Determination of Screw Withdrawal Strength of Heat-Treated and Reinforced Laminated Veneer Lumber

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The withdrawal resistance of screws in heat-treated and reinforced laminated veneer lumber (RLVL) was determined in the radial, tangential, and transverse directions. For this reason, laminated veneer lumber (LVL) and RLVL with carbon fibers were produced from heat-treated oak (*Quercus petraea* (Liebl.)) veneers using phenol formaldehyde as the adhesive. Wood samples were heat-treated at 140, 170, 200, and 230 °C for 2 h. According to the results of the study, screw withdrawal strength values of LVL increased for heat-treated samples at 140 °C, but decreased at 170, 200, and 230 °C. However, in all groups, the screw withdrawal strength values of the RLVL were higher than those of the LVL. The highest screw withdrawal strength values were identified in the tangential direction, and the lowest were in the transverse directions.

Keywords: Laminated veneer lumber; Heat treatment; Screw withdrawal strength; Carbon fiber

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INTRODUCTION

After stone, wood is the oldest natural renewable material used by humans for construction purposes. It can be used in a variety of forms and situations (Kozlovska *et al.* 2015). Although wood is a renewable natural resource, the amount of wood in the world is gradually decreasing (Kılıç 2011). One way to increase forest resources, thereby protecting the natural forest, was developed wherein composite products from solid wood are manufactured (Shukla and Pascal 2008). Veneer products, such as plywood and laminated veneers, have been developed as an alternative to solid wood products (Aydin *et al.* 2004). Laminated veneer lumber (LVL) is a versatile, high-strength, and engineered wood product used primarily for structural applications in civil construction (Melo and Menezzi 2014). It is produced by adhering wood veneers of equal or varied thicknesses to each other, ensuring that the grains are parallel (Burdurlu *et al.* 2007; Wei *et al.* 2013). Laminated veneer lumber possesses various advantages over conventional solid wood, such as increased dimensional stability, greater mechanical strength and stiffness, improved stress distributing properties, reduced processing cost, and availability in larger sizes (Shukla and Kamdem 2009; Souza *et al.* 2011).

The importance of wood as a building material has been increasing because of greater ecological awareness as well as wood's ability to store carbon, which trees absorb as carbon dioxide from the atmosphere through photosynthesis. New processes for improving the properties of wood have been developed, which increase the scope of its use and the variety of possible applications (Kariz *et al.* 2013). Heat-treated wood has drawn a great deal of attention as being a protective treatment that does not use any harmful chemicals. Therefore, heat treatment can be considered an ecologically friendly alternative to the impregnation of wood (Yildiz *et al.* 2011). The heat treatment process involves exposing wood to elevated temperatures ranging from 120 to 240 °C (Militz 2002; Kocaefe *et al*. 2010). Thermal treatment is an effective method to improve the dimensional stability and biological durability of wood. However, heat treatment also decreases the mechanical properties of wood (Tjeerdsma *et al.* 1998; Nuopponen *et al.* 2003; Kocaefe *et al.* 2007).

The stability and durability of any building system, composed of interconnected components, is directly related to the performance of its fastening elements. Screws are the most widely used fastening elements that are found in the connections of solid wood materials. Therefore, knowledge of the withdrawal strength of screws for wooden building elements will provide useful information about the durability and stability of the whole system. It is also worthwhile to have information about the withdrawal strength of nails in addition to screws, to achieve the most efficient use of materials in the building system (Celebi and Kilic 2006). The strength and stability of any structure depends, to a large extent, on the joints that hold its parts together. The design and construction of timber joints is very critical because joints are the weakest links in most engineered wooden structures (Mohamad and Smith 1996). In most wooden structures, connections are one of the most important, but least understood, components. Connections provide continuity to the members, strength, and stability of the structure (Taj *et al.* 2009). Screws and nails are widely used as joint components in the furniture and construction industries, and because each wood species has its own properties, the corresponding screw and nail withdrawal strengths vary (Aytekin 2008).

Carbon fiber material is one of the most important engineering materials used in the manufacture of advanced composite materials. Carbon fiber is lightweight, fatigue resistant, flexibility material that possess high strength and high stiffness. These excellent properties result from the orientation of graphite layer along the fiber axis during the production process (Chung 1994).

The heat treatment process has been widely used over the past few decades. Heat treatment decreases the equilibrium moisture content of wood and improves its dimensional stability, however it decreases the wood's mechanical properties, including screw withdrawal strength (Bekhta and Niemz 2003; Shi *et al.* 2007; Ayrilmis 2010; Kocaefe *et al.* 2010; Kariz *et al.* 2013). The carbon fiber technology has been applied to a wide range of timber and glulam to determine the physical and mechanical properties of timber and glulam, but not screw withdrawal strength of heat treated LVL. This study evaluates the influence of carbon fiber on screw withdrawal resistance properties of laminated wood reinforced with carbon fiber after applied heat treatment.

EXPERIMENTAL

Materials

Oak (*Quercus petraea* (Liebl.)) wood was selected as the preferred wood material for the experiments. The wood was obtained from timber merchants in İnegöl-Bursa, Turkey. Oak specimens were cut to dimensions of 75 mm wide, 800 mm long, and 10 mm thick according to the standards of TS 4176 (1984) and ISO 4471 (1982). Thereafter, veneer panels were conditioned at 20 ± 2 °C and 65% ± 5% relative humidity (RH) in a climatic chamber to reach equilibrium moisture content. The total heat treatment was performed in three continuous stages. In the first phase, heat and steam were used to increase the temperature of the oven to 100 °C for 8 h, and then to 130 °C for 16 h. In the second phase, the temperature was increased from 130 °C to a desired final temperature 140 °C (or 170, 200, and 230 °C) for 8 h, and the veneer panels were kept at these temperatures for 2 h. In the third phase, the temperature was reduced, and this continued until the moisture of the wood had reached 4% to 6% using water vapor for 16 h (Fig. 1). The heat treatment was performed at four different temperatures: 140, 170, 200, and 230 °C. Thereafter the veneer panels were cut to the net dimensions of 70 mm x 770 mm x 5 mm. The heat-treated veneers were conditioned in a relative humidity of 65 ± 5% and 20 ± 2 °C temperature until their weights became stable. Finally, these panels were used in the preparation of test specimens. Thus, a total of 100 samples (5 x 2 x10) were prepared for screw withdrawal resistance test.

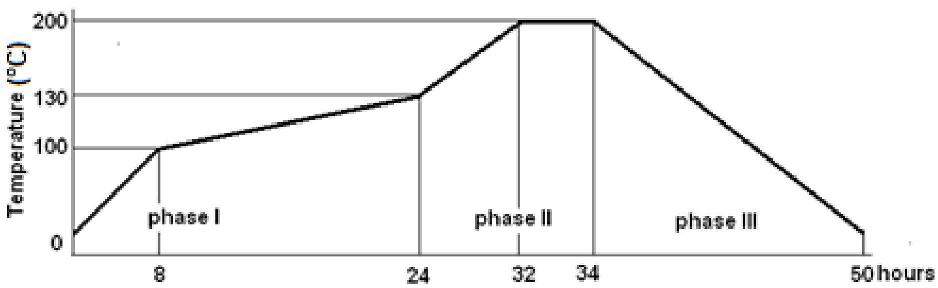

Fig. 1. Applied heat treatment process

In the preparation of test specimens, phenol-formaldehyde (PF) adhesive was used. The adhesive was obtained from the Gentaş Kimya Company in Istanbul, Turkey, and its properties are given in Table 1.

Table 1. Properties of Phenol Formaldehyde Adhesive

Density (g/cm^3)	pH	Viscosity (Cp)	Time to solidify (at 130 °C)	Solid content (%)	Amount applied (g/m^2)
1.12	8.4 to 8.8	350 to 450	6 to 7 min	47 ± 1	200

Method

The test samples were prepared according to the principles described in ASTM D1101-92 (1992). For this reason, approximately 200 g/m^2 of adhesive was spread with a cylindrical adhesive spreading apparatus on the one side of the veneer panels, while approximately 300 g/m^2 of adhesive was used on the other side because of the surface roughness of the carbon fiber. Carbon fiber was obtained from Dost Kimya Company in Istanbul, Turkey. The weight of the carbon fiber fabric was 122 g/m^2, plain weave-PW was the type of woven used, and the thickness of carbon fiber was 0.14 mm. After spreading the adhesive on 10 wood veneer panels, nine carbon fiber sheets were laminated. The wood veneer panels and carbon fiber sheets were pressed under 11 kg/cm^2 for 90 min. at 120 °C. Then, test samples were prepared having 50 mm x 50 mm x 152 mm for each group, as shown in Fig. 2, according to ASTM D1761 (2000). Control samples were prepared from unheat-treated wood with reinforced and unreinforced LVL.

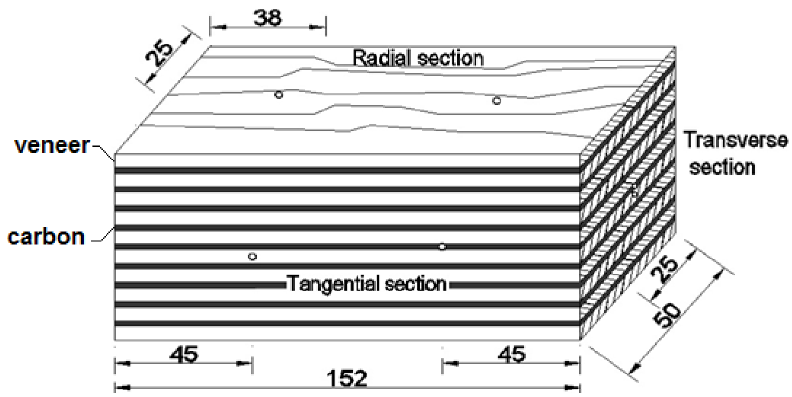

Fig. 2. Screwing points and specimen used in the tests

The pilot holes were drilled as 70% of screw root diameter and 16 ± 0.5 mm deep in the test samples, according to the procedure of ASTM D1761 (2000). One type of screw (4 x 50) was used in this study. Each of six screws was embedded to previously opened pilot holes. All of the screws were embedded 33 ± 0.5 mm deep in the surface of the test samples. The withdrawal strength was determined for the radial, tangential, and transverse surfaces. Pilot holes are shown in Fig. 2. The prepared samples were conditioned at 20 ± 2 °C temperature and at 65 ± 5% relative humidity until their weights became stable. The withdrawal strength of screws was determined according to the standard EN 1382 (TS EN 1382 2003). During these tests, a pulling speed of 2 mm/min was applied until the screws were completely separated from the test samples. The withdrawal strength of the screws (σ_s) was calculated according to the following formula:

$$\sigma_s = \frac{P_{max}}{2\pi r h} \tag{1}$$

where σ_s is the withdrawal strength of screw (N/mm^2), P_{max} is the maximum load (N), and h is the screw depth embedded in the surface member (mm).

Data analyzes

In the evaluation of the data, the MSTAT-C statistic package software program was used. In the data analysis, the values of the factor effects of heat treatment temperature and carbon fiber were determined using the analysis of variance (ANOVA) procedure, and the differences in the means were accepted at a significance of $P<0.05$. Afterwards, the least significant differences (LSD) of the means were used, and the causation factors were determined. The data obtained was analyzed at a 95% confidence level.

RESULTS AND DISCUSSION

Average density and equilibrium moisture content (EMC) values of LVL and RLVL are shown in Table 2. According to Table 2, the density value of LVL and RLVL decreased as temperature increased. Unheat-treated LVL had a density of 0.635 N/mm^2 while those treated at 230 °C had the lowest density, 0.582 N/mm^2. The reduction of density may be due to the degradation of hemicelluloses and cellulose.

Table 2. Density and Equilibrium Moisture Content Values of LVL and RLVL

Heat treatment	Type of LVL	Density (g/cm^3)		EMC (%)	
		X	sd	X	sd
Unheat-treated (control)	LVL	0.635	0.0085	12.25	0.742
	RLVL	0.679	0.0136	11.69	0.490
140 °C	LVL	0.629	0.0120	8.81	0.495
	RLVL	0.671	0.0142	8.22	0.401
170 °C	LVL	0.613	0.0075	6.61	0.350
	RLVL	0.661	0.0139	6.07	0.310
200 °C	LVL	0.601	0.0117	5.59	0.326
	RLVL	0.648	0.0098	4.86	0.185
230 °C	LVL	0.582	0.0116	4.94	0.260
	RLVL	0.626	0.0120	4.16	0.304

X: average value; sd: standard deviation

Degradation of hemicellulose into volatile substances and evaporation of extractives are considered to be the main parameters responsible for the density reduction of wood exposed to heat (Esteves and Pereira 2009). Gunduz *et al.* (2009) reported that hornbeam (*Carpinus betulus* (L.)) wood treated at high temperature (170, 190, and 210 °C for 4, 8, and 12 h) lost some of its weight and at the same time became reduced in density. On the other hand, treatment at 230 °C resulted in the lowest values of EMC for LVL and RLVL. At the same time, the highest EMC value was found in the unheat-treated samples for LVL and RLVL. Cellulose crystallinity increases because of the degradation of amorphous cellulose, resulting in a decreased accessibility of hydroxyl groups to water molecules, which contributes to the decrease of EMC (Bhuiyan and Hirai 2005; Boonstra and Tjeerdsma 2006). In the present study, the EMC values of reinforced LVL were significantly lower than that of LVL. This situation may result from the lower water absorption and restraining properties of carbon fiber compared to wood material (Choi *et al.* 2001). Results of variance analyses are given in Table 3.

Table 3. Results of Variance Analyzes

Anatomical direction	Source of Variance	Degrees of Freedom	Sum of Square	Mean Square	F Value	Probably % 5 (Sig.)
Radial direction	Heat treatment	4	1057.448	264.362	1091.3426	0.0000
	Type of LVL	1	50.837	50.837	209.8656	0.0000
	Heat treatment x Type of LVL	4	3.174	0.793	3.2753	0.0148
	Error	90	21.801	0.242	-	-
	Total	99	1133.260	-	-	-
Tangential direction	Heat treatment	4	742.733	185.608	154.2343	0.0000
	Type of LVL	1	961.620	961.620	799.0741	0.0000
	Heat treat x LVL type	4	12.737	3.184	2.6461	0.0385
	Error	90	108.308	1.203	-	-
	Total	99	1825.398	-	-	-
Transverse direction	Heat treatment	4	703.098	175.774	278.3588	0.0000
	Type of LVL	1	76.563	76.563	121.2455	0.0000
	Heat treat x LVL type	4	20.560	5.140	8.1398	0.0000
	Error	90	56.832	0.631	-	-
	Total	99	857.053	-	-	-

The heat treatment, type of LVL, and interactions of this factor were found to be statistically significant (P ≤ 0.05) for the radial, tangential, and transverse directions. Single comparison analysis for the factor of heat treatment, and type of LVL for radial direction are shown in Table 4.

Table 4. Single Comparison Analysis of Heat Treatment and Type of LVL in Radial Direction (N/mm^2)

Factors	Types	*X* (N/mm^2)	HG
Heat treatment*	Control	26.52	B
	140 °C	27.53	A
	170 °C	26.33	B
	200 °C	22.70	C
	230 °C	18.73	D
LVL**	LVL	23.14	B
	RLVL	25.59	A

*LSD: ±0.3087; **LSD: ±0.06957; X: mean value; HG: homogeneous group

With respect to the means in Table 4, during the single comparison of the factor types, the effect of heat treatment on screw withdrawal resistance was found to be significant. Regarding heat treatment temperatures, the highest screw withdrawal resistance value (27.53 N/mm^2) was found in the samples heat-treated at 140 °C, while the lowest screw withdrawal resistance (18.73 N/mm^2) was found in the samples heat-treated at 230 °C. The screw withdrawal performance loss was 29.4% heat-treated at 230 °C, when compared to the control (un-heat-treated) samples. Single comparison analysis for the factor of heat treatment, and type of LVL for tangential and transverse directions are shown in Tables 5 and 6, respectively.

Table 5. Single Comparison Analysis of Heat Treatment and Type of LVL in Tangential Direction (N/mm^2)

Factors	Types	*X* (N/mm^2)	HG
Heat treatment*	Control	30.95	B
	140 °C	32.45	A
	170 °C	30.49	B
	200 °C	28.61	C
	230 °C	24.66	D
LVL**	LVL	25.94	B
	RLVL	32.92	A

*LSD: ±0.6882; **LSD: ±0.4353

Table 6. Single Comparison Analysis of Heat Treatment and Type of LVL in Transverse Direction (N/mm^2)

Factors	Types	*X* (N/mm^2)	HG
Heat treatment*	Control	24.02	A
	140 °C	24.18	A
	170 °C	23.06	B
	200 °C	19.83	C
	230 °C	17.42	D
LVL**	LVL	20.33	B
	RLVL	23.08	A

*LSD: ±0.4984; **LSD: ±0.9969

According to Tables 5 and 6, the screw withdrawal strength of heat-treated LVL and RLVL decreased as heat treatment temperature increased in the tangential and transverse directions. The maximum decrease for all parameters was recorded at 230 °C. The lowest screw withdrawal strength values obtained was 24.66 N/mm^2 for tangential direction (Table 5). Total loss compared to the control groups was calculated to be 20.3%. Similarly, the lowest screw withdrawal strength values, 17.42 N/mm^2 for transverse direction, were also obtained for samples treated at 230 °C (Table 6). The strength loss, compared to the control groups, was 27.5%. These strength losses for the three directions were partially caused by the overall decrease in wood density (as mentioned above), which generally leads to the deterioration of all mechanical properties (Mayes and Oksanen 2003). Gašparík *et al.* (2013) reported screw withdrawal strength of heat-treated wood decreased depending on lower density and moisture content of wood. In the present study, the highest screw withdrawal strength values were determined to be in the tangential direction and the lowest values were detected for the transverse surface.

In this study, regarding LVL type, the screw withdrawal resistance of RLVL was higher than LVL for radial, tangential, and transverse directions; 10.5%, 27%, and 13.5%, respectively. This situation shows that a portion of the increase in the screw withdrawal resistance values originated from the increase in density and decrease in EMC. Madhoushi *et al.* (2010) examined the effect of densification on withdrawal strength of nails and screws fasteners in eastern cottonwood (*Populus deltoides*). The results showed that the percentage of densification may significantly influence the density of the samples. Furthermore, it was found that the amount of densification has a significant influence on the withdrawal strength of screws (up to 140%). In previous studies it has been shown that reinforcing material has a positive effect on the mechanical properties of wood (Micelli *et al.* 2005; Yang and Liu 2007; Lu *et al.* 2015; Fossetti *et al.* 2015). Meekum and Mingmongkol (2011) studied the press process parameters on the mechanical properties of LVL reinforced composites, derived from rubber wood veneer reinforced with woven fiber-glass and epoxy adhesive, were performed via the design of experimental approach. The test results showed that the LVL wood can have superior properties when compared with solid woods. It was also found that the withdrawal strength of reinforced LVL was higher than that of the solid woods. Also, screw withdrawal strength depends on wood equilibrium moisture content (EMC) (Pirnbacher and Schickhofer 2009). In general, a decrease of equilibrium moisture content (EMC) improves the mechanical strengths of the wood material (Bomba *et al.* 2014; Gaff 2014). Ringhofer *et al.* (2014) reported that in case of increased moisture content above 12%, test results indicate a significant decrease in withdrawal capacity of self-tapping screws.

Results of the Duncan test for the total comparison of the heat treatment, and type of LVL on screw withdrawal strength for radial, tangential, and transverse direction are shown in Table 7. As shown, the highest screw withdrawal strength was found in heat-treated reinforced LVL at 140 °C, while the lowest in heat-treated at 230 °C and un-reinforced LVL for radial, tangential, and transverse directions. The results of the statistical analysis showed significant differences between the LVL and RLVL samples ($P \leq 0.05$). The screw withdrawal strength values of the tangential direction were higher than those of radial and transverse directions. The screw withdrawal strengths were decreased as heat treatment temperatures increased, with the exception of heat-treated samples at 140 °C. However, in all groups, the strength values of the RLVL were higher than those of LVL. The withdrawal strength of screw from laminated wood that was heat-treated at temperatures of 200 and 230 °C decreased significantly compared with the unheat-treated LVL. At higher temperatures, the thermal degradation of the wood gradually diminishes the screw withdrawal performance of laminated wood, especially above 170 °C; thus, it becomes less resistant to screw withdrawal strength. The lower density is one of the reasons for the lower screw withdrawal strength from heat-treated wood. The density of wood plays an important role in determining the mechanical strength of wood (Romagnoli *et al.* 2014). Kariz *et al.* (2013) reported the screw withdrawal strength of heat-treated spruce wood decreased with heat-treatment temperature. Chen and Natterer (2001) assessed the mechanical performance of dowel-type timber joints reinforced by fiberglass fabrics as reinforcements and reported that the fiberglass reinforcements led to better performance and provided a good security factor to the timber joints.

Table 7. Results of Duncan Test

Heat treatment	Type of LVL	Radial Direction*			Tangential Direction**			Transverse Direction***		
		X (N/mm^2)	HG	sd	*X* (N/mm^2)	HG	sd	*X* (N/mm^2)	HG	sd
Unheat-treated	LVL	25.42	D	1.46	27.75	DE	2.58	22.89	B	1.85
	RLVL	27.62	B	1.57	34.15	B	2.44	25.15	A	2.27
140 °C	LVL	26.08	C	2.24	28.59	D	2.11	22.71	B	1.82
	RLVL	28.98	A	1.67	36.32	A	1.31	25.65	A	1.98
170 °C	LVL	24.89	E	1.70	27.04	E	1.79	21.01	C	2.18
	RLVL	27.78	B	1.87	33.93	B	2.31	25.11	A	2.04
200 °C	LVL	21.57	G	2.21	24.75	F	1.27	18.29	D	1.94
	RLVL	23.83	F	2.44	32.46	C	1.80	21.37	C	1.64
230 °C	LVL	17.74	I	2.16	21.57	G	1.79	16.74	F	1.38
	RLVL	19.72	H	1.73	27.75	DE	2.01	18.11	E	1.82

*LSD: ±0.4365; **LSD: ±0.9733; ***LSD: ±0.7049

Because of the lower screw withdrawal strength of heat-treated LVL, carbon fiber can be used between the heat-treated wood veneers to provide sufficient holding strength for many applications.

CONCLUSIONS

1. In all tests, the screw withdrawal strengths of RLVL were found to be higher than those of LVL.
2. High heat-treatment temperature reduces the withdrawal strength of screws.
3. The highest values were determined to be in the tangential direction.
4. The lowest values were detected in the transverse surface.
5. The highest screw withdrawal strength was found in reinforced LVL thermally modified at 140 °C, while the lowest was found for un-reinforced LVL samples thermally modified at 230 °C in the radial, tangential, and transverse directions.

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Article submitted: November 9, 2015; Peer review completed: December 16, 2015; Revised version received and accepted: December 17, 2015; Published: January 5, 2016.
DOI: 10.15376/biores.11.1.1729-1740