Performance of Laminated Veneer Lumber Panels from Fast-Growing Species with Different Layering Arrangements

Mohammad Arabi,[a,]* Moharam Hazrati,[b,]* and Akbar Rostampour-Haftkhani [c]

This study investigated the effect of various layer arrangements and their impact on the properties of laminated veneer lumber (LVL). Seven different layer arrangements (CCCCCCC, DDDDDDD, PPPPPPP, CDDDDDC, CPPPPPC, CDDCDDC, CPPCPPC, CDCDCDC, CPCPCPC, CCDDDCC, CCPPPCC, CCDCDCC, and CCPCPCC) were used in the manufacturing of the LVL, with each arrangement represented by a combination of the three wood species: hornbeam (C), paulownia (P), and poplar (D). The veneers were bonded with a polyurethane adhesive and pressed under 1 MPa pressure. The physical and mechanical properties of the laminated veneer lumber, including modulus of rupture, modulus of elasticity, block shear, delamination, and swelling, were measured under both dry and cyclic conditions (boil and dry). The modulus of rupture and modulus of elasticity of the LVLs increased when the proportion of hornbeam in the lamination increased. In the cyclic boil-dry condition, the laminated veneer lumbers with the configurations CPCPCPC and CDCDCDC showed the best structural performance. Furthermore, the study found that when one or two upper layers of poplar and paulownia were replaced with hornbeam layers, cracks were observed in the laminated veneer lumber samples. However, when the layers of poplar and paulownia were replaced with hornbeam alternately, no cracks were observed after saturating the laminated veneer lumber with water. The utilization of an alternating arrangement of poplar and paulownia layers with hornbeam in LVL can be used as an effective and cost-efficient approach for enhancing and reinforcing the LVL performance.

DOI: 10.15376/biores.19.2.2546-2561

Keywords: Laminated veneer lumber (LVL); Layer arrangement; Hornbeam; Poplar; Paulownia; MOR; MOE; Delamination

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INTRODUCTION

The use of wood laminated composite panel in building materials and construction has been increasing over the past few decades due to its advantages such as availability, lower processing costs, and ease of dismounting and disposal at the end of its service life (Xue and Hu 2013; Wessels *et al*. 2020). Laminated veneer lumber (LVL) and plywood are two of the most commonly used multi-layer wood boards, which are created by gluing and pressing wood veneers. They differ based on the arrangement of the wood veneers, with LVL having all layers arranged in the same direction, and plywood arranged in both horizontal and vertical directions. These differences result in varying structures and performance capabilities, each with unique strengths and stability. ISO 16978:2003 defines laminated lumber as a structural component produced by gluing layers on top of each other, with the grain directions parallel to each other (Burdurlu *et al*. 2007). Laminated veneer lumber (LVL) is a type of structural composite lumber that offers a consistent and high-performance alternative to solid lumber for various structural applications, including framing, rafters, joists, lintels, trusses, beams, formwork, scaffold planks, headers, and rim boards (Lam and Prion 2003). In 1995, Baldwin compiled detailed information on the technological properties, production techniques, advantages, and disadvantages of LVL (Baldwin 1995). In today's world, there is a severe shortage of wood resources, which has led to a focus on utilizing fast-growing trees to supply wood for manufacturing wood products (Bal 2016; Murata *et al*. 2021; Alamsyah *et al*. 2023). In a study conducted by Prakash *et al.* (2019), the feasibility of producing LVL from fast growing plantation timber (*Melia dubia*) was examined, with the conclusion that LVL could be utilized for door and window frame applications. Additionally, Khoo *et al.* (2019) investigated the physical properties and bonding quality of LVL produced with veneers peeled from small-diameter rubberwood logs. However, while fast-growing trees can be a reliable resource for supplying wood for engineered wood products, it has been noted that the structural performance of such products may not meet the requirements for heavy timber structures (Rostampour Haftkhani and Hematabadi 2022). This is due to the numerous drawbacks associated with wood from fast-growing species, including the presence of numerous knots, as highlighted by Purba *et al.* (2019), who demonstrated that an increasing knot proportion in veneers resulted in a decrease in LVL's modulus of elasticity (MOE) and modulus of rupture (MOR). Therefore, it is necessary to reinforce them with a suitable and economical approach. Various reinforcement methods have been used to improve the properties of fast-growing trees (low-density wood species) for supplying wood to manufacture wood engineering composite (Bal and Bektaş 2012). One of these methods is layer arrangements in laminated wooden materials (Kim 2020). The combination of veneers of different species is an environmentally friendly modification method that does not require any additional chemicals and can be a good strategy for obtaining panels with a good cost-benefit relationship (Kallakas *et al*. 2020; Bekhta *et al*. 2023). Numerous attempts have been made to investigate the reinforcing effect of layer arrangement on the physical and mechanical properties of laminated veneer lumber made from different wood species. Kiliç *et al*. (2010) studied the effect of layer arrangement on expansion, bending strength, and modulus of elasticity of solid wood and laminated veneer lumber (LVL) produced from pine and poplar and found that the strength characteristics of the LVL increase as the percentage of European pine increases. Bal (2016) indicated that both poplar and eucalyptus veneers can be used to produce laminated veneer lumbers, and poplar laminated veneer lumbers can be reinforced with eucalyptus veneers. Alamsyah *et al*. (2023) studied the physical and mechanical properties of LVL and LVB of three fast-growing tropical species and found that their properties generally meet the standards for use in construction. Ilce (2018) showed that using lighter layers in combination with denser layers leads to greater strength and helps improve the structural performance of LVL. McGavin *et al.* (2019) indicated blending even a small amount of spotted gum veneer with plantation hoop pine veneer resulted in improved mechanical performance, especially in flatwise bending. Murata *et al*. (2021) conducted a study on the mechanical properties of LVL by alternating eucalyptus and poplar veneer layers. They found that although the quality of eucalyptus veneer layers was not consistent, alternating lamination with poplar layers helped absorb the quality variations and improve the variation in the MOE. Sulastiningsih *et al*. (2020) mentioned that incorporating jabon or mahoni wood veneers in oil palm LVL improved its physical and mechanical properties. When it comes to LVL used in exterior applications, a major concern is the risk of layers losing bond strength and delamination when exposed to atmospheric impacts and water absorption (Abd Malek *et al* 2019; Juciene *et al*. 2023). Moisture content and wood species can affect on the bonding strength of glued wood. Too high a moisture content of wood often leads to excessive penetration of glue, resulting in a starved joint with inferior strength (Markwardt and Wilson 1935; Li *et al*. 2023).Wong *et al*. (1996) showed that soaking LVL samples in boiling water for 5 h followed by a 1-h cold water soak and drying at 60 ± 3°C for 24 h resulted in less than 4% delamination. The deformation and swelling of wood composites after exposure to humid conditions can be greatly influenced by the densities of the laminated veneers and the standard values of physical and mechanical properties can be achieved through layer arrangements during the production of laminated wood composites (Chiniforush *et al*. 2019; Fu *et al*. 2023; Pang and Jeong 2020).

Wood resources for LVL production, previously obtained from natural forests, are now being sourced from plantation forests due to the increasing demand for wood products and the limitations of natural forests. Rapid forestry naturally produces wood resources in small areas within short periods. Paulownia and poplar, as fast-growing trees, can be used as sustainable wood resources, and the technology for stabilizing wood material quality is effective for natural forest conservation. Hence, the aim of this study was to devise a cost-effective method to enhance the mechanical properties of LVL manufactured from fast-growing trees such as poplar and paulownia by integrating denser wood, such as hornbeam, in a suitable arrangement.

EXPERIMENTAL

Materials

Wood

Hornbeam (*Carpinus betulus*), poplar *(Populus alba*), and paulownia (*Paulownia fortunei*) wood were sourced from Mazandaran province in northern Iran. The logs were peeled into 2 mm thick veneers using a wood rotary peeling machine in Neka Choob Factory, Sarai, and Mazandaran, Iran. The logs were not steamed before peeling. Veneers were dried to a moisture content of 6 to 8%.

Adhesives

Polyurethane (PU ML -514) adhesive was used to bond the veneers together. PU adhesive is commonly used in wood product construction, particularly for outdoor use in humid environments, which is why it was chosen for this study. The PU adhesive had a solid content of 100% and a density of 1.3 g/cm^3. It was composed of two premeasured parts (resin A and hardener B) that were combined in a ratio of 77:23 (A:B) (w/w) according to the manufacturer's recommendations. It was obtained from Omran Sanaat Company, Tehran, Iran.

Preparation of LVL

7-ply LVL panels in various arrangements, including CCCCCCC, DDDDDDD, PPPPPPP, CDDDDDC, CPPPPPC, CDDCDDC, CPPCPPC, CDCDCDC, CPCPCPC, CCDDDCC, CCPPPCC, CCDCDCC, and CCPCPCC were constructed, where C, D, and P represent hornbeam, poplar, and paulownia woods, respectively (Fig. 1). The adhesive was applied uniformly to one side of the veneer at a level of 180 g/m² and then immediately cold-pressed for 1 h at a pressure of 1 MPa and a temperature of 20 ± 1 °C to create 50×50×1.4 cm (length×width×thickness) LVL panels. The panels were then conditioned in a climate room at a relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C until they reached a constant weight. The assembly time was considered 20 min based on the manufacturer's instructions.

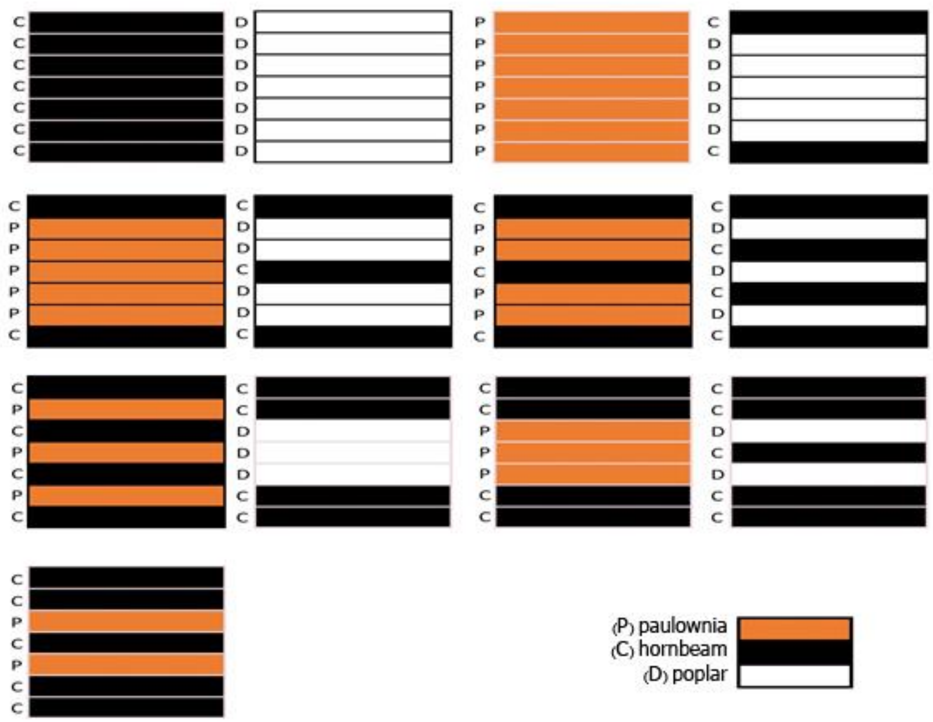

Fig. 1. LVL arrangements of the specimens: (C) hornbeam, (D) poplar, and (P) paulownia

Methods

Bending strength (MOR) and modulus of elasticity (MOE) tests were conducted perpendicular to the glue line in both dry and cyclic (boil and dry) conditions, following the guidelines of EN 408, 2010. In addition, shear block tests (ASTM D 905, 2003), shear strength of solid wood (ASTM D 143, 2003), shear strength of LVL(ISO 10033-1:2011(E)) (fig. 2), delamination (ISO 10033-2, 2011), and thickness swelling (EN 318, 2003) were performed to assess their physical and mechanical performances under different environmental conditions.

The percentage of delamination in the LVL panels was calculated using Eq. 1:

$$\text{Delamination (\%)} = \frac{\text{Total length of delamination on 4 sides}}{\text{Total length of glueline on 4 sides}} \times 100 \qquad (1)$$

Mechanical tests were conducted using a computer-controlled INSTRON machine (Instron company, model 4486, USA, 2003), at University of Teran, Tehran, Iran.

Statistical Analysis

The collected data were statistically analyzed using SPSS software. Nine replicates were tested for each treatment. Duncan’s multiple range test was used to group the means. All comparisons were made at a confidence level of 95%. The results of the multiple Duncan’s test were presented using English alphabet.

RESULTS AND DISCUSSION

The effects of layer arrangements on the density of the LVLs produced in this study are shown in Table 1. The lowest and highest densities of the LVLs were 0.41 and 0.68 g/cm^3 for the PPPPPPP and CCCCCCC arrangements, respectively. The ANOVA results demonstrated that the density of the LVLs was significantly influenced by the layer combinations.

The density values of the LVLs increased with an increase in the number of hornbeam layers incorporated in the LVLs in place of fast-growing tree layers (paulownia and poplar wood). The LVLs composed entirely of paulownia and poplar veneers exhibited the lowest densities (0.41 and 0.51 g/cm^3), while the highest densities were found in the LVLs with five layers of hornbeam veneers replacing them in the CCPCPCC and CCDCDCC arrangements, respectively (0.63 and 0.68 g/cm^3). This finding is consistent with the studies conducted by Kilic *et al*. (2010) and Bal and Bektaş (2012), who also observed an increase in density when high-density veneers were incorporated into the LVLs. Thus, the incorporation of high-grade species veneers in the layer arrangements can result in a more uniform and denser LVL.

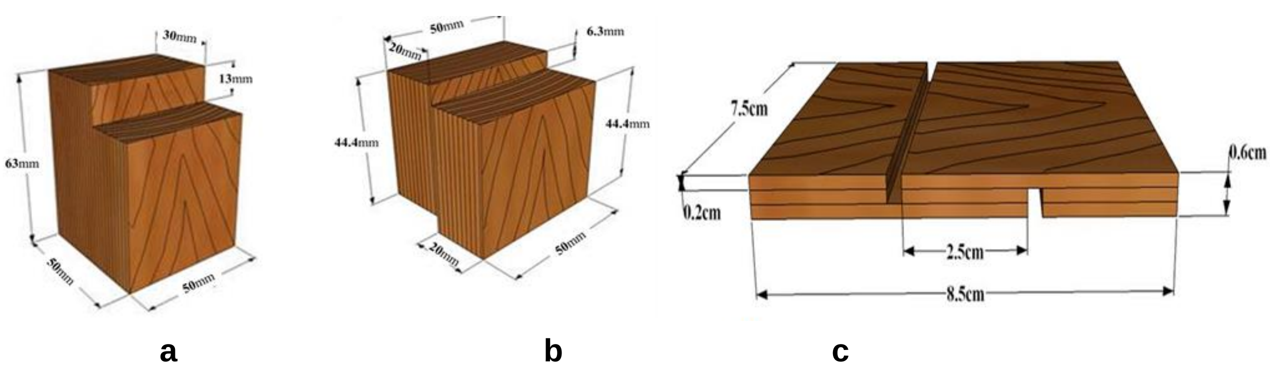

Fig. 2. Standard form and dimensions of the shear strength and shear block test specimen of solid wood and LVL: shear strength test of solid wood (a), shear block test of solid wood (b), and tensile shear strength of LVL (C).

Modulus of Rupture (MOR)

The effects of layer arrangements on the MOR values of the manufactured LVLs are presented in Table 2. The MOR values of LVLs made from hornbeam, poplar, and paulownia were 12%, 24%, and 52% higher than those of solid wood with the same species, respectively. This could be attributed to the effects of press pressure and resin consumption during the manufacturing process of LVLs (Ilce 2018). Moreover, LVLs made from hornbeam layers exhibited higher MOR values compared to those made from poplar and paulownia layers. This difference is likely due to the density of the hornbeam veneers, as wood density has been shown to have positive effects on various wood and wood composite properties (Kiliç *et al*. 2010; Bal 2016; Kim 2020; Rostampour Haftkhani and Hematabadi 2022). Table 2 presents the results of the analysis of variance, which showed a significant statistical difference among the MOR values of LVLs made with different layer arrangements of paulownia, poplar, and hornbeam under dry and cyclic (boiling and dry) conditions (all p-values were less than 0.05). Also, as shown in Table 2, Substituting paulownia with hornbeam in the CPPPPPC, CPPCPPC, CPCPCPC, CCPPPCC, and CCPCPCC layer combinations could result in a significant improvement in the MOR value, with increases of 64%, 67%, 77%, 102%, and 149%, respectively.

Table 1. Dry Density of Wood Species and LVL Samples

Treatments	Dry Density (g/cm^3)	Treatments	Dry Density (g/cm^3)
Paulownia	0.26	CCPCPCC	0.63
Poplar	0.36	DDDDDDD	0.51
Hornbeam	0.64	CDDDDDC	0.61
PPPPPPP	0.41	CDDCDDC	0.63
CPPPPPC	0.49	CCDDDCC	0.64
CPPCPPC	0.53	CDCDCDC	0.64
CPCPCPC	0.58	CCDCDCC	0.68
CCPPPCC	0.58	CCCCCCC	0.68

Table 2. MOR Values of Constructed LVL in Dry and Cyclic (Boil and Dry) Conditions

Layer Arrangements	**MOR (MPa)**		**Reduction Percentage (%)**
	Dry condition	**After exposure to cyclic boil and dry condition**	
Solid hornbeam	153.92 *(4.61)^{K}	…	
Solid poplar	68.4633 (8.07)^{C}	…	
Solid paulownia	46.61 (2.60)^{A}	…	
PPPPPPP	57.77 (3.30)^{B}	52.70 (6.53)^{A}	4.9
CPPPPPC	94.55 (3.01)^{D}	89.96 (5.57) ^{DEFG}	7.4
CPPCPPC	95.54 (5.02)^{D}	87.48 (6.50) ^{CDEF}	8.5
CPCPCPC	102.06 (6.96)^{E}	94.57 (8.83) ^{EFG}	8.8
CCPPPCC	116.79 (9.14)^{HI}	96.00 (5.05) ^{FG}	14.2
CCPCPCC	143.80 (4.91)^{J}	75.59 (11.03) ^{BC}	17.8
DDDDDDD	104.37 (5.90)^{EF}	82.85 (7.09) ^{BCDE}	20.7
CDDDDDC	109.10 (11.90)^{FG}	80.93 (11.27) ^{BCD}	25.8
CDDCDDC	111.58 (5.19)^{GH}	71.62 (4.62) ^{B}	32.1
CDCDCDC	117.73 (6.57)^{HI}	101.64 (10.18) ^{G}	35.8
CCDDDCC	121.52(5.81)^{I}	82.59 (21.87) ^{BCDE}	39.3
CCDCDCC	145.10 (8.07)^{J}	88.16 (8.48) ^{CDEF}	47.5
CCCCCCC	172.02 (5.08)^{L}	80.72 (6.39)^{BCD}	53.1

* The value in the parenthesis is standard deviation and the alphabetic letters show results of multiple Duncan's test results (there is no significant difference between two or more groups when they were categorized based on the same letter).

Similarly, replacing poplar with hornbeam in the CDDDDDC, CDDCDDC, CDCDCDC, CCDDDCC, and CCDCDCC layer arrangements resulted in MOR increases of 5%, 7%, 13%, 17%, and 40%, respectively. Because LVLs are commonly used in exterior applications, they are often exposed to cyclic boil-dry conditions. The MOR reductions observed in the CPPPPPC, CPPCPPC, CPCPCPC, CCPPPCC, CCPCPCC,

CDDDDDC, CDDCDDC, CDCDCDC, CCDDDCC, CCDCDCC, CCCCCCC, PPPPPPP, and DDDDDDD samples after exposure to cyclic boiling and dry conditions were 8%, 4%, 9%, 18%, 47%, 20%, 32%, 14%, 35%, 39%, 54%, 8%, and 25%, respectively. These findings are consistent with previous studies (Kallakas *et al*. 2020; Murata *et al*. 2021; Fu *et al*. 2023).

Modulus of Elasticity (MOE)

The results of the MOE values for different layer arrangements are presented in Table 3. An analysis of variance indicated that the differences of MOE of LVLs fabricated using various combinations of poplar and hornbeam, as well as paulownia and hornbeam, in both dry and cyclic boil and dry conditions, were statistically significant (P-value < 0.05). As shown in Table 3, the MOE values increased with an increase in the number of hornbeam layers in the LVLs. The MOE values of LVLs made from hornbeam, poplar, and paulownia were 17%, 36%, and 57% higher than those of solid wood with the same species, respectively. According to Table 3, incorporating more than three layers of hornbeam into low-density LVLs (LVLs made from poplar and paulownia veneers) resulted in a significant increase in the MOE of hybrid LVLs. However, substituting two or three hornbeam layers into low-density LVLs did not show a significant effect on the modulus of elasticity of the LVL samples. Previous studies have consistently demonstrated that the MOE values shift to higher values as the number of high-density layers in the LVL arrangements increases (Kiliç *et al*. 2010; Ilce 2018). Notably, the mechanical properties of hornbeam wood species surpassed those of the two low-density wood species. Consequently, the more hornbeam veneers are utilized in the production of LVLs, the better the strength and stiffness of the LVLs. The results also demonstrated that substituting hornbeam veneers in CPPPPPC, CPPCPPC, CPCPCPC, CCPPPCC, and CCPCPCC layer arrangements can enhance the MOE value of hybrid LVLs by 84%, 85%, 101%, 102%, and 131%, respectively. Additionally, according to the findings presented in Table 3, it is evident that the MOE value of CDDDDDC, CDDCDDC, CDCDCDC, CCDDDCC, and CCDCDCC arrangements increased by 18%, 20%, 28%, 30%, and 49%, respectively, through the replacement of poplar veneers with hornbeam veneers. The higher modulus of elasticity of hornbeam wood in comparison to poplar and paulownia is the reason behind the overall increase in the modulus of elasticity of the LVLs when the substitution rate (number of layers) of hornbeam in lamination is elevated. This could be attributed to the high density of hornbeam used in LVL production, as indicated in Table 3. This conclusion is consistent with previous studies in the literature conducted by Kiliç *et al*. (2010), Ilce (2018), and Bal and Bektaş (2012). Additionally, Kim (2020) reported that incorporating high-grade materials into low-grade LVLs leads to a significant increase in stiffness and strength. When the constructed LVLs were exposed to cyclic boiling and dry conditions, their MOE values exhibited a decrease. The MOE reductions for the different layer arrangements, namely CPPPPPC, CPPCPPC, CPCPCPC, CCPPPCC, CCPCPCC, CDDDDDC, CDDCDDC, CDCDCDC, CCDDDCC, CCDCDCC, CCCCCCC, PPPPPPP, and DDDDDDD, after exposure to cyclic boiling and dry conditions were found to be 23%, 10%, 24%, 31%, 31%, 22%, 38%, 22%, 34%, 39%, 72%, 15%, and 22%, respectively. Based on these findings, it could be recommended that the CPPPPPC, CPPCPPC, CDDDDDC, and CDDCDDC layer arrangements, in terms of stiffness and strength, are ideal for the fabrication of furniture pieces instead of solid wood species. The images in Fig. 3 depict the failure modes observed during the MOR tests conducted in dry conditions for various arrangements of LVLs made of poplar. When a LVL beam was subjected to a bending load, its lower layers failed in a tensile and splintering mode, its upper layers failed in a compression mode, and its middle layers failed in a shear mode. When LVL made of poplar or paulownia was reinforced with hornbeam on the surfaces, the stress concentration in the reinforcing layers increased. However, with the distribution of stress in the inner layers, failure occurred in the lighter layers of poplar or paulownia, as observed in parts e, f, g, h, and i of Fig. 3. The addition of hornbeam layers to the reinforced LVL reduced the stress concentration on the poplar or paulownia layers, according to the distribution of compression, tension, and shear stress across the cross-section of the LVL board under bending loading. Since the reinforced LVLs exhibit high strength, by transferring the stress to the poplar or paulownia layers, failure was observed in these layers, which were the weak points of the reinforced LVLs.

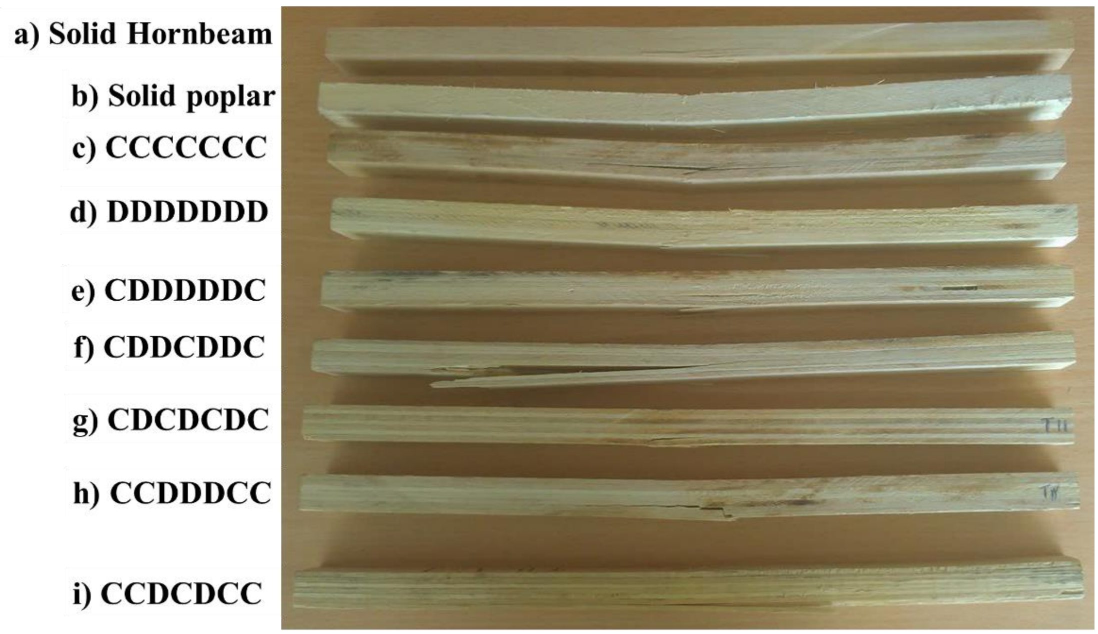

Fig. 3. The failure mode pictures from the MOR tests and the analysis of the differences in failure modes between different LVL specimens

Shear Block Test

Table 4 presents the shear strength values of wood in block tests and shear parallel to the grain, both in dry conditions and after exposure to cyclic boil and dry conditions. Among the wood species tested, hornbeam exhibited the highest shear strength parallel to the grain. Similarly, the highest shear strength in the block test was observed in blocks made of hornbeam + hornbeam.

In dry conditions, the shear strength parallel to the grain of solid hornbeam wood was approximately 2 and 3.5 times higher than that of poplar and paulownia wood, respectively. This difference could be attributed to the density of the specimens, as hornbeam wood demonstrated a higher density compared to poplar and paulownia wood. These findings align with the results reported by Abd Malek *et al*. (2019), which indicated a positive correlation between density and shear strength parallel to the grain of solid wood.

Table 3. MOE Values of Constructed LVL in Dry and after Being Exposed to Cyclic Boil and Dry Conditions

Layer Arrangements	MOE (MPa)		Reduction Percentage (%)
	Dry condition	After exposure to cyclic boil-dry condition	
Solid hornbeam	14384.17 *(265.83)[I]	…	
Solid poplar	7724.50 (402.07)[C]	…	
Solid paulownia	4282.50 (115.97)[A]	…	
PPPPPPP	6739.78 (140.00)[B]	5176.83 (329.17)[A]	1.5
CPPPPPC	12377.78 (297.02)[E]	10504.17 (313.98)[DE]	10.5
CPPCPPC	12420 (219.15)[E]	11110.83 (471.12)[E]	15.1
CPCPCPC	13302.11 (159.72)[G]	9101.67 (566.36)[C]	22.4
CCPPPCC	13594.78 (210.47)[H]	10354.33 (924.80)[D]	22.5
CCPCPCC	15616.89 (226.03)[J]	10866.67 (619.03)[DE]	23.2
DDDDDDD	10499.22 (179.38)[D]	10341.67 (278.48)[D]	23.8
CDDDDDC	12409.89 (403.44)[E]	9622.83 (333.74) [C]	30.4
CDDCDDC	12682.11 (281.43)[F]	8354.67 (232.34) [B]	31.6
CDCDCDC	13405.56(371.21)[GH]	10403.17 (270)[D]	34.1
CCDDDCC	13452.50 (154.80)[H]	8472.83 (987.62)[B]	37.0
CCDCDCC	15687.67 (284.61)[J]	9610.83 (375.81) [C]	38.7
CCCCCCC	16712.22(138.88)[K]	4644.17(97.13)[A]	72.2

* The value in the parenthesis is standard deviation and alphabet shows results of multiple Duncan's test

The shear strength in blocks made of hornbeam + hornbeam was also about 2 and 3.5 times higher than that of poplar + poplar and paulownia + paulownia wood, respectively. Additionally, the shear strength in blocks made of hornbeam + poplar was 82% higher than that of hornbeam + paulownia blocks. However, after exposure to cyclic boil and dry conditions, the shear strength in blocks of hornbeam + hornbeam, poplar + poplar, paulownia + paulownia, hornbeam + poplar, and hornbeam + paulownia decreased by 750%, 139%, 12%, 545%, and 260%, respectively. Moisture was found to have a negative impact on the measured properties of wood strength, as reported by Markwardt and Wilson in 1935. They observed that the shear strength of wood changed by 3% for every 1% change in moisture content.

Li *et al*. (2023) conducted a study on the bonding strength of glued wood, examining the impact of wood type and moisture. Their results revealed that bonding strength and deformation increased with an increase in the relative humidity of wood. In the shear block test, it is expected that failure would occur in the glue line when two blocks of wood are loaded. However, in this study, failure predominantly occurred in the wood surface area of the shear block test. Figure 4 illustrates the modes of failure in the wood shear block test, showing that shear failure in the grain direction primarily occurred in the wood surface area of the block test.

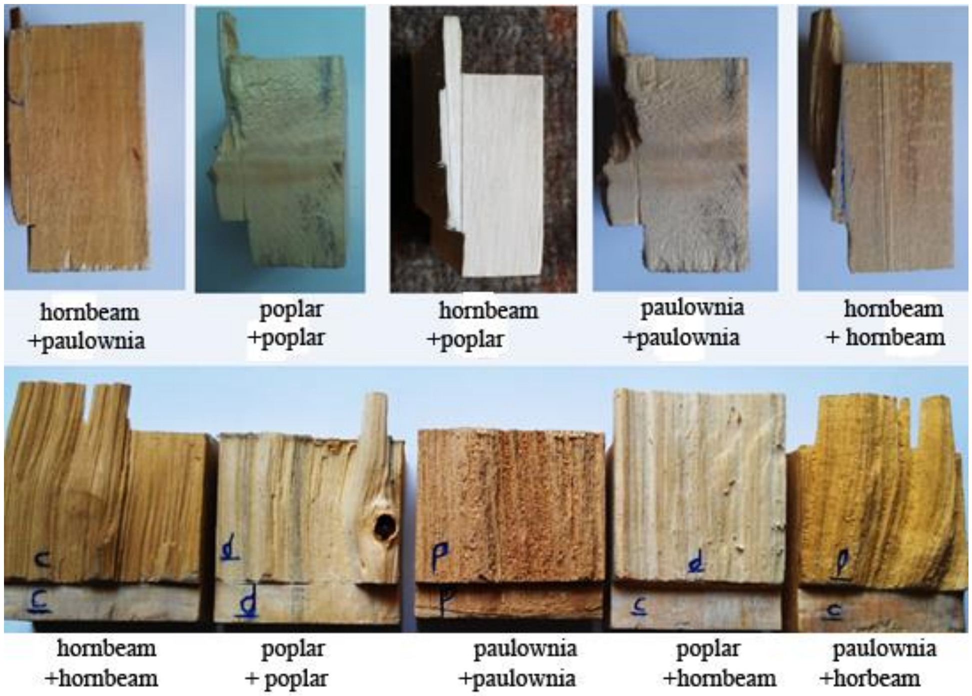

Fig. 4. Failure modes of specimens in shear block test in dry condition

The failure frequency in the wood surface area and glue line varied depending on the density of the wood species. For the hornbeam + hornbeam block shear test, the failure rate in the wood surface area and glue line were 97.7% and 2.3%, respectively. The failure frequency on the wood surface increased as the density of the wood species decreased, indicating that samples with higher density exhibited lower failure rates in the wood area.

Table 4. Values of Shear Strength in Block Test and Shear Strength Parallel to Grain in Dry and after Exposure to Cyclic Boil and Dry Conditions

	Layer	**Dry Condition**	**After exposure to cyclic boil and dry condition**	**Reduction Percentage (%)**
Shear strength parallel to grain (MPa)	Solid hornbeam	14.63 (0.75) *	---	
	Solid poplar	7.45 (0.39)	---	
	Solid poulownia	3.74 (0.51)	---	
Shear strength in block test (MPa)	hornbeam+ hornbeam	14.65 (0.63)	1.72 (0.71)	88.3
	poplar+poplar	7.64 (0.52)	3.19 (0.94)	58.2
	poulownia+poulownia	4.13 (0.41)	3.68 (0.9)	10.9
	Hornbeam+poplar	7.49 (0.4)	1.16 (0.63)	84.5
	hornbeam+ poulownia	4.11 (0.85)	1.14 (0.98)	72.3

* The value in the parenthesis is standard deviation

The results of tensile shear strength of LVL indicated that the highest tensile-shear strength of the LVL was associated with the CCCCCCC arrangement, where the shear occurred between the hornbeam layers. Conversely, the lowest shear resistance of the LVL was linked to the PPPPPPP arrangement, resulting in the detachment of the Paulownia layers. The failure of the samples under tensile-shear strength revealed that when there was a potential for failure between the hornbeam-hornbeam and hornbeam-paulownia or hornbeam-poplar layers, the failure occurred primarily between the hornbeam-paulownia or hornbeam-poplar layers. This can be attributed to the greater resistance and density of the hornbeam layers compared to the poplar and paulownia layers. The failure mode of the tensile-shear strength of the LVL samples is depicted in Fig. 5.

Fig. 5. Failure modes of LVL specimens in shear strength test

Delamination and Swelling

Table 5 presents the delamination percentage of solid wood and constructed LVLs after undergoing cyclic boil-dry treatment, as well as thickness and transverse swelling after saturation with water. No delamination was observed in LVLs constructed with PPPPPPP, DDDDDDD, CPPPPPC, and CDDDDDDC layer arrangements. According to the requirement of JAS for Structural LVL: 1993, the allowable delamination percentage was reported to be approximately 10%. Therefore, all constructed LVLs in this study met the standard requirement, except for CCCCCCC (16%). It was also observed that an increase in the proportion of hornbeam in the lamination resulted in enhanced thickness and transverse swelling of the LVL. The thickness and transverse swelling of solid hornbeam were higher compared to poplar and paulownia wood. In LVLs, due to the difference in thickness and transverse swelling among bonded layers, swelling cracks tended to occur, especially under moist conditions (Fig. 6). In the saturating conditions, when poplar and paulownia veneers in the middle layers of the LVL were replaced with hornbeam, numerous cracks were observed in the LVL samples due to this difference. However, when the layers of poplar and paulownia were alternated with hornbeam, no cracks were observed after saturation with water.

The results indicated that the delamination percentage of LVLs increases with an increase in the number of hornbeam layers, leading to cracking when saturated with water. Delamination in LVLs can be reduced by alternately replacing the lighter poplar and paulownia layers with denser hornbeam layers. Similar findings were reported by Sulastiningsih *et al*. (2020), who indicated that density is the dominant parameter in determining the shrinkage behavior of wood, with denser wood generally experiencing more shrinkage from the green to oven-dry condition.

Table 5. Delamination, Thickness, and Transverse Swelling in Solid Wood and Constructed LVL

Layer Arrangement	Delamination (%)	Thickness Swelling (%)	Transverse Swelling (%)
Solid paulownia	---	4.84	3.37
Solid poplar	---	6.06	6.25
Solid hornbeam	---	9.37	13.08
PPPPPPP	No delamination	4.63	6.66
CPPPPPC	No delamination	4.23	6.60
CPPCPPC	1.52	4.05	2.86
CPCPCPC	0.78	4.97	6.97
CCPPPPCC	5.2	5.02	7.16
CCPCPCC	7	5.78	7.30
DDDDDDD	No delamination	5.33	5.73
CDDDDDC	No delamination	6.07	6.08
CDDCDDC	1.2	6.77	6.09
CDCDCDC	3.33	5.93	5.79
CCDDDCC	4.4	6.51	6.48
CCDCDCC	8.33	7.32	6.82
CCCCCCC	16	7.99	8.35

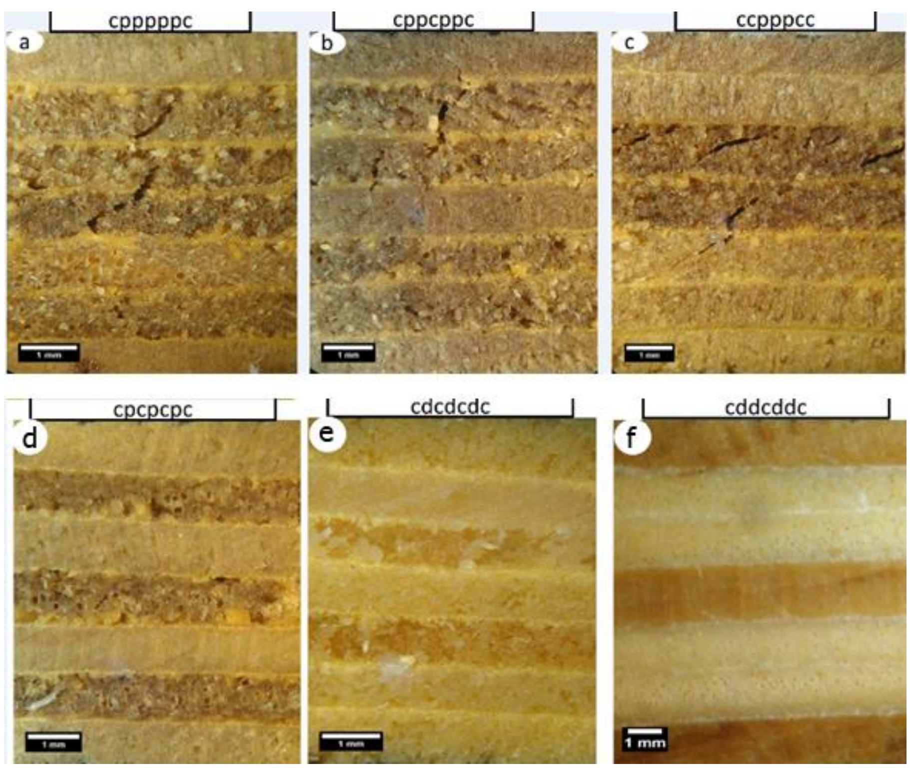

Fig. 6. Effect of layer arrangement on the development of cracks after saturation of LVL

Based on the results, it is recommended to enhance the physical and mechanical properties of LVL by replacing the layers of fast-growing species such as poplar and paulownia with denser wood like hornbeam in an alternating manner. This approach can help prevent cracking and delamination when the LVL is exposed to outdoor and humid environments.

CONCLUSIONS

The results of this study indicated the effects of layer arrangement on the structural performance of laminated veneer lumber, including modulus of elasticity, modulus of rupture, delamination, and swelling. Based on the experimental results, the following conclusions can be drawn:

1. Increasing the proportion of hornbeam in the laminated veneer lumber led to increased modulus of elasticity and modulus of rupture values in dry conditions. The laminated veneer lumber with the CCCCCCC layer arrangement exhibited the highest modulus of elasticity and modulus of rupture, while the PPPPPPP layer arrangement had the lowest values, where C is hornbeam, P is paulownia, and D is poplar.
2. After undergoing cyclic boil-dry conditions, the CDCDCDC layer arrangement showed the highest modulus of rupture, while the PPPPPPP layer arrangement had the lowest modulus of rupture. In the cyclic boil-dry conditions, it was observed that the highest percentage of reduction in modulus of rupture were related to CCCCCCC (53.1%) and CCPCPCC (47.5%), and the lowest percentage of reduction were related to CPPPPPC (4.9%) and CPCPCPC (7.4%). And also, the CPPPPPC, CPCPCPC, CPPCPPC, and PPPPPPP layer arrangements exhibited a modulus of elasticity reduction below 10%.
3. Alternating the poplar and paulownia layers with hornbeam in the laminated veneer lumber was found to be a suitable and cost-saving method for reinforcing and improving the laminated veneer lumber’s performance, compared to using fiber-reinforced polymer (FRP). By replacing poplar and paulownia layers with hornbeam layers in laminated veneer lumber, not only was there a significant increase in the modulus of elasticity and modulus of rupture, but the strength was also maintained after exposure to cyclic boiling and dry conditions. The reduction in modulus of elasticity and modulus of rupture of laminated veneer lumbers for the CPCPCPC arrangement was 7.4% and 31.6%, respectively, and for the CDCDCDC arrangement, it was 14.2% and 22.4%, respectively. In contrast, the increase in modulus of elasticity and modulus of rupture of laminated veneer lumber for the CPCPCPC arrangement compared to the PPPPPPP arrangement was 76.7% and 97.4%, respectively. The corresponding percentage increase for CDCDCDC compared to DDDDDDD was 12.8% and 27.7%, respectively.
4. Using different mixtures of wood quality, including and light and fast-growing types, can be beneficial for construction applications. This approach can help to reduce the use of forest species and preserve forests, while also enabling continuous production of wood products despite increasing consumption. This could be a promising strategy for suppliers.

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Article submitted: October 28, 2023; Peer review completed: November 27, 2023; Revised version received: December 25, 2023; Accepted: January 1, 2024; Published: March 1, 2024.
DOI: 10.15376/biores.19.2.2546-2561