Optimization of Press time and Properties of Laminated Veneer Lumber Panels by Means of a Punching Technique

Halimeh Pangh [a,]* and Kazem Doosthoseini [b]

The impact of veneer punching pattern and density (343, 356, and 1424 hole·m^{-2}) was tested relative to selected physic-mechanical properties of 5-ply laminated veneer lumber (LVL) panels fabricated from poplar wood (*Populus deltoides*) under different press time (5, 6, and 7 min). Samples were made with urea-formaldehyde resin using hot press technology at a uniform pressure of 10.8 N·mm^{-2} and temperature of 120 °C. The results indicated that punching the inner veneers (except the core veneer) of LVL significantly improved the average values of shear strength, modulus of elasticity, and bending strength (both parallel and perpendicular to the grain). In contrast to control samples, the veneer punching technique showed an overall negative impact on the water resistance of LVL (after either 2 or 24 h of immersion in water). Nevertheless, specimens with punching densities of 1424 hole·m^{-2} pressed for a maximum of 5 min were more dimensionally stable than the control samples. The physic-mechanical properties of LVL were significantly affected by press time as well. Considering the data obtained, the press time of LVL could be reduced to nearly 16.7%, or 1 min, by using a punching density of 1424 hole·m^{-2} without any significant negative change in the major physic-mechanical properties.

Keywords: Hot pressing conditions; Layered wood-composite; LVL; Physico- mechanical properties; Press time; Punching density

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INTRODUCTION

Laminated veneer lumber (LVL) is a timber-like product that is generally constructed from layered wood veneer composites and synthetic resins. Considering the aesthetic beauty of natural wood, LVL technology encourages extensive usage of timber. However, unlike sawn timber, LVL can be produced in any size and length (depending on the dimensions of the press machine) and simultaneously offers the advantages of higher reliability, which can be achieved through the process of defect removal (Nzokou *et al.* 2005; Xue and Hu 2012), higher dimensional stability (Keskin 2001; Hayashi *et al.* 2005; Deam *et al.* 2008), and higher strength properties in certain directions (Kurt 2010; Kiliç 2011; Peker *et al.* 2015). The production process of LVL is very similar to that of plywood composite boards. In fact, the only distinguishing difference between LVL and plywood is the orientation of the veneers. In LVL panels, the grain direction of all veneer layers is the same, whereas for plywood boards, the grain direction in each layer can be varied. Apart from the mechanical and physical characteristics of wood materials and the type of adhesive used, the hot pressing characteristics (press time, pressure, press temperature, *etc*.) are among the most important factors that directly affect the properties of LVL panels (Döngel 1999; Shukla and Kamdem 2008, 2009; Bal and Bektaş 2012; Peker *et al.* 2015). In this context, hot press time is known as a bottle-neck for most wood-composite manufacturing factories (Doosthoseini 2001). Hence, shortening the hot press time can effectively reduce the waste of energy, as well as the production time of wood-composite materials.

The possibility of reduced hot pressing time has been studied in previous works on certain kinds of wood-based composite panels such as plywood (Mirski *et al.* 2011), particleboard (Lehmann *et al.* 1973; Ashori and Nourbakhsh 2008; Taghiyari *et al.* 2011), oriented strand board (Yapici *et al.* 2013), and medium-density fiberboard (Zhong *et al.* 2002; Pourtahmasi *et al.* 2007). However, only a few references could be found in the existing literature regarding the impact of pressing time on the properties of LVL panels. Kurt *et al.* (2011) demonstrated that the press-time significantly affects the dimensional stability, thickness swelling, water absorption, bending strength, and compression strength parallel to the grain of LVL panels made with fast growing hybrid poplar clones. These researchers reported that the press time had no important effect on the oven-dry density, weight loss, and modulus of elasticity of the tested LVLs.

The press time of LVL is generally determined by the time that is required for the stack core to reach a specific temperature for curing (*i.e.*, the temperature in which the adhesive is cured). The press time could be simply reduced if the pressing temperature was increased. However, even slight increases in the optimum press temperature can negatively affect the surface quality (as a result of temperature degradation on the board surface) and strength properties of LVL panels (Xue and Hu 2012; Peker *et al.* 2015). Hence, an alternative solution is to establish new techniques to reduce press duration without changing the optimum pressing temperature. Thus, the main goal of the present study was to optimize the hot pressing process of LVL by means of a punching technique. It was assumed that punching the inner veneers of LVL causes the stack core to reach the curing temperature faster than un-punched LVL, which would subsequently reduce the press time using this procedure. This study addresses the following specific objectives: a) to determine the impact of punching pattern and density on the physical and mechanical properties of LVL panels, b) to determine the impact of press time on the properties of the panels, and c) to statistically compare the properties of punched versus un-punched panels made under different press time.

EXPERIMENTAL

Materials

The veneers used in the study were rotary-cut from fast growing species of poplar (*Populus deltoides*) to the specifications of 500 mm × 500 mm × 1.7 mm (length, width, and thickness). The veneers were oven-dried at a temperature of 103 °C for 7 h. The average moisture content of the veneers after the drying process was 4 to 5%. A commercial urea-formaldehyde resin (UF, Arianchemie, Sari, Iran) was used in the bonding process of 5-ply LVL boards. The adhesive was spread uniformly on a single surface of each veneer using a controlled spread rate of 200 g/m^2.

Preparation of Test Specimens

To determine the impact of punching density on the properties of 5-ply LVL boards, the inner veneers of the LVLs (except the core veneer) were subjected to punching. Veneer B and veneer D (above and below the core veneer of the boards) were punched in order to obtain different punching densities, varying between 343 hole·m^{-2} (4 mm diameter holes), 356 hole·m^{-2} (3 mm diameter holes), and 1424 hole·m^{-2} (1.5 mm diameter holes) (Fig. 1). Un-punched 5-ply boards were also constructed to serve as the control samples, providing a basis for comparisons in the study.

All punched and un-punched boards were pressed in a hot press machine (Burkle-la-160, BURKLE, Germany) with a pressing area of 50 × 50 cm at a constant pressure of 10.8 N·mm^{-2} under different press time of 5, 6, and 7 min. The press temperature was held constant at 120 °C. The final thickness of the LVL boards was 8.5 mm, and their width and length after an edge cutting process was 47 and 47 cm, respectively. Prior to the testing processes, the boards were kept in a conditioning room with a relative air humidity of 65 ± 5% and a temperature of 20 ± 2 °C for two weeks.

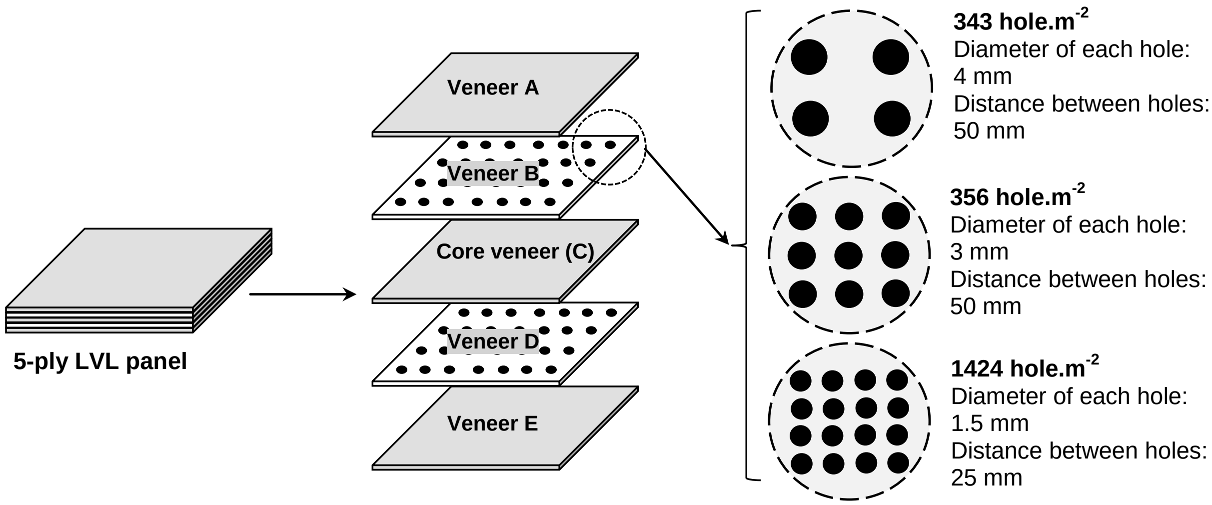

Fig. 1. General configuration and assembly pattern of the punched LVL boards with different punching densities

Testing Methods

Physical properties

The oven-dry density of each board type was measured in accordance with the procedure described in the ISO 9427 standard. Thickness swelling (TS) after 2 and 24 h of water saturation was also computed according to ISO 16983 as follows,

$$TS_{(2,24)} = [\frac{t_{(2,24)} - t_1}{t_1}] \times 100 \tag{1}$$

where $TS_{(2, 24)}$ refers to the thickness swelling after either 2 or 24 h of immersion in water (%), $t_{(2, 24)}$ is the thickness of the test specimen after immersion for either 2 or 24 h (mm), and t_1 is the thickness of the test specimens before immersion (mm).

Likewise, the water absorption after either 2 h (WA_2) or 24 h (WA_{24}) of immersion in water was computed for each specimen in accordance with ISO 16983 (2003), based on the oven-dry weight (W1) and wet weight, using the formula,

$$WA_{(2,24)} = [\frac{w_{(2,24)} - w_1}{w_1}] \times 100 \quad (2)$$

where $WA_{(2, 24)}$ refers to the water absorption after either 2 or 24 h of soaking in water (%), $W_{(2, 24)}$ is the weight of the specimens after 2 or 24 h (g), and W_1 is the oven-dry weight (g).

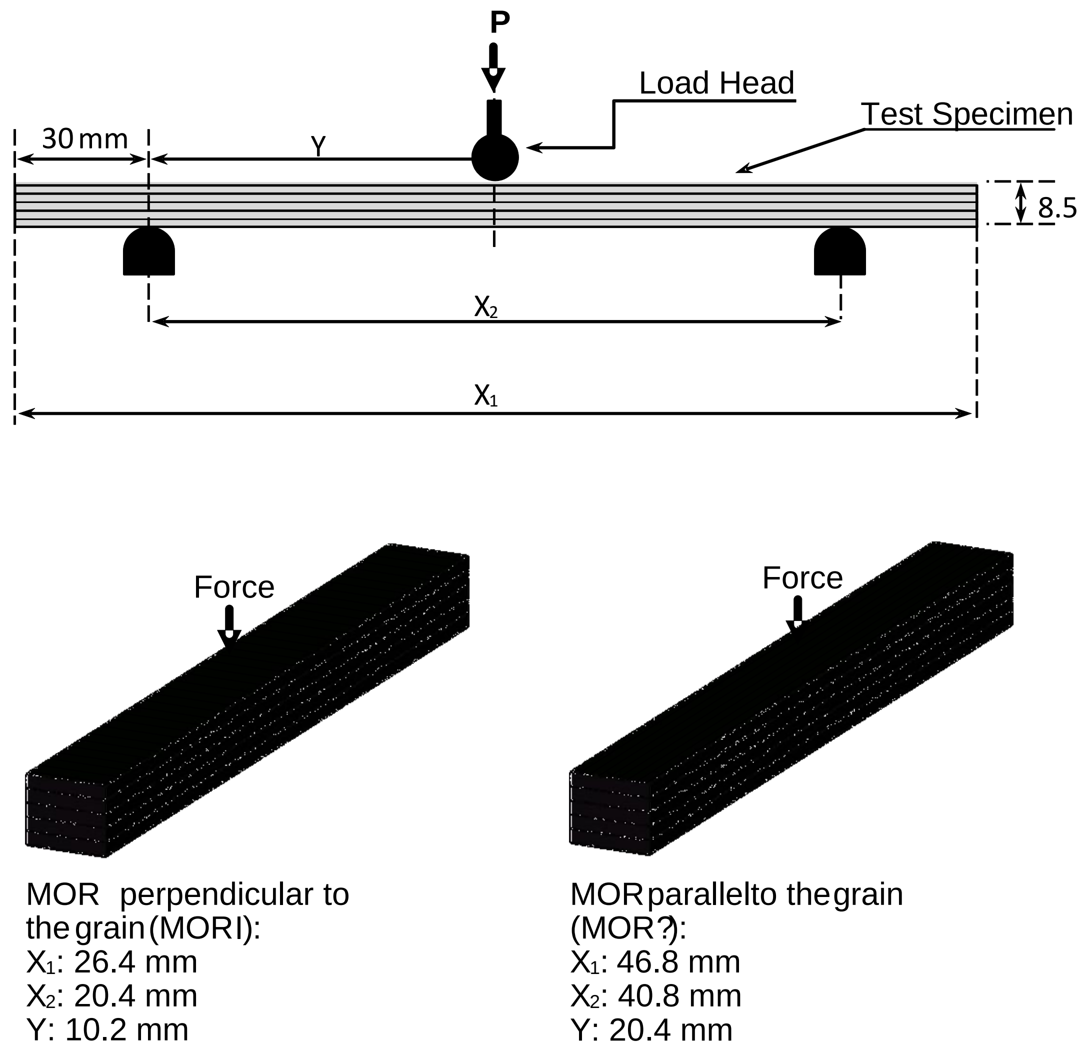

Fig. 2. Evaluation of bending strength perpendicular (MOR I) and parallel (MOR II) to the grain of specimens

Modulus of rupture (static bending strength)

The values of modulus of rupture for the specimens, parallel (MOR II) or perpendicular (MOR I) to the grain, were determined in accordance with the ISO 16978 (2003) standard procedure using the following equation,

$$MOR = \frac{1.5 P_{max} L}{bh^2} \quad (3)$$

where MOR is the modulus of rupture (MPa), P_{max} is the maximum load (N), L is the span (mm); b is the width of the specimen (mm), and h is the thickness of the specimens (mm).

Configurations and dimensions of the LVL boards, as well as the test set-ups used for the evaluation of static bending strength of the test specimens are illustrated in Fig. 2. The tests were carried out by placing the specimens in the test equipment in such a way that the loading direction of the applied force would come in the direction of the thickness of the panels. Six replicates of each board type were tested on an Instron testing machine (model 4486, Norwood, MA, USA) with a loading velocity of 10 mm/min.

Modulus of elasticity

The modulus of elasticity, perpendicular (MOE I) or parallel (MOE II) to the grain, was measured according to the procedure described in ISO 16978 (2003) as follows,

$$MOE = \frac{P_{PL} \times L}{4bh^2 D} \tag{4}$$

where MOE is the modulus of elasticity (MPa), P_{PL} is the load at the limit of proportionality (N), L is the span (mm), b is the width of the specimen (mm), h is the thickness of the specimen (mm), and D is the deflection (mm).

Experiments were conducted on an Instron testing machine (model 4486) with a loading rate of 10 mm/min according to the relative standard test method. The test set-up and specimen dimensions for the evaluation of MOE values were the same as those in the bending strength test described in the previous section (Fig. 2). Likewise, six replicates were tested for each board type.

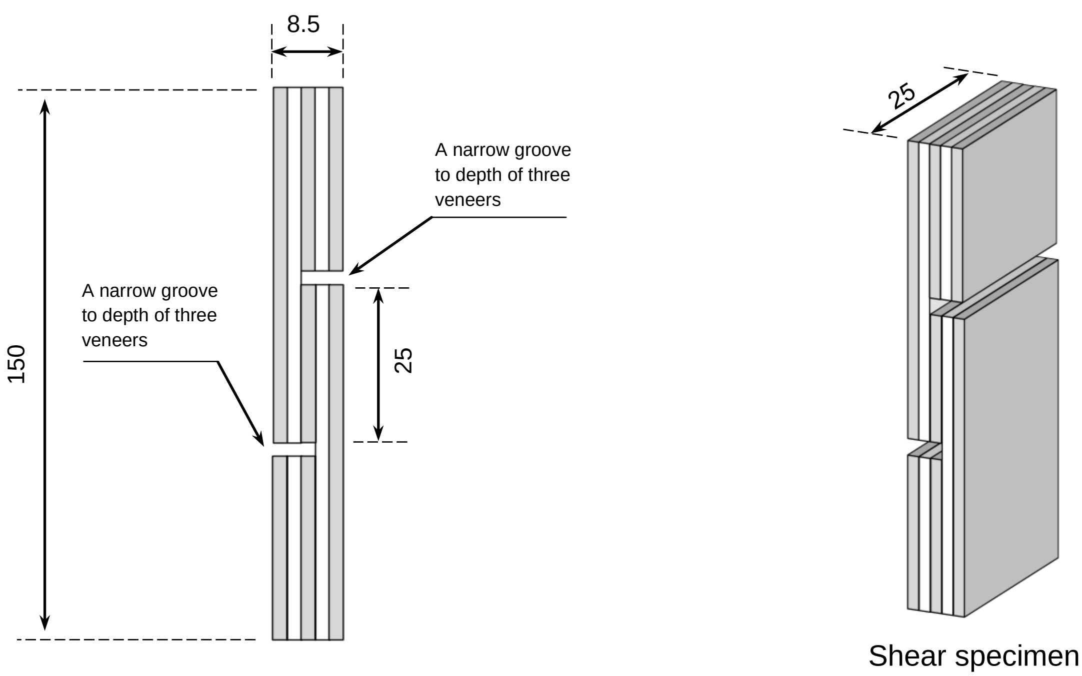

Fig. 3. Geometry and dimensions of specimens used for shear strength determination (measurements in mm)

Tensile shear strength

As shown in Fig. 3, the length, width, and thickness of the shear samples were 150, 25, and 8.5 mm, respectively. To create an overall shear area of 25 mm × 25 mm, according to EN 314-1 (2004), two grooves were made on each side of the samples (to a depth of three veneers on either side) using a table saw. The width of the grooves was 3 mm.

Tensile shear tests were conducted on a Wolpert testing machine (model Anslr-5 ton, Norwood, MA, USA) with a feed rate of 10 mm/min. Six replicates were constructed and tested for each group. Maximum loads at the failure point were recorded with an accuracy of 1 N. Tensile shear strength values were then calculated using Eq. 5,

$$\tau = \frac{P}{A} \tag{5}$$

where τ is the shear strength (MPa), P is the maximum applied load (N), and A is the shear area (625 mm^2).

Data Analysis

A factorial experimental design was used to determine the impact of test variables on the properties of LVL panels (Table 1).

Table 1. Experimental Design Used in the Study

Punching Density (3 levels) (hole.m^{-2})	Press time (3 levels) (minute)	Replicates for Each Test					
		Density	MOE	MOR	Shear	Thickness swelling	Water absorption
343	5	9	6	6	6	9	9
356	6	9	6	6	6	9	9
1424	7	9	6	6	6	9	9
343	6	9	6	6	6	9	9
356	7	9	6	6	6	9	9
1424	5	9	6	6	6	9	9
343	7	9	6	6	6	9	9
356	5	9	6	6	6	9	9
1424	6	9	6	6	6	9	9
Control (without punching)	6	9	6	6	6	9	9
	Total	90	60	60	60	90	90

The results obtained in the study were analyzed using SPSS software (version 13.0, IBM Corporation, Armonk, NY, USA). Analysis of variance (ANOVA) and Duncan's multiple range tests were performed on the data set to examine the significance of the differences between various treatments at a 95% confidence level.

RESULTS AND DISCUSSION

Physical Properties

According to ANOVA results (Table 2), mean values of density, WA_2, WA_{24}, TS_2, and TS_{24} of LVLs were significantly affected by press duration. Except for the thickness swelling after 24 h (TS_2), the impact of punching density on the physical properties was highly significant ($p < 0.001$). The interaction effect of the test factors on density, WA_2, WA_{24}, TS_2, and TS_{24} was also significant at a 95% confidence level.

Table 2. ANOVA for the Effect of Press Time and Punching Density on Physical Properties of LVLs

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	*p* value
Press time (A)	Board density	.066	2	0.033	124.033	0.000
	WA_2	3875.644	2	1937.822	154.105	0.000
	WA_{24}	4462.325	2	2231.162	200.165	0.000
	TS_2	29.456	2	14.728	21.585	0.000
	TS_{24}	11.827	2	5.914	20.486	0.000
Punching Density (B)	Board density	.011	3	0.004	13.172	0.000
	WA_2	272.738	3	90.913	7.230	0.000
	WA_{24}	1158.182	3	386.061	34.635	0.000
	TS_2	13.832	3	4.611	6.757	0.000
	TS_{24}	2.279	3	0.760	2.632	0.056
A × B	Board density	.055	4	0.014	51.850	0.000
	WA_2	161.563	4	40.391	3.212	0.017
	WA_{24}	489.232	4	122.308	10.973	0.000
	TS_2	58.224	4	14.556	21.33	0.000
	TS_{24}	16.921	4	4.230	14.654	0.000
Total	Board density	22.286	90			
	WA_2	137355.966	90			
	WA_{24}	410109.337	90			
	TS_2	1557.401	90			
	TS_{24}	2441.036	90			

The average density values of the test boards and Duncan's tests are shown in Fig. 4. Regardless of the board type, the oven-dry density of the test samples decreased with increasing press duration. However, press duration had no meaningful impact on the density of LVLs with a punching density of 343 hole/m^2. The highest average density value for oven-dry samples was found in LVLs with a punching density of 1424 hole/m^2; this was followed by the oven-dry densities of LVLs with punching densities of 343 and 356 hole/m^2, respectively. The oven-dry densities of the control samples were comparable to those of LVLs with a punching density of 1424 hole/m^2 and a press time of 6 min.

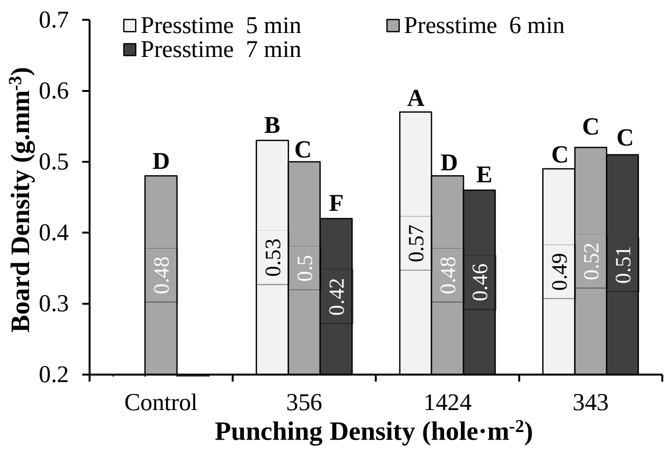

Fig. 4. Average density values according to board type and press time; Latin letters indicate Duncan group

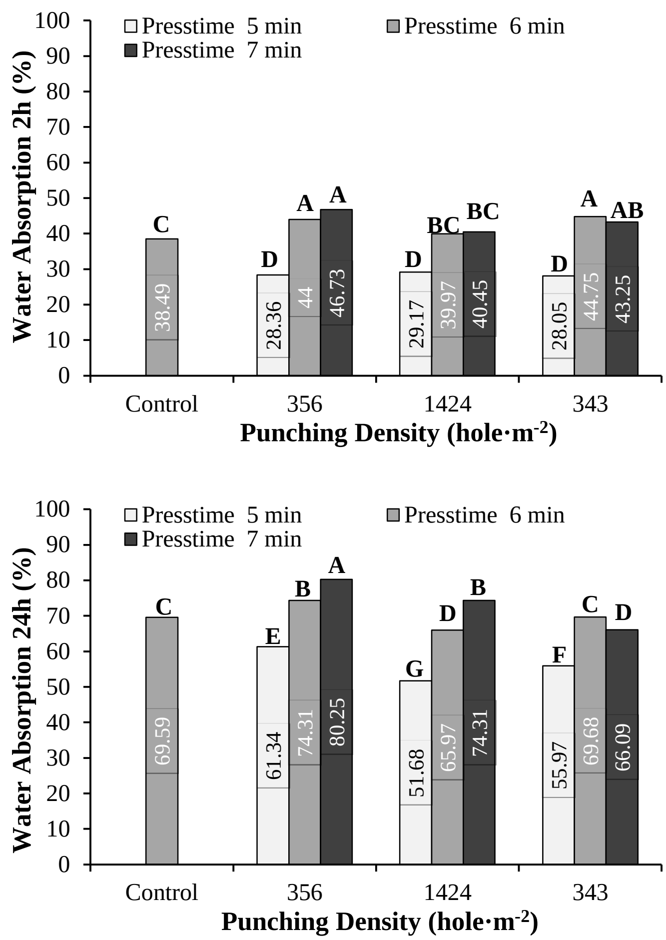

Fig. 5. Average values of water absorption after 2 h (top) and 24 h (below) of immersion in water

Mean LVL water absorption values, as well as their respective Duncan's test results, are shown in Fig. 5. In all cases, water absorption increased with press duration. Overall, LVL boards with a punching density of 356 hole/m^2 that were pressed for a minimum 6 min contained the highest average values of water absorption. The lowest water absorption was also found in LVL boards with a punching density of 1424 hole/m^2 that were constructed at 5 min hot press time. As expected, the average values of WA_{24} were significantly greater than those of WA_2. According to the Duncan's test, when a comparison is made only between the control samples and comparable punched LVLs that were produced with press time of 6 min, the punching technique increased WA_2 values. However, its increasing influence on WA_{24} values was much less important. The lower water resistance of punched boards could be related to an increase in the overall area of the side surfaces of the boards that occurred as a result of punching. Any increase in the contact area between water and the side surfaces of LVL could increase the amount of water that is absorbed by the boards.

As shown in Fig. 6, the worst dimensional stability was observed in the LVLs with punching densities of 343 hole/m^2 and press time of 6 min.

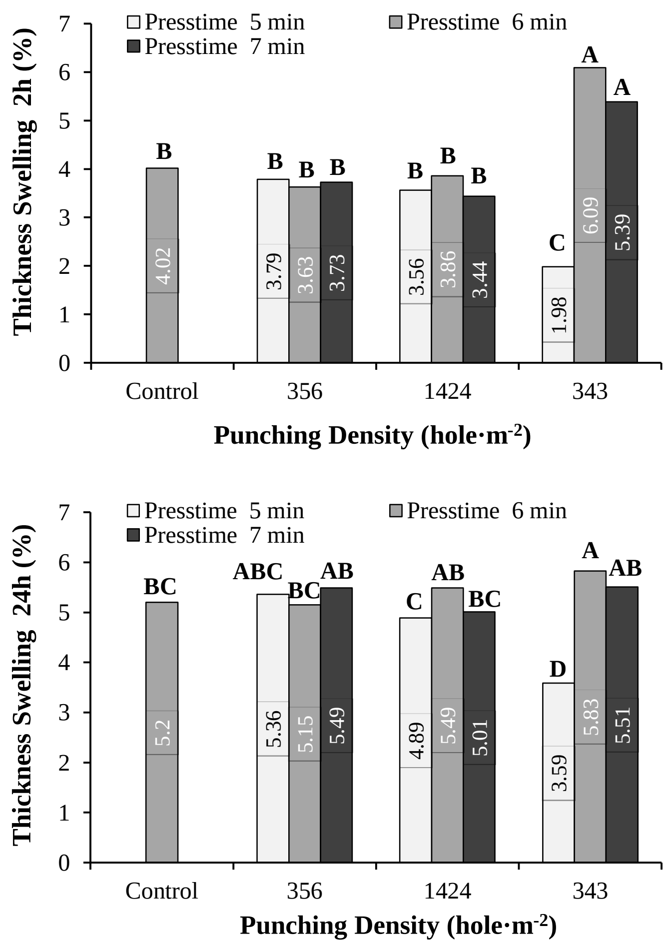

Fig. 6. Thickness swelling after 2 h (top) and 24 h (below) of immersion in water

Except for the LVLs with a punching density of 343 hole/m^2, there was no significant difference between the control samples and the punched samples with respect to either TS_2 or TS_{24} values. The lowest average values of both TS_2 and TS_{24} were also obtained by LVLs with punching densities of 343 hole/m^2 and press time of 5 min, followed by LVLs with punching densities of 1424 hole/m^{-2} and press time of 5 min. On average, LVLs with a punching density of 1424 hole/m^2 showed better dimensional stability than the other LVL boards.

Overall, considering the oven-dry density, water absorption, and dimensional stability characteristics, the LVL samples with a punching density of 1424 hole/m^2 that were constructed with 5 min of hot pressing showed excellent physical properties, in contrast to the control samples (un-punched LVLs). These results indicate that the press time of LVL could be reduced to by 1 min using the punching technique without causing any considerable change in the board physical properties.

Mechanical Properties

The ANOVA results regarding the influence of punching density and press time on the mechanical properties are given in Table 3. The results revealed that mean values of MOR-II, MOE-I, MOR-I, and shear strength of LVLs were significantly correlated to press time. However, the impact of press time on MOR-II values was not statistically significant. Furthermore, although the impact of punching density on mean values of MOR-I and shear strength was statistically significant, it had no meaningful impact on MOR-II, MOR-I, and MOE-II values. The interaction effect of the two factors on MOR-I and shear strength was also significant (p > 0.05).

Table 3. ANOVA Results for the Effect of Press Time and Punching Density on Mechanical Properties of LVLs

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	*p* value
Press time (A)	MOR-II	6706.196	2	3353.098	6.150	0.004
	MOE-II	484400.333	2	242200.167	0.066	0.936
	MOR-I	10.724	2	5.362	13.285	0.000
	MOE-I	180635.148	2	90317.574	23.681	0.000
	Shear strength	2.184	2	1.092	6.102	0.004
Punching density (B)	MOR-II	2834.490	3	944.830	1.733	0.172
	MOE-II	1.750E7	3	5832761.963	1.593	0.203
	MOR-I	.931	3	0.310	0.769	0.517
	MOE-I	52513.940	3	17504.647	4.590	0.006
	Shear strength	11.757	3	3.919	21.896	0.000
A × B	MOR-II	1882.465	4	470.616	0.863	0.493
	MOE-II	3.113E7	4	7783136.833	2.125	0.091
	MOR-I	10.294	4	2.574	6.376	0.000
	MOE-I	37589.296	4	9397.324	2.464	0.057
	Shear strength	25.780	4	6.445	36.009	0.000
Total	MOR-II	789726.290	60			
	MOE-II	1.343E10	60			
	MOR-I	1022.550	60			
	MOE-I	1.281E7	60			
	Shear strength	282.094	60			

The average MOE values (perpendicular (I) or parallel (II) to the grain) of LVLs associated with the Duncan's test results can be seen in Fig. 7. At first glance, it is clear that press time had a decreasing influence on the MOE-I values of punched samples. LVL panels with punching densities of 343 hole/m^2 and pressed for durations of 5 min were characterized by the highest average MOE-I value. The lowest average value of MOE-I was obtained with the control samples and LVL panels punched with a punching density of 356 hole/m^2 and pressed for 7 min. In all cases, MOE-I decreased with increasing press time.

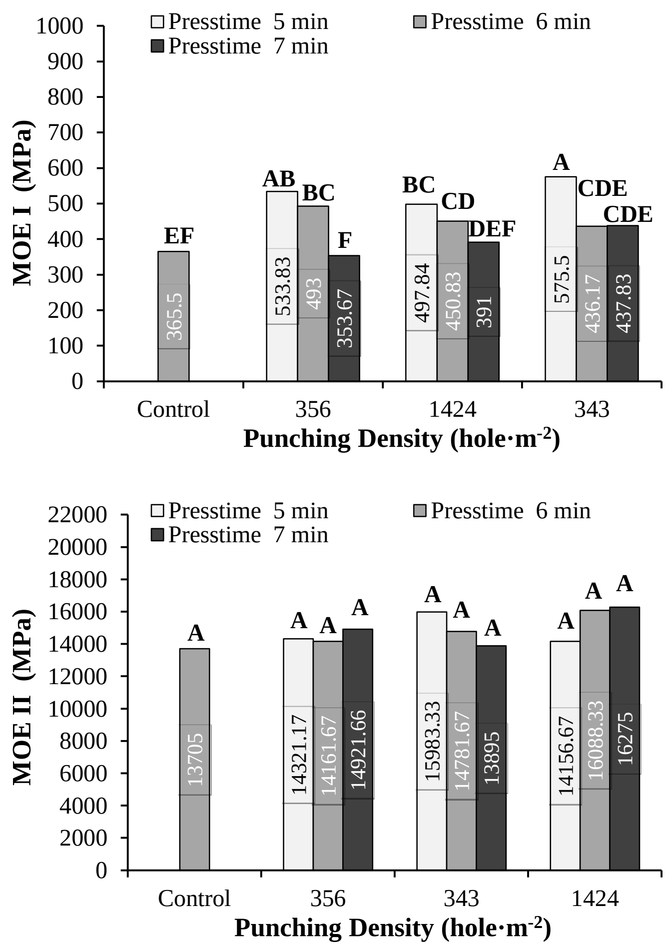

Fig. 7. Average modulus of elasticity values perpendicular (top) and parallel (below) to the grain

It was surprising to observe a lack of any significant difference in MOE-II values between the punched and control samples. However, although not meaningfully different, the punched samples exhibited higher MOE-II values than the control samples. In addition, there was no important difference between MOE-II values of LVLs made at different press times. This agreed with results obtained by Kurt *et al.* (2011) concerning the impact of press time on the modulus of elasticity of poplar LVLs. It is obvious from Fig. 6 that the averages values of MOE-II were significantly higher than the MOE-I values. On average, MOE-II values were about 35 times greater than their corresponding MOE-I values. The highest average MOE-II was for the LVLs with punching densities of 1424 hole·m^{-2} and a press time of 5 min.

The mean values of MOR-II and MOR-I for the tested LVLs are illustrated in Fig. 8. The press time factor had a negative impact on the bending strength of the tested specimens (for both MOR-I and MOR-II values). The highest values of both MOR-I and MOR-II were achieved by the LVLs with punching densities of 1424 hole/m^2 that were pressed for 5 min. Except for the punching density of 1424 hole/m^2, the punching density had no important impact on mean values of MOR-II. Overall, as expected, the average values of bending strength parallel to the grain (MOR-II) were significantly higher than those of bending strength perpendicular to the grain (MOR-I).

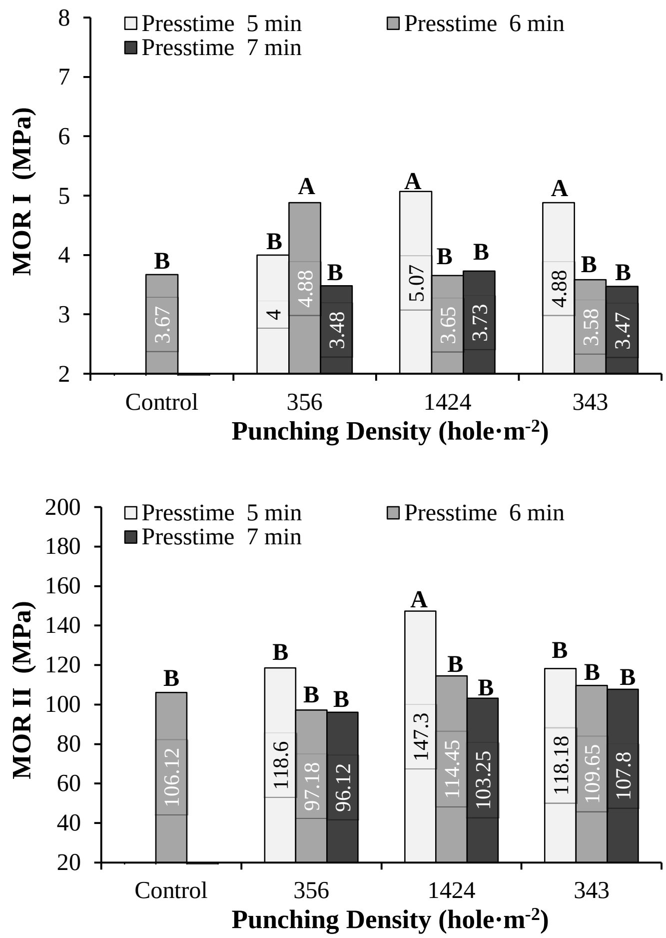

Fig. 8. Average values of MOR-I and MOR-II of punched and un-punched samples

The average shear strength values of the specimens, along with the Duncan's test results, are depicted in Fig. 9. The shear strengths of LVLs with punching densities of 356 and 1424 hole/m^2 were higher than the shear strengths of the control samples. The highest shear strength was obtained by LVLs with punching densities of 1424 hole/m^2 and press times of 5 min. Although not significantly different from control samples, the lowest shear capacity was observed in specimens with punching densities of 343 hole/m^2 that were made using a 5 min press time. For both punching densities of 343 and 356 hole/m^2, the shear strength increased with increasing press time, but the press time exhibited a decreasing effect on the shear strength of the samples with punching densities of 1424 hole/m^2.

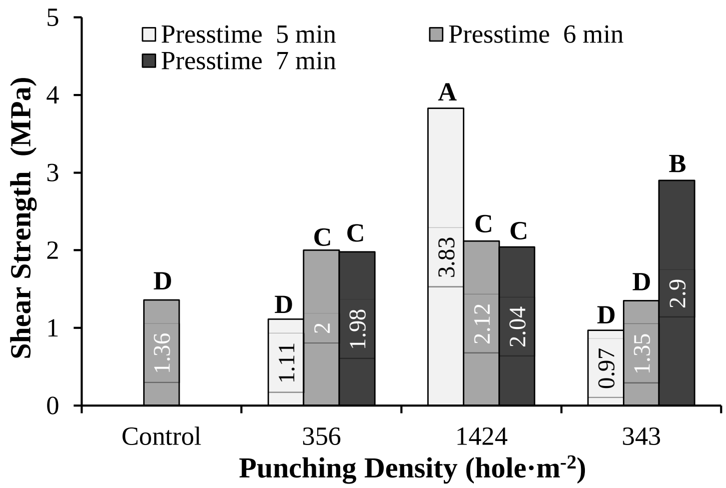

Fig. 9. Shear strength of punched and un-punched samples

CONCLUSIONS

1. Punching of the inner layers (except the core layer) of LVL had an improving effect on bending strength (both parallel and perpendicular to the grain), modulus of elasticity (both parallel and perpendicular to the grain), and shear strength. However, punched LVL boards had slightly higher water absorption in contrast to un-punched boards, resulting in lower dimensional stability.
2. Both physical and mechanical properties of LVL were affected by press time. The mechanical strengths of LVL (MOE, MOR, and shear strength) decreased with increasing hot press time. Furthermore, water resistance and dimensional stability of LVL decreased with increments in hot press time.
3. Overall, the press time could be reduced from 6 min to 5 min by a punching technique without any significant effect on the properties of LVL boards. Considering the results obtained, a punching density of 1424 hole/m^2 is recommended.

ACKNOWLEDGMENTS

The authors are grateful to Mr. Reza Ghasemi-Rajaie, the managing director of Sina Sanat the Seventh Art Innovative Engineering Co., for supplying some of the laboratory equipment used in the study.

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Article submitted: June 2, 2016; Peer review completed: August 27, 2016; Revised version received and accepted: January 27, 2017; Published: February 2, 2017.
DOI: 10.15376/biores.12.2.2254-2268