Screw Withdrawal Strength of Heat-Treated and Laminated Veneer Lumber Reinforced with Carbon and Glass Fibers

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The strength of a structural system often depends on the interconnections between the components of the structure. Screws are one of the most widely used fasteners in construction. In this study, the screw withdrawal strength of heat-treated scotch pine (*Pinus sylvestris* L.) samples reinforced with glass and carbon fibers *via* Desmodur-vinyl trie ketonol acetate adhesive was investigated. Before manufacturing the laminated veneer lumber, the wood samples were subjected to heat treatment at a temperature of 150 °C, 170 °C, 190 °C, and 210 °C for 2 h. Test results showed that the reinforcement fiber type and heat treatment temperatures had a considerable effect on the screw withdrawal strength. Heat treatment reduced the screw withdrawal strength, while the samples reinforced with both fibers had higher screw withdrawal strengths than those without reinforcement. Reinforcement with glass and carbon fibers increased the screw withdrawal strength up to 38% and 49% in the tangential, 13% and 20% in the radial, and 17% and 25% in the axial direction, respectively, compared to solid wood. In addition, the laminated veneer lumber samples reinforced with carbon fiber had a considerable increase in the screw withdrawal strength compared with the solid wood and glass fiber reinforced samples.

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Keywords: Reinforcement; Laminated veneer lumber; Scotch pine; Carbon fiber; Glass fiber

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INTRODUCTION

Wood is one of the oldest and most commonly used building and construction materials. Although various other materials, *e.g.*, plastic, metal, aluminum, concrete, and cement, are used instead of wood due to developing technologies, wood is always preferred in the wood working industry due to its many desirable features, *e.g.*, its aesthetical appearance, being easily obtained and processed, its insulation properties, thermal comfort, electrical properties, acoustic properties, *etc*. In addition, wood is considered a renewable and sustainable building material that is alternative to other construction materials (Atar *et al.* 2009; Aytin *et al.* 2015). The use of engineered wood material in the woodworking industry has been increasing in recent years (Hildebrandt *et al.* 2017). Nevertheless, wood still has some undesirable characteristics, *e.g.*, dimensional instability, biodegradability, flammability, and degradability by ultraviolet light and acids (Gao *et al.* 2012).

The properties of wood materials, which has the potential for widespread use in many areas, can be changed and improved by means of different treatment methods. The heat treatment of wood is one such method, and it is an environmentally friendly alternative that can be applied to wood (Kocaefe *et al.* 2008; Jones *et al*. 2019; Kamperidou, 2019; Torniainen *et al.* 2021; Sandberg *et al.* 2021). Heat treatment is typically conducted by treating wood at a temperature of 150 to 230 °C to change the chemical composition of the wood cells and thus improve its properties (Yang *et al.* 2016). As such, this method has been studied for a very long time and it includes several different methods (Sandberg *et al*. 2013; Sandberg and Kutnar 2016).

There is an increasing demand for heat treated wood materials in the woodworking sectors (Esteves and Pereira 2009). Heat-treated wood is increasingly used in many applications, *e.g.*, garden furniture, door and window joinery, exterior cladding, and decking. In addition, it is used in several interior applications, *e.g.*, kitchen furnishings, paneling, flooring, and the interiors of bathrooms and saunas (Jirouš-Rajković and Miklečić 2019). One of the biggest disadvantages of heat-treated wood materials is the loss of mechanical strength, depending on the heat treatment conditions (Gündüz *et al.* 2008). Due to the losses in mechanical properties, the use of heat-treated wood materials is not suitable for load-bearing construction (Hill *et al.* 2021).

The strength and stabilization of any building structure depends on the properties of the used materials and the fasteners that hold its parts together *via* a connection. Connecting elements, *e.g.* screws, nails, bolts, wooden dowels, glue, *etc.*, are widely used in the manufacture of wooden structures. At the connection of wooden elements, the connection materials are one of the most important factors for the safety of the system (Taj *et al.* 2009; Rammer 2010; Kariz *et al.* 2013). It is believed that the connection elements play an important role in the entire construction system and in general, the durability of the construction is dependent on fastening the members at the connection points (Bal 2017). Screws are one of the most commonly used fastening elements for connecting wood-based materials together (Maleki *et al.* 2017).

Kjucukov and Encev (1977) studied the pull-out resistance of screws of different lengths (13 to 60 mm) and diameters (1.5 to 8 mm) on European silver fir (*Abies alba*) in three different directions. They reported that there was no relationship between the screw withdrawal strength and screw length, but there was a linear relationship between the screw withdrawal strength and screw diameter. Özçifçi (2009) researched various parameters on the screw withdrawal strength of laminated veneer lumbers (LVL) manufactured from Uludag fir (*Abies bornmülleriana* Mattf.) and oak (*Quercus petraea* spp.) wood at different veneer thicknesses using melamine-formaldehyde (MF) and phenol-formaldehyde (PF) adhesives. Özçifçi (2009) reported that the parameters affected the screw withdrawal strength of the LVL samples at different rates. The highest strength was obtained in oak samples with a 4 mm veneer thickness bonded with PF adhesive. In another study, the screw withdrawal strength of beech (*Fagus orientalis* L.), alder (*Alnus glutinosa* subsp. *barbata* (C.A. Mey) Yalt., chestnut (*Castanea sativa* Mill.), spruce (*Picea orientalis* L.), and scotch pine (*Pinus sylvestris* L.) woods were investigated. It was reported that wood moisture negatively affected the screw withdrawal strength properties of the wood samples (Akyıldız and Malkoçoğlu 2001).

Laminated veneer lumber (LVL) is a high-strength engineered wood product that it has the potential to be used in structural and non-structural applications, *e.g.*, the construction and furniture industries, wooden buildings, and various other applications (Burdurlu *et al.* 2007; Shukla and Kamdem 2008; Bal and Bektaş 2012).

With the increasing popularity of heat-treated wood material and laminated veneer lumber (LVL) constructions around the world, there have been attempts to produce LVL using local wood species in different countries. Screw fasteners are one of the most versatile types of fasteners that are most commonly used in wood construction, with many types, sizes, and forms of screws. Therefore, knowledge of the withdrawal performance of screws for wooden building elements will provide useful information about the durability and stability of the whole construction system (Celebi and Kilic 2006). While screw connections are one of the most important parts of a construction system, connection points are the weakest parts of the whole system. Therefore, the design and determination of the screw pull-out resistance in wood-based materials is an important factor in ensuring the integrity, strength, and stiffness of the whole structure (Rajak and Eckelman 1993). In addition, the mechanical properties of heat-treated wood materials and reinforced wood and wood-based materials, as well as the performance of the connection points of reinforced materials, have been examined separately in the literature.

As is well known, heat treatment reduces the mechanical properties of the wood material including the screw withdrawal strength (Kariz *et al.* 2013; Gašparík *et al.* 2015). On the other hand, reinforcement with fiber composites is an effective method for improving the mechanical strength of LVL made of low quality wood (Auriga *et al*. 2020). In recent years, the use of fibers reinforced with polymer in the reinforcement of wood elements has received increasing attention (Fiorelli and Dias 2003). When the literature is examined, carbon and glass fiber have been widely used in reinforcing wood materials. Therefore, it is necessary to investigate the screw withdrawal strength of heat treated and reinforced LVL composite material in detail. The primary aim of this work is to determine the screw withdrawal strength of LVL using heat-treated wood veneers reinforced with glass and carbon fiber fabric.

EXPERIMENTAL

Materials

Scotch pine (*Pinus sylvestris* L.) wood was used in this study. It is widely used in the woodworking industry and was chosen randomly from a commercial supplier. During the selection of the wood materials, care was taken to ensure that they were knotless, non-deficient, normally grown, without insect and fungal damages, and without reaction wood, according to TS standard 2470 (1976).

In the preparation of test specimens D-VTKA (Desmodur-vinyl trie ketonol acetate) (D4) adhesive was used. Desmodur-VTKA is suitable for applications in outdoor conditions and humid spaces. In addition, it is commonly preferred for the assembly process of furniture and in the woodworking industry. It has a pH of approximately 7 and a viscosity of 5500 to 7500 MPa at a temperature of 25 °C ± 2 °C. Its density is 1.11 g/cm^3 ± 0.02 g/cm^3, and the period of solidification at a temperature of 20 °C ± 2 °C with a relative humidity of 65% ± 5% is 24 h. According to the advice by the manufacturer, it is recommended that approximately 180 to 190 g/m^2 of the adhesive should be applied to one surface and the bonding surface should be clean, dry, and dust-free. In addition, the bonding process should be done under normal conditions (Keskin *et al.* 2009; Uysal and Yorur 2013).

Two types of fiber reinforcement materials were used in this study; 200 g/m^2 of plain weave carbon fiber and 202 g/m^2 of plain weave glass fiber fabrics. The carbon and glass fiber fabrics were obtained from the Dost Kimya Industrial Raw Materials Industry and Trade. Ltd. Co., located in Istanbul, Turkey. The carbon and glass fiber reinforcement materials are widely used in the construction sector, and many other manufacturing industries (Pirvu *et al.* 2004; Rajak *et al.* 2019).

Methods

Heat treatment

Scotch pine (*Pinus sylvestris* L.) wood samples (10 mm thick by 80 mm wide by 850 mm long) were cut from the sapwood region of the planks and climatized at a temperature of 20 °C ± 2 °C and a relative humidity of 65% ± 5% to reach the equilibrium moisture content of all the samples. Each heat treatment process consisted of three phases. In the initial phase, the temperature was increased to 100 °C for 5 h and to 130 °C for 10 h. The main phase of the heat treatment was carried out at four different target temperature values, *i.e.*, 150, 170, 190, and 210 °C, for 5 h. Test samples were exposed to heat treatment at these temperatures for 2 h. During the last phase, the temperature was decreased to 50 °C for 10 h (as shown in Fig. 1).

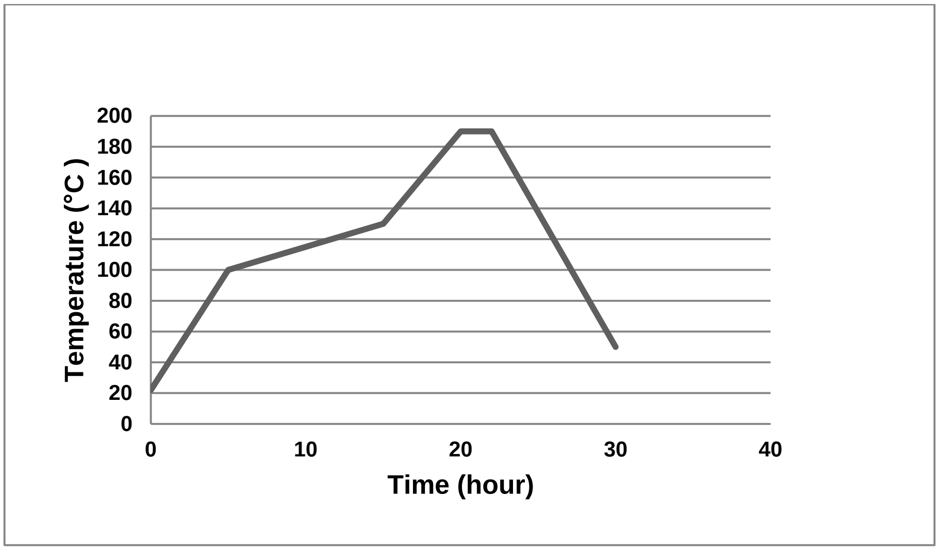

Fig. 1. Schematic diagram of the heat treatment process (at a temperature of 190 °C)

Manufacture of reinforced laminated veneer lumber (LVL) composites

One side and surface of the heat-treated panels were planned and sanded to 5 mm thick by 70 mm wide by 800 mm long panels. The manufactured reinforced LVL panels consisted of ten veneers, with nine layers of carbon and glass fibers between them. The adhesive had an application amount of approximately 180 to 200 g/m^2 for a single bonding surface of the wood veneer, while approximately 280 g/m^2 to 300 g/m^2 of adhesive was applied to the bonding surface of the carbon and glass fiber sheets. The higher amount of adhesive spread was due to the weaker adhesion of the adhesive resin to the carbon and glass fibers compared to wood veneer and the surface roughness of the fiber fabrics. In the bonding process, the samples were pressed for 240 min in a hydraulic press at room temperature and at a pressure of 9 N/mm^2. After that, ten specimens were prepared with dimensions of 50 mm x 50 mm x 150 mm for each test group (as shown in Fig. 2) according to ASTM standard D1761 (2020).

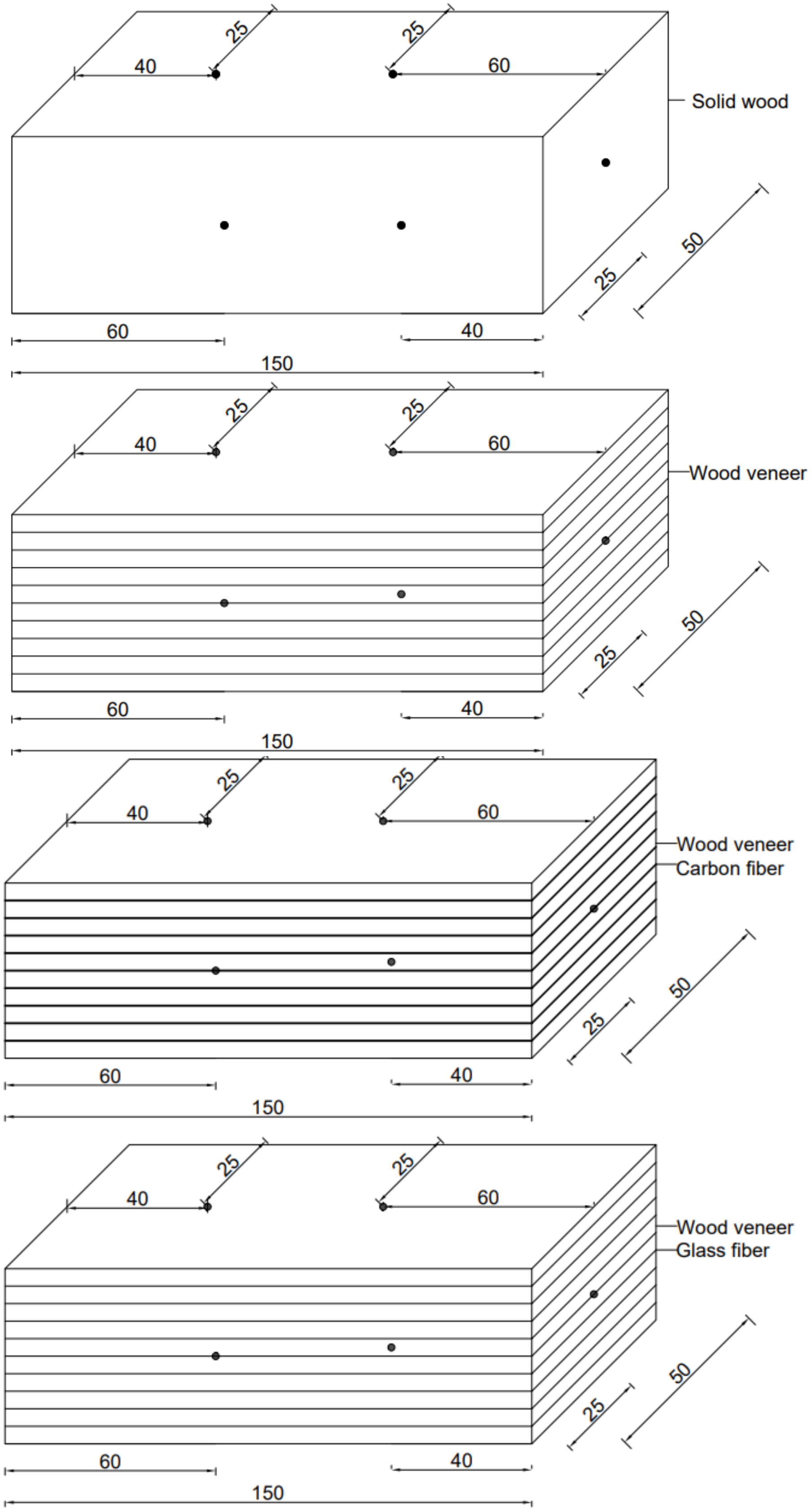

Fig. 2. Schematic view and dimensions of the solid wood and reinforced LVL samples (mm)

A total of 6 screws (4 mm x 50 mm) were driven into pilot holes, which were 70% of the core diameter of the screw and a 22 mm depth drilled on the face of the specimens. The depth of penetration of the screws from the sample surface was 35 mm (Fig. 3). All tests were carried out in a universal test machine (Instron-5969) according to the standard of ASTM standard D1761 (2020). During the tests, a pulling speed of 2 mm/min was applied until the screws were completely separated from the test samples. The screw withdrawal strengths on the laminated test samples were performed in three different directions (Fig. 3).

Fig. 3. Test samples and setup used for the screw withdrawal tests

The maximum holding strength (in Newtons) was recorded as the screw withdrawal strength of the samples during the test process. The screw withdrawal strength (SWS) was calculated by the following expression, as shown in Eq. 1,

$$f = \frac{F_{max}}{2 \cdot \pi \cdot r \cdot d} \left(\frac{N}{mm^2}\right) \quad (1)$$

where f is the screw withdrawal strength (N/mm^2), F_{max} is the maximum withdrawal load (N), and $2 \cdot \pi \cdot r \cdot d$ is the surface area between the screw and test material (Celebi and Kilic 2006; Pang *et al.* 2020).

Data analysis

The MSTAT-C software (Version 1.42, Michigan State University, East Lansing, MI) was used for the statistical analysis. The factors were the inclusion of carbon and glass fiber and the heat treatment temperatures. The analysis of variance was performed based on a multivariate analysis of variance (MANOVA). When the difference between the groups was significant according to the F test, the difference between the mean values was compared by the Duncan test. In the case of significant differences between the factors, the least significant difference (LSD) test was applied, and the mean values were grouped according to alphabetical orders.

RESULTS AND DISCUSSION

The air-dry density values of the solid wood and reinforced LVL samples are shown in Table 1. As can be seen from Table 1, the air-dried density values of the solid wood and LVL samples decreased as the temperature increased. The highest density losses were found in the solid wood samples at the highest temperature, *i.e.*, 210 °C, (0.471 g/cm^3). This result was compatible with the findings in the study carried out by Durmaz *et al.* (2019), who investigated the impact of heat treatment applied at a temperature of 120, 150, 180, and 210 °C for 4 and 6 h on the technological properties of Scots pine (*Pinus sylvestris* L.) wood. They found a 4% decrease in the density due to heat treatment at a temperature of 210 °C. In another study, Korkut and Bektas (2008) studied the effect of heat treatment on the physical properties of Uludag fir (*Abies bornmuelleriana* Mattf.) and Scots pine (*Pinus sylvestris* L.) wood. They reported that the highest density reduction of Scots pine was found in the samples that were heat-treated at a temperature of 180 °C for 10 h (12.55%).

Table 1. Air-dried Density Values of the Test Samples

Sample Group	Heat Treatment (°C)	Average (g/cm^3)	Minimum (g/cm^3)	Maximum (g/cm^3)	SD	NS
Solid Wood	Unheated	0.495	0.478	0.509	0.0117	10
	150	0.491	0.468	0.518	0.0170	10
	170	0.487	0.478	0.499	0.0068	10
	190	0.479	0.458	0.496	0.0117	10
	210	0.471	0.447	0.495	0.0151	10
LVL	Unheated	0.518	0.502	0.555	0.0155	10
	150	0.515	0.507	0.531	0.0018	10
	170	0.512	0.491	0.551	0.0181	10
	190	0.499	0.479	0.525	0.0159	10
	210	0.495	0.476	0.518	0.0151	10
GF-LVL	Unheated	0.581	0.563	0.593	0.0114	10
	150	0.578	0.559	0.595	0.0105	10
	170	0.572	0.565	0.581	0.0063	10
	190	0.566	0.553	0.586	0.0127	10
	210	0.560	0.532	0.582	0.0165	10
CF-LVL	Unheated	0.580	0.565	0.595	0.0089	10
	150	0.576	0.569	0.588	0.0063	10
	170	0.572	0.561	0.587	0.0089	10
	190	0.566	0.551	0.585	0.0115	10
	210	0.559	0.543	0.579	0.0119	10

Note: LVL: Unreinforced test samples; GF-LVL: LVL test samples reinforced with glass fiber; CF-LVL: LVL test samples reinforced with carbon fiber; SD: Standard deviation; and NS: Number of samples

Table 1 shows that the air-dried density values of both the GF-LVL and CF-LVL samples changed significantly. An increase in the air-dried density was observed for all LVL samples with the addition of carbon and glass fibers compared to the solid wood and LVL samples. The reasons for this increase were the greater spread amount of the adhesive in the both the GF-LVL and CF-LVL samples, and the higher density values of density of the carbon and glass fiber; thus, these factors might contribute to the increased density. Similar results regarding the increase in the density values of reinforced LVL samples were reported by Wei *et al.* (2013), Bal (2014), Bal and Efe (2015), Wang *et al.* (2015), and Auriga *et al.* (2020).

The results of the screw withdrawal strength tests in three directions for the treated and untreated test materials are presented in Table 2. As shown in Table 2, in general, the screw withdrawal strength decreased as the heat treatment temperature increased in all three directions for the test samples, but there was a slight increase in the reinforced samples for both glass and carbon fiber at a temperature of 150 °C. The SWS decreased due to heat treatment in the solid wood samples more than in both the glass and carbon fiber reinforced LVL samples in the tangential, radial, and axial direction.

When Table 2 was analyzed, the SWS values at all three directions of both the reinforced GF-LVL and CF-LVL samples were higher than the solid wood and LVL samples. In Table 1, it is seen that the density values of the reinforced LVL materials were significantly higher than solid wood.

The mechanical properties increase depending on the increase in the density value, and that the increases in the mechanical properties are closely related to the increase in density (Zhang 1994). It is thought that the amount of adhesive used and reinforcing material play an important role in this increase. It can be said that the both the carbon and glass fibers and adhesive used as binder to reinforce the LVL composites enhanced the SWS of the reinforced composites. In addition, similar findings were reported by Bal (2017), Perçin (2016), and Durmaz *et al.* (2020).

Table 2. Screw Withdrawal Strengths of Test Samples

Material Type	Heat Treatment (°C)	Tangential Direction (N/mm^2)*	Radial Direction (N/mm^2)**	Axial Direction (N/mm^2)***
Solid Wood	Unheated	26.85 FG ^{a}(1.09) ^{b}(4.09)	25.97 FG ^{a}(1.05) ^{b}(4.26)	20.17 FG ^{a}(1.31) ^{b}(6.51)
	150	25.45 HI ^{a}(0.99) ^{b}(3.91)	25.04 GH ^{a}(1.32) ^{b}(5.29)	19.72 FG ^{a}(1.29) ^{b}(6.56)
	170	24.81 HI ^{a}(1.30) ^{b}(5.24)	23.82 IJ ^{a}(1.23) ^{b}(5.19)	18.42 H ^{a}(1.09) ^{b}(5.86)
	190	23.45 K ^{a}(1.23) ^{b}(5.25)	22.35 JK ^{a}(1.25) ^{b}(5.59)	16.88 I ^{a}(1.05) ^{b}(6.23)
	210	22.37 K ^{a}(1.29) ^{b}(5.77)	20.45 L ^{a}(1.13) ^{b}(5.59)	15.05 J ^{a}(1.31) ^{b}(8.75)
LVL	Unheated	27.43 F ^{a}(1.34) ^{b}(4.91)	26.19 EF ^{a}(1.29) ^{b}(4.94)	19.42 FGH ^{a}(1.27) ^{b}(6.58)
	150	26.98 F ^{a}(1.45) ^{b}(5.37)	25.78 FG ^{a}(1.23) ^{b}(4.80)	18.42 H ^{a}(1.32) ^{b}(7.18)
	170	25.78 GH ^{a}(1.13) ^{b}(4.40)	23.65 IJ ^{a}(1.57) ^{b}(6.63)	17.21 I ^{a}(1.32) ^{b}(7.67)

	190	24.33 IJ ^{a}(1.14) ^{b}(4.70)	22.71 JK ^{a}(1.17) ^{b}(5.17)	16.23 I ^{a}(1.29) ^{b}(7.96)
	210	23.17 JK ^{a}(1.10) ^{b}(4.78)	21.75 K ^{a}(1.18) ^{b}(5.42)	14.67 J ^{a}(1.01) ^{b}(6.93)
GF-LVL	Unheated	35.46 C ^{a}(1.40) ^{b}(3.95)	28.47 BC ^{a}(1.10) ^{b}(3.89)	22.89 ABC ^{a}(1.40) ^{b}(6.14)
	150	35.75 C ^{a}(1.52) ^{b}(4.25)	28.98 AB ^{a}(1.30) ^{b}(4.49)	23.01 ABC ^{a}(1.06) ^{b}(4.62)
	170	33.49 D ^{a}(1.03) ^{b}(3.13)	27.16 DE ^{a}(1.49) ^{b}(5.50)	21.72 EF ^{a}(1.39) ^{b}(6.43)
	190	32.65 DE ^{a}(1.36) ^{b}(4.17)	25.72 FG ^{a}(1.29) ^{b}(5.03)	20.43 EF ^{a}(1.48) ^{b}(7.29)
	210	31.75 E ^{a}(1.03) ^{b}(3.26)	24.12 HI ^{a}(1.13) ^{b}(4.70)	19.14 GH ^{a}(1.16) ^{b}(6.07)
CF-LVL	Unheated	37.85 AB ^{a}(1.34) ^{b}(3.55)	29.81 A ^{a}(1.45) ^{b}(4.86)	23.56 AB ^{a}(1.46) ^{b}(6.22)
	150	38.33 A ^{a}(1.38) ^{b}(3.60)	29.12 AB ^{a}(1.14) ^{b}(3.93)	23.79 A ^{a}(1.30) ^{b}(5.50)
	170	36.92 B ^{a}(1.33) ^{b}(3.62)	28.45 BC ^{a}(1.47) ^{b}(5.19)	22.65 BC ^{a}(1.38) ^{b}(6.12)
	190	35.33 C ^{a}(1.41) ^{b}(3.99)	27.63 CD ^{a}(1.56) ^{b}(5.67)	21.94 CD ^{a}(1.11) ^{b}(5.09)
	210	34.86 C ^{a}(1.33) ^{b}(3.84)	26.85 DEF ^{a}(1.29) ^{b}(4.65)	21.01 DE ^{a}(1.11) ^{b}(5.31)

Note: Different letters show which values are statistically different at the 0.05 level. LVL: Unreinforced test samples; GF-LVL: LVL test samples reinforced with glass fiber; CF-LVL: LVL test samples reinforced with carbon fiber; a: Standard deviation; b: Coefficient of variation (%); and *LSD: 1.163; **LSD: 1.134; ***LSD: 1.120

According to Table 2, in general, the SWS of the heat-treated samples decreased as the temperatures increased. A similar trend was found in the SWS in all three directions. Bal (2016) stated that the SWS was dependent on the wood moisture content level. Heat treatment considerably reduces the equilibrium moisture content of the wood material. The SWS varies depending on the wood type, material density, fiber direction of the wood material, moisture content of the wood, screw properties, surface coating of the wood material, and screw depth (Kılıç *et al.* 2006). All the heat-treated test samples had lower SWS properties than the unheated groups (except for the GF-LVL-150 °C samples in all three directions, the CF-LVL-150 °C samples in the tangential direction, and the CF-LVL-150 °C in the axial direction). The SWS properties of both the GF-LVL and CF-LVL samples were considerably higher than the solid wood samples in all three directions. In this case, it can be said that the reinforcement process considerably increased the SWS. It was concluded that the CF-LVL samples yielded a higher SWS than the GF-LVL samples.

The average values of the screw withdrawal strength, according to the type of wood material and heat treatment temperature in the tangential direction, are shown in Fig. 4.

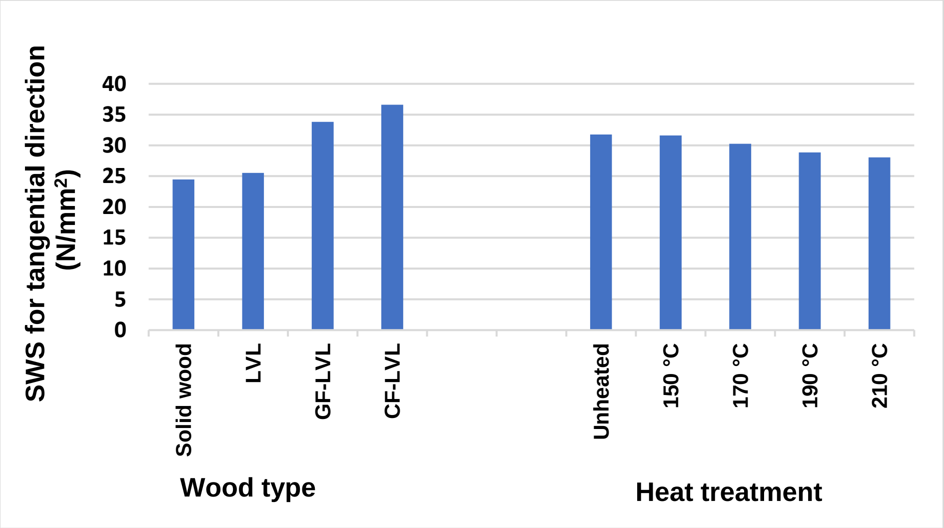

Fig. 4. SWS values according to the type of wood material and the heat treatment temperature in the tangential direction

According to Fig. 4, the SWS of the CF-LVL samples was higher than the GF-LVL, LVL and solid wood samples. The results indicated that the SWS of the LVL, CF-LVL and GF-LVL samples increased by 4%, 38%, and 49%, respectively, compared to the solid wood samples in the tangential direction. In addition, heat treatment decreased the SWS values in all test groups. Depending on the heat treatment temperature, the highest SWS value in the tangential direction was obtained in the unheated group. The decreases in the SWS values ranged from 1% to 11% because of the heat treatment. The average values of the screw withdrawal strength, according to the type of wood material and heat treatment temperature in the radial direction, are shown in Fig. 5.

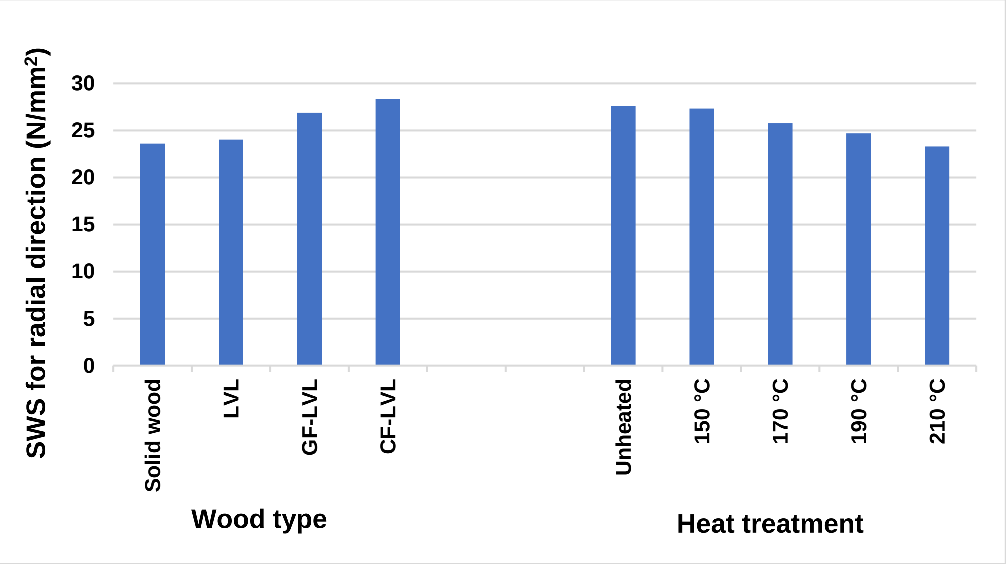

Fig. 5. SWS values according to the type of wood material and the heat treatment temperature in the radial direction

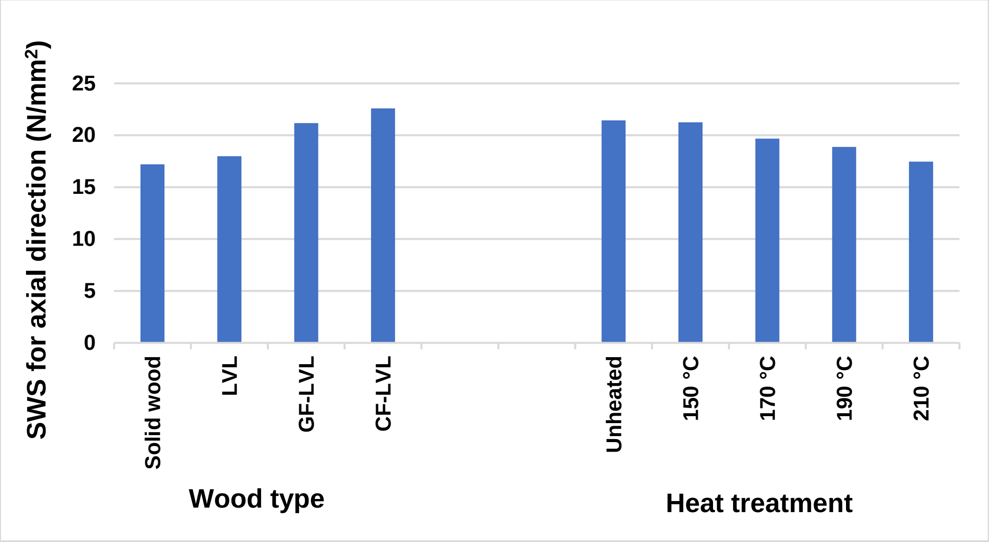

Fig. 6. The SWS values according to the type of wood material and the heat treatment temperature in the axial direction

According to these findings, based on the wood material and the heat treatment temperature, the screw resistance in the radial direction yielded similar trends to the tangential direction. Depending on the wood material and heat treatment temperature, the highest SWS values were obtained in the CF-LVL and unheated groups. The values indicated that the SWS of the LVL, CF-LVL and GF-LVL samples increased by 2%, 13% and 20%, respectively, compared to the solid wood. In addition, in the radial direction, the decreases in the SWS values ranged from 1% to 15%, based on the heat treatment temperature.

The average values of the screw withdrawal strength, according to the type of wood material and heat treatment temperature in the axial direction, are shown in Fig. 6. As shown, the SWS values of the solid wood samples were lower than the GF-LVL and CF-LVL samples. In the axial direction, the SWS values of the LVL, GF-LVL and CF-LVL samples were higher than the solid wood samples by 4%, 23% and 31%, respectively. In addition, considering the heat treatment temperature, SWS values decreased as the heat treatment temperature continued to increase. The decreases in the SWS values ranged from 1% to 18% depending on the temperatures in the axial direction.

CONCLUSIONS

1. The reinforcement fiber type and heat treatment temperatures had a significantly effect on the screw withdrawal strength (SWS).
2. Depending on the type of reinforcing material, the carbon fiber yielded more positive effects in terms of the SWS.
3. The SWS values of the test samples that were reinforced with both fiber materials are higher than solid wood and unreinforced (LVL) samples.
4. In general, the heat treatment temperatures reduced the SWS values, while satisfactory results were obtained using the D-VTKA (vinyl ketone acetate) adhesive between the wood and reinforcement fibers.

5. Reinforcement with glass and carbon fibers increased the SWS up to 38% and 49% compared to the solid wood in the tangential, 13% and 20% in the radial, and 23% and 31% in the axial directions, respectively, compared to the solid wood.
6. The results indicated that the LVL samples reinforced with carbon fiber yielded a significant increase in the SWS compared with the solid wood, LVL and GF-LVL samples.

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