Original scientific paper

UDK 666.972:[661.666:620.179
DOI 10.7251/COMEN2501046Z

ADHESIVE TYPE INFLUENCE ON THE COMPRESSIVE STRENGTH OF BEECH LVL REINFORCED WITH CARBON FIBER FABRIC

Vladislav Zdravković[1*], Aleksandar Lovrić[1], Neda M. Sokolović[2], Nenad Šekularac[2]

[1] Faculty of Forestry, Wood Science and Technology Department, University of Belgrade, Serbia
[2] Faculty of Architecture, Department of Architectural Technologies, University of Belgrade, Serbia

[*] Corresponding author: vladislav.zdravkovic@sfb.bg.ac.rs

Summary: In this research, nine-layer reinforced laminated veneer lumber (RLVL) was produced using beech veneer by inserting woven carbon fibers between the veneer sheets. Panels were made in industrial conditions with two types of adhesives - phenol-formaldehyde (PF) and polyurethane adhesive (PUR). The research aims to determine the influence of adhesives on the compressive strength in two directions of beech LVL reinforced with woven carbon fibers and its potential for use in load-bearing building structures. The experimental data was verified by the ANOVA model. Reinforced LVL produced using PF adhesive was stronger than those produced using PUR adhesive by 17.88% in longitudinal direction and by 31.89% in transverse direction. This research is part of an effort to encourage the implementation of hardwoods, especially beech, as renewable and ecologically sustainable material with long term use in load-bearing building structures.

Keywords: beech laminated veneer lumber, CFRP, reinforcement, polyurethane adhesive, phenol-formaldehyde adhesive, compressive strength.

1. INTRODUCTION

Due to climate change and the lack of quality wood [1] , hardwood species are becoming increasingly important. Ozarska [2] presented the possibilities of using hardwoods in producing LVL (Laminated Veneer Lumber). The results of some researches [3–7] have shown the suitability of using hardwoods in the production of 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, researches has been focused on lower quality, small-diameter logs in the production of LVL. In some studies, the combined beech-poplar LVL was investigated [8] and in the others poplar LVL reinforced with carbon fabric [8] .

The lower prevalence of the use of hardwood for load-bearing structures in Europe is also reflected in the regulations. European Standard EN 1995-1-1 (Eurocode 5) [10] gives definitions, classification and specifies the requirements for LVL (EN 14374 : 2004 [11] and EN 14279 : 2004 + A1: 2009 [12]. It is referenced in the European harmonized standard for wood-based panel products EN 13986: 2004 +A1:2015 [13]. Eurocode 5 defines strength classes for softwood timber [14] (EN 338:2016) and numerical values for partial factors and other reliability parameters recommended as basic values that provide an acceptable level of reliability. However, for hardwoods, strength classes and other requirements are not defined in this way, and they should be determined separately through unique documents for each wood species or product.

For instance, in that sense, in correspondence to EU Regulation No 305/2011 European Technical Assessment ETA-14/0354 of 20.02.2015 [15], applies to the glued laminated timber, which is composed of structural laminated lumber (LVL) lamellae of beech (Fagus sylvatica L.). Lamella conforms to EN 14374 [11]. Adhesives used for LVL are adhesives type I according to EN 301[16] or adhesives type I according to EN 15425 [17] and EN 14080:2016 [18].

Reinforcement with FRP can also have a significant impact on technically better-quality hardwood. This way, exceptional mechanical properties of veneer-based products for structural applications can be achieved. Some research on the LVL and reinforcement of birch LVL were made. Töpler and Kuhlmann [20] tested in-plane buckling behaviour of columns made of beech. Study of the influence of three different types of wood: beech, poplar and eucalyptus and different types of adhesives urea-formaldehyde (UF), melamine-urea formaldehyde (MUF), and phenol formaldehyde (PF) adhesives on the mechanical properties of LVL panels showed the best bending properties and the greatest model elasticity for LVL panels formed from beech veneer and PF adhesive [21]. Study of the effects of glass and carbon fiber on mechanical properties of LVL composite produced from using heat-treated beech veneer and phenol formaldehyde (PF) adhesive showed that carbon fibers are more effective on the module of rupture (MOR) and module of elasticity (MOE), while glass fiber on compressive strength parallel to the grain (CS) and bonding strength parallel to the grain (SS) values [22]. Percin and Altunok [23] tested some mechanical properties of LVL produced from heat-treated beech veneer and concluded that carbon fibers significantly affected some physical and mechanical properties of LVL.

Veneer-based panels have significant applications in construction as planar or linear elements. For linear elements, their use as beam elements is particularly noteworthy, as they are exposed to bending within the plane or act as columns. LVL columns in architecture can be formed from surface elements either as a single-piece element or, due to their small thickness which affects in-plane buckling, as a multipart cross-section. The primary load these elements bear is axial stress in the direction of the fibers, typically manifested as compressive force. For LVL boards to be suitable for these purposes, they must exhibit both good compressive strength and resistance to in-plane buckling. In architecture, veneer-based planar elements are also utilized in reciprocal constructions or surface-active structures, such as folds or shells [24]. In such structures, it is essential for the continuity of structural elements to be maintained in two directions, and these elements must possess good resistance to compression, tension, and shear [25]. The elements forming these structures must have membrane potential, meaning they are subjected to stresses parallel to the surface itself. It is especially important for shells and folds that the surface elements exhibit strong resistance to both compression and tension within the plane of the plate, in both directions. This ensures that the load is distributed across the surface in two directions and subsequently transferred to adjacent structural elements [26]. These structures, due to their geometry, accommodate axial and shear forces in the plane of the plate forces parallel to the edge of the plate, which are transferred to other elements through shear at the contact of adjacent surfaces.

2. MATERIALS

2.1. Veneer Preparation

In this study, constructive beech (*Fagus silvatica L.*) veneers, produced by peeling (rotary-cut veneers) 2.3 mm thick and at the humidity of 7±1%, manufactured by "Simpo ŠIK", Kuršumlija, Serbia, were selected for the formation of LVL panels. All full sheets and free of defects, veneers were cut to dimensions of approx.1300x850x2.3 mm.

2.2. 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. Both adhesives fulfill requirements of corresponding standards EN 301 *Adhesives, phenolic and aminoplastics, for load-bearing timber structures – Classification and performance requirements* [16] and EN 15425 *Adhesives, One component polyurethane for load-bearing timber structures – Classification and performance requirements[17]*. PF adhesive fulfill the requirements in terms formaldehyde emission (at least class E1 according EN 717-1 classification) [19].

2.3. Woven Carbon Fiber

The unidirectional "plain-weave" type of knitting carbon fiber, MapeWrap C UNI-AX 300/40", weighing around 300 g/m^2, was used as reinforcement. The physical and mechanical properties of the CFRP fabric are shown in Table 1.

Table 1. *Physical and mechanical properties of MapeWrap C UNI-AX 300*

Technical properties	MapeWrap C UNI-AX 300
Mass (g/m²):	300
Density (kg/m³):	1800
Equivalent thickness of dry fabric (mm):	0.164
Load resistant area per unit of width (mm²/m):	164.3
Tensile strength (MPa)	≥ 4900
Maximum load per unit of width (kN/m):	-

3. METHODS

3.1. RLVL Production

According to experimental design, six beech nine-layer LVL boards, the 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 (Figure 1).

All panels were produced as nine-layer panels with veneer sheets, eight oriented in the longitudinal direction, and the central one was oriented perpendicular to outer layers. Reinforcements were placed between the veneer layers according to the following scheme, as shown in Figure 2.

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. Reinforced LVL F_{K1} with PF adhesive was hot pressed under the two-stage pressing regime, including heating, curing at a high temperature of 135°C-140°C and cooling under pressure to approx. 65°C. The specific

Figure 1. *RLVL construction assembly for PF adhesive combination (F_{k1})*

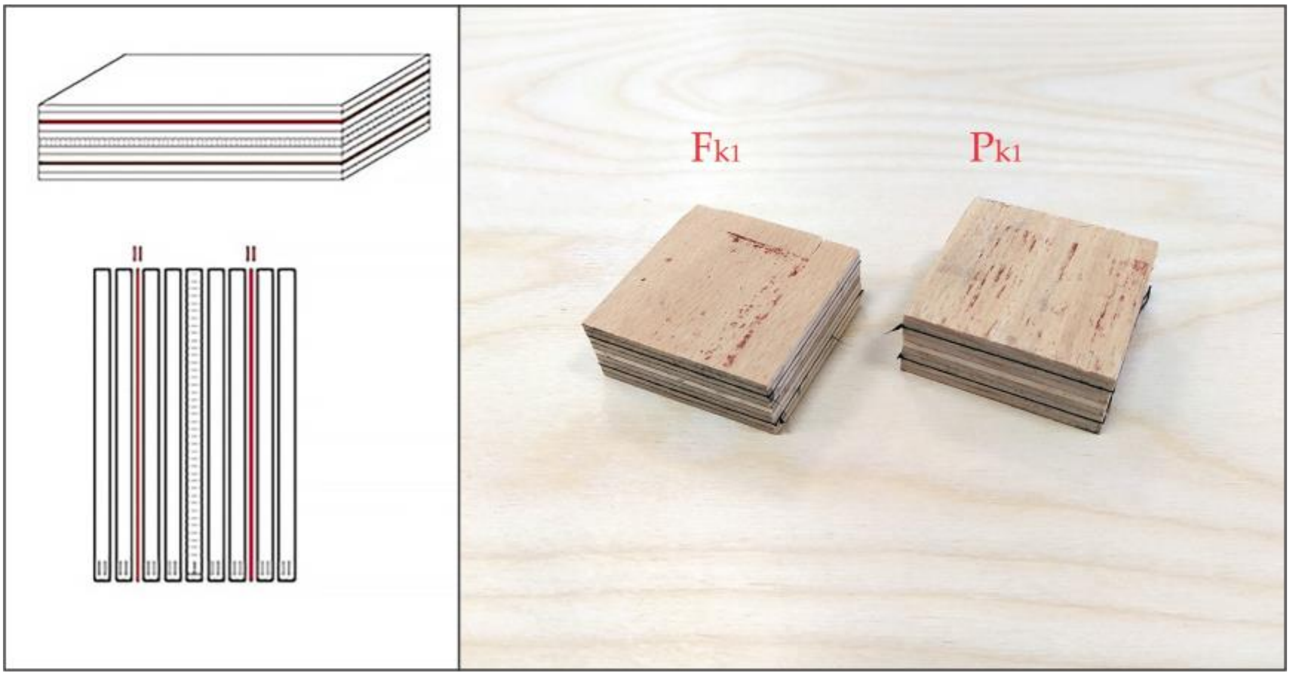

Figure 2. *Left: Schematic of combination (K_I) – reinforcement placed in the second and seventh glueline, parallel oriented as outer veneers (S2‖S7‖); Right: Sample glued with PF glue (F_{kI}) and sample glued with PUR glue (P_{kI})*

pressure was 2MPa, pressing time under temperature of 135°C-140°C was 18min, and the water-cooling stage under pressure to 65°C was 10min. The cooling stage under pressure is not very common in LVL production, but it was introduced to prevent high-pressure steam forming in the gluelines near the carbon mesh, which could form blisters (some kind of failure-splitting) in the gluelines.

The second LVL panel with PUR adhesive was cold pressed in the industrial multi-daylight press *Filli Pagnonni, Monza, Italy,* at aprox. 25°C (it was the 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 spatula. 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.

3.2. Compressive Strength

Compressive strength testing was performed according to the SRPS CEN/TS 14966:2010 protocol [27] , on a computer-guided machine for testing the mechanical properties of wood and wood-based products "Wood Tester WT-4", with a maximum force capacity of 40 kN (Fig. 3). Samples with dimensions of 20x20x50 mm for compressive strength were prepared for each group and each adhesive. There were four groups of samples, 13 samples in each group. All test samples were conditioned in a climatic room at 20 ± 1 °C and 65 ± 5% relative humidity prior to the tests.

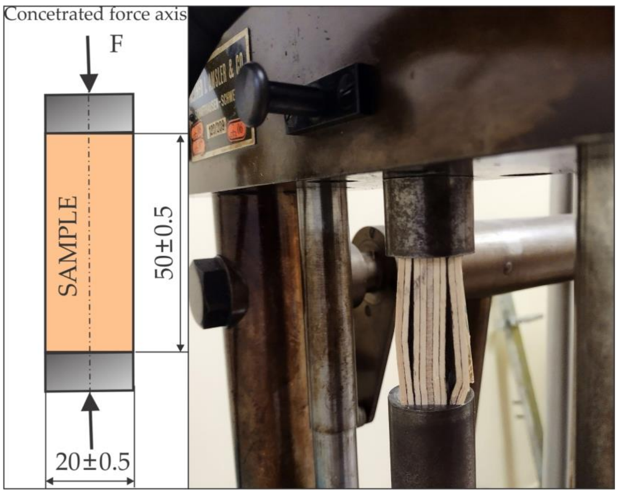

Figure 3. *Left: Compressive Strength Sample according SRPS CEN/TS 14966:2010;*
Right: Sample on the computer-guided testing machine

4. RESULTS AND DISCUSSION

4.1. Compressive Strength

Following the SRPS CEN/TS 14966:2010 protocol, compressive strength and the main statistics has been calculated as shows Table 2. The values of the factor effects 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 $p<0.05$. The ANOVA model showed significance both in relation to the type of applied adhesive and in relation to the force direction. PF adhesive showed higher compressive strengths than PUR adhesive by 17.88% in longitudinal direction and by 31.89% in transverse direction in average. No less important are significantly lower coefficients of variation in the case of PF adhesive compared to PUR adhesive, which could cause more reliable calculations in the models for building structures design.

Table 2. *Compressive strength and main statistics*

Compressive strength (MPa) SRPS CEN/TS 14966:2010				
TYPE	**No (pcs)**	**Mean (MPa)**	**SD (Mpa)**	**KOV (%)**
F_{K1}L	12	**72.88**	2.02	2.77
F_{K1}C	13	**22.85**	1.69	7.39
P_{K1}L	13	**61.82**	3.96	6.41
P_{K1}C	13	**17.32**	2.40	13.85
LEGEND				
F_{K1}L- RLVL sample Lengthwise, PF adhesive F_{K1}C- RLVL sample Crosswise, PF adhesive P_{K1}L- RLVL sample Lengthwise, PUR adhesive P_{K1}C- RLVL sample Crosswise, PUR adhesive No - number of samples SD - standard deviation KOV - coefficient of variation				

Structures must be made of construction materials and products defined in the Eurocodes or their harmonized standards or in other harmonized technical specifications. The mechanical properties of structural LVL are determined according to the harmonized product standard EN 14374 [11]. New European strength classes defined by Federation of the Finnish Woodworking Industries [28] are shown in Table 3. Strength classes for LVL-P without crossband veneers, for structural LVL made of spruce or pine the most relevant class is LVL 48 P for beam applications. LVL 32 P is suitable for stud applications where mechanical property requirements are lower.

Strength class LVL 80 P refers to beech hardwood LVL. Compressive strengths for both adhesives are significantly higher than what is prescribed. Compressive strength for PF adhesive parallel to grain was 72.88 MPa while strength class LVL 80 P prescribes 69 MPa (Table 3), for service class 1. On the same way, compressive strength for PUR adhesive parallel to grain was 61.82 MPa while strength class LVL 80 P prescribes 57 MPa, but for service class 2, according to EN 1995-1-1.

Service class 1 (SC1) is characterized by a moisture content of the materials corresponding to a temperature of 20 °C and the relative humidity of the surrounding air only exceeding 65% for a few weeks per year. This corresponds typically to heated indoor air conditions. In service class 1 the average

moisture content (MC) of softwood LVL is usually between 6 and 10%. The MC of most solid woods is in those conditions some higher, but will not exceed 12% [29].

Service class 2 (SC2) is characterized by a moisture content of the materials corresponding to a temperature of 20 °C and the relative humidity of the surrounding air only exceeding 85% for a few weeks per year. This corresponds to ventilated outdoor conditions under a roof protecting from direct weather exposure. In service class 2 the average moisture content of softwood LVL is usually between 10 and 16%, but will not exceed 20% [29].

Similar results were obtained in the research of Percin and Altunok [23]. They have got slightly higher strength of five-layer RLVL for PF and PUR adhesive of 82.19 Mpa and 76.45 Mpa respectively, but the veneers were twice as thick and carbon was inserted between all veneer layers.

Prescribed compressive strength perpendicular to grain, edgewise, for strength class LVL 80 P is 14 MPa. In this direction compressive strength for PF adhesive was 22.85 MPa and for PUR adhesive was 17.32 MPa, so the compressive strengths for both adhesives are higher than what is prescribed.

Table 3. *Strength classes for structural LVL-P without crossband veneers [28]*

Compression strength	Symbol	STRENGTH CLASS (MPa)				
		LVL 32 P	LVL 35 P	LVL 48 P	LVL 50 P	LVL 80 P*
Parallel to grain for service class 1	$f_{c,0,k}$	26	30	35	42	69
For service class 2 according to EN 1995-1-1	$f_{c,0,k}$	21	25	29	35	57
Perpendicular to grain, edgewise	$f_{c,90,edge,k}$	4	6	6	8,5	14
Perpendicular to grain, flatwise (except pine)	$f_{c,90,flat,k}$	0,8	2,2	2,2	3,5	12
Perpendicular to grain, flatwise, pine	$f_{c,90,flat,k,pine}$	MDV*	3,3	3,3	3,5	-

*Strength class LVL 80 P refers to beech hardwood LVL.
*Strength class is expressed as individual manufacturer´s declared value (MDV).

4.2. Failure Mode

The most common failure modes are illustrated in Figure 4. RLVL samples produced using PF adhesive ($F_{K1}L$ and $F_{K1}C$) were more compact than RLVL samples produced using PUR adhesive ($P_{K1}L$ and $P_{K1}C$).

The sample $F_{K1}L$ had a typical compression fracture with no visible separation in the carbon layer. The sample $F_{K1}C$ had crushing, and splitting failure with slight splitting in the carbon layer in the final phase of loading.

On the other hand, RLVL samples produced using PUR adhesive showed different behavior. Samples $P_{K1}L$ had splitting in the wood-adhesive-wood phase as so in carbon layer in the final sequence of loading.

In the final sequence of loading, since separation in carbon layer has occurred, fracture in the carbon-free veneer layers followed, due to buckling of the veneers ($F_{K1}C$, $P_{K1}L$ and $P_{K1}C$ samples).

In the transverse direction also there was definitely some influence of veneer lathe checks which caused stress concentrations.

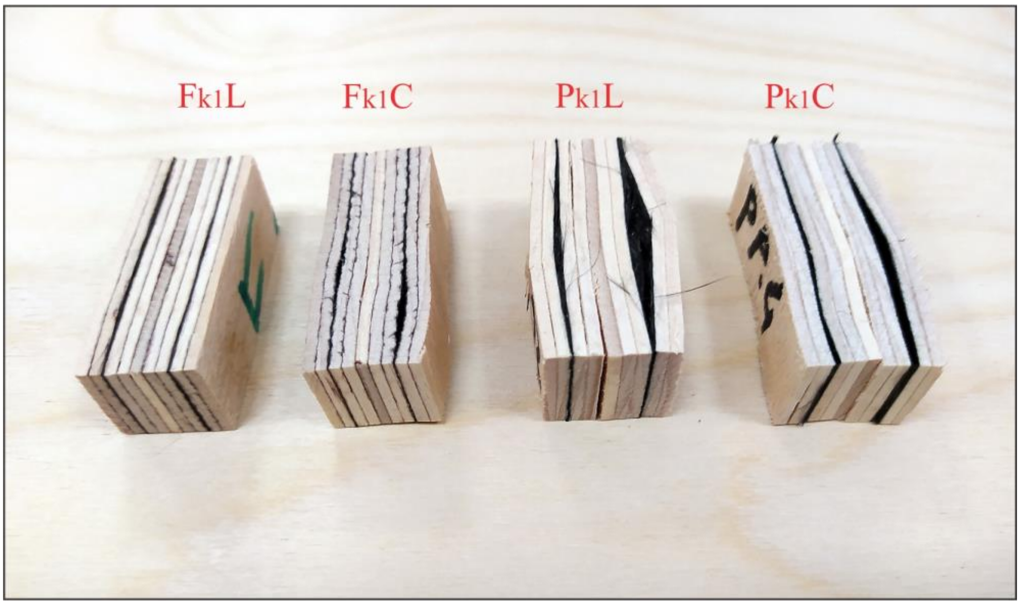

Figure 4. *Common failure modes for all types of samples*

4.3. Load Bearing Capacity

The comparative analysis of compressive strength values obtained in experimental testing of RLVL produced using PF and PUR adhesive for longitudinal and transverse direction is shown in Figure 5.

Observing the direction of applied force, average compressive strength of $F_{K1}L$ samples was 72.88 MPa while average compressive strength of $F_{K1}C$ was 22.85 MPa what gives the ratio approximately 3.2/1. In the case of PUR adhesive average compressive strength of $P_{K1}L$ samples was 61.82 MPa while average compressive strength of $P_{K1}C$ was 17.32 MPa what gives the ratio approximately 3.6/1.

Observing the type of adhesive, RLVL produced using PF adhesive was stronger than those produced using PUR adhesive by 17.88% in longitudinal direction and by 31.89% in transverse direction.

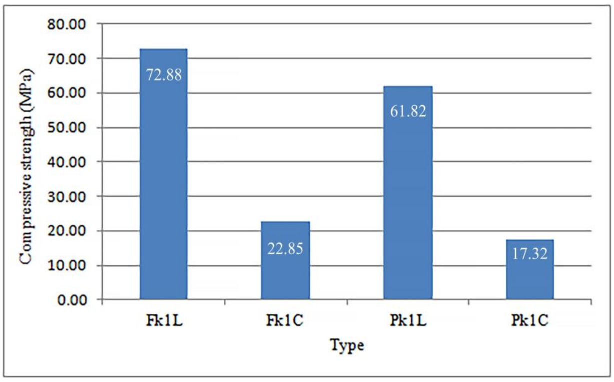

Figure 5. *Diagram of compressive strength values for all types of samples*

3.4. Adhesive Selection

Mechanical strength is not the only criterion in the choice of adhesive. From the point of view of LVL producer, other aspects such as ecological, energy consumption in production process, adhesive price, labor cost and productivity should be considered.

Polymerization of PF adhesive takes place at high temperatures (140°C and more) which requires a greater amount of energy, the adhesive must fulfill the requirements in terms formaldehyde emission (atleast class E1 according EN 717-1 classification). Despite of that PF adhesive is still a better choice for large scale production of LVL than some others.

On the other hand PUR adhesive, as cold setting adhesive, can be interesting in the design of smaller residential buildings. It is even suitable for gluing some elements on the construction site, so it could be combined with prefabricated RLVL produced using PF adhesive, which would make easier to design more complex building constructions.

5. CONCLUSIONS

It was obvious from experimental results, that PF adhesive provided better results compared to PUR adhesive. RLVL produced using PF adhesive was stronger than those produced using PUR adhesive by 17.88% in longitudinal direction and by 31.89% in transverse direction.

Considering compressive strength, both adhesives meet the highest requirements of EN 14374 and European strength classes standard for beech LVL defined as LVL 80 P class. Consequently, this means that both adhesives can be used in load-bearing building structures.

Beside of higher compressive strengths in both directions, RLVL produced using PF adhesive showed smaller coefficients of variation than RLVL produced using PUR adhesive, which might means more reliable calculations with smaller cross-sections in building structures.

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 application of PUR adhesive in load-bearing constructions already has been proved in products such as Glue Laminated Timber (Glulam) or Cross Laminated Timber (CLT), but there are some opportunities in LVL or RLVL production. In architectural design, this research indicates the possibility of combining prefabricated RLVL or LVL elements glued using PF adhesive and assembling them later using PUR adhesive in order to obtain larger and more complex sections.

Acknowledgments: This research was supported by the University of Belgrade, Faculty of Forestry – Wood Science and Technology Department, chair of primary wood processing, laboratory for veneers and plywood; University of Belgrade, Faculty of Architecture; We specially would like to thank Simpo ŠIK Kuršumlija, Serbia for veneer and technical support in LVL production; Piramida d.o.o Sremska Mitrovica, Serbia; and Mapei SRB d.o.o Beograd for carbon mesh for testing.

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УТИЦАЈ ВРСТЕ ЛЕПКА НА ПРИТИСНУ ЧВРСТОЋУ БУКОВОГ ЛВЛ-а ОЈАЧАНОГ КАРБОНСКОМ ТКАНИНОМ

Сажетак: У овом истраживању деветослојна ојачана ламелирана фурнирска грађа (РЛВЛ) произведена је коришћењем буковог фурнира, уметањем карбонске тканине између листова фурнира. Плоче су израђене у индустријским условима са две врсте лепка: фенол-формалдехидним (ПФ) и полиуретанским лепком (ПУР).

Истраживање има за циљ да утврди утицај лепкова на чврстоћу на притисак у два правца буковог ЛВЛ-а ојачаног карбонском тканином и његов потенцијал за примену у носивим грађевинским конструкцијама. Експериментални подаци верификовани су АНОВА моделом. Ојачани ЛВЛ произведен коришћењем ПФ лепка био је јачи од оног произведеног коришћењем ПУР лепка за 17,88% у уздужном правцу и за 31,89% у попречном правцу. Ово истраживање део је настојања да се подстакне примена лишћара, посебно букве, као обновљивог и еколошки одрживог материјала за дуготрајну употребу у носивим грађевинским конструкцијама. Истраживање је показало да ојачани ЛВЛ произведем употребом обе врсте лепка у погледу притисне чврстоће испуњава захтеве Новог европског стандарда за ЛВЛ и да се може користити у носивим грађевинским конструкцијама.

Кључне речи: букова ламелирана фурнирска грађа, ЦФРП, арматура, полиуретански лепак, фенол-формалдехидни лепак, чврстоћа на притисак.

Paper received: 27 August 2024 **Paper accepted: 27 March 2025**