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ABSTRACT

In this study, carbon fibers were added as a reinforcement layer between wood veneers bonded with melamine-urea–formaldehyde (MUF) resin to improve properties of standard wood laminated composite. Two different fiber orientations were tested, being parallel and perpendicular to the veneers. In addition, two different locations were evaluated. Internal, surrounding the core veneer, and external, below the surface veneer. Flexural properties, water absorption, density, cutting force, and tensile shear strength were tested and evaluated. Results showed that reinforcing plywood panels with carbon fibers increased both MOR and MOE. The cutting force showed better results for composite panels with CF in a perpendicular orientation. Moreover, the water uptake and thickness swelling after 24 h showed better results for fibers in the core layer, either parallel or perpendicular.

1. Introduction

Wood and wood-based composites are widely applied in construction, furniture, decking, façades, etc. due to their excellent properties, their natural origin, and their appearance. Wood-based composites are often used in structural applications as alternative materials to solid wood, as they present better dimensional stability and durability. Among the most used wood-based composites are layered materials, such as plywood or laminated veneer lumber (LVL), which are layered composites with better strength properties than the raw material itself. In some applications, as a construction, wood-based materials are better than other engineered materials such as concrete, plastics, or steel, as a particularly important aspect is to meet the high requirements for strength properties at a relatively low weight. Several factors affect the properties of wood-based laminated composites; some of them come from the production technology (time, pressure, and press temperature). In contrast, others come from the raw material itself, e.g., wood species, veneer thickness, layers set up, and type of resin [1–3]. Fiber-reinforced polymers (FRP) are used to strengthen wood-based composites for such composites; the matrix is usually epoxy or phenol–formaldehyde resin. Fibrous FRP composites are responsible for the strength of the wood composite, while the adhesive acts as a stress transferor [4]. The three main types of fibers used in the polymer matrix include glass fibers, carbon fibers, and synthetic polymer fibers (such as Kevlar and aramid). In recent years, these fibers have been used for reinforcing LVL [5–9]. Reinforcement technology with fiber composites is an effective method for improving the mechanical properties of LVL made of low-quality wood. Therefore, reinforced LVL can be an alternative to high-quality solid wood [5]. A previous study by Bal et al. [7] tested some physical and mechanical properties of LVL reinforced with glass fibers using phenol–formaldehyde (PF) resin as the binder. The obtained results showed a significant increase in the shear strength value for reinforced LVL samples. Physical properties were also more favorable for reinforced LVL. In another work, it was found that plain weave carbon fiber to strengthen LVL produced from heat-treated (160, 190, 220 °C) beech veneers (*Fagus orientalis L.*) [10].

Carbon fiber can be divided into different types depending on the weave; these can be plain, satin, twill, harness, unidirectional or

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bidirectional, etc. Nevertheless, plain and satin weaves are the most commonly used for carbon fabrics and are preferred in many industries [11]. Among the most common adhesives used to bond CF, phenol–formaldehyde (PF) resin is one of the most used, as it improves the adhesion between carbon fibers and wood, and also contributes to reducing the water absorption [12]. However, due to the health risks involving the use of PF resins, epoxy resins have gained more popularity in the elaboration of carbon fiber composites [5,13,14].

Carbon fibers have low-density and superior tensile strength, modulus of elasticity, as well as fatigue properties [15]. For this reason, they have been used in diverse applications that require resistance to fatigue [16], carrying capacity of beams [5,17] thermal and sound insulation [12], among others. Analysis of selected physical and mechanical properties showed that the reinforcement of the composite had a positive effect on mechanical properties, increasing density, bending strength, modulus of rupture, and modulus of elasticity [10]. Another derivative, carbon fiber reinforced plastic composite sheets (CFRP) have shown that the value of flexural strength for beams reinforced with them is increased depending on the number of layers [18].

The present work is aimed to determine the effect of the addition of non-woven unidirectional carbon fibers between wood layers bonded with melamine-urea–formaldehyde (MUF) resin on selected mechanical and physical properties of the manufactured panels. For this, 5-layer plywood boards were produced reinforced with carbon fibers in the form of strands using two different arrangements. The final composites were compared to reference plywood manufactured according to industrially available technology with no addition of carbon fibers.

2. Experimental

2.1. Materials

2.1.1. Wood materials

Scots pine (*Pinus sylvestris* L.) veneers with a thickness of 1.7 mm and dimensions of 300 mm × 300 mm were used to produce the plywood panels. For tensile shear strength, lamellas of 300 mm × 130 mm × 5 mm were used. The veneers and lamellas were conditioned under normal conditions (20 ± 2 °C, 65 ± 5 RH %) for at least seven days.

2.1.2. Carbon fibers

Carbon fibers were obtained from carbon fabric, which consists of a strand of carbon fibers woven together from which individual fibers were separated. According to data provided by the manufacturer, tensile strength is of 4300 MPa, modulus of elasticity is 240 000 MPa, and the average density is 1.77 g cm^{-3}.

2.1.3. Adhesive

Melamine–urea–formaldehyde resin (MUF) was used as a binder as it is a common adhesive used in the plywood industry. A 30% water solution of ammonium sulfate $(NH_4)_2SO_4$ was applied as a hardener, and wheat flour was used as filler. The mass composition of the adhesive was as follows 100:10:16, resin, hardener water solution, and filler, respectively.

2.2. Methods

2.2.1. Manufacture of composite panels

The manufactured plywood panels consisted of five veneers with fiber orientation 0–90-0–90-0 and two layers of carbon fibers between them. The carbon fibers in a single layer were distributed evenly over the entire surface in an amount of 16.3 g m^{-2}. Four panels were made with two different orientation methods of the carbon fibers. In the first, fibers (310 mm long) were laid in parallel bands throughout the entire veneer. This way of arranging carbon fibers is referred to as "parallel". In the second case, the fibers were laid perpendicular to each other, with the same weight of fibers used for parallel and perpendicular bands. This way of arranging the fibers is referred to as "cross". Additionally, two forms of positioning carbon fibers were followed. External (E), in which carbon fibers were located near the surface veneers, and internal (I), in which carbon fibers were situated on both sides of the core veneer. The configuration of the different elaborated composite panels is shown in Table 1.

The adhesive spread was 220 g m^{-2} for veneer-veneer bonding and 440 g m^{-2} for veneer-carbon fibers bonding. In the case of veneer-carbon fiber, the higher amount of adhesive spread was due to the weaker adhesion of the adhesive resin to the carbon fibers compared to wood. The pressing of all samples was made with a ZUP-NYSA PH-1LP25 hydraulic press with a pressure of 1 MPa and a temperature of 120 °C during 400 s. The manufactured panels were conditioned under normal conditions (20 ± 2 °C, 65 ± 5% air humidity) for at least seven days.

2.2.2. Mechanical properties

The static bending strength (MOR) and modulus of elasticity (MOE) were tested based on the EN 310 standard [19]. The samples for this test were prepared to align the wood fiber course parallel to the long edge of the test specimen. Internal bonding was determined through the tensile test perpendicular to the surface of the board, according to EN 319 standard [20]. The analysis of screw withdrawal strength was done according to EN 320 standard [21]. All tests were done with an INSTRON 3369 universal testing machine and conducted at least ten times. The results of the determination of the physical and mechanical properties of plywood were statistically analyzed using Statistica version 13 (TIBCO Software Inc.). For significant differences between factors, analysis of variance (ANOVA) at a 0.05 significance level was used. A comparison of the means was performed by Tukey test, with 0.05 significance level.

2.2.3. Water absorption and thickness swelling

Thickness swelling and water absorption after 24 h of soaking in water were measured according to EN 317:1993[22]. Briefly, samples were soaked in distilled water at room temperature for 2 h and 24 h. Water uptake was calculated from the following equation (1):

$$WU = (m_f - -m_o)V_o^{-1} \quad (1)$$

Where WU is water uptake [mg mm^{-3}], m_o is the weight of the sample before soaking [g], and m_f is the weight of the sample after soaking [g]. Thickness swelling was calculated from the same samples with the following equation (2):

$$TS = (t_f - -t_o)\, t_o^{-1} \quad (2)$$

Where TS is the thickness swelling [mm mm^{-1}], t_o is the thickness of the sample before soaking [mm] and t_f is the thickness of the sample after soaking [mm].

2.2.4. Density

The density of plywood panels was measured according to EN 323 [23]. In addition, a density profile was recorded for each panel set. For this, samples of 50 mm × 50 mm were analyzed on a Grecon DA-X measuring instrument (Alfeld, Germany) with direct scanning X-ray densitometry across the sample thickness with an incremental step of 0.02 mm. Results correspond to the average of three scans.

2.2.5. Cutting force

The cutting force was determined during the milling of samples with dimensions 100 mm × 150 mm × 6 mm. The panels were placed in a measuring platform with a piezoelectric transducer (Kistler 9601), with an amplifier (Kistler 5036), and a data acquisition card (National Instruments PCI-6111). Measurements were made in the X- and Y-axes

Table 1
Composition of panel sets.

Panel set	Description	Construction[V-veneer, CF- carbon fibers]
RE	Reference plywood (industrial type)	V-V-V-V-V
PE	Parallel structure/ external system	V-CF-V-V-V-CF-V
PI	Parallel structure/ internal system	V-V-CF-V-CF-V-V
CE	Cross structure/ external system	V-CF-V-V-V-CF-V
CI	Cross structure/ internal system	V-V-CF-V-CF-V-V

with a frequency of 50 kHz. For the milling process, a single-blade mandrel head (Faba SA) with a cemented carbide blade was used (FTS-07.01) for formatting and rebating. The measurements were carried out at a spindle speed of 18000 rpm and a feed rate of 3.6 m min^{-1}. The milling process was carried out throughout the entire thickness of the composite panels. Recorded measurements were analyzed in LabVIEW software. The cutting force index was calculated from the following equations (3 and 4):

$$F = \left(RMS_X{}^2 + RM_Y{}^2\right)^{0.5} \quad (3)$$

$$CFI = F_{RE}F_n{}^{-1} \quad (4)$$

In which F_{RE} is the average resulting force of the reference sample, F_n is the average resulting force of each sample, and RMS is the root mean square of each axis.

2.2.6. Tensile shear strength

The tensile shear strength of lap joints was measured according to EN 205 standard [24]. For this, three different sets of panels with dimensions of 150 mm × 20 mm × 10 mm were prepared. The samples were pressed with a ZUP-NYSA PH-1LP25 hydraulic press under a pressure of 1 MPa with a temperature of 120 °C for 8 min. Eight test specimens were prepared for each sample; samples were pre-cut to the bonding line, to reach bonding line dimensions of 20 mm × 10 mm. The achieved results of shear strength and in-wood damage ratio were evaluated statistically by using Fisher exact test with probability level p = 0.05 to establish whether the average values reached are statistically equal.

3. Results and discussion

An increase of static bending strength was observed for all plywood made with the addition of carbon fibers compared to the unmodified plywood (RE) (Fig. 1). However, only in the case of PE, the increase in strength was significant. A similar dependence was observed for the modulus of elasticity. Compared to the modulus of elasticity obtained for unmodified plywood, only PE presented significant differences. The increase in strength of the plywood by the reinforcements of carbon fibers is consistent with the literature [5,25]. The MOR and MOE show that the panels elaborated with a parallel orientation had higher MOR and MOE than those made with the perpendicular orientation. Besides, a better reinforcement effect was obtained when carbon fibers were positioned near the external veneers for parallel orientation, while for perpendicular orientation, the higher values were obtained with fibers near the core veneer. While there is a clear trend in the reinforcement, the statistical analysis showed no significant improvement when placing the carbon fibers near the core veneer. These results are consistent with the findings of Liu et al. [25]. They showed that the strengthening of plywood with carbon fiber in the face layer is much more efficient than when the reinforcement is located in the core layer of the material. Moreover, Liu et al.

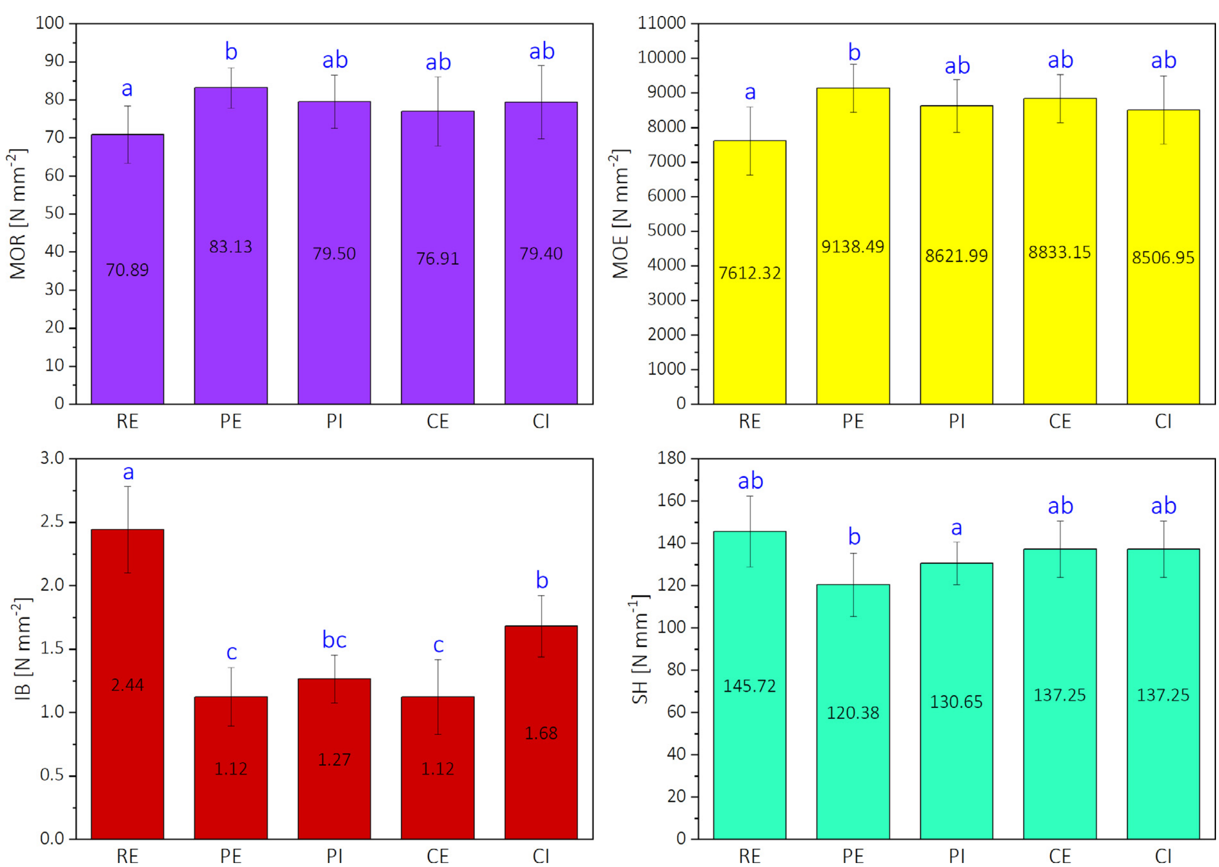

Fig. 1. Mechanical properties of tested plywood, abcd correspond to the homogeneous groups by Tukey test (α = 0.05).

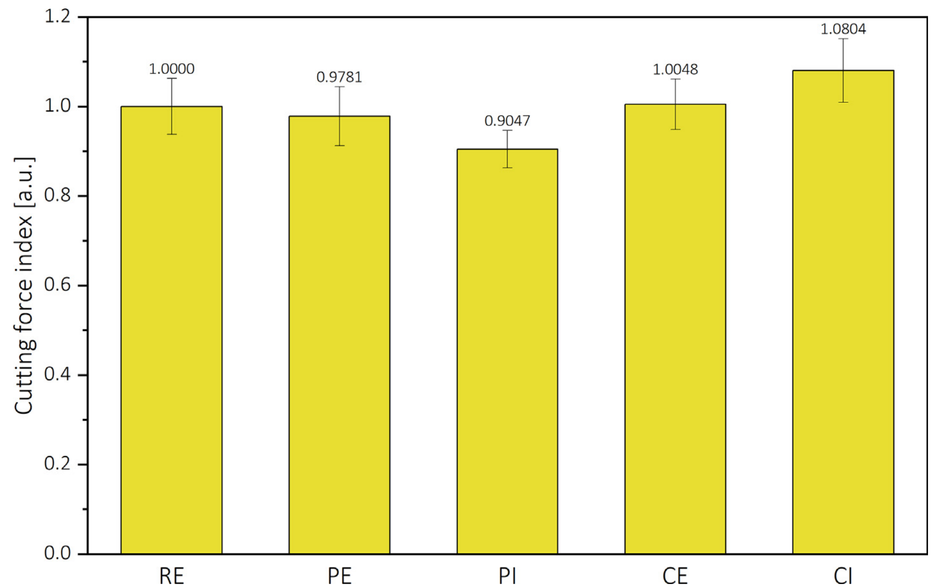

Fig. 2. Cutting force during milling.

[25] and Borysiuk et al. [26] report that composites reinforced in the face layer with carbon fiber and epoxy resin are characterized by an almost two-fold increase in strength concerning unreinforced materials. In the present study, in the case of plywood glued with MUF resin, only a 17% increase in MOR and a 20% increase in MOE for PE were recorded.

The internal bond test showed a significant decrease in bonding strength for all the panels made with carbon fibers compared to the reference. In terms of bonding resistance, CI had the lowest drop (≈31%) compared to RE, while the rest of the samples had a reduction of their bonding strength of ≈50%. Moreover, samples with CF near the core layer presented higher bonding strength than those with CF near the external layers, with a predominance of the perpendicular orientation over the parallel one. The lower bonding strength may be due to poor adhesion of MUF resin to the CF [25]. The effect of carbon fiber reinforcement on screw-holding (SH) capability is not significantly noticed for most of the samples; however, there was a decrease of the SH in all the samples containing CF. Moreover, PE was the only presenting significantly different values, which were, in any case, lower than RE.

The cutting force index (CFI) is a relative indicator of the force of samples to be cut; it is calculated by dividing the average cutting force by that of a reference (in this case, RE), so the reference sample will have a CFI of 1. Fig. 2 shows the CFI of the elaborated panels. It can be noticed that samples with parallel orientation had lower CFI than the reference, while samples with perpendicular orientation had higher; moreover, the lowest cutting force was that of PI, while the highest was CI. In terms of CFI, samples with CF in the external layer

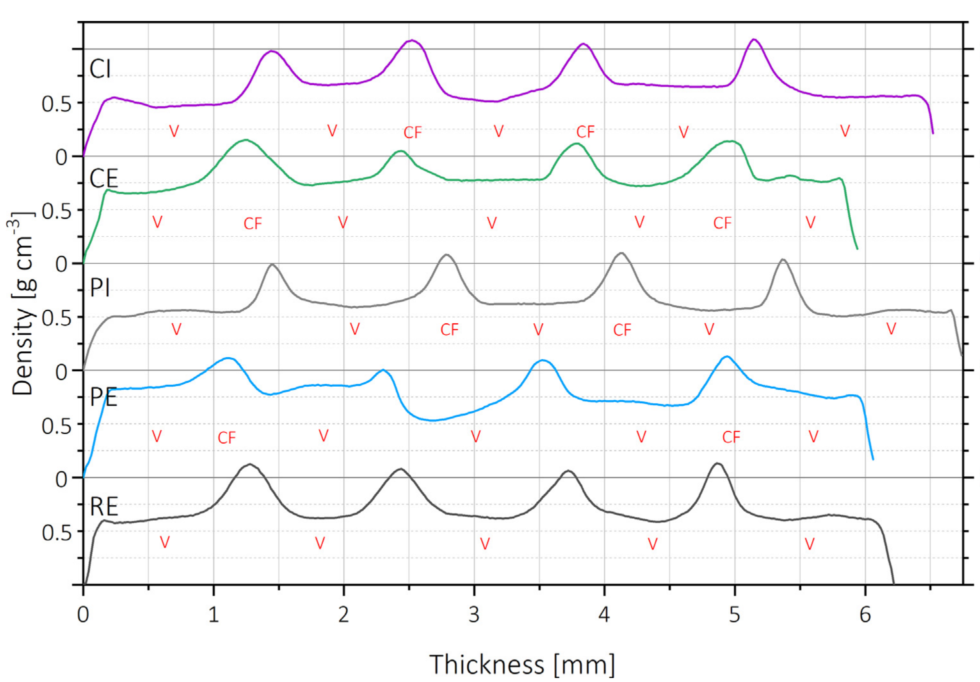

Fig. 3. Density profile of the composite panels.

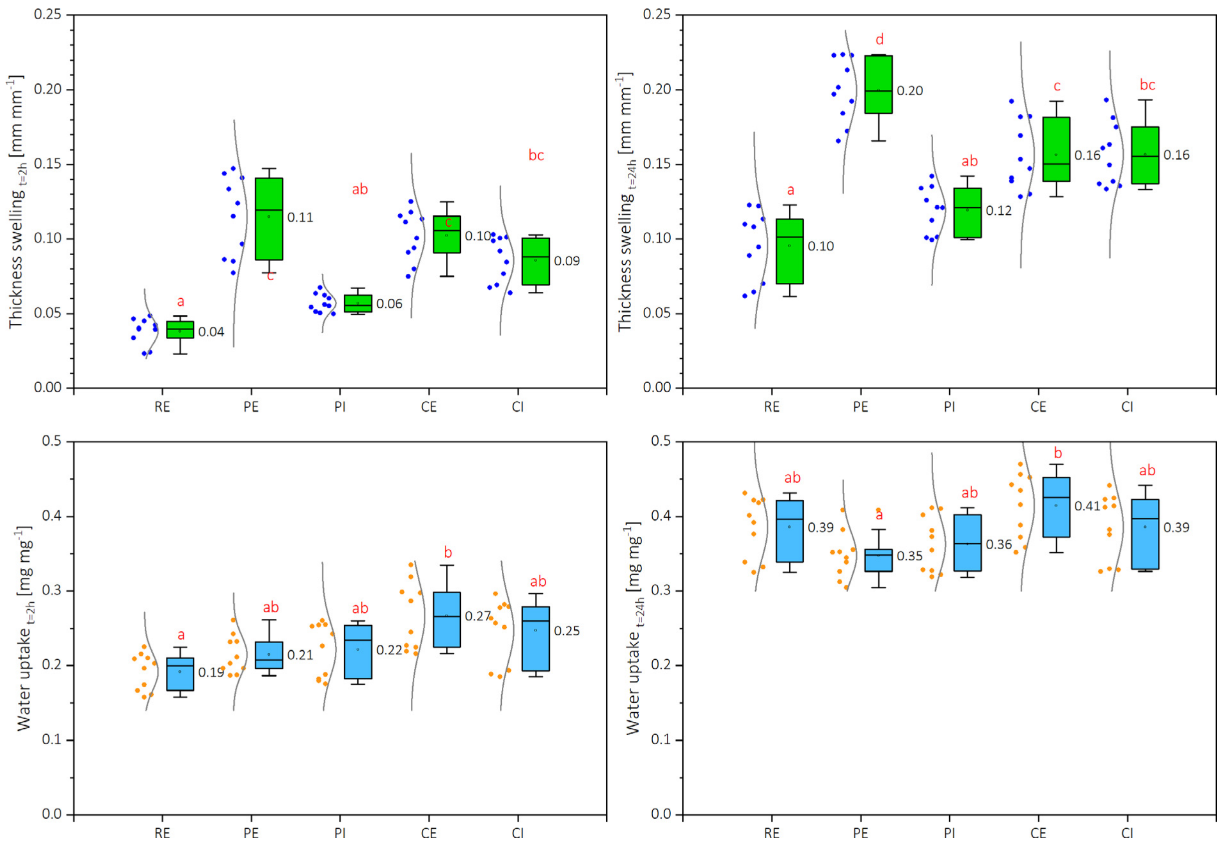

Fig. 4. Water uptake and thickness swelling after 2 and 24 h. abcd correspond to homogeneous groups by Tukey test (α = 0.05).

has similar values than the reference, while in case of panels with CF near the core layer had significant differences depending on the fiber orientation, being parallel orientation 16% less resistant than RE. In comparison, the perpendicular one had an 8% higher force than RE.

Density values help to understand the interaction between the bonding agent and the bonded components of a composite [27]. In this case, while the density of the scots pine veneer was 0.507 g cm^{-3}, it was further increased to 0.707 g cm^{-3} in the case of RE. Regarding the composite panels containing CF, densities were 0.784 g cm^{-3} for PE, 0.726 g cm^{-3} for PI, 0.750 g cm^{-3} for CE, and 0.727 g cm^{-3} for CI. It should be marked that the density is different across plywood thickness; therefore, to overcome this issue, vertical density profiles (VDP) were recorded for each sample; results are shown in Fig. 3. The first noticeable aspect of VDP is that panels with CF near the core veneer showed an increase in their thickness compared with RE, while panels with CF near the surface layer had a lower thickness. These results are concurrent with the densities, having an inversely proportional relation.

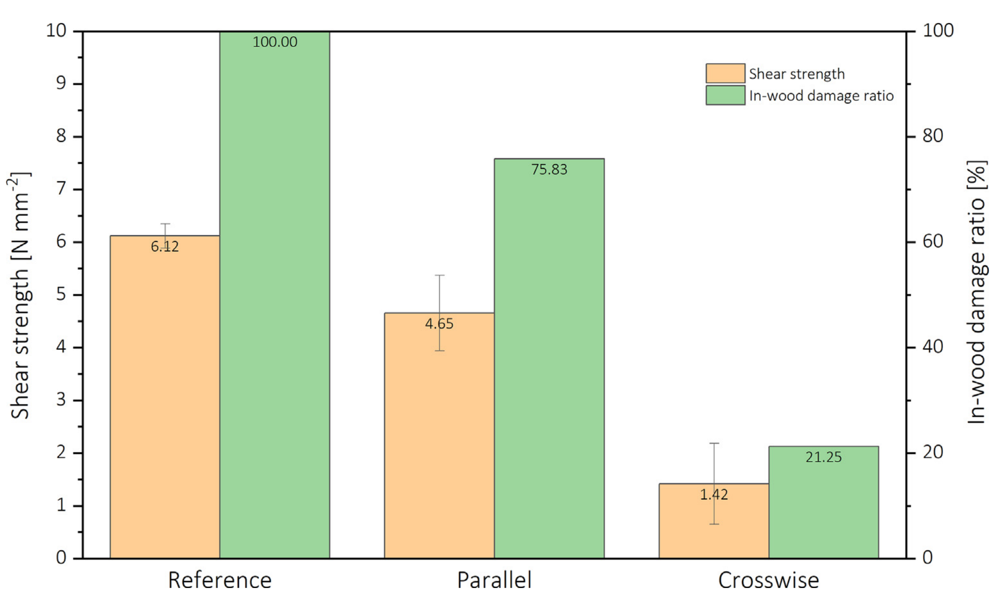

Fig. 5. Shear strength and in-wood damage ratio of tested bond connections with various carbon fibers orientation.

Fig. 6. Bond section of shear strength samples after testing.

Moreover, in the CF regions, it can be observed a thickness broadening due to the presence of such fibers, which have a lower density than MUF. However, the use of twice as much resin when bonding CF resulted in those sections maintaining the peak density similar to binding zones with no CF. On the other hand, PE panels had a lower density at the core, which means that there was a weaker pressure transfer at that zone (see CE).

The results of the thickness-swelling and water absorption after soaking for 2 h and 24 h are presented in Fig. 4. As can be appreciated from Fig. 3, composite thicknesses were PE > CE > CI > PI > RE. After 24 h soaking, this trend had kept but with less uniform distributions, meaning that at a short time, there is an increase in swelling at the inner layers. This increase may be related to the lower density of inner veneers and the broader regions due to the presence of CF and MUF resin in that region (see Fig. 3). The composites prepared with perpendicular orientation showed an almost equal swelling after 24 h; this means that after more extended exposure to water, the swelling is at some point equilibrated [28]. Moreover, panels with CF near the surface layer increase their thickness, which may happen after soaking the wood fibers that were densified during hot pressing (c.f. Fig. 3) are relaxed and therefore increase the dimensions of the composite panels, thus resulting in higher swelling.

In the case of water uptake (WU), no significant differences were found between the different panels. The highest WU was that of CE both after 2 h and after 24 h. Composites with CF followed the same trend after 2 h and 24 h, being CE > CI > PI > PE, thus meaning that perpendicular orientation favored the water uptake. Regarding the CF position, there was no clear trend as for parallel orientation; the highest WU was for CF near the core veneer, while for perpendicular orientation, the highest was for CF near the surface veneer.

The results of shear strength and in-wood damage ratio of the samples of composite panels with different orientations of CF in the bonding line are presented in Fig. 5. As can be seen, the highest value of average shear strength (6.12 N mm^{-2}) has been noted for RE. In this case, the in-wood damage ratio was the highest. It was found that all the tested samples were damaged in the wood structure to a greater or lesser degree. In the case of bonding lines containing carbon fibers, the higher value of shear strength was found for the parallel orientation. The average shear strength for parallel samples was 4.65 N mm^{-2}, and it is almost 24% lower than for reference samples; moreover, the average in-wood damage ratio was 76%. The lowest average shear strength (1.42 N mm^{-2}) was found for crosswise carbon fibers orientation in the bonding line. This value is about 77% lower than for reference samples. The average in-wood damage ratio for perpendicular or crosswise samples was 21%. All the investigated average values of shear strength and in-wood damage ratio are statistically different. It can be concluded that the application of carbon fibers reduces the shear strength of the bonding line based on MUF resin.

Fig. 6 presents the bonding sections of composite sticks after shear strength testing. In the displayed images, the in-wood damage can be appreciated better. As can be seen, the parallel samples had more significant wood damage, which is contrasted by the cross or perpendicular oriented fibers, in which the failure occurred mostly in the MUF-CF region. From these results, it can be concluded that the perpendicular orientation has a significantly weaker resistance to shear stress in the bonding, which, on the other hand, represents lower wood damage. The higher strength of parallel orientation can be related to a stress transfer through the axial direction of the fibers, which increases the resistance against shear stress. On the other hand, the crosswise oriented fibers had the stress applied tangentially, which in addition to the low bonding interaction with MUF resin, resulted in a weaker strength against shear stress.

4. Conclusions

Composite panels elaborated with CF bonded with MUF resin resulted in an increase of MOR and MOE compared to industrial-type 5-ply boards. The highest increase corresponded to the composite panels with carbon fibers in parallel orientation and close to the surface veneer. On the other hand, the addition of carbon fibers decreases the tensile strength perpendicular to the planes. However, no apparent impact of the carbon fibers was found on the resistance at axial screw removal. The addition of a layer with carbon fibers caused an increase in thickness swelling after 2 and 24 h soaking in water; however, the water uptake after 24 h presented no significant differences between the different samples. On the other hand, cutting force was influenced by both the position of the fibers and their orientation.

CRediT authorship contribution statement

Radosław Auriga: Conceptualization, Methodology, Formal analysis, Writing - original draft, Project administration. **Aneta Gumowska:** Conceptualization, Writing - original draft. **Karol Szymanowski:** Investigation, Writing - original draft. **Anita Wronka:** Conceptualization, Methodology, Investigation, Writing - original draft. **Eduardo**

Robles: Formal analysis, Visualization, Writing - review & editing. **Przemysław Ocipka:** Investigation, Writing - original draft. **Grzegorz Kowaluk:** Conceptualization, Methodology, Investigation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The raw data required to reproduce these findings are available to download from https://data.mendeley.com/datasets/hkgstm9sxg/draft?a = 01cff086-a35f-4542-9f44-b78194cd5db4.

The processed data required to reproduce these findings are available to download from https://data.mendeley.com/datasets/hkgstm9sxg/draft?a = 01cff086-a35f-4542-9f44-b78194cd5db4.

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