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Physical-Mechanical Properties of Glued Laminated Timber Made from Tropical Small-Diameter Logs Grown in Indonesia[1]

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ABSTRACT

The aim of this study was to determine the physical and mechanical properties of glued laminated timber (glulam) manufactured from small-diameter logs of three wood species, *Acacia mangium* (mangium), *Maesopsis eminii* (manii), and *Falcataria moluccana* (sengon), with densities of 533, 392, and 271 kg/m^3, respectively. Glulam measuring 5 cm by 7 cm by 160 cm in thickness, width, and length, respectively, was made with three to five lamina, or layers, and isocyanate adhesive. The glulams contained either the same wood species for all layers or a combination of mangium face and back layers with a core layer of manii or sengon. Solid wood samples of the same size for all three species were included as a basis for comparison. Physical-mechanical properties and delamination tests of glulam referred to JAS 234:2003. The results showed that the properties of same species glulam did not differ from those of solid wood, with the exception of the shear strength of glulam being lower than that of solid wood. Wood species affected glulam properties, but three- and five-layer glulams were not different except for the modulus of elasticity. All glulams were resistant to delamination by immersion in both cold and boiling water. The glulams that successfully met the JAS standard were three- and five-layer mangium, five-layer manii, and five-layer mangium-manii glulams.

Keywords : Glulam, solid wood, small-diameter logs, physical and mechanical properties, delamination

1. INTRODUCTION

Logs from community and plantation forests play important roles in fulfilling the log demand of the wood industry in Indonesia. Approximately 10 million hectares of land is being developed for fast-growing species, such as mangium (*Acacia mangium*), sengon (*Falcataria moluccana*), and manii (*Maesopsis eminii*) (Ministry of Forestry 2012). Wood from fast-growing species generally has a small diameter (less than 30 cm), with short cutting cycles (5-10 years), and it generally has inferior properties in terms of the amount of defects, durability, and strength compared to mature wood from a natural forest. Currently wood from fast-growing species is

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not used for structural purposes, but the three species mentioned here are commonly planted and could feasibly replace timber from natural forests (Massijaya *et al.* 2011).

Wood for structural purposes requires high strength as well as large dimensions and a long span of distance. To meet the requirements for structural components with dimensions that do not depend on the wood log diameter, glued laminated timber (glulam) was developed. Glulam is a constructed form that can be modified to achieve high strength, which enables its use in vertical columns or horizontal beams; it can also be formed to construct arches or curved shapes (Moody *et al.* 1999). Making glulam from small-diameter logs and low-quality wood, rather than from large-diameter and high-quality logs, is a more efficient way of using wood resources (Massijaya *et al.* 2011). The underlying factors for glulam production are an increase in world demand for wood and the declining amount of large-sized solid wood available (Bahtiar 2008).

The characteristics of glulam are influenced by the properties of each lamina, and the laminas can be arranged to improve the strength properties of the glulam. In principle, various types of wood can be used in glulam products by using suitable adhesives, and different combinations allow altering properties such as strength (Cheng and Gu 2010). Glulam can be created by arranging laminas of different thicknesses horizontally, so that as the laminas become increasingly thinner, a greater number and more areas of adhesive are needed (Sulistyawati *et al.* 2008). Faherty and Williamson (1999) suggested that the chosen adhesive be stronger and have greater weather resistance than the wood. The type of adhesive for glulam is selected based on its technical and economic suitability. According to Ruhendi *et al.* (2007), the advantages of isocyanate are that less adhesive is needed, a lower temperature and a shorter compression cycle can be used, and the final product has higher dimensional stability and does not contain formaldehyde.

The aim of the current research was to determine the physical and mechanical properties of glulam made from small-diameter logs of mangium, manii, and sengon.

2. MATERIALS and METHODS

2.1. Materials

The wood was harvested from fast-growing tree species, and the logs varied from 15 to 25 cm in diameter. The three wood species used, mangium, manii, and sengon, were from Bogor, West Java, Indonesia. The adhesive was isocyanate PI-3100, a water-soluble polymer that consisted of base resin and hardener obtained from PT Polychemi Asia Pasifik, Jakarta.

2.2. Methods

Laminas of 1- and 1.7-cm thicknesses, 7-cm width, and 160-cm length were dried in the kiln to a moisture content of approximately 12%. Lamina sorting was performed by modulus of

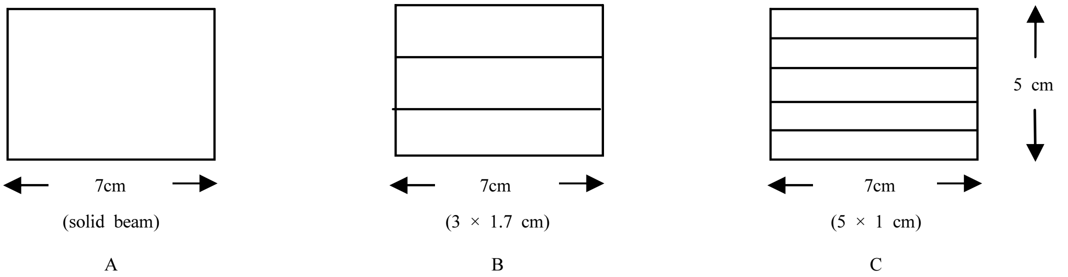

Fig. 1. Solid and glulam cross-section.

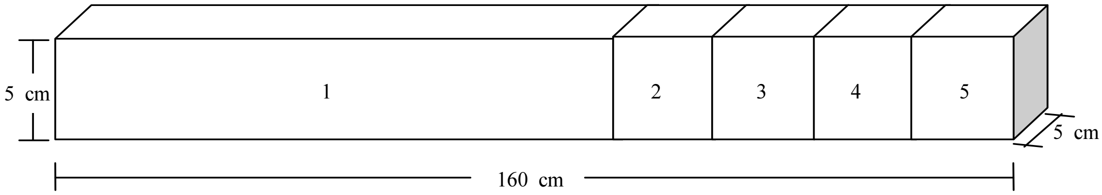

Fig. 2. Cutting pattern sample of glulam.

Where,
1. Sample testing for MOE/MOR (5 cm × 5 cm × 76 cm)
2. Sample testing for delamination (in cold water) (5 cm × 5 cm × 5 cm)
3. Sample testing for delamination (in boiling water) (5 cm × 5 cm × 5 cm)
4. Sample testing for shear strength (5 cm × 5 cm × 5 cm)
5. Sample testing for moisture content and density (5 cm × 5 cm × 5 cm)

elasticity (MOE) prediction using a nondestructive testing system with a panter wood grading machine (Surjokusumo *et al.* 2003). Laminas used for the face or back layers of glulam had higher MOE values, while the core and crossband laminas had lower MOE values. The glulams contained either the same wood species for all layers or a combination of mangium face and back layers with a core layer of manii or sengon All laminas were constructed with a parallel fiber orientation. The solid beam size was 5 cm by 7 cm by 160 cm in thickness, width, and length, respectively (type A, solid wood); laminas with a thickness of 1.7 cm were used for three-layer construction (glulam type B); and 1 cm laminas were used for five-layer construction (glulam type C) (Fig. 1). Adhesive was prepared according to the technical standards specified by the manufacturer. Before the adhesive was applied, the resin and hardener were mixed in a 100 : 15 ratio (by weight). Adhesive spreading was done with a spatula, using 280 g/m^2 per single glue line. The cold press was applied for 3 hours at 0.98 N/mm^2 pressure, followed by conditioning for 1 week and finishing. Manufacture of sample test was done with sizing glulam to 5 cm by 5 cm by 160 cm. Cutting pattern of glulam panel as shown in Fig. 2.

Assessments of physical and mechanical properties, including moisture content, density, MOE, modulus of rupture (MOR), and shear strength, and delamination tests were performed according to Japan Agricultural Standard (JAS) for Glued Laminated Timber (JAS 2003). MOE and MOR were obtained by the bending tests by using an Instron UTM machine (type 3369). Testing was done through a single point load on the span of a sample with a loading speed of 3.5 mm/min.

Moisture content was calculated by the following formula:

$$\text{Moisture Content}(\%) = \frac{\text{Initial Weight - Oven Dry Weight}}{\text{Oven Dry Weight}} \times 100$$

Density was calculated by the following formula:

$$\text{Density (kg/m}^3\text{)} = \frac{\text{Air Dry Weight}}{\text{Air Dry Volume}}$$

The MOE and MOR could be expressed as follows:

$$\text{MOE(N/mm}^2\text{)} = \frac{\Delta PL^3}{4\,\Delta Y\,bh^3};$$

$$\text{MOR (N/mm}^2\text{)} = \frac{3PL}{2\,b\,h^2}$$

where ΔP is the difference between the upper and lower loading limits in the proportional limit region (N), ΔY is the deflection with respect to ΔP (mm), L is span (mm), b is the width of the glulam (mm), h is the thickness of the glulam (mm), and P is the maximum loading (N).

The shear strength was calculated as follows:

$$\text{Shear Strength (N/mm}^2\text{)} = \frac{\text{Rupture Load (N)}}{\text{Area of Bonding Layer (mm}^2\text{)}}$$

Delaminating ratio was calculated by the following formula:

$$\text{Delaminating Ratio}(\%) = \frac{\text{Sum of Delaminated Lengths of Two Cross Sections}}{\text{Sum of Gluing Lengths of Two Cross Sections}} \times 100$$

Analysis of data comparing solid wood and glulam was done using Student's *t*-test, and glulam properties were analyzed by using a 5 × 2 factorial in a completely randomized design with three replications. The first factor was wood species (mangium, manii, sengon, mangium-manii, and mangium-sengon), and the second factor was the number of layers in the glulam (three and five). If the first and/or interaction factors were significantly different, Duncan's multirange test was used for further analysis.

3. RESULTS and DISCUSSIONS

3.1. Sorting and Preparing Lamina

Laminas were sorted based on MOE estimates obtained by using a nondestructive method with a panter grading machine (Surjokusumo *et al.* 2003). Estimated MOE values were then

Table 1. MOE value of lamina constituents for each types glulam

Wood species	No. of layers	Mean ± STD MOE lamina (10^3 N/mm^2)		
		Group EA	Group EB	Group EC
Mangium	3	10.65 ± 1.26	-	8.66 ± 0.84
	5	10.78 ± 0.98	8.25 ± 0.38	7.12 ± 0.22
Manii	3	8.82 ± 0.60	-	7.35 ± 0.57
	5	10.36 ± 0.25	8.77 ± 0.87	7.14 ± 0.35
Sengon	3	6.77 ± 0.69	-	4.91 ± 0.58
	5	5.97 ± 0.14	5.33 ± 0.17	4.18 ± 0.24
Mangium-manii	3	11.61 ± 1.03	-	8.25 ± 0.21
	5	10.09 ± 0.37	8.34 ± 0.63	6.85 ± 0.34
Mangium-sengon	3	6.24 ± 1.11	-	3.52 ± 0.06
	5	6.90 ± 0.40	5.70 ± 0.26	4.60 ± 0.58

* Note: EA (face/back), EB (crossband), EC (core).

grouped by the type of glulam made. Three-layer glulams were divided into two groups, while the five-layer glulams comprised three groups. The estimated lamina MOE values were used as the rationale for making 10 types of glulam based on the principle that the laminas with the highest MOE were used for the outer layer and laminas with the lower MOE were placed on the inside. This method was used to increase the stiffness of glulam produced.

Table 1 shows that the average estimated MOE value for mangium lamina was equal to those for manii lamina, which were used for crossband and core layers groups. However, for the group with face or back layers the average estimated MOE value for mangium lamina was higher than that of manii lamina. The average estimated MOE value was the lowest for sengon lamina. Estimated MOE values were related to the density of the three types of wood as well as the presence of defects such as knots and sloping grain. The average density of sengon was the lowest (271 kg/m^3), and the density of mangium (533 kg/m^3) was the highest; the density of manii (392 kg/m^3) was intermediate. Defects such as knots and grain sloping were the most numerous in manii, and manii wood and mangium had large proportions of sapwood and heartwood. The results showed a high variation in estimated MOE values because the minimum or maximum estimated MOE values for laminas were not limited when manufacturing glulams. Sorting was done with the intent to classify lamina into a group of face or back (EA), crossband (EB), or core (EC) so all the laminas could be used for glulam manufacturing.

3.2. Physical Properties

3.2.1. Density

Wood strength is directly related to its density, with fiber wall thickness contributing to a larger strain capacity for high-density wood.

Table 2. Physical properties of glulam and solid wood

Wood species	No. of layers	Density (kg/m^3)	Moisture content (%)
Mangium	Solid	533 ± 40	12.2 ± 0.3
	3	587 ± 11	16.9 ± 1.0
	5	440 ± 28	16.6 ± 1.0
Manii	Solid	392 ± 35	12.6 ± 1.9
	3	389 ± 63	14.7 ± 0.3
	5	483 ± 20	14.4 ± 0.3
Sengon	Solid	271 ± 5	12.8 ± 0.3
	3	294 ± 22	14.2 ± 1.9
	5	290 ± 12	15.1 ± 0.3
Mangium-manii	3	497 ± 15	13.8 ± 0.3
	5	447 ± 21	15.6 ± 0.5
Mangium-sengon	3	377 ± 38	13.9 ± 0.2
	5	390 ± 46	13.8 ± 0.7
JAS Standard			Max 15.0

Consequently, high-density wood has greater strength, hardness, and rigidity than low-density wood (Ruhendi *et al*. 2007). Table 2 shows that sengon glulam and solid wood had the lowest density, while mangium glulam and solid wood mangium had the highest density. The other specimens showed intermediate values in terms of density. The Student's *t*-test in Table 3 shows that solid wood and glulam made from the same species did not significantly differ in terms of density, indicating that the pressing processes did not affect glulam density. There was a high variation in density of solid wood and glulam due to the high variability of the raw material though, especially with regard to the proportion of sapwood and heartwood, with sapwood dominating.

Wood species affected glulam density (Table 4) because of the large variation in density among them, 270 to 530 kg/m^3. The anatomical properties varied largely depending on the species, especially in young trees because they contained a lot of juvenile wood. Even within a single species, wood density can vary based on the location within a tree and the site conditions (Mandang and Pandit 1997). The number of glulam layers did not affect density, but it was affected by the interaction between wood species and the number of layers. Based on further Duncan's tests (Table 5), three-layer mangium glulam had the highest density and was differed significantly from the other nine types of glulam. All sengon glulams had lower densities compared to the other glulams.

3.2.2. Moisture Content

Moisture content results for each type of glulam are presented in Table 2. The average moisture content was 13-15% for manii, sengon, mangium-manii, and mangium-sengon of

Table 3. Student's *t*-test of solid wood and glulam

Parameter	Treatment	Mean ± STD	P-value	Remarks
Density	Solid	399 ± 117	0.59	NS
	Glulam	419 ± 92		
Moisture content	Solid	12.5 ± 1.0	0.00	*
	Glulam	14.9 ± 1.3		
MOE	Solid	(9,378 ± 2,668)	0.25	NS
	Glulam	(10,761 ± 3,355)		
MOR	Solid	45.52 ± 9.22	0.16	NS
	Glulam	54.35 ± 17.26		
Shear strength	Solid	7.67 ± 2.46	0.05	*
	Glulam	5.49 ± 1.72		

* Significance level 0.05, NS = Not Significant

Table 4. ANOVA of the physical and mechanical properties of glulam

Parameter	Species (A)	Layer (B)	Interaction A × B
Density	*	NS	*
Moisture content	*	NS	NS
MOE	*	*	*
MOR	*	NS	NS
Shear strength	*	NS	NS
Delamination in cold water	NS	NS	NS
Delamination in boiling water	NS	NS	NS

* Significance level 0.05.

three- and five-layer glulams, while mangium glulams had 17% moisture content for both layer types. Mangium had a higher moisture content because of its higher density (533 kg/m^3), which made drying more difficult compared with manii (392 kg/m^3) and sengon (271 kg/m^3); mangium needed a longer drying time to reach a lower moisture content. This value is similar to that reported by Sulistyawati *et al.* (2008) who found an average moisture content of 16.3% for mangium glulam. Both three- and five-layer glulam from manii and mangium-sengon had a moisture content that met the JAS 234 : 2003 standard for a maximum of 15%. Meanwhile, neither type of mangium glulams nor the five-layer sengon and five-layer mangium-manii glulams met the standard, because the moisture content of the glulams was affected by the moisture content of each lamina (the glulams were made during the wet season, December to April).

The moisture content of solid wood was lower than that of glulam, which was indicated by the Student's *t*-test differences shown in Tables 2

Table 5. Duncan analysis for density

Parameter	N	Subset[a]				
		1	2	3	4	5
Sengon 5	3	290				
Sengon 3	3	294				
Mangium-sengon 3	3		377			
Mangium-sengon 5	3		390	390		
Manii 3	3		389	389		
Mangium 5	3			440	440	
Mangium-manii 5	3			447	447	
Manii 5	3				483	
Mangium-manii 3	3				497	
Mangium 3	3					587
Significance		0.90	0.63	0.05	0.05	1.00

[a] Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is mean square (error) = 0.001.

and 3. The lamina was thinner than solid wood, so it adjusted to equilibrium moisture more rapidly, especially in the wet season. In addition, the water in the adhesive did not completely leave the glulam, resulting in a higher moisture content for the glulam. The wood species affected the moisture content of the 10 types of glulam (Table 4). The difference occurred because mangium glulam was composed of the highest density laminas; consequently, the cell wall was thicker and had a higher amount of bound water (Ruhendi *et al.* 2007).

3.3. Mechanical Properties

3.3.1. Modulus of Elasticity

Table 6 shows that the MOE of all glulam types except sengon glulams exceeded the minimum requirement established by JAS 234:2003; sengon wood had a very low density (271 kg/m^3) resulting in a low MOE. The MOE of glulam was directly related to the MOE of its individual laminas, especially the outermost lamina on the tension side, and the density of the species (Moody *et al.* 1999). This is consistent with Sulistyawati *et al.* (2008), who reported the MOE of mangium to be 9.3 × 10^3 N/mm^2. Mixed use of wood species, except sengon, in manufacturing glulam was effective because wood with the lower density can safely be used as a core layer. The core layer experiences lower compressive and tensile stresses compared to the face and back layers.

Based on the Student's *t*-test presented in Table 3, the MOE of glulam did not differ from that of the related solid wood, but there was a high standard deviation due to high variability of the raw material. This variability arose from large proportions of visible sapwood, but little heartwood, especially for mangium.

Table 6. Mechanical properties of solid wood and glulam

Species	Layer	MOE (N/mm^2)	MOR (N/mm^2)	Shear strength (N/mm^2)	Delamination	
					Cold water (%)	Boiling water (%)
Mangium	1 (solid)	11,930 ± 830	54.38 ± 0.91	10.72 ± 0.32	-	-
	3	13,154 ± 338	72.79 ± 12.92	6.58 ± 3.25	0	3.8 ± 3.6
	5	8,709 ± 2,202	48.66 ± 3.18	5.70 ± 0.26	0	3.8 ± 6.6
Manii	1 (solid)	10,166 ± 512	48.55 ± 1.71	7.12 ± 0.45	-	-
	3	9,027 ± 909	48.79 ± 3.24	5.29 ± 1.88	0	0
	5	9,696 ± 427	59.61 ± 7.83	6.95 ± 0.29	0	2.2 ± 3.9
Sengon	1 (solid)	6,037 ± 312	33.82 ± 0.83	5.15 ± 0.14	-	-
	3	6,514 ± 259	31.12 ± 10.08	4.98 ± 0.75	0	0
	5	6,209 ± 653	33.08 ± 4.63	3.62 ± 0.53	0	1.4 ± 2.4
Mangium-manii	3	16,181 ± 1,692	76.61 ± 23.28	5.12 ± 1.42	0	0
	5	12,872 ± 1,530	63.91 ± 10.72	7.74 ± 1.32	0	2.9 ± 2.5
Mangium-sengon	3	11,658 ± 777	50.21 ± 10.46	3.93 ± 0.49	0	0
	5	14,015 ± 1,912	58.62 ± 11.15	4.95 ± 1.04	0	1.7 ± 2.9
Standard JAS		Min 7,358	Min 29.43	Min 5.3	Max 5	Max 10

Note: Values in bold type did not meet standard JAS.

This finding indicates that the gluing process of laminas did not affect the MOE, with the result that the MOE of glulam was equivalent to that of solid wood from the same species.

The analysis of variance showed that wood species, number of layers, and the interaction between these two factors affected the MOE of glulam as shown in Table 4. Based on further Duncan's test (Table 7), three-layer mangium-manii glulam had the highest MOE, which was significantly different from that of the other nine types of glulam. This finding seems reasonable because MOE was affected by density; wood with a higher density had a higher MOE, and the density of mangium was higher than that of the other species. Furthermore, all mangium glulams, except for the five-layer mangium glulam had higher MOE values compared with the other glulams, indicating that mangium, which had the highest wood density, played a role in achieving higher MOE.

3.3.2. Modulus of Rupture

In accordance with Student's *t*-test, the MOR of glulams did not differ from that of the solid wood from the same species (Table 3); however, based on the analysis of variance, the wood species affected MOR, but the other factors did not (Table 4). Each wood species had characteristic physical, mechanical, and anatomical properties as well as defects. Defects that may reduce the strength of timber include knots; slanted, cracked, or broken fiber; and compression wood (Tsoumis 1991).

Sengon, with the lowest density had the lowest MOR; mangium, with the highest density had the highest MOR; and the MOR of manii was between those of the other two species. The re-

Table 7. Duncan analysis for MOE

Parameter	N	Subset (10^3)					
		1	2	3	4	5	6
Sengon 5	3	6.21					
Sengon 3	3	6.51					
Mangium 5	3		8.71				
Manii 3	3		9.03				
Manii 5	3		9.70	9.70			
Mangium-sengon 3	3			11.66	11.66		
Mangium-manii 5	3				12.87	12.87	
Mangium 3	3				13.15	13.15	
Mangium-sengon 5	3					14.02	
Mangium-manii 3	3						16.18
Significance		0.77	0.38	0.07	0.19	0.31	1.00

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is mean square (error) = 16.25 × 10^3.

lationship between the MOR values of glulam and solid wood was linear, and all glulams met the standard requirement of 30 N/mm^2 set by JAS 234 : 2003 for decorative structural glulam mentioned for sugi wood (*Cryptomeria japonica*) and beisugi (*Thuja plicata*) (Table 6). The results were similar to those of another study showing that the MOR of mangium glulam was 53-59 N/mm^2 (Sulistyawati *et al*. 2008).

3.3.3. Shear Strength

Shear strength testing was conducted to determine the performance of the glue line contained in the glulam. Shear strength of solid wood was higher than that of glulam in the same wood species, and the failure of glulam mostly happened along the glue line, indicating that the gluing process did not produce a maximal result (Table 3). Moisture content of glulam was higher than that of solid wood, which can reduce shear strength capacity. For glulam properties, shear strength was affected by wood species but not other factors (Table 4). Different physical, anatomical, and chemical properties of individual wood species would affect the gluing process. Three- and five-layer glulams did not differ with regard to shear strength, so three-layer glulam could be considered for manufacturing with a minimum adhesive consumption. None of the sengon glulams met the standard requirement because solid sengon had a low shear strength, which in turn caused the glulam to have a low shear strength. Mangium, five-layer manii, and mangium-manii glulams met the minimum standard requirement of 5.3 N/mm^2 for shear strength of a glulam grade as previously mentioned (Table 6). According to Vick (1999), quality adhesion was influenced by wood species, lamina thickness, and pressure process.

3.3.4. Delamination

Delamination by immersion in cold and boiling water is reported in Table 6. Delamination in cold water was 0%, which indicates that the bondline was resistant to the cold water. Delamination in boiling water was 0%-3.8%, but these results had a large standard deviation because only one sample was damaged. The factors wood species and number of layer apparently did not affect delamination by cold and hot water immersion (Table 4), but three-layer glulams appeared to fare better than the five-layer glulams in terms of the boiling water test, because they had fewer bondlines. All types of glulam met standard JAS 234 : 2003 for delamination, indicating that the gluing process achieved a good bondline, but the strength was still not equal to the solid wood.

4. CONCLUSION

It can be concluded that glulam and solid wood of the same species did not differ except for the moisture content and shear strength. With regard to wood species, both mangium and manii produced good-quality glulam; both species had a higher density compared to sengon, which had a very low density. The three- and five-layer glulams were not different, so three-layer glulam may be preferable given that less adhesive is needed for its manufacture. In the delamination test, all glulams were resistant to cold- and boiling-water immersion, but the three-layer glulam appeared more resistant than five-layer glulam in the boiling test. The glulams that successfully met the JAS 234 : 2003 standard for decorative structural glulam outlined for sugi and beisugi woods were three- and five-layer mangium glulams, five-layer manii glulam, and five-layer mangium-manii glulam, with drying treatment or longer conditioning being needed to obtain proper moisture content.

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