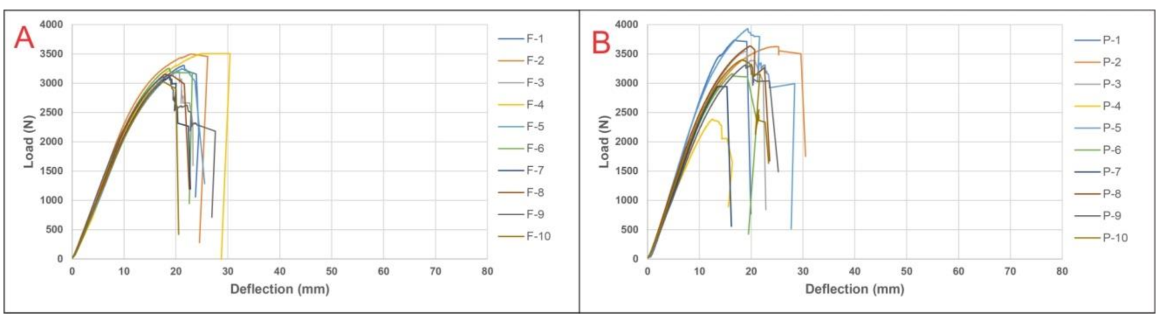

Fig. 8. Load-deflection diagrams designed for flatwise bending of FK (A) and PK (B) control samples

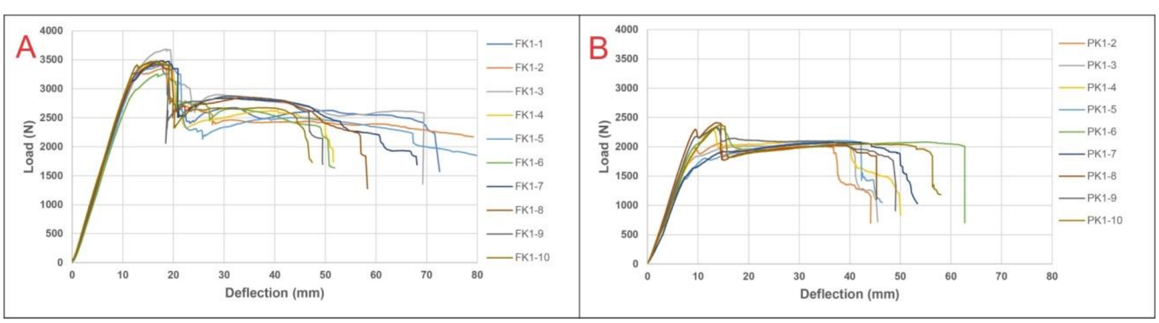

Fig. 9. Load-deflection diagrams designed for flatwise bending of FK1 (A) and PK1 (B) samples

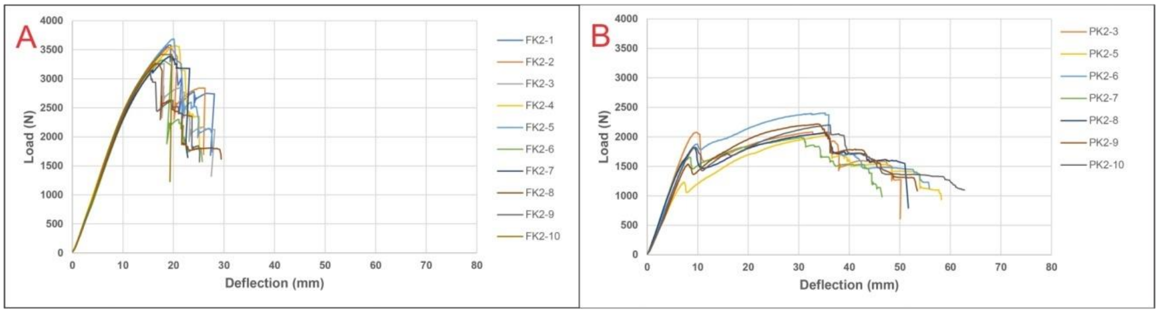

Fig. 10. Load-deflection diagrams designed for flatwise bending of FK2 (A) and PK2 (B) samples

The nature of the glue could explain the important difference between behavior of samples bonded with PF and PUR adhesive. Namely, PF glue is water-based, and its lower viscosity and higher pressing temperature contributed to better wetting of the carbon fibers, so the CFRP mat was deeply glued. In contrast, PUR adhesive is more viscous, so the wetting of the carbon fibers was not as deep, and CFRP behaved as a separate, laterally weak layer.

For those reasons, in general, CFRP in the edgewise direction improved the strength of both adhesives, while in the flatwise direction, in the case of PUR adhesive, the strength was weakened.

Load-Bearing Capacity

The comparative analysis of values obtained in experimental testing of LVL and RLVL mechanical properties are shown in Fig. 11 for edgewise bending and Fig. 12 for flatwise bending tests. Considering samples bonded with PF, compared to non-reinforced samples, those in the edgewise direction exhibited greater values of bending strength and MOE, while in the flatwise direction, carbon reinforcement did not affect the increase of MOR; the value difference was negligible. A significant increase of flatwise MOE was noticeable for FK1 samples, where the CFRP layers were positioned symmetrically in the outer layers of the LVL cross section (between the second and third veneer layer and between the seventh and eighth veneer layer). Observing results for samples bonded with PUR adhesive, CFRP did not significantly affect the improvement of flexural strength, even more so in flatwise direction values, which were incomparably lower for reinforced samples, which was the consequence of shear failure. As with MOR, MOE values did not significantly improve. The PF adhesive generally provided stronger bonds between the veneer and the CFRP, resulting in the above values. This research confirmed the statement of the previous research (Bal and Bektaş 2012) that the best improvement of MOE and bending properties of beech RLVL is achieved by applying PF adhesive.

Observing the position of reinforcement in the construction of the LVL board, the value differences between K1 and K2 samples were not particularly significant, which in most cases was confirmed by the ANOVA tests. For edgewise bending this was the expected result, as the amount of reinforcement was equal and its position in the tension zone had no significant influence. The ANOVA analysis showed a significant difference between PK1 and PK2 (PUR adhesive) for both MOE and MOR at an edgewise direction, which, based on previous explanations, was not the expected result. Also, a significant difference was shown between FK1 and FK2 for MOE in a flatwise direction. This finding aligns with existing literature (Brezović *et al.* 2002; Lui *et al.* 2019), which indicates that placing reinforcement further from the neutral axis leads to a modest increase in the modulus of elasticity. This reinforcement positioning would typically be expected to yield improved MOR; however, this was not the case in the FK1 samples. Based on the above, this research cannot fully confirm statements from the literature. However, the reinforcement K1, placed closer to the outer layers for PF adhesive, showed slightly better results.

The direction of further research would be to examine other properties, such as tensile strength, shear strength, and compressive strength of RLVL. Research will be particularly focused on FK1 type of construction (glued with PF glue), because the results showed that this combination proved to be the best. The expectation is that this data would be the basis for computer models for calculating more complex but lighter and more reliable load-bearing structures, made of composite wood, compared to existing ones.

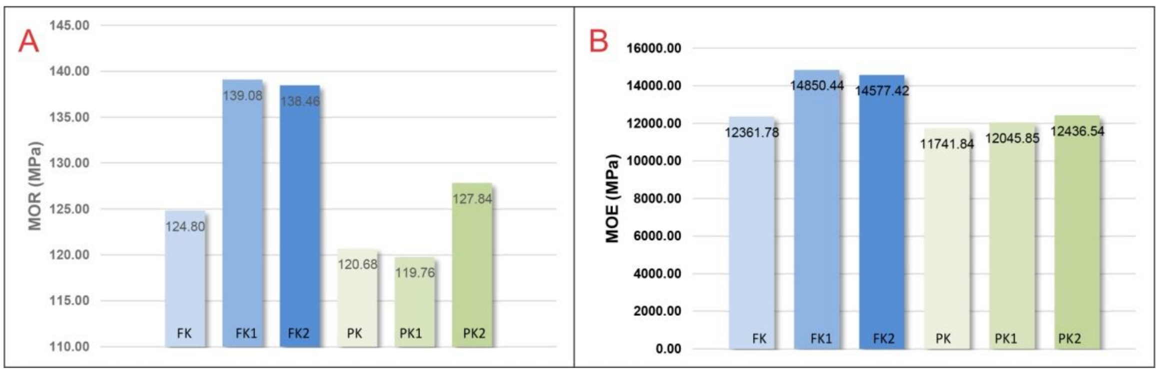

Fig. 11. Diagram of values MOR (A) and MOE (B) at edgewise bending test

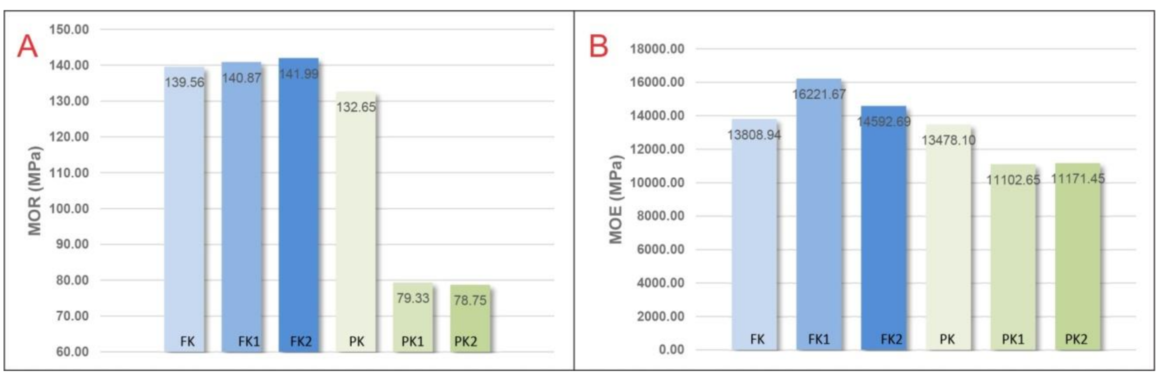

Fig. 12. Diagram of values MOR (A) and MOE (B) at flatwise bending test

In perspective, in full-size production of RLVL each structural element must be carefully designed and dimensioned. Structural elements are intended to be reusable, and the presence of reinforcement should not limit their reusability. The carbon layer, in combination with the adhesive, acts as reinforcement, preventing stress concentration around the holes during service. On the other hand, the presence of carbon layers makes machining process difficult, as have been observed during samples preparation. Consequently, the inclusion of reinforcement must be planned and specified in advance. Furthermore, depending on the specific requirements of the structure, each element must be precisely engineered, particularly concerning the position and orientation of the reinforcement within the cross-section.

CONCLUSIONS

This research defined some physical and mechanical properties using European beech (*Fagus sylvatica* L.) to produce LVL reinforced with CFRP fabric intended for load-bearing structures. To bring the results of this research closer to practical application, instead of a laboratory experiment, an experiment in controlled industrial conditions was chosen, together with widely used industrial adhesives.

1. The moisture content (MC) and density of reinforced laminated veneer lumber (RLVL) increased more compared to LVL. This was influenced by the adhesives used, the addition of carbon fiber fabric, as well as the position of the reinforcement in the panel. A greater change was noticeable in reinforced phenol formaldehyde (PF) samples, while these changes were not significant for polyurethane (PUR) samples. Volumetric swelling was greater for RLVL samples compared to control ones, because water penetrated more easily through the carbon layers than through gluelines. This suggests that RLVL could be sensitive to direct contact with water in operation even if the adhesive is waterproof.
2. The modulus of rupture (MOR) and modulus of elasticity (MOE) values mostly increased in RLVL samples relative to control samples, except for the PK1 sample in the edgewise direction and the PUR samples in the flatwise direction. This increase is greater in the edgewise direction, and a higher percentage of reinforcement observed at PF adhesive samples. The PUR adhesive samples in a flatwise direction had a reduction of MOE, which is an undesirable and unexpected result, caused by interlaminar shear in the carbon fiber reinforced polymer (CFRP) layer.
3. Considering all observed aspects, including MOR, MOE, failure modes, and small differences in ANOVA statistics, it can be concluded that the FK1 combination showed the best prospects for potential application in load-bearing structures.
4. At reinforced samples bonded with PUR adhesive (PK1 and PK2) after sheer failure and force reduction in the flatwise bending test, veneers in the tensioned zone, under the carbon reinforcement, continued to accept the load until failure.
5. The PF adhesive proved to be good for bonding in the FRP-wood layer and for adhesion in the wood-wood layer. The RLVL beams manufactured using PF adhesive can be used as structural load-bearing elements.

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