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Mechanical Properties of Laminated Veneer Lumber (LVL) Fabricated from Three Malaysian Hardwood Species

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Abstract: The application of laminated veneer lumber (LVL) has long been limited to non-structural elements in Malaysia. LVL is commonly fabricated with veneer from low to medium density (290 to 630 kg/m^3) softwood or temperate hardwood. The data on the properties of LVL made from medium to high density (567 to 687 kg/m^3) tropical hardwood species is very limited. Therefore, this study investigated the mechanical properties of LVL fabricated from Malaysian hardwood species namely Kasai (*Pometia* spp.), Mengkulang (*Heritiera* spp.) and Kedondong (*Canarium* spp.). Different variables were studied: i) wood species; ii) loading direction (flatwise or edgewise), iii) grain direction (parallel and perpendicular), iv) treatment condition. The bending and compression test was carried out in accordance with EN 408:2012, while the block shear test was conducted based on EN14374:2004 and EN 314-1:2004. The results show that the grain direction has the most significant effect ($P \leq 0.01$) on bending, compressive and bonding properties of the samples tested. The treatment conditions for block shear test also displayed significant effect on its shear strength. The samples loaded parallelly displayed 320-450% higher bending values than the samples loaded perpendicularly. The compressive strength and compressive modulus were 323-365% and 523-2530% higher respectively when loaded parallelly. LVL performed the best mechanically when loaded parallelly and when subjected to Treatment A which was the least extreme treatment condition.

Keywords: Malaysian hardwood, bending strength, compressive strength, shear strength, bonding performance

1. Introduction

Timber has been used as structural components since the beginning of the construction history. It is a biologically based and renewable material with many advantages. One of the many benefits of using timber in construction is its high strength to weight ratio and competitive engineering properties compared to more commonly used building materials

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such as concrete and steel. It indicates that for the same strength required for a structure made by concrete and steel, the weight of timber material is lighter compared to both material [1]. Besides that, as a green material, timber can reduce 2.1 tonne of CO_2 emissions in the construction process if 1 t of concrete were to be substituted by 1 tonne of timber [2]. Timber has become increasing popular in the construction industry as its natural advantages are starting to get recognised globally. However, high grade timber log with desirable diameter for the construction industry is decreasing and lower grade timber is not favourable due to its low engineering performance and poor biological resistance with additional treatment needed to improve the properties [3], [4].

New technologies and scientific advancement have allowed engineered timber product (ETP) to be introduced as the solution for the construction industry that required high performance structural timber components [5]. Unlike solid sawn timber that is cut by sawing the logs into individual single solid members, ETPs are fabricated into the required shape and bonded together under heat and pressure from veneers, strands or flakes that were obtained by peeling, chipping or slicing. As a result, producing ETP frequently results in less waste products because the full timber log can be utilised. The ETPs also have more uniformed structural properties because its defects were removed during the manufacturing processes, thus having the potential to perform better than a solid timber with the same dimension due to its increased load-carrying capacity [6]. In contrast to the solid timber members that were normally logged and utilised directly, the ETPs were developed with enhanced strength. In addition, the ETPs could be manufactured by using the combination of high grade and also lower grade timbers hence reducing the wastage of timber resources. Some examples of the ETPs are glued laminated timber (Glulam), laminated veneer lumber (LVL), laminated strand lumber (LSL) and parallel strand lumber (PSL).

The mechanical properties of LVL were the focus of this research. LVL is a type of ETP first developed in the late 1960s, which made up of numerous veneers that are mostly laminated in the same grain direction [7]. Although less used, LVL with veneers bonded in the perpendicular grain direction can also be found. Because the defects of timber are either removed or spread uniformly over the panel during the peeling and fabrication process, causing its strength to be consistent throughout the entire panel, LVL is an ideal material for timber structures [8]. The desired performance of LVL that meets certain building standards can be achieved by strategically selecting the veneers. This is one of the upmost important technical advancements in the manufacturing of engineered timber products [9, 10]. The LVL is suitable for various structural applications, including as beams, headers, joists, rafters, scaffold boards, and truss chords, due to its decent performance qualities that is better than its solid timber counterparts [11]. However, LVL produced from low-density tree species generally has relatively low mechanical properties without any reinforcement and treatment [12]. Therefore, LVL fabricated from medium to high density species is highly favourable in the construction industry for its naturally high performance. Rahayu et al. [9] stated that, the application of LVL in many structural applications was due to its high mechanical properties.

Based on the available literatures, most LVL in the studies were fabricated from low to medium density (290 to 630 kg/m^3) softwood or temperate hardwood species [1], [7], [13], [14]. In Asian country such as Japan, Malaysia and China, tropical hardwood LVL panels were mostly fabricated from plantation species with poor mechanical properties. For other literatures that did include high density timber such as Beech, other variables were missing. For example, Bal & Bektaş [13] conducted an experiment to determine how timber species, loading direction and adhesives affected the bending properties of LVL samples. The chosen species were Poplar (444 to 449 kg/m^3), Eucalyptus (627 to 638 kg/m^3) and Beech (653 to 680 kg/m^3) where the testing on the bending properties of the LVL in flatwise loading direction considering parallel and perpendicular grain direction. However, the study only focussed on the flatwise loading direction of the LVL only. On the other hand, Burdurlu et al. [15] carried out a study to evaluate the bending strength and stiffness of LVL samples and the effects of loading direction of the samples. The test was made on two different species, oriental Beech and Poplar with average density of 700 kg/m^3 and 400 kg/m^3 respectively. In their study, bending test was carried out with the samples loaded at flatwise parallel and edgewise parallel direction. Although, the researchers did include Beech which is a high-density timber, the effect of perpendicular grain direction was however not studied.

It can be concluded from the literatures that the experimental data on the effects of timbers species, grain direction and loading direction on the mechanical properties and bonding quality of medium to high density LVL made from veneer of medium to high density tropical hardwood species are very limited. However, the necessity and interests to use native timber species efficiently has prompted research on hardwood ETPs. Therefore, in this study, veneer from medium to medium-high density (567 to 687 kg/m^3) Malaysian hardwood species were used in the fabrication of LVL panels. The Malaysian hardwood timbers selected for this study were Kasai (*Pometia* spp.), Mengkulang (*Heritiera* spp.) and Kedondong (*Canarium* spp.) which belong to strength group (SG) 4, SG 5 and SG 5 respectively as stated in MS 544: Part 2 [16]. Kasai and Mengkulang are medium hardwood with density ranged from 647-687 kg/m^3 and 579-597 kg/m^3 respectively. Meanwhile, Kedondong is light hardwood with density ranging from 567-574 kg/m^3. The three species selected were based on market availability and the suggestion given by the manufacturer. The objective of this study was to determine the effects of timber species, loading direction, grain direction and treatment conditions on the bending, compression and bonding properties of LVL panels. The desired outputs for bending test were modulus of rupture (MOR), local modulus of elasticity (LMOE) and global modulus of elasticity (GMOE). Compression test was conducted to determine the compressive strength and modulus. Bonding properties were evaluated based on block shear test. The bending and compression test were carried out in accordance with BS EN 408:2012 [17], while the block shear test was conducted based on EN14374:2004 [18] and EN 314-1:2004 [19].

2. Materials and Methods

2.1 Preparation of LVL Panels

All the LVL panels were prepared at the manufacturing factory at Pei Cheong Timber Sdn. Bhd. In, Ayer Tawar, Perak, Malaysia. The logs were sawn to approximately 1.5 meter before subjected to rotatory peeling process at the factory to produce the veneer with 2.4 mm thickness required for the fabrication of 22-ply LVL panel. The veneers were dried at 60 °C to 7-9% moisture content. After the desired moisture content was achieved, the veneers were bond together using Phenol Formaldehyde (PF) and the LVL panels were then dried to the target moisture content of 11%. The pressing temperature and time were set at 150 °C and 1.5min/mm respectively. The LVL panels were fabricated with the dimension of (1200 x 2400) mm from three different timber species namely Kasai (*Pometia* spp.), Mengkulang (*Heritiera* spp.) and Kedondong (*Canarium* spp.) with 50 mm nominal thickness. The mean density for Kasai, Mengkulang and Kedondong were measured at 647-687 kg/m^3, 579-597 kg/m^3 and 567-574 kg/m^3 respectively. The MC of all the LVL samples ranged from 10.06-11.34%.

2.2 Bending Test

This study aimed to determine the bending properties of LVL made from three different Malaysian hardwood timbers namely Kasai, Mengkulang and Kedondong. The desired outputs from the bending test were modulus of rupture (MOR), local modulus of elasticity (LMOE) and global modulus of elasticity (GMOE) of LVL beam loaded on the flatwise and edgewise surface with grain direction parallel and perpendicular to the span. The different configurations of the bending samples are shown in Fig. 1.

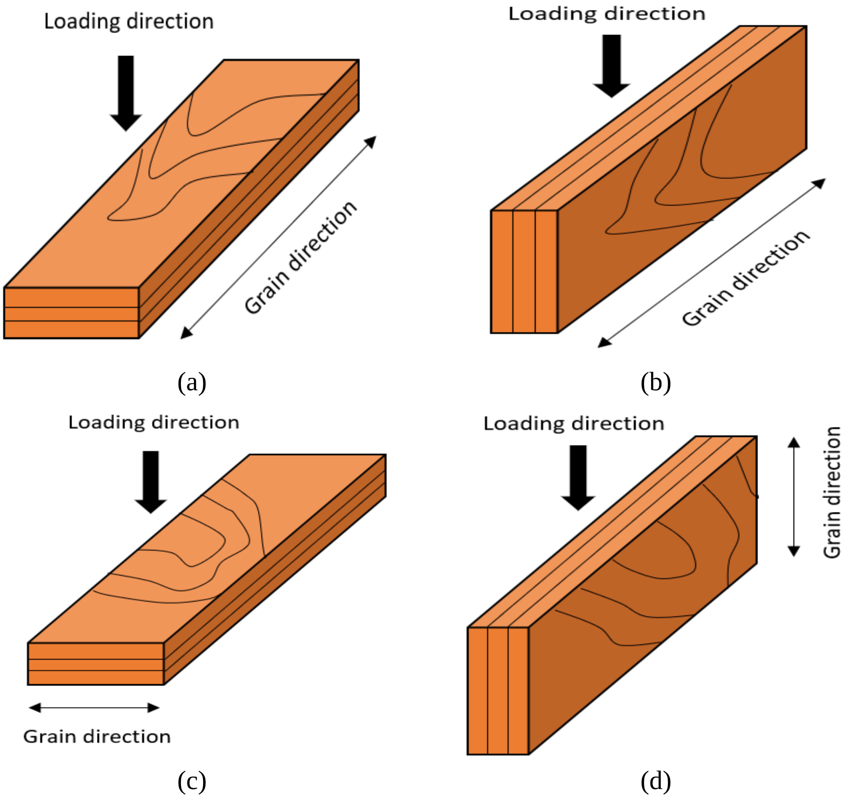
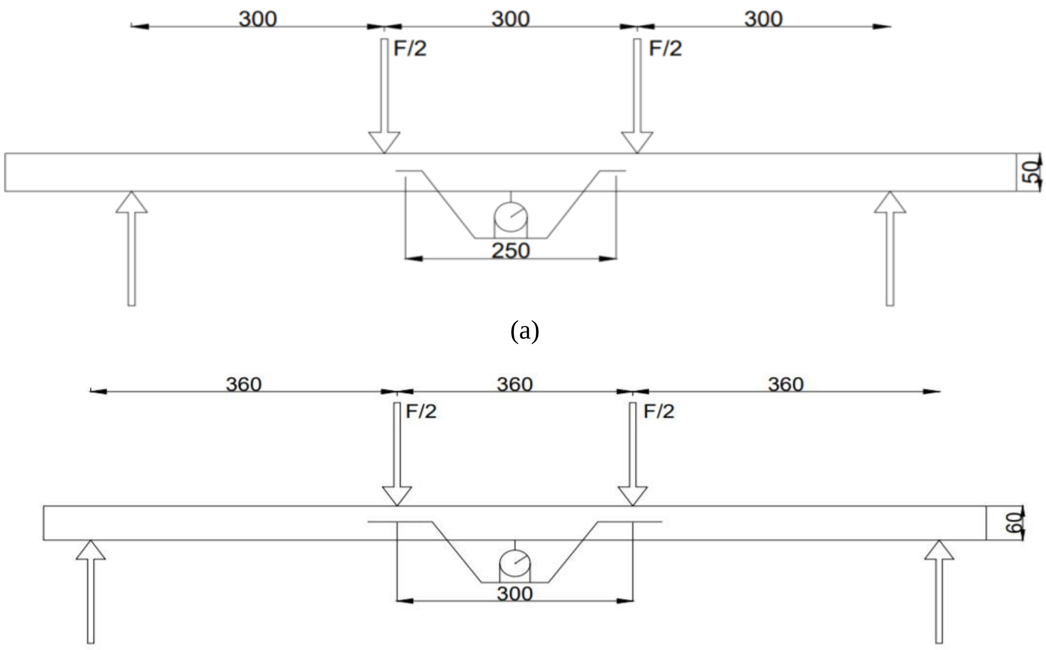


Fig. 1 - Configurations of LVL sample in bending test (a) flatwise bending parallel to the grain; (b) edgewise bending parallel to the grain; (c) flatwise bending perpendicular to the grain, and; (d) edgewise bending perpendicular to the grain

The bending samples were prepared and tested in accordance with EN 408:2012 [17]. A total of 48 bending samples with the dimension of (50 x 60 x 1200) mm was prepared and labelled. The density was determined accordioning to BS EN 323:1993 [20] while the MC was determined based on BS EN 322:1993 [21]. Bending test measures the force that is required by a sample to achieve total failure under 4-point loading condition. All the test samples were symmetrically loaded, bending at two points over a span of 18 times the depth. Fig. 2 shows the schematic diagram for four-point bending test for all the LVL beams under different testing configurations.



(a)

(b)

Fig. 2 - Schematic diagram for four-point bending test loaded at (a) flatwise direction, and; (b) edgewise direction

The bending test was conducted using a Universal Testing Machine (UTM) with maximum capacity of 250kN. The local modulus of elasticity is derived from the measurements of the relative displacement in the vertical direction between the mid-height point at the centre of the span and a matching point on a rod that lies parallel to the neutral axis in during the deformed beam condition and is symmetrically pinned to the side face of the beam with a length between the pins equalling 5 times the height of the beam. The global modulus of elasticity was derived from measurements of the absolute displacement in the vertical direction of bottom side of the beam at mid span. Fig. 3 shows the placement of linear variable differential transformer (LVDT) for the measurement of local and global MOE.

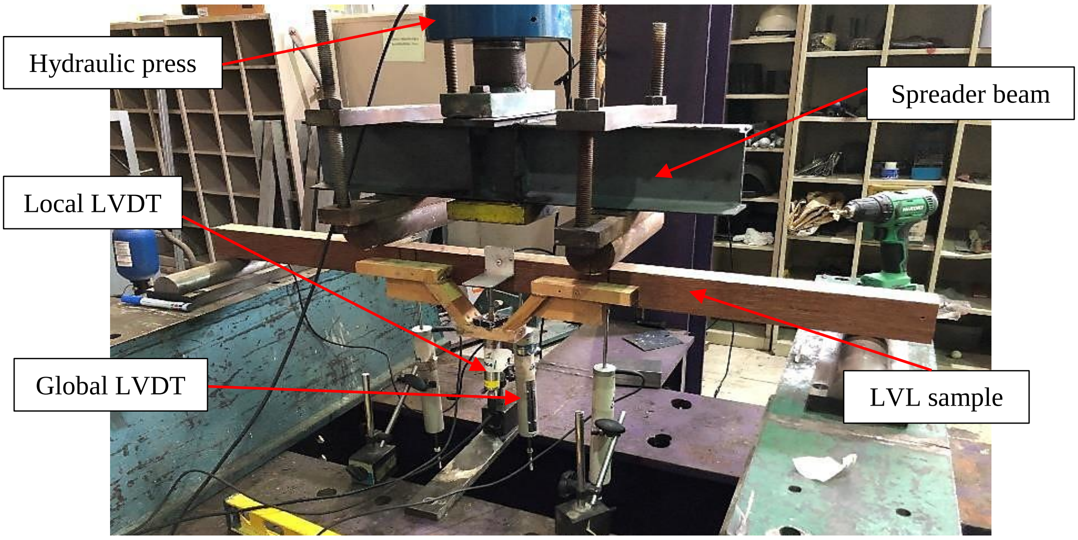


Fig 3 - Test setup for the determination of bending properties of LVL sample

Prior to the bending testing, the loading rate for each timber species (Kasai, Mengkulang and Kedondong) were determined so that the maximum load of the samples was reached within (300 ± 120) seconds as specified in EN 408:2012 [17]. The load was applied at a constant rate and the rate of movement of the loading head was not greater than 0.003 h mm/s. The loading rate for Kasai, Mengkulang and Kedondong was set at 0.08, 0.08 and 0.15 mm/s respectively. The constant recording of the load and displacement readings was done digitally using a computerised data acquisition system (data logger) until the achievement of ultimate load. The bending strength (MOR) and also the stiffness (LMOE and GMOE) of the individual test piece were calculated using the Eq. (1), Eq. (2) and Eq. (3) respectively:

$$\text{MOR (N/mm}^2\text{)} = \frac{3Fa}{bh^2} \tag{1}$$

where F = load at a given point on the load deflection curve, in N; a = distance between a loading point and the nearest support, in mm; b = beam width, in mm; h = beam height, in mm.

$$\text{Local MOE (N/mm}^2\text{)} = \frac{a l_1^2 \left(F_2 - F_1\right)}{16 I \left(w_2 - w_1\right)} \tag{2}$$

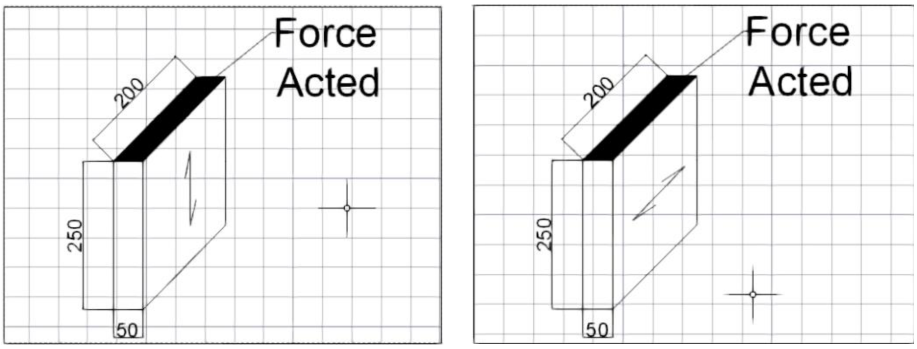
where a = distance between a loading point and the nearest support, in mm; I_1 = distance between the pinning point of the attached rod, in mm; I = moment of inertia ($I = b \times h^3/12$); b = beam width, in mm; h = beam height, in mm; $F_{2-}F_1$ = increasement of load in the linear range with a correlation coefficient of 0.99 or higher, in N, $w_{2-}w_1$ = corresponding increase in the relative vertical displacement between the midpoint of the beam and the attached rod, in mm.

$$\text{Global MOE (N/mm}^2\text{)} = \frac{3al^2 - 4a^3}{2bh^3\left(2\frac{w_2 - w_1}{F_2 - F_1}\right)} \tag{3}$$

where a = distance between a loading point and the nearest support, in mm; l = span in bending, or length of test piece between the testing machine grips, in mm; b = beam width, in mm; h = beam height, in mm; $F_2 - F_1$ = increasement of load in the linear range with a correlation coefficient of 0.99 or higher, in N; $w_2 - w_1$ = corresponding increase in the (absolute) vertical displacement at mid span, in mm.

2.3 Compression Test

The desired outputs from the compression test were compressive strength and compressive modulus. The samples for compression test were prepared according to EN 408:2012 [17]. For compression test, samples with the dimension of (50 × 200 × 250) mm were cut from the LVL panels. For compression samples parallel to grain, the length was parallel to grain while the width was perpendicular to grain. For compression samples perpendicular to grain, the length was perpendicular to grain while the width was parallel to grain. Each of the sample was labelled according to its species and direction of compression. The density of each sample was determined and recorded prior to testing while the MC was determined after testing. The density was determined accordioning to EN 323:1993 [20] while the MC was determined based on EN 322:1993 [21]. Fig. 4 shows the dimension of the LVL sample and the direction of grain against the acted compression force. The compressive test was conducted using an IPC Universal Testing Machine (UTM).



(a) (b)

Fig. 4 - LVL Sample dimension and the direction of grain against the compression load (a) compression parallel to grain; (b) compression perpendicular to grain

Two LVDTs were placed at both sides of the sample to measure to displacement in order to determine the compressive modulus of the sample. The maximum compressive load for each sample was recorded and used for the determination of compressive strength. The compressive strength and also compressive modulus of the individual test piece were calculated using Eq. (4) and Eq. (5) respectively:

$$\text{Compressive strength (N/mm}^2\text{)} = \frac{F_{\max}}{A} \tag{4}$$

where $F_{\max}$ = maximum load, in N; A = cross-sectional area, in mm^2.

$$\text{Compressive modulus (N/mm}^2\text{)} = \frac{l_1(F_2 - F_1)}{A(W_2 - W_1)} \tag{5}$$

where $F_2 - F_1$ = is an increment of loads on the straight-line portion of the load deformation curve, in N; $W_2 - W_1$ = is the increment of deformation corresponding to $F_2 - F_1$, in mm; l_1= gage length for the determination of modulus of elasticity, in mm; A = cross-sectional area, in mm^2.

2.4 Block Shear Test

The bonding performance of LVL made from two different Malaysian hardwood timbers namely Kasai and Mengkulang and were determined. The desired outputs from block shear test were shear strength and wood failure percentage (WFP). The bonding quality of LVL panels was evaluated by determining the shear strength value. The test was carried out for both LVL samples parallel and perpendicular to the grain direction. The dimension of the test samples was (50 x 50 x 50) mm for block shear test. A total of 120 samples were prepared from the cutting of the LVL panels with (1200 x 2400) mm. The block shear test was conducted using a block shear fixture (Fig. 5) and IPC Universal Testing Machine (UTM). The block shear samples were subjected to three different conditions prior to testing. The different conditions were given in Table 1. The experiment and treatment of the samples were carried out in accordance with EN14374:2004 [18] and EN 314-1:2004 [19]. The load was applied so that the failure occurred within (30 ± 10) s.

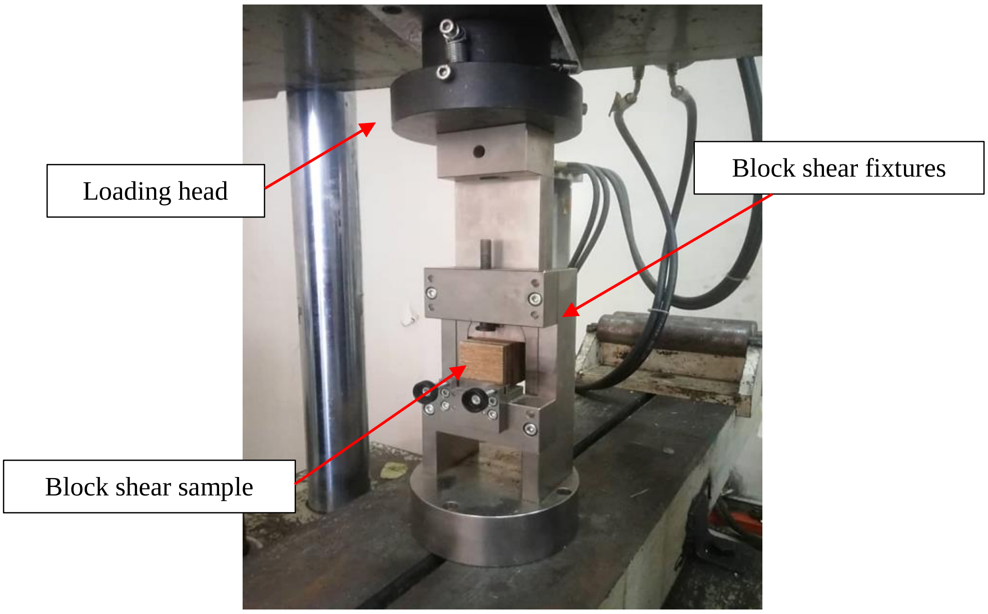


Fig. 5 - Test setup for block shear test

Table 1: Treatment condition prior to block shear testing

Treatment	Condition
A	The samples were immersed in water at room temperature (20±3 °C) for 24 hours
B	The samples were immersed for 6 hours in boiling water and followed by cooling in water at room temperature (20±3 °C) for at least 1 hour
C	The samples were immersed for 4 hours in boiling water, followed by drying in ventilated drying oven for 16-20 hours at (60±3 °C), followed by immersion in boiling water for 4 hours again and lastly in cooling water at (20±3 °C) for 1 hour

The block shear strength of the individual test piece was calculated using Eq. (6) as follow:

$$\text{Shear strength (N/mm}^2\text{)} = \frac{F_{\max}}{A} \qquad (6)$$

where $F_{\max}$ = maximum load, in N; A = cross-sectional area, in mm^2.

2.5 Statistical Analysis

All the data were analysed using statistical package for the social sciences procedure (SPSS) for the analysis of variance (ANOVA) at 95 % confident level ($P \leq 0.05$). Tukey's Honest Significant Difference test was then used to further determine the significant level of average values for each testing.

3. Results and Discussions

3.1 Bending Properties

Analysis of variance (ANOVA) for bending properties and all the study variables was conducted and the results are summarised in Table 2. The mean value of MOR, local MOE and global MOE for different species, loading direction and grain direction are shown in Table 3.

Table 2 - Summary of analysis of variance (ANOVA) at P ≤ 0.05 for the interaction between species, loading direction, grain direction and bending properties of LVL samples

Study variables	**MOR**		**Local MOE**		**Global MOE**	
	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Species	0.040	0.960^{ns}	1.219	0.305^{ns}	1.467	0.241^{ns}
Loading direction	0.196	0.660^{ns}	0.065	0.799^{ns}	0.000	0.999^{ns}
Grain direction	978.669	0.000***	379.320	0.000***	277.113	0.000***

Note: *** indicates significance level at $P \leq 0.01$; ^{ns} indicates no significance

Table 3 - Bending properties of LVL fabricated from Kasai, Mengkulang and Kedondong with different sample configurations during testing.

Species	**Loading Direction**	**Grain Direction**	***n***	**MOR (N/mm^2)**	**Local MOE (N/mm^2)**	**Global MOE (N/mm^2)**
Kasai (SG4)	F	//	4	48.31 ± 4.74^{c}	945 ± 40.51^{ab}	11894 ± 1651^{a}
	F	⊥	4	16.26 ± 3.27^{d}	237 ± 30.18^{d}	2484 ± 322^{c}
	E	//	4	63.49 ± 3.94^{a}	1108 ± 181.22^{a}	12587 ± 1889^{a}
	E	⊥	4	15.11 ± 1.98^{d}	214 ± 21.29^{d}	2289 ± 311^{c}
Mengkulang (SG5)	F	//	4	56.55 ± 2.63^{ab}	916 ± 114^{ab}	10781 ± 2222^{a}
	F	⊥	4	12.56 ± 1.22^{d}	148 ± 20.43^{d}	1635 ± 225^{c}
	E	//	4	55.57 ± 2.06^{abc}	909 ± 67.30^{b}	9974 ± 1189^{ab}
	E	⊥	4	10.83 ± 1.91^{d}	146 ± 17.51^{d}	1647 ± 251.4^{c}
Kedondong (SG5)	F	//	4	51.70 ± 3.01^{bc}	703 ± 22.47^{c}	7790 ± 183.4^{b}
	F	⊥	4	13.43 ± 2.10^{d}	109 ± 11.23^{d}	1228 ± 98.99^{c}
	E	//	4	56.27 ± 2.82^{abc}	709 ± 20.71^{c}	7811 ± 108.5^{b}
	E	⊥	4	14.16 ± 1.99^{d}	143 ± 18.59^{d}	1511 ± 57.53^{c}

Note: //: Grain parallel to span; ⊥: Grain perpendicular to span; F: Flatwise; E: Edgewise; *n*: number of replicates
*Means followed by the different superscript letters in the same column are significantly different according to Tukey's Honest Significant Difference test at $P \leq 0.05$.

Based on Table 2, it can be observed that, bending properties of LVL samples was only significantly influenced by the grain direction of the samples to the span. All other study variables (species, flatwise and edgewise arrangement) have no significance effect ($P > 0.05$) on the bending properties. According to Table 3, generally, samples loaded parallel to the grain show much higher mechanical properties than the samples loaded perpendicular to the grain. This is because wood consists of cellulosic fibre bonded by lignin and it is much harder to separate the bonding within the fibre and lignin by bending effect when the sample were loaded parallelly then to separate the bonding between lignin and wood fibre by rolling effect when the samples were loaded perpendicularly. On the other hand, flatwise and edgewise arrangement of the LVL samples has less significant effect on the bending properties except for Kasai. This result is in agreement with the results obtained by Burdurlu et al. [15] and Kılıç [22]. The authors studied the bending properties of beech (*Fagus orientalis* L.) and lombardy poplar (*Populus nigra* L.) and found that the relationship between bending properties and flatwise and edgewise arrangement was statistically insignificant. However, the results of this study contradict with the conclusion by de Melo & Del Menezzi [23]. This phenomenon was explained Palma & Ballarin [24], which stated that bending properties for samples tested in the flatwise position is more sensitive to the veneer quality than samples tested in edgewise position. Thus, higher quality veneer must be used to fabricate LVL components loaded in flatwise position in order to obtain higher bending performance. As shown in Table 3, Kasai (SG4) samples with edgewise and load parallel to the grain arrangement shows the highest MOR value which is 63.49 N/mm^2. The same samples also exhibit the highest local and global MOE which are 1108 N/mm^2 and 12587 N/mm^2. Contrarily, Mengkulang (SG5), with samples edgewise and load perpendicular to the grain arrangement show the lowest MOR value which is 10.83 N/mm^2. Kedondong (SG5), with samples flatwise and load perpendicular to the grain arrangement show the lowest local MOE and global MOE value which are 143 N/mm^2 and 1511 N/mm^2. From observation, Kasai which belong to SG 4 performed better in bending test compared to Mengkulang and Kedondong which both belong to SG 5. This is due to the fact that timber from SG 4 generally has higher density than timber from SG 5 which translate to higher fibre content per volume. The fibre of wood-based products acts as the loading bearing elements of the materials. Therefore, higher density also resulted in better resistance to load and better bending properties.

Conclusively, the effect of the grain direction is most significant on the bending properties, which include MOR ($P = 0.000$), local MOE ($P = 0.000$), and global MOE ($P = 0.000$) value. MOR, or the bending strength of the LVL sample, is recorded to be much higher when loaded in grain parallel to span as compared to perpendicular direction. For example, the MOR of Kasai samples loaded at edgewise and parallel direction is 320% higher than the samples loaded at edgewise and perpendicular direction. Both MOE values also are greater when the samples were loaded at parallel direction to span as compared to perpendicular direction. For example, the local MOE and global MOE of Kasai samples loaded at edgewise and parallel direction is 417% and 450% higher than the samples loaded at edgewise and perpendicular direction, respectively. These results conclude that the LVL samples performed better in term of stiffness and strength when loaded in parallel grain direction. Contrarily, the flatwise and edgewise arrangement has little effect on the bending properties of LVL beams. The is because load distributed along the grain direction regardless of the loading direction and grain direction is highly dependent on the anatomy of wood. Meanwhile, this effect was minimized by the homogeneity of PF resin when the load was being applied at flatwise and edgewise direction.

3.2 Compressive Properties

Table 4 summarises the findings of Analysis of variance (ANOVA) conducted for compressive properties and all the research variables. Table 5 displays the timber species, sample grain direction, compressive strength, and compressive modulus of all LVL compression samples.

Table 4 - Summary of analysis of variance (ANOVA) at $P \leq 0.05$ for the interaction between species, grain direction and compressive properties of LVL samples.

Study variables	Compressive Strength		Compressive modulus	
	F Value	Pr > F	F Value	Pr > F
Species	0.299	0.744^{ns}	1.046	0.365^{ns}
Grain direction	581.016	0.000***	41.520	0.000***

Note: *** indicates significance level at $P \leq 0.01$; ^{ns} indicates no significance.

Table 5 - Compression properties of LVL fabricated from Kasai, Mengkulang and Kedondong loaded under different grain directions.

Species	Grain Direction	*n*	Compressive Strength (N/mm^2)	Compressive Modulus (N/mm^2)
Kasai (SG4)	//	5	41.32 ± 2.75^a	10820 ± 3598^a
	⊥	5	9.77 ± 0.46^c	1736 ± 1301^b
Mengkulang (SG5)	//	5	35.16 ± 2.25^b	5394 ± 2188^b
	⊥	5	10.61 ± 0.30^c	1000 ± 241^b
Kedondong (SG5)	//	5	33.70 ± 1.65^b	8680 ± 4257^a
	⊥	5	7.24 ± 0.38^c	330 ± 81.24^b

Note: //: Grain parallel to span; ⊥: Grain perpendicular to span; *n*: number of replicates

*Means followed by the different superscript letters in the same column are significantly different according to Tukey's Honest Significant Difference test at $P \leq 0.05$

It is worth noting that, the MC of all compression samples ranged from 10.06-11.34%. The compression properties are significant more sensitive to the MC than other mechanical properties, therefore, it is important to ensure that all the samples have consistent MC for fair comparison [25]. Based on Table 4, it can be observed that, compressive strength ($P = 0.000$) and compressive modulus ($P = 0.000$) of LVL samples were significantly influenced by the grain direction of the sample under compression load. The other study variable, species has no significance effect on the compressive strength ($P = 0.744$) and compressive modulus ($P = 0.365$). For compressive properties, samples tested under loading parallel to the grain shows better compressive value than samples loaded perpendicular to the grain. This finding is similar to the trend shows by samples tested under bending load. The highest compressive strength is exhibited by Kasai (41.32 N/mm^2) follow by Mengkulang (35.16 N/mm^2) and Kedondong (33.70 N/mm^2). For the compressive modulus, Kasai shows the highest compressive modulus which is 10820 N/mm^2, follow by Kedondong (8680 N/mm^2) and Mengkulang (5394 N/mm^2). This phenomenon might be explained by higher density of Kasai samples which resulted in more fibre content per volume and better resistance of the fibre against compressive load and thus produce higher compressive properties.

The compressive strength of Kasai, Mengkulang and Kedondong samples loaded parallel direction is 323%, 231% and 365% higher than the samples loaded at perpendicular direction, respectively. On the other hand, the compressive modulus of Kasai, Mengkulang and Kedondong samples loaded at parallel direction is 523%, 439% and 2530% higher than the samples loaded at perpendicular direction, respectively. This is because compression samples mostly failed due to shear failure that occurred at the mid length and it is well known that wood has a better resistance against shear across the grain in parallel samples compared to shear parallel to the grain in perpendicular samples. As such the LVL samples performed significantly better in term of stiffness and strength when loaded at parallel direction to the span. Contrarily, the timber species has little effect on the compressive properties of LVL samples.

3.3 Bonding Strength and Wood Failure Percentage

Analysis of variance (ANOVA) in Table 6 summarises the effects of the study variables (species, grain direction and treatment condition) on block shear strength. Meanwhile, shear strength and wood failure percentage of the LVL as function of timber species, grain direction and treatment conditions are listed in Table 7.

Table 6 - Summary of analysis of variance (ANOVA) at P ≤ 0.05 for the interaction between species, grain direction, treatment condition and shear properties of LVL samples

Study variables	Shear Strength	
	F Value	Pr > F
Species	3.125	0.081^{ns}
Grain direction	5.252	0.025^{*}
Treatment condition	4.661	0.005^{**}

Note: ** indicates significance level at $P \leq 0.01$; * indicates significance level at $P \leq 0.05$; ^{ns} indicates no significance.

Table 7 - Shear strength and wood failure percentage of LVL fabricated from Kasai and Mengkulang and loaded under different grain directions

Condition	Species	Grain Direction	*n*	Shear Strength (N/mm^2)	Wood Failure Percentage (%)
Control	Kasai (SG4)	//	5	3.83 ± 1.54^{a}	70
		⊥	5	2.57 ± 0.40^{abcd}	55
	Mengkulang (SG5)	//	5	3.16 ± 0.37^{abc}	65
		⊥	5	2.66 ± 0.79^{abcd}	40
A	Kasai (SG4)	//	5	3.51 ± 0.58^{ab}	75
		⊥	5	1.44 ± 0.56^{cd}	35
	Mengkulang (SG5)	//	5	3.24 ± 1.13^{abc}	40
		⊥	5	2.91 ± 0.61^{abcd}	55
B	Kasai (SG4)	//	5	2.93 ± 0.55^{abcd}	55
		⊥	5	2.74 ± 0.37^{abcd}	15
	Mengkulang (SG5)	//	5	3.67 ± 0.57^{a}	55
		⊥	5	2.70 ± 0.48^{abcd}	40
C	Kasai (SG4)	//	5	1.72 ± 0.69^{bcd}	25
		⊥	5	1.25 ± 0.78^{d}	30

Mengkulang (SG5)	//	5	1.77 ± 0.76^{bcd}	80
	⊥	5	3.26 ± 0.92^{abc}	75

Note: //: Grain parallel to span; ⊥: Grain perpendicular to span; *n*: number of replicates
*Means followed by the different superscript letters in the same column are significantly different according to Tukey's Honest Significant Difference test at $P \leq 0.05$

Based on Table 6, it can be observed that, study variables, species has no significance effect on the shear strength of the LVL samples. However, the shear strength is significantly influenced by the other study variables, grain direction ($P \leq 0.05$) and treatment condition ($P \leq 0.01$). According to Table 7, generally, shear samples tested parallel to the grain shows higher shear strength compared to the samples tested perpendicular to the grain. This result was expected as it is well known that wood is stronger against shear across the grain direction than it is parallel to the grain. However, these results are not in agreement with de Melo & Del Menezzi [23], which stated that parallel samples exhibited lower shear strength than perpendicular samples. Further study needs to be carried to confirm this contradiction. It was also observed that treatment conditions of the samples decreased the shear strength. Based on the Table 7, control samples of Kasai show the highest shear strength (3.83 N/mm^2) followed by Mengkulang (3.16 N/mm^2). This result is aligned with the results of bending and compressive test of LVL, both showing that Kasai exhibit better strength than Mengkulang. The lowest shear strength is exhibited by Kasai perpendicular samples which were subjected to treatment Condition C with shear strength value of 1.25 N/mm^2. Regarding wood failure percentage (WFP), overall, the samples show decreasing wood failure percentage after subjected to different treatment conditions. This phenomenon can be explained by the repeat swelling and shrinkage of the samples which adversely affect the bonding integrity between the veneer and adhesive as both veneer and adhesive had different degree of swelling and shrinkage. Besides that, the introduction of water molecules during the treatment process also has the ability to disrupt the bonding between veneer and adhesive which resulted in lower resistant to applied load. Generally, Kasai which has the highest density exhibits the highest WFP, followed by Mengkulang. These results are in line with the study by Ahmad et. al [26] which concluded that Malaysian hardwood species with a higher density displayed poorer bonding performance. However, it is worth noting that, Kasai samples subjected to Condition C exhibit lower WFP than Mengkulang samples subjected to the same condition. Therefore, it could be suggested that higher density timbers perform better in extreme condition compared to timbers of lighter density.

3.4 Failure Modes

3.4.1 Failure Mode of Four-Point Bending Test

Generally, two types of failure modes were observed for all the bending samples namely tension failure as shown in Fig. 6 (b) and Fig. 6 (c) and horizontal shear failure which are shown in Fig. 6 (a). From observation, the tension failure commonly occurred at the lower tension zone while horizontal shear failure or splitting failure often occurred at the middle layer of the samples.

For most samples loaded at the flatwise surface and parallel direction, the total failure often occurred more slowly after the first crack and splitting was observed at the middle layer of the samples which is shown in Fig. 6 (a) together with fracture at the lower surface of the tension zone. However, for most samples loaded at the flatwise and perpendicular direction, the total failure often occurred abruptly at mid span along the direction of the grain of the fibre as shown in Fig. 6 (c).

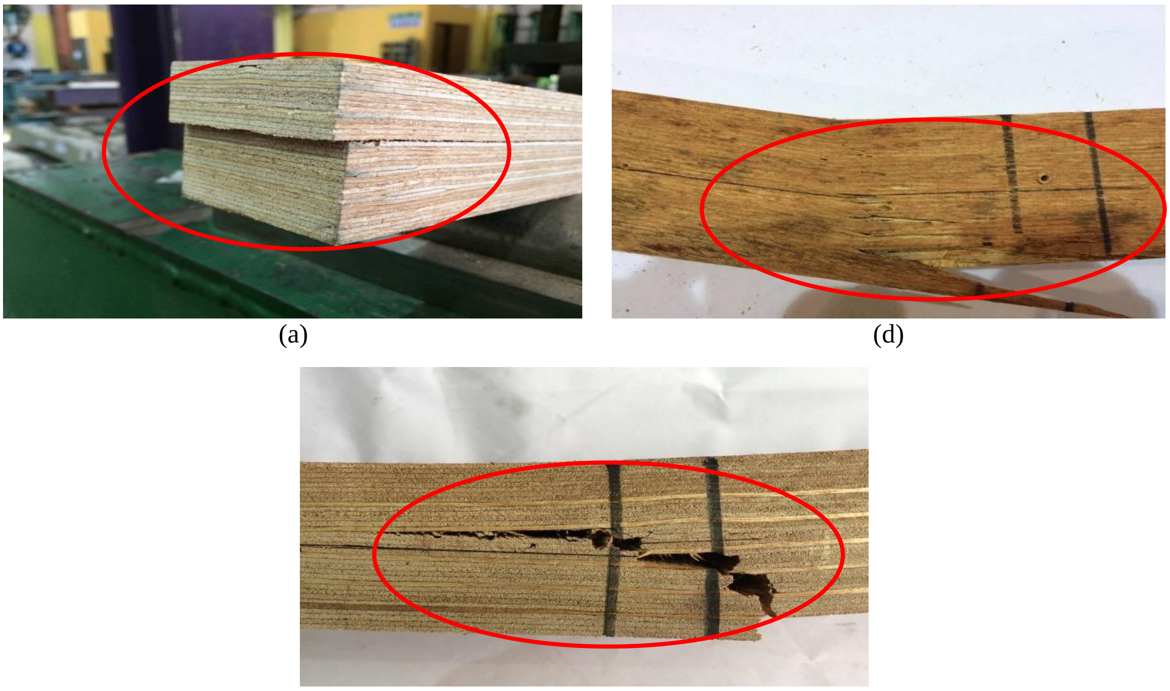
On the other hand, for samples loaded at edgewise and parallel direction, the failure only occurred to the fibre at the lower surface of tension zone (Fig. 6 (b)), no splitting of glue line was observed at the middle layer. For samples loaded at edgewise and perpendicular direction, the failure mode was similar to the failure mode of the samples loaded at flatwise perpendicular direction (Fig. 6 (c)).

Based on the study, it can be concluded that the grain direction of the samples to the span has significant influence on the failure modes of the LVL beams. Contrarily, flatwise and edgewise arrangement has minimal impact on the failure modes of the samples. This is in line with the results of MOR and MOE values which shows that the bending strength and stiffness of LVL samples were largely governed by its grain direction.

3.4.2 Failure Mode of Compression Test

The failure modes of the LVL samples subjected to compression test parallel and perpendicular to the grain are shown in Fig. 7. From observation, there were four failure modes for compression test parallel to the grain and three failure modes for compression test perpendicular to the grain. Both compression samples loaded parallelly and perpendicularly generally demonstrated the same failure modes which were crushing and splitting (Fig. 7(b) and Fig. 8(a)) and shearing (Fig. 7(c) and Fig. 8(c)). However, buckling failure (Fig 8 (b)) only occurred in perpendicular samples while end rolling (Fig. 7(a)) and wedge splitting (Fig. 7(d)) only occurred in parallel samples. Samples loaded perpendicularly failed more abruptly compared to samples loaded parallelly. This is because, for samples parallel to the grain, the load propagated parallelly along the grain direction and the longitudinal fibre in the wood provide a better resistant against the applied compression load.

Fig. 7(a) and Fig. 7(d) show similar failure pattern which is failure near the end of the samples. The mid span of the samples is virtually intact. Fig. 8(b) shows that the failure caused by initial splitting of the glue line along the entire span of the sample that eventually led to shear failure transverse to the grain. Fig. 8(c) shows the initial shear failure of the sample transverse to the grain direction that eventually led to glue line splitting at the upper end of the sample. For samples loaded perpendicular to the grain, the failure mostly occurred at the mid span of the sample with the combination of glue line splitting, bulking and shear failure. It can be concluded from the failure modes that samples loaded parallel to the grain under compression force are stronger and are able to withstand higher load than samples loaded perpendicularly.



(a) (d)

(c)

Fig. 6 - Failure modes of four-point bending test for LVL samples (a) horizontal failure at middle layer; (b) tension failure at lower tension zone, and; (c) tension failure and glue line splitting at mid-span

(a) (b)

(c) (d)

Fig. 7 - Failure modes for compression test parallel to the grain of LVL beams (a) end rolling & brooming; (b) crushing and splitting; (c) shearing at top, and; (d) wedge splitting at bottom

(a) (b) (c)

Fig. 8 - Failure modes for compression test perpendicular to the grain of LVL beams (a) crushing and splitting;(b) buckling, and; (c) shearing at mid length

4. Conclusions

The mechanical properties and bonding performance of LVL made from Kasai, Mengkulang and Kedondong were determined experimentally. The main results are summarised as follows:

- Bending properties are significantly influenced by the grain direction of the LVL samples. All the samples loaded with grain direction parallel to the span have better bending properties than samples loaded perpendicularly. Kasai LVL has the highest bending performance followed by Mengkulang and Kedondong.
- Similarly, the grain direction of the LVL samples exerted significant impact on their compressive properties. Samples loaded parallel to the compression force show better performance in terms of compressive strength and compressive modulus. Generally, Kasai LVL has a better compressive performance followed by Mengkulang and Kasai.
- The treatment conditions and grain direction of the samples demonstrated significant effect on their shear strength. LVL samples made from Kasai has better shear strength than samples made from Menkulang. However, Mengkulang LVL shows lower WFP compared to Kasai LVL. Increasing the extremity of the treatment conditions decreases the shear strength and WFP.
- The failure of bending samples is mostly due the tension failure, horizontal failure or a combination of both failure patterns. Tension failure often occurred at the lower end of the samples at mid-span. Horizontal failure often occurred at the middle layer of the samples near the support which cause the glue line to split. Meanwhile, compression samples generally fail due glue line splitting, shearing, buckling or a combination of the failure patterns.

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