THE EFFECTS OF SOME FACTORS ON THE IMPACT BENDING STRENGTH OF LAMINATED VENEER LUMBER

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In this study, the impact bending strengths and specific impact bending strengths were determined for solid wood and laminated veneer lumber (LVL) produced from eucalyptus (*Eucalyptus grandis* W. Hill ex Maiden), poplar (*Populus x euramericana* I-214), and beech (*Fagus orientalis* L.) woods using urea formaldehyde (UF), melamine urea formaldehyde (MUF), and phenol formaldehyde (PF) adhesives. The tests were conducted in the flatwise and edgewise directions. In addition, specific impact bending strengths were calculated. Three-way ANOVA test results indicated that the effects of the species of tree and the direction of the load on the impact bending and specific impact bending were statistically significant. The type of adhesive was found to be insignificant. In addition, the results showed that impact bending strengths of solid beech and eucalyptus woods were greater than those of LVLs made of beech and eucalyptus, and no statistical differences were determined between solid poplar wood and LVL made of poplar.

Keywords: LVL; Laminated veneer lumber; Impact bending; Specific impact bending

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INTRODUCTION

The impact bending strength of wood and other engineering materials is one of the most important mechanical properties affecting its use under dynamic loads. Impact bending is different from static bending and other mechanical properties due to the loading time of the test. Unlike other mechanical tests, the time span is very short.

Siewert *et al*. (1999) noted that impact machine designers and manufacturers have offered three major types of equipment: Drop Weight, Pendulum Impact, and Flywheel. In addition, impact data is measured using toughness machines that were developed by the USDA Forest Products Laboratory. The toughness tester imparts loading on the specimen via an aluminum tip chain attachment to the pendulum system, while Amsler and Izod tests involve a direct pendulum impact (Janowiak and Bukowski 2000). Generally, the units for impact bending strength are expressed as kgm/cm^2, kJ/m^2, J/cm^2, or $ft\text{-}Ib/in^2$.

Structural composite lumbers (SCL), such as laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL) are preferred over solid wood because of their superior mechanical properties. LVL is manufactured and used extensively as a construction material, and many different species of trees have been evaluated for their viability in making this material (Ozarska 1999). LVL has many benefits compared to solid wood. The LVL process can be used to produce large-scale parts by adjoining smaller pieces together to form a homogeneous structure, avoiding the weakest point of one piece.

Many other researchers have conducted laboratory studies of the mechanical properties of LVL. The bending properties and bonding performance of LVL made from eucalyptus, poplar, and beech have been studied extensively (Carvalho *et al.* 2004; Aydın *et al.* 2004; Çolak *et al.* 2007; Saviana *et al.* 2009; Erdil *et al.* 2009; Kurt 2010; Kılıç 2011). However, the impact bending strength of LVL made of different species of trees has been evaluated in only a few studies (Janowiak and Bukowski 2000; Bao *et al*. 2001; Çolak *et al*. 2007; Adachi *et al.* 2010). For these reasons, the main aims of this study were: to determine and compare the effect of the direction of load on impact bending strength of LVL made of some hardwood species, to determine how some formaldehyde-based adhesives affect the impact bending strength of LVL, and to determine and compare impact bending strength and specific impact bending strength of solid wood and LVLs.

MATERIALS AND METHODS

Solid Wood and Veneer Preparation

Beech and poplar logs were cut from the Yenice-Karabük region, and eucalyptus logs were cut from the Karabucak-Tarsus region in Turkey. To reduce variability of properties, test samples of solid wood and veneers of LVLs were obtained from the same logs. Pieces from the ends of the logs were used to prepare of solid wood test samples. The rest of the logs were used to produce rotary-peeled veneers. The beech logs and eucalyptus logs were steamed at 80 °C for 50 and 15 hours, respectively. Poplar logs were not steamed because poplar wood is soft and has low density and it can be peeled without steaming. Then, 3 mm thick rotary-peeled veneers were obtained from those logs, and veneers were dried in a plywood factory until the moisture content was 7±1%.

Adhesives

Veneers were used to manufacture LVLs using UF, MUF, and PF adhesives from Gentaş Kimya company in Turkey. The UF adhesive contained 100 units of adhesive, 30 units of wheat flour, and 10 units of hardener (15% ammonium sulfate), while the MUF adhesive contained 100 units of adhesive, 15 units of wheat flour, and 10 units of the same hardener. Neither additives nor filler were used with the PF adhesive. The press temperatures of the UF, MUF, and PF adhesives were 110, 110, and 140 °C, respectively. Because poplar wood has lower density than beech and eucalyptus, the press pressures for poplar, beech, and eucalyptus plywood were 8, 12, and 12 kg/cm^2, respectively. The press duration was 24 min. Almost 200 g/m^2 of adhesive was spread manually on the loose side of the veneers.

LVL Manufacture

After gluing, seven veneer sheets (600 x 600 x 3 mm; length x width x thickness) were laid with the fiber directions parallel to each other. These stacks were pressed in a hot press in the laboratory. Five panels were produced per group. Panels were stored for a week after pressing. Thereafter, impact bending test samples were prepared from these boards. Three flatwise and three edgewise test samples were cut from each LVL board for per group.

Tests and Measurements

Values for air-dried density (D_{12}), equilibrium moisture content (EMC), and impact bending (IB) were determined according to Turkish standards TS 2471, TS 2472, and TS 2477, respectively. The samples were conditioned at 20±3 °C and 65±5% relative humidity until constant weight (approximately 3 weeks). The IB tests of solid woods were performed on tangential direction. The IB tests of LVLs were performed in flatwise and edgewise direction. The dimensions of IB test samples were 20 mm wide, 20 mm high, and 300 mm long. The tests were performed on a pendulum impact bending machine (Losenhausen model). In addition, specific impact bending (SIB) was also calculated to reduce the effect of density from findings. After the impact bending tests, as shown in Fig. 1, two test samples to determine the density and equilibrium moisture content were obtained from each of the test samples. Fifteen flatwise and fifteen edgewise test samples were prepared for each groups. Before the test, the dimensions of the samples were measured to a precision of 0.01 mm.

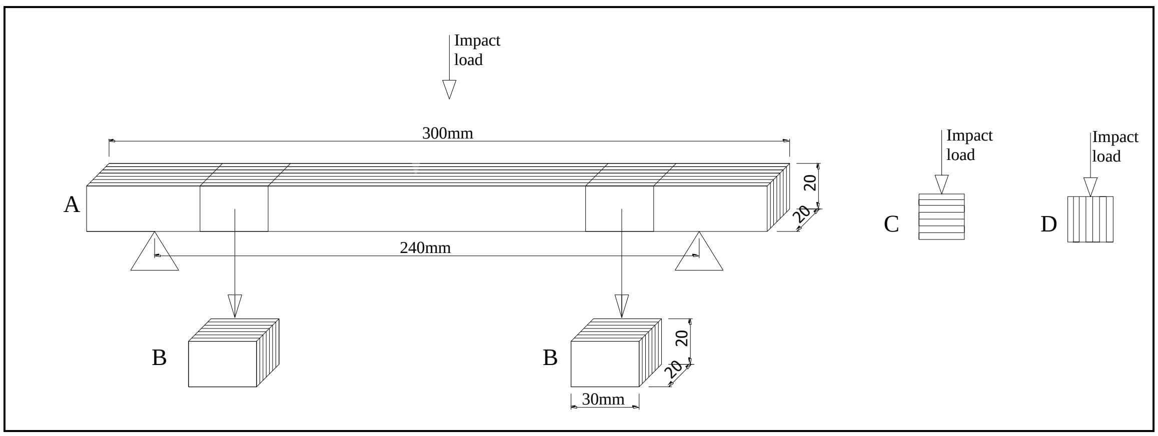

Fig. 1. (A) IB test samples, (B) D_{12} and EMC test samples, (C) flatwise direction, and (D) edgewise direction

IB and SIB were calculated using Equation (1) and (2), respectively. After the test, the moisture content of the samples was determined and the IB values were corrected using the strength conversion, Equation (3), to reduce the effect of the moisture content on the results,

$$IB = Q/(a \times b) \tag{1}$$

where IB is impact bending (kgm/cm^2), Q is absorbing energy (kgm), a is the width of sample (cm), and b is the thickness (cm). Also,

$$SIB = IB/D_{12} \tag{2}$$

where SIB is specific impact bending (m^2), IB is impact bending (kgm/cm^2), and D_{12} is the air-dried density (g/cm^3) at 12% moisture content. Finally,

$$IB_{12} = IB_M \,(1+\alpha\,(M - 12)) \qquad (3)$$

where IB_{12} is the impact bending at 12% moisture content, IB_M is the impact bending at M% moisture content, α is a constant (α = 0.025 for impact bending), and M is the moisture content of the test sample during the test.

The results were analyzed using ANOVA. One-way ANOVA tests were used to determine differences of IB between solid wood and LVLs. Three-way ANOVA, (p = 0.05) (General linear model-univariate) from the SPSS statistical software program, were used to determine the effects of tree species, load direction, and adhesives types and significant differences were determined by Tukey HSD (Honestly Significant Difference) Multiple Comparison Test (α = 0.05).

RESULTS AND DISCUSSION

Table 1 lists the D_{12}, EMC, IB, and SIB values of solid poplar, beech, and eucalyptus woods. The air-dried density of solid beech wood was higher than the air-dried densities of both solid eucalyptus and poplar woods, with the density of poplar wood being the lowest. On the contrary, the IB and SIB values of eucalyptus wood were greater than those of beech wood. This result was unexpected, since there is a strong relationship between the mechanical properties of solid wood and its density. The mechanical properties of woods that have higher densities are generally better than those of woods that have lower densities. Another factor that could have influenced IB is steaming. The beech logs (the average diameter of beech and eucalyptus logs are 55 and 30 cm, respectively) were steamed for a longer time than were the eucalyptus logs, and research has shown that the steaming process negatively impacts the mechanical properties of solid wood. Similar results for steamed solid beech wood were noted by Çolak *et al.* (2007) and Yılgör *et al.* (2001).

Table 1. D_{12}, EMC, IB, and SIB of Solid Poplar, Beech, and Eucalyptus Woods

Wood Type	D_{12} (g/cm^3)		EMC (%)		IB (kgm/cm^2)		SIB (m^2)	
	x	s	x	s	x	s	x	s
Poplar (n:60)	**0.375**	0.42	**12.3**	1.01	**0.379**	0.093	**10.1**	0.14
Beech (n:50)	**0.656**	0.45	**12.3**	1.36	**0.720**	0.265	**11.0**	0.16
Eucalyptus (n:60)	**0.604**	0.78	**12.6**	1.04	**0.764**	0.245	**12.6**	0.18

x: average value; s: the standard deviation; D_{12} and EMC values were measured on the same samples.

Table 2 provides the D_{12} and EMC of LVL made of poplar, beech, and eucalyptus woods using UF, MUF, and PF adhesives. The densities of the air-dried LVLs were greater than those of the solid woods from which the LVLs were produced. The greatest increase in density occurred in the LVLs made of poplar wood. It is known that the density of LVLs and other veneer-based products increases due to the pressure applied during the pressing process. Kurt and Çil (2012) proved the effects of press pressure in a detailed study on LVL. The density can be used to predict the physical and mechanical properties of wood and wood-based materials.

Table 2. D_{12} and EMC Values of LVLs

n : 60 for each group		Poplar			Beech			Eucalyptus		
		UF	MUF	PF	UF	MUF	PF	UF	MUF	PF
D_{12} (g/cm^3)	x	**0.450**	**0.443**	**0.449**	**0.665**	**0.653**	**0.677**	**0.641**	**0.623**	**0.640**
	s	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.03	0.02
EMC (%)	x	**9.35**	**8.50**	**8.45**	**9.15**	**8.55**	**8.55**	**9.90**	**9.55**	**9.25**
	s	0.3	0.7	0.3	0.2	0.2	0.2	0.2	0.5	0.3

D_{12} and EMC values were measured on the same samples.

The EMC values of the LVLs were between 8.45% and 9.90%, and they were lower than the values for solid wood. This phenomenon is known to be due to hysteresis, which occurs in wood-based materials that are produced in a hot press. In addition, glue lines can also be caused by reduced moisture transport across veneers. Similar results about EMC have been reported by other researchers (Bao *et al.* 2001; Çolak *et al.* 2004). Because of this phenomenon, comparisons were made after all of the results of the impact bending tests were converted to 12% moisture content to reduce the effect of moisture content.

Table 3 contains the IB and SIB values for the LVLs that were tested. The greatest IB values were determined to be 0.718 kgm/cm^2 in the LVL made of eucalyptus using PF adhesives in the flatwise direction. The highest SIB value was 11.32 m^2 in the LVL made of eucalyptus using MUF adhesives in the flatwise direction. The lowest IB was determined as 0.373 kgm/cm^2 in the LVL made of poplar using UF in the edgewise direction, and the lowest SIB value was determined to be 6.77 in the LVL made of beech in the edgewise direction.

Table 3. IB and SIB Values of LVLs

n:15 for each group		UF				MUF				PF			
		IB (kgm/cm^2)		SIB (m^2)		IB (kgm/cm^2)		SIB (m^2)		IB (kgm/cm^2)		SIB (m^2)	
		x	s	x	s	x	s	x	s	x	s	x	s
Poplar	EW	**0.373**	0.11	**8.04**	1.91	**0.389**	0.07	**8.88**	1.41	**0.397**	0.10	**8.78**	2.03
	FW	**0.445**	0.13	**10.04**	2.58	**0.425**	0.07	**9.44**	1.54	**0.43**	0.08	**9.57**	1.71
Beech	EW	**0.449**	0.09	**6.77**	1.23	**0.452**	0.06	**6.92**	0.87	**0.518**	0.07	**7.63**	0.89
	FW	**0.564**	0.11	**8.41**	1.51	**0.638**	0.08	**9.77**	1.18	**0.637**	0.07	**9.41**	1.00
Eucal.	EW	**0.682**	0.06	**10.6**	0.76	**0.644**	0.1	**10.35**	1.38	**0.614**	0.09	**9.66**	1.45
	FW	**0.715**	0.12	**11.16**	1.66	**0.708**	0.09	**11.32**	1.19	**0.718**	0.15	**11.16**	2.33

EW: Edgewise, FW: Flatwise

Tang and Pu (1997) and Lee *et al.* (1999) stated that the specific bending strength and specific bending stiffness are considered to be the indices by which the efficiency and effectiveness of a material to be used in structural applications can be determined. In addition, Bal and Bektaş (2012) used the specific bending strength and specific bending stiffness from their previous study, and they noted that these values may be good predictors in research related to mechanical properties.

In addition, the IB values of solid wood were higher than those of the LVLs made from beech and eucalyptus veneer. According to one-way ANOVA, the differences were significant ($P < 0.01$), but no differences were found between the IB values of LVLs made of poplar and solid poplar wood.

Many studies have determined that the static mechanical properties of LVL are greater than those for solid wood (Bao *et al*. 2001; Shukla and Kamdem 2009; Kurt 2010). However, since the IB values were determined under dynamic loading, the IB values of the LVLs were lower than those of solid wood. On this topic, Çolak *et al.* (2007) stated that the IB values of LVLs may be lower than those of solid wood because the glue line is more brittle than solid wood. In another study, Bao *et al.* (2001) determined that the impact toughness of LVL made of poplar in the flatwise direction was higher than that of solid wood in the radial direction. In addition, the impact toughness of LVL in the flatwise direction was higher than in the edgewise direction. Bao *et al.* stated that, "when LVL was impacted radially, the glue lines were in series with one another; thus, only the wood veneer in the contacted LVL surface absorbed or buffered the impact energy. On the other hand, when LVL was impacted tangentially, the alternate veneers and adhesive films were in parallel with one another, therefore, the adhesive restricted the absorbing action of contiguous veneers to reduce the impact toughness."

Table 4 presents the results of a three-way ANOVA related to the effect of tree species, load direction, and type of adhesive on IB and SIB values. The results of ANOVA indicate that the differences among tree species and load direction had significant ($p < 0.001$) effects on the values of IB and SIB. The effect of the type of adhesive on the IB and SIB values was insignificant ($p > 0.05$). The effect of the interaction of tree species and load direction was significant ($p < 0.01$ and $p < 0.05$, respectively), and the other interactions were insignificant ($p > 0.05$).

Table 4. Three-way ANOVA Results of IB and SIB Values (P = 0.05)

	IB		SIB	
Source of variation	F value	Sig. level	F value	Sig. level
Tree species (TS)	179.9	0.000	61.7	0.000
Load direction (LD)	52.8	0.000	54.9	0.000
Adhesive type (AT)	0.5	0.585	0.8	0.468
TS*LD	6.0	0.003	3.3	0.039
TS*AT	2.3	0.062	1.6	0.173
LD*AT	0.3	0.733	0.0	0.977
TS*LD*AT	1.2	0.304	1.9	0.106

Table 5 shows the effects of the tree species on the IB and SIB values according to the results of the Tukey HSD multiple comparison test. The IB value of the LVL made with poplar wood was the lowest (0.409 kgm/cm^2) and LVL made with eucalyptus wood was the highest (0.680 kgm/cm^2). However, the SIB value of the LVL made from poplar wood (9.1 m^2) was higher than that of beech (8.1 m^2), and the LVL made from eucalyptus wood had the highest value (10.7 m^2).

The effects of the adhesives on the IB and SIB values are given in Table 5. The IB and SIB values of the LVL with the UF adhesive were the lowest at 0.538 kgm/cm^2 and 9.1 m^2, respectively, whereas the LVL with the PF adhesive had the highest IB and SIB values at 0.552 kgm/cm^2 and 9.3 m^2, respectively. No significant differences were observed between the three different types of adhesives, but Adachi *et al.* (2010) observed significant differences among some other types of adhesives, *i.e.*, epoxy, poly-vinyl acetate, silicon elastomer, and acrylic pressure-sensitive adhesives, in their Charpy impact bending test results.

Table 5. Tukey Test Results Related to the Effects of Tree Species, Adhesive Type, and Load Direction on the Values of IB and SIB (α = 0.05)

Tree species				Adhesive type				Load direction			
Source of variance	*n*	IB kgm/cm^2	SIB m^2	Source of variance	*n*	IB kgm/cm^2	SIB m^2	Source of variance	*n*	IB kgm/cm^2	SIB m^2
Poplar	90	0.409A	9.1B	UF	90	0.538A	9.1A	Edgewise	135	0.502A	8.62A
Beech	90	0.543B	8.1A	MUF	90	0.542A	9.4A	Flatwise	135	0.586B	10.03B
Eucalyptus	90	0.680C	10.7C	PF	90	0.552A	9.3A				

The direction of load affected the IB and SIB values, which, in the edgewise direction, were determined to be 0.502 kgm/cm^2 and 8.62 m^2, respectively, and in the flatwise direction were determined to be 0.586 kgm/cm^2 and 10.03 m^2, respectively. The values were higher in the flatwise direction than they were in the edgewise direction, and the differences were significant. Similar results were determined for modulus of rupture and modulus of elasticity of LVL by Bal and Bektaş (2012). It is thought that the reason for this is the pressure of the press. Pressure exerts a significant influence in the flatwise direction during the hot pressing process, and Kurt and Çil (2012) showed that mechanical properties are affected as a result of an increase in density. Similar results were obtained by Janowiak and Bukowski (2000), who reported that the toughness properties of several composite lumber materials (LVL, PSL, and LSL) were greater in the flatwise direction than in the edgewise direction.

CONCLUSIONS

In this study, the effects of tree species, type of adhesive, and direction of the load on the IB and SIB values of LVLs bonded with formaldehyde-based adhesives were determined. In addition, LVLs produced from eucalyptus and poplar, which are fast-growing trees, were compared with LVL made from beech. The results showed that:

1. IB and SIB values of LVLs made of eucalyptus were higher than those of LVLs made of beech, and the differences were statistically significant.
2. The effect of adhesive type on the IB and SIB values was insignificant.
3. The effect of load direction on the IB and SIB values were significant, and the values were higher in the flatwise direction than they were in the edgewise direction.
4. IB and SIB values of solid beech and eucalyptus wood were higher than those of LVLs made of beech and eucalyptus.
5. The densities of the LVLs were higher than those of the solid woods, but the EMC values of LVLs were lower than those of the solid woods.

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