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The Effect of Wood Species and Laminae Composition on the Properties of Cross-Laminated Beam Made from Community Forest Wood

Efek Jenis dan Komposisi Lamina Kayu terhadap Sifat Balok Laminasi Silang dari Kayu Hutan Rakyat

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ABSTRACT

Community forests offer diverse wood species and quantities, potentially meeting the increasing demand for wood-building materials driven by the green building concept. The diverse species have varied specific gravity. Combining wood species and cross-lamination engineering could improve the strength and dimensional stability of low-density and medium-density wood from community forests. Therefore, this research aimed to determine the effect of wood species and laminae composition on the properties of 5-ply cross-laminated beams (CLB). The 5-ply CLB was made in 5 cm x 5 cm x 112 cm with 1 cm laminae thickness. The species used were sengon, jabon, and mahogany, with acacia as enforcement. This research also compared homogeneous and heterogeneous laminae composition. The results showed that wood species and laminae composition significantly affect the mechanical properties. Heterogeneous compositions had higher mechanical properties than homogeneous compositions. The delamination test revealed that the CLB had high water resistance on cold and hot immersion even though the beams used up to three wood species.

KATA KUNCI

balok laminasi silang,
kayu hutan rakyat,
komposisi lamina,
sifat fisika dan mekanika,
jenis kayu

INTISARI

Ragam jenis dan kuantitas pasokan kayu di hutan rakyat dapat memenuhi kebutuhan material konstruksi bangunan kayu yang meningkat akibat konsep green building*. Ragam jenis kayu berkolerasi dengan ragam sifat terutama berat jenis. Pengkombinasian jenis kayu dan rekayasa laminasi silang dapat meningkatkan sifat kekuatan dan stabilitas dimensi kayu berberat jenis rendah/sedang dari hutan rakyat. Penelitian ini bertujuan untuk mengetahui efek jenis kayu dan komposisi lamina kayu terhadap sifat balok laminasi silang (CLB) 5 lapis. CLB 5 lapis dibuat dalam ukuran 5 cm x 5 cm x 112 cm (tebal masing-masing lapisan/lamina 1 cm). Jenis kayu yang digunakan adalah kayu sengon, jabon, dan mahoni dengan akasia sebagai penguat. Penelitian ini juga membandingkan komposisi lamina homogen dan heterogen. Hasil penelitian menunjukkan bahwa komposisi heterogen memiliki sifat mekanika lebih tinggi dibanding komposisi homogen. Uji delaminasi menunjukkan balok laminasi silang tahan terhadap perendaman air dingin dan panas walaupun menggunakan variasi jenis kayu hingga tiga jenis.*

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Introduction

Wood from community forests plays a crucial role in fulfilling the demand for building materials, mainly due to Indonesia's continuous decline in natural forest areas, with deforestation rates reaching 2.49 million ha from 2013 to 2017 (FWI 2020). Environment and Forestry Statistics (2019) stated that community forests produced the second-highest amount of logs after plantation forest between 2017 and 2018. Therefore, the community forests become essential sources with diverse wood species. The wood diversity of community forests varied based on the region, socio-economic conditions, and local wisdom. Sengon (*Falcataria moluccana*), mahogany (*Swietenia mahagoni*), jabon (*Anthocephalus cadamba*), acacia (*Acacia mangium* and *Acacia auriculiformis*), teak (*Tectona grandis*), pine (*Pinus merkusii*), and rosewood (*Dalbergia latifolia*) become common species cultivated in Java community forests (Jariyah & Wahyuningrum 2008). These diverse species have varied specific gravity, ranging from low (<0.40) to medium (0.40-0.75). Wood with low specific gravity positively tends to have low strength and be unsuitable for building construction (Wahyudi et al. 2014). However, the demand for wood construction materials has increased for green building constructions to lower energy consumption, carbon impact, and emissions (FPL 2010).

Layer engineering with high-specific gravity wood on the surface and cross-laminated timber technology could increase the wood's strength. Komariah et al. (2015) combined sengon and *Acacia mangium* wood as face and back layers in isocyanate-adhesive 5-layer glue-laminated timber (glulam) to improve the glulam's mechanical properties in meeting the Japanese Agricultural Standard (JAS). Borgstorm and Fröbel (2019) suggested that cross-laminated timber (CLT) resulting from crossed laminae gluing (forming a 90° angle) had an advantage over glue-laminated timber (glulam). The CLT/cross-laminated beam (CLB) had distribution of loads in the longitudinal (x-axis), transverse (y-axis), and perpendicular both directions (x-axis), which were distributed more evenly and earthquake resistant. The CLB had a stable dimension due to its crossed laminae. The dimensional stability of CLB is also more excellent due to the lack of shrinkage-swelling originating from the crossed-layers. Therefore, the CLB technology is suitable for gluing laminae combinations with different wood species and the risk of shrinkage.

The selection and arrangement of laminae affect the properties of laminated products (Lam et al. 2003). In this context, the compositions of wood species with different specific gravity can influence the properties of CLB. Therefore, this research aimed to determine the effect of wood species and laminae composition on CLB's physical and mechanical properties from community forest wood.

Methods

Material

The raw materials for Sengon wood (S) and white Jabon wood (J) were from community forests in Bulaksalak Hamlet, Wukirsari Village, Cangkringan District, Sleman Regency, Yogyakarta. Mahogany (M) was obtained from Sambilegi Village, Maguwoharjo District, Sleman Regency, Yogyakarta while acacia (*Acacia mangium*) (A) was from Gading Village, Playen, Gunung Kidul Regency, Yogyakarta. The raw materials were in the form of logs, which were cut, dried, and planed or shaved into boards with a thickness of 1 cm. In addition, the materials were defect-free and air-dried, with homogenized moisture content ranging from 12.5-14.4% to avoid inner stresses and cracks in laminated-timber (Vanya 2012). British Standard European Norm (BS EN) 386 required the moisture content of unpreserved laminae in glulam to range from 8-15%, with the difference between laminae not exceeding 4% (CEN 2001). The specific gravity and surface roughness of the laminae on each wood species after being shaved using a planner was presented in Table 1. Meanwhile, Polyvinyl acetate (PVAc) from PT Aica Indria, Pasuruan, was used as the adhesive without dilution.

Manufacture of CLB

The CLB consisted of five laminae layers with laminae of 1 cm thickness. The CLB size was 112 cm x 5 cm x 5 cm. The laminae was arranged with the wood grain direction crossed between layers, forming a 90° angle, similar with the arrangement in plywood. The crossband layers (second and fourth layers) consisted

Table 1. Wood-specific gravity and surface roughness

Wood Species	Specific gravity	Specific gravity category*	Surface roughness (μm)	
			Parallel to the grain direction	Perpendicular to the grain direction
Sengon wood (S)	0.26-0.30	Low	5.00±2.20	12.57±2.35
Jabon wood (J)	0.40-0.47	Medium	4.84±1.47	11.00±1.78
Mahogany wood (M)	0.46-0.49	Medium	4.50±1.46	8.57±1.48
Acacia wood (A)	0.62-0.66	Medium	3.50±1.28	9.16±2.03

Description: *Based on International Association of Wood Anatomist criteria (IAWA 1989)

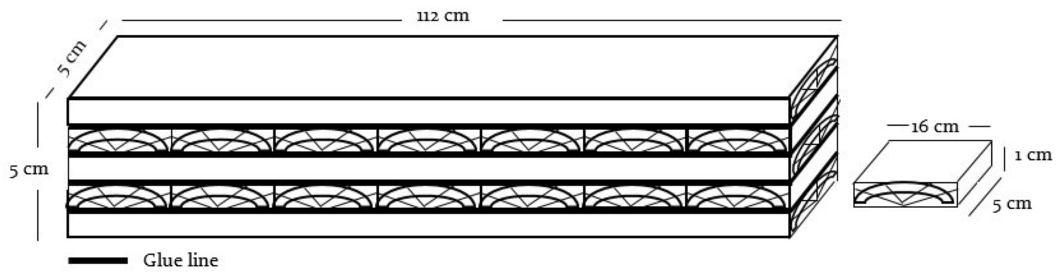

Figure 1. Cross-laminated beam illustration

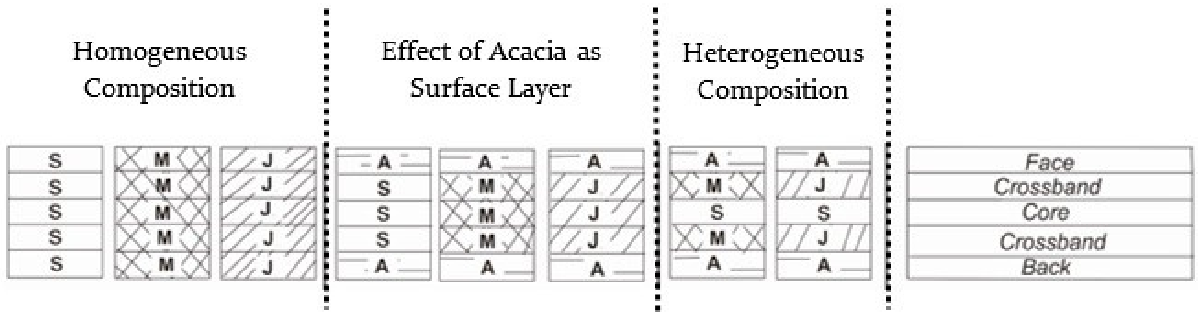

Figure 2. The laminae composition of cross-laminated beam (S = sengon, M = mahogany, J = jabon, A = acacia)

of seven wooden laminae in a 16 cm x 5 cm x 1 cm size arranged to form the length of cross-laminated beam with an unglued thick side (Figure 1). The interlayer glue spread was 50 #MSGL (1000 square feet single glue line) or 244 g/m2 with the adhesive applied only on one surface of the laminae. The CLB was made in the combination of wood species and laminae composition shown in Figure 2. The combination process used the increasing specific gravity principle from the core layer to the surface (face and back) to increase the static bending strength. In the static bending strength test, the face and back layers receive the highest compressive and tensile forces when loaded perpendicular to the wood surface, respectively (Li et al. 2022). Therefore, the surface layer should be use wood with high specific gravity. Acacia had the highest specific gravity at 0.62-0.66 (Table 1) and became the surface layer. Compression process was carried out for 24 hours at room temperature with a specific pressure of 250 psi (specific pressure of 1.7 MPa) and followed by conditioning for approximately seven days.

Testing of CLB

The testing of CLB included physical (moisture content and density) and mechanical properties (modulus of rupture, modulus of elasticity, and shear strength), as well as delamination tests (cold water and hot water). Moisture content measurement used British standard 373 (BSI 1957) by calculating the percent change in weight of a 2 cm x 5 cm x 5 cm sample against kiln-dried weight. Lestari et al. (2015, 2018) conducted cold and hot water delamination tests based on JAS 234-2007 (JSA 2007). However, this research modified the test using only one sample for cold and hot water delamination tests due to CLB's relatively high dimensional stability. In the cold water delamination test, the 5 cm x 5 cm x 5 cm CLB sample was soaked in room temperature water (±27°C) for six hours and put in the oven at 40±3°C for 18 hours before measuring the delamination length at four adhesive lines. Subsequently, the same CLB sample was tested for hot water delamination by immersing in boiling (100°C) for four hours, room temperature water for one hour, and putting in the oven at 70±3°C for 18 hours before measuring the delamination length at the four adhesive lines. The delamination length was measured when the opened-adhesive line was 1 mm thick or more. The delamination ratio was calculated by dividing the total delamination length by the length of adhesive lines and multiplying by 100.

The modulus of rupture and elasticity (3-point out-of-plane static bending strength) was tested based on ASTM D143 (ASTM 1994) with a sample size of 80 cm x 5 cm x 5 cm (Figure 3), a loading speed of 0.25 cm/minute and a span length of 71 cm. The ASTM D905 (ASTM 1998) was used in the test of shear strength on notched samples with a notch length of 0.25 inch or 0.6 cm each. The adhesive lines (four per sample) were tested at a loading speed of 0.5 cm/minute and averaged to result in a shear strength value. An Instron type 3360 universal machine (UTM) was utilized to analyze the modulus of rupture, elasticity, and internal adhesive strength. One-way analysis of variance (one-way ANOVA) at 1% and 5% significance levels followed by the Tukey (honestly significant difference) test were conducted to determine the effect of treatments on the CLB properties. IBM SPSS Statistic software was employed to the statistical analysis.

Results and Discussion

Compared to the initial wood-specific gravity (Table 1), the density of each wood species in homogeneous CLB increased. However, the increase varied between species. The highest and lowest increases occurred in Sengon (23%) and Jabon (7.5%). Laminated products of lower specific gravity wood tended to have a higher increase in density than those with higher specific gravity. This increase also occurred in the 3-layer homogeneous composition cross-laminated timber (CLT). Sengon had the highest increase in density, followed by sendok-sendok (*Endospermum malaccensis*), rubber (*Hevea brasiliensis*), and ambarella wood (*Canarium sp.*), which had the highest specific gravity (Yusoh et al. 2021). The increase in density was due to the additional weight of the adhesive and the pressure during the CLB manufacturing process. The density of homogeneous composition CLB was significantly different between wood species. The density of homogenous mahogany CLB was significantly higher than that of Jabon and Sengon. Wood species affected the density of 3-layer CLT as well as 3-layer, and 5-layer glulam (Komariah et al. 2015; Yusoh et al. 2021).

Acacia mangium as face layer significantly increased the density of CLB compared to the homogeneous composition of each wood species, except for mahogany. Komariah et al. (2015) reported a similar

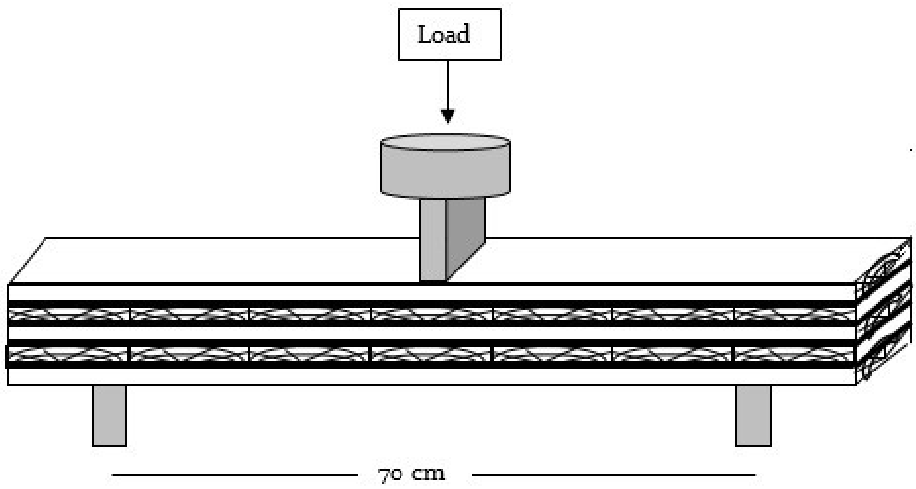

Figure 3. Illustration of CLB static bending strength test (out-of-plane type)

Table 2. The density, moisture content, and delamination ratio of various CLB

Treatment	Density (kg/m³)	Moisture content	Delamination Ratio	
			Cold water	Hot water
SSSSS	321±17 a	13.97±0.76 a	0.0- 1.0% a	0.2-4% a
JJJJJ	432±34 b	13.93±0.11 a	0.0% a	0.0-0.9% a
MMMMM	531±14 d	13.56±0.38 a	0.0% a	0.0-0.3% a
ASSSA	444±11 b	13.10±0.34 a	0.0-1.9% a	0.0-2.4% a
AJJJA	499±28 c	13.51±0.60 a	0.0% a	0.0% a
AMMMA	534±29 d	13.34±0.32 a	0.0% a	0.0% a
AJSJA	463±9 bc	13.36±0.33 a	0.0% a	0.0-0.3% a
AMSMA	514±12 cd	13.69±0.48 a	0.0% a	0.0-0.1% a

increase in density within 5-layer glulam from sengon wood with the surface of *Acacia mangium*. However, a downward trend occurred in glulam from the Manii (*Maesopsis eminii* Engl.) wood with *Acacia mangium* surface compared to the homogeneous composition. The density changes that occurred in laminated wood product depended on the wood species. The density of ASSSA CLB was not significantly different from JJJJJ CLB (Table 2). Replacing core layer using sengon in the composition of AJJJA and AMMMA to AJSJA and AMSMA insignificantly reduced the density. The density was an important factor to predict the strength of wood and wood composite product (Bodig & Jayne 1982; Tran & Jeong 2021).

The moisture content of the CLB in this research ranged from 13.1-13.9% (Table 2). Kukk et al. (2021) suggested that 5-layer CLT could become an airtight layer in external wall construction, as long as the CLT initial moisture content remained low (about 13%) and maintained throughout the construction lifetime. Therefore, the CLT product of this research could become an external airtight layer. The moisture content properties tended to be similar in all treatments, showing that the effects of wood species and laminae composition did not affect the CLB moisture content values. Lestari et al. (2015) also stated that the type of wood did not affect the moisture content of the 3-layer homogeneous glulam from pine, jabon, and sengon. The moisture content of all treatments met the JAS 234-2007 standard for laminated beams (JSA 2007), which is less than 15%.

The delamination ratio indicated the adhesion quality and resulted from internal shear stress between the bonded surfaces caused by swelling and shrinkage (Sikora et al. 2016). The CLB delamination ratios for the cold and hot water ranged from 0-1.9% and 0-4%, respectively (Table 2). The delamination ratios for the cold and hot water of homogenous sengon CLB (SSSSS) and acacia-sengon CLB (ASSSA) were the highest among the other treatments but statistically insignificant. This might be related to sengon had low dimensional stability with higher total volume shrinkage than other species such as gmelina (*Gmelina arborea*), jackfruit (*Artocarpus heterophyllus*), manii, and *Acacia mangium* (Wahyudi & Harijadi 2010; Rahayu et al. 2020). Wood species and laminae composition did not affect the CLB delamination ratio of cold and hot water, which was similar to glulam (Komariah et al. 2015). The delamination ratio resulting in this research met the decorative structural glulam standard JAS 234 (JSA 2007), which required a maximum of 5% for cold water and 10% for hot water. The low delamination ratio indicated that the CLB had good adhesion and high dimensional stability. The CLB possessed high dimensional stability due to minimal swelling and shrinkage due to *cross-wise layering* (Brandner et al. 2016).

In the homogeneous CLB, the wood species affected the modulus of rupture (MOR). The MOR of homogeneous sengon CLB was significantly lower than that of Mahogany and Jabon due to its lower density (Figure 4). The MOR of homogeneous sengon CLB resulting from this research was lower than a 5-cm thick solid sengon wood (33.82 MPa) and 5-layer glulam with 5-cm thick using isocyanate adhesive (33.08 MPa) (Komariah et al. 2015). Cross-laminated timber had lower modulus of rupture and modulus of elasticity than glulam (Choi et al. 2015; Li et al. 2022).

Using acacia on the surface increased the MOR of CLB compared to the homogeneous CLB, similar to Acacia-Sengon and Acacia-many glulam (Komariah et al. 2015). The Mahogany-Acacia CLB had the highest increase of MOR (45%), although the CLB density increased insignificantly. The ASSSA and AJJJA CLB had an insignificant increase in MOR compared to the homogeneous Sengon and Jabon CLB due to the drastic changes in specific gravity from the surface to the crossband and core layers of the CLB. The crossband layer that also received compressive and tensile forces during the loading was held by other wood species (namely Sengon and Jabon) which had significantly different specific gravity and strength from acacia. Due to different stress-strain behavior and strength among wood species (Kretschmann, 2010), lower specific density and strength of Sengon and Jabon compared to Acacia lead to rapid damage during the loading.

Using sengon with the lowest specific gravity as the core layer in AJSJA and AMSMA compositions did not significantly affect the MOR when compared to the AJJJA and AMMMA compositions. The CLB core, which experienced the lowest compressive and tensile forces compared to other parts (Hein & Brancheriau 2018), could use low specific gravity wood species without significantly changing the bending strength. Therefore, the CLB core could use cheaper sengon wood species to reduce production costs. The MOR of AJSJA and AMSMA compositions was significantly higher than all homogeneous composition and those with acacia as surface layer, except AMMMA composition.

Similar with MOR, the Jabon and Mahogany CLB

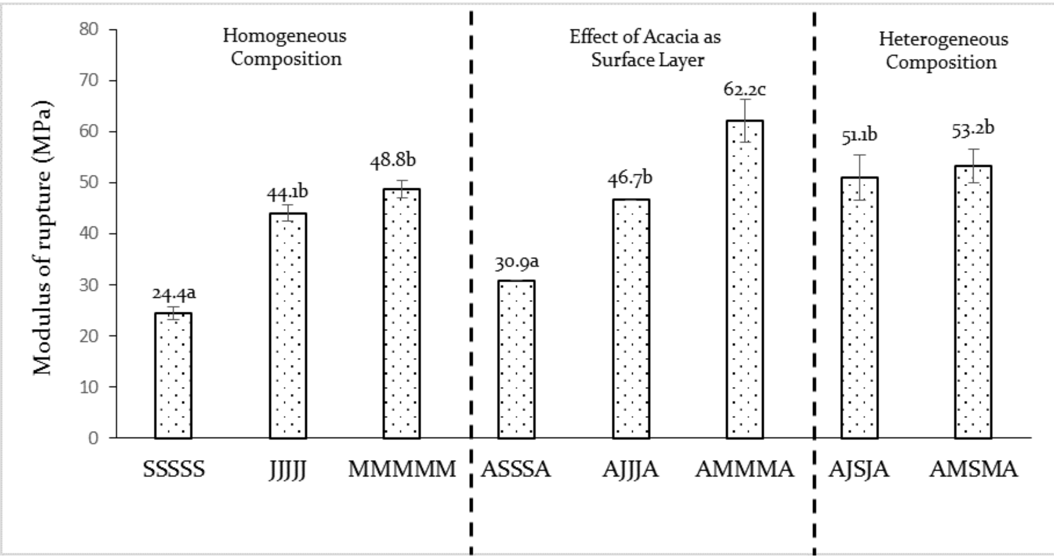

Figure 4. Modulus of rupture of cross-laminated beam

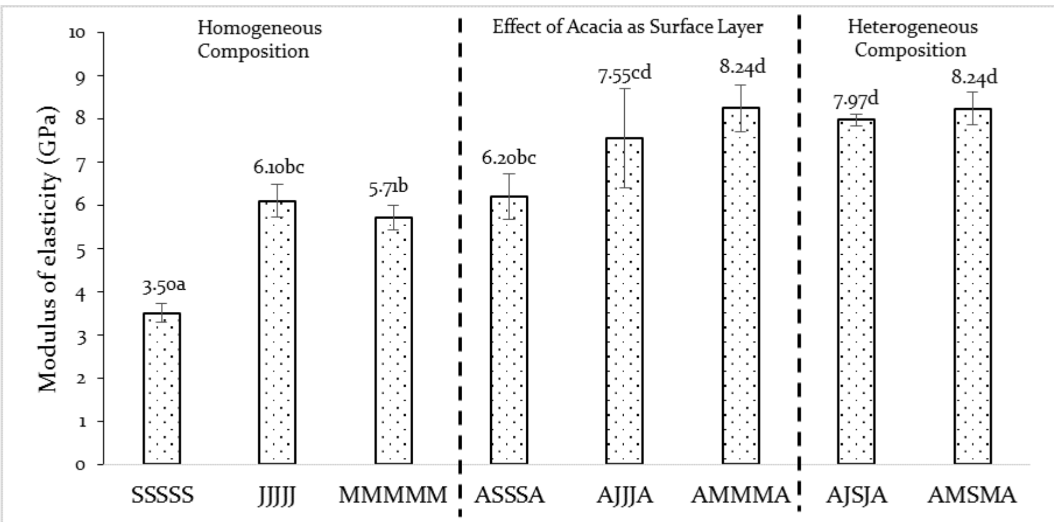

Figure 5. Modulus of elasticity of cross-laminated beam

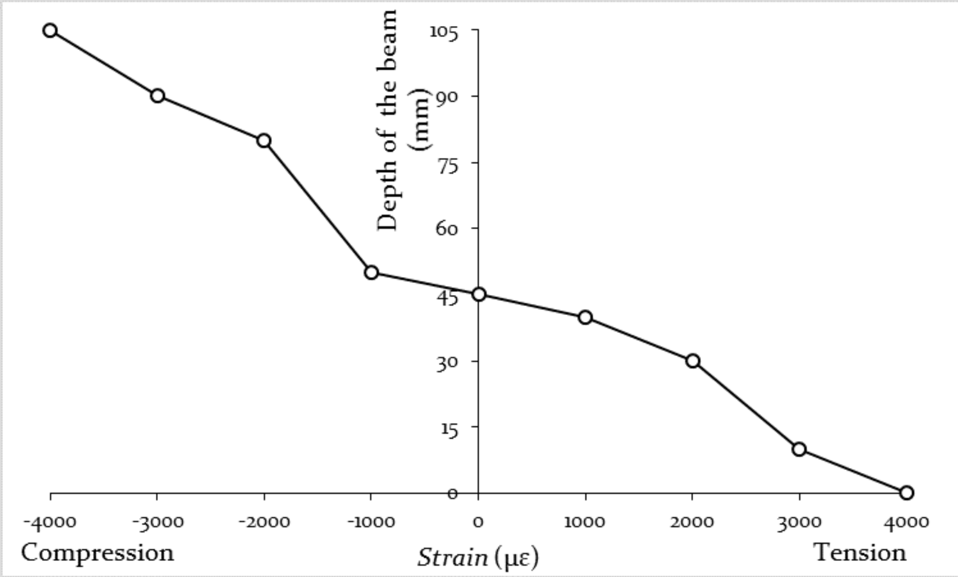

Figure 6. Strain distribution illustration towards beam depth in static bending test

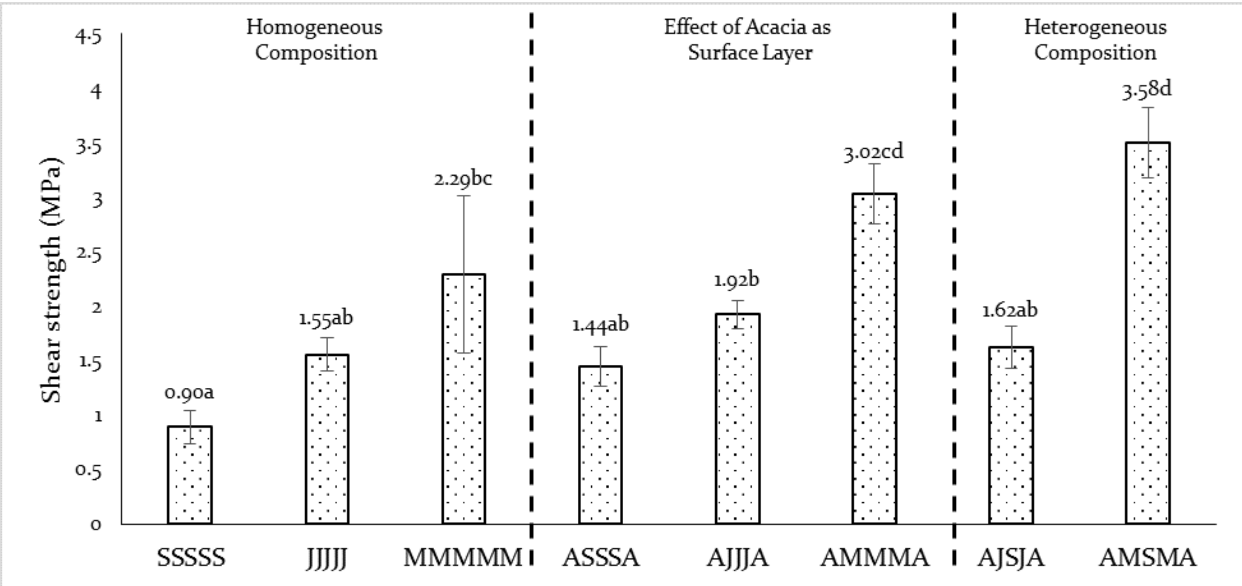

Figure 7. Shear strength of cross-laminated beam

had a higher modulus of elasticity (MOE) than Sengon CLB, with Jabon CLB having the highest value (Figure 5). Statistically, the MOE of homogenous Jabon and Mahogany CLB was not significantly different. The MOE of Sengon CLB was 42% lower than that of 5 cm thick solid sengon wood (6.037 GPa) (Komariah et al. 2015). Using acacia as surface layer (AJJJA) resulted in an equivalent MOE to a solid sengon. The Acacia layer increased the CLB's MOE. Li et al. (2022) revealed that the mechanics and geometry characteristics of the outermost layer contributed dominantly to the MOE of glulam as well as 3- and 5-layer CLT. During static bending tests, the highest strains occurred at the wood surface in both CLT and glulam, gradually decreased to 0 (zero) towards the core (Figure 6). The MOE of AJJJA, AMMMA, AJSJA, and AMSMA CLB was not significantly different. The substitution of the core layer with sengon wood insignificantly changed the MOE.

The shear strength of the 5-layer CLB ranged from 0.90-3.58 MPa (Figure 7), and the type of wood affected the shear strength of homogeneous CLB. The homogeneous mahogany CLB had 154.4% and 47.7% higher shear strength than homogeneous sengon CLB and homogeneous jabon CLB, respectively. The wood density was directly proportional to the shear strength in glulam and CLT (Jiang et al. 2014; Aicher et al. 2018; Yusoh et al. 2021). Using acacia as surface layer increased the CLB density and shear strength. An increase in shear strength of up to 60% occurred from the homogeneous composition of sengon (SSSSS) to ASSSA. This increase was higher than the increase in 5-layer glulam (37%) using isocyanate adhesives of the same wood species and composition (Komariah et al. 2015), probably due to the higher density of the laminated wood products in this research. The shear strength of AJSJA was significantly lower than that of AMSMA. Using different wood species in the crossband layer affected the density of CLB and the bonding between layers. The highest shear strength occurred in the AMSMA composition. However, the shear strength did not meet the JAS 234 (JSA 2007) standard, which required a minimum of 5.3 MPa. Aicher et al. (2018) suggested that low bond strength might be tolerated in a certain areas for products with wider surfaces, such as CLT. In the case of beam-type construction, a strong bond was required in all areas for short-term and long-term safety.

Conclusion

Combining wood species and laminae composition affects the mechanical properties of 5-layer CLB. Homogeneous CLB with mahogany wood species had higher mechanical properties than other species. Using acacia wood as surface layer improved the mechanical properties of Sengon, Mahogany, and Jabon CLB. Replacing the core layer in AJJJA and AMMMA with Sengon into AJSJA and AMSMA did not significantly change the static bending strength. CLB with AMMMA laminae composition had the highest physical and mechanical properties, potentially as raw materials for construction. Further investigation on stress-strain and failure patterns during the loaded bending test for different species combinations and laminae compositions is required. Another crucial aspect is to analyze the relation between the failure pattern and the mechanical values of the CLB.

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