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Manufacturing Study on Different Glue Spread and Press Pressure for Glued Laminated Timber Made from Laran

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ABSTRACT

Amidst challenges such as dwindling timber log supply from natural forests, concerns about timber quality, and rising timber costs, the timber industry has increasingly turned to engineered lumber solutions, including glued laminated timber (glulam) crafted from fast-growing species. However, the performance of glulam derived from plantation trees, notably swift-growing varieties like Laran, remains an area warranting exploration. This study addresses critical aspects of glulam production, encompassing adhesive selection, spread rate, and press pressure, which collectively influence material performance. The objectives of this research encompass an assessment of the bonding integrity of glulam originating from Laran plantation species and an evaluation of the optimal adhesive spread rate and press pressure for Laran-derived glulam. Various adhesive spread rates (200 g/m^2, 250 g/m^2, 350 g/m^2 and 400 g/m^2) and press pressures (0.7, 1.0 and 1.4 MPa), utilizing Phenol-Resorcinol Formaldehyde (PRF) adhesives, were systematically investigated in alignment with the guidelines stipulated in MS 758: 2020. Bonding integrity was evaluated via block shear and cyclic delamination tests. The study reveals that these parameters indeed exert a tangible influence on the bonding efficacy of PRF adhesive with Laran species. Remarkably, an optimal adhesive spread rate of 399.78 g/m^2 and press pressure of 1.18 MPa emerged as pivotal thresholds for superior bonding outcomes. Notably, the significance of adeptly designed glulam beams within wooden structural frameworks is underscored, particularly in light of the multifaceted imperatives of sustainability, economics, and environmental conscientiousness.

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1. Introduction

Glued laminated timber (glulam) is one of an engineered timber products that widely utilized in industrialized countries particularly in the United States, Europe, and Japan. Glulam is now well recognized as a high-performance timber composite material for use in buildings. Glulam is a structural product timber that is manufactured by gluing together separate parts of dimensioned and strength-graded timber under specified manufacturing conditions [1]. Based on the needed specifications, glulam can be manufactured and engineered to address the requirements of the construction sector. Its versatility, strength, and aesthetic appeal have led to the incorporation of glulam into diverse architectural designs and construction projects, making it a sought-after choice for sustainable and innovative building solutions.

In Malaysia, the application of glulam is still relatively new. The first glulam component in Malaysia is the roof beam of Masjid Jamek located in Forest Research Institute of Malaysia (FRIM), Kepong, Selangor back in the 1970s. There are several benefits and advantages of using glulam as a construction material. One of the benefits is that the glulam has strong durability and long-lasting quality. The durability of glulam depends on the species of wood, the glue, and the type of preservative used. It can help to enhance the strength of the glulam [2]. In comparison to steel and concrete, these timber products have a higher strength to weight ratio when applied to the same load. Additionally, the price of this material is less expensive than the price of the materials used in buildings made of steel and reinforced concrete [3,4].

Many previous studies reported on the strength performance such as bending and bonding performance of glulam utilized from softwood or hardwood species [5-10]. Through the studies, these researchers proved that the bending strength of glulam is better compared with the conventional solid timber. However, the bending performance of this glulam is more dependent on its manufacturing process resulting from the bonding quality of its glue lines [11].

One of the most important processing parameters in establishing an acceptable bonding quality is the glue spread rate. The glue spread rate affects the strength properties of glulam [12,13]. Moreover, increased glue application does not always improve bonding strength, but can rather decrease it. Besides, along with glued spreading, press pressure is one of the most important components in controlling the glulam. Manufacturing of glulam should be kept under control because it has a direct impact on the strength of timber composites. Because synthetic resin-based structural timber adhesives such as PRF have a low viscosity, pressure must be exerted evenly and effectively.

Malaysia is endowed with abundant area of tropical rainforest consisting of various types of hardwood and timber densities such as heavy, medium and light hardwoods. However, due to urbanization, agricultural fires, and other forms of agriculture, the supply of solid tropical hardwoods has diminished drastically. To resolve this concern, Malaysia's Ministry of Plantation Industries and Commodities (MPIC) has devised a strategy which includes the implementation of a long-term forest replanting initiative through a fast-growing tree plantation such as, Laran, Eucalyptus, and other indigenous re-growth pioneers like Meranti [14].

The use of fast-growing trees and plantation species can be easier to work with and lower the cost of glulam production, but it may also lead to less robust and consistent-quality wood [15]. Utilizing fast-growing trees and plantation species for producing glulam is advantageous due to their rapid growth, enabling easier timber acquisition without detrimental impacts on natural forests. Glulam quality relies on various factors, such as wood type and quality, manufacturing procedures, and storage conditions. Meticulous wood selection and rigorous quality control measures are necessary to ensure that the final product meets the requisite standards for strength, durability, and performance.

Given that the production of glulam derived from Malaysian tropical plantation species remains a relatively novel endeavor, comprehensive information concerning its bonding quality is presently limited. Therefore, acquiring an understanding of its bonding performance and behavior holds paramount importance, as these factors inherently contribute to its overall strength characteristics. In this study, the focus was on developing glulam from the plantation timber species known as Laran (*Neolamarckia cadamba*). The study focused specifically on two manufacturing factors: the distribution of adhesive and the pressure applied during pressing. The proposition of various glue spread rates (ranging from 200 g/m^2 to 400 g/m^2) and press pressures (ranging from 0.7 MPa to 1.4 MPa) renders these elements pivotal in the pursuit of achieving an optimal glue line thickness, as indicated by earlier research [16]. To discern the most suitable combination of glue spread and press pressure for ensuring optimal bonding quality in the glulam, two vital bonding integrity tests were executed-namely, block shear and delamination tests-aligned with the guidelines set forth in MS 758:2020 [17,18].

2. Methodology

A total of 12 glulam samples from Laran species that were shipped from Sapulut, Sabah and were made in a glulam factory in Konsortium PEKA, Karak, Pahang in accordance with MS 758:2020 [17]. During manufacturing, the glulam sample was applied to Phenol-Resorcinol Formaldehyde (PRF) glue with different volumes of glue spread and press pressure as presented in Table 1. All glulam samples were produced with dimensions of 135 mm width x 105 mm depth (35 mm thick for each lamella) x 1500 mm length. The flow chart of the process in making glulam beam was shown in Figure 1. The manufacture of glulam must follow recognized national standards to justify the specified engineering design values.

Table 1
Description of beam test specimens for manufacturing study

No.	Specimens	Glue type	Glue spread (g/m^2)	Press pressure (MPa)
1	L/PRF/200/0.7	PRF	200	0.7
2	L/PRF/200/1.0	PRF	200	1.0
3	L/PRF/200/1.4	PRF	200	1.4
4	L/PRF/250/0.7	PRF	250	0.7
5	L/PRF/250/1.0	PRF	250	1.0
6	L/PRF/250/1.4	PRF	250	1.4
7	L/PRF/350/0.7	PRF	350	0.7
8	L/PRF/350/1.0	PRF	350	1.0
9	L/PRF/350/1.4	PRF	350	1.4
10	L/PRF/400/0.7	PRF	400	0.7
11	L/PRF/400/1.0	PRF	400	1.0
12	L/PRF/400/1.4	PRF	400	1.4

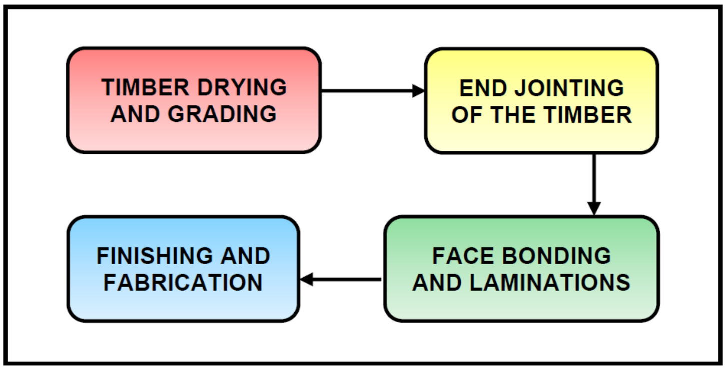

Fig. 1. Process in manufacturing glulam beam

From this beam, each beam will be cut according to divide it into several tests such as delamination test, block shear test, moisture content and density test. The number of specimens for all tests were shown in Table 2 after fully utilizing the manufactured glulam without taking 300 mm from the end for each side of beam.

Table 2
Description of testing for manufacturing study

Item	Test	Width (mm)	Depth (mm)	Length (mm)	Number of specimens per beam
A	Delamination test	135	105	75	8
B	Block shear test	50	105	50	6
C	Moisture content and density test	135	105	25	3

All the glulam samples were tested for bonding quality in this study due to block shear and delamination tests. This bonding quality test followed the procedures as stated in MS 758:2020 [17]. Based on the observation, Laran glulam is Service Class 3 and Method A will be used in delamination test as shown in Figure 2 and further procedural information can be found in ISO 12580:2007 [19]. The delamination test was conducted to evaluate the total delamination and the maximum delamination for each sample of glulam. The total delamination, $Delam_{tot}$ of a test piece shall be calculated from Eq. (1) in %. While, the maximum delamination, $Delam_{max}$ of a single glue line in a test piece shall be calculated from Eq. (2). For all delamination methods, the maximum delamination percentage of any single glue line shall be less than or equal to 20%.

$$Delam_{tot} = 100 \frac{l_{tot.delam}}{l_{tot.glue line}} \ (in\,\%) \tag{1}$$

$$Delam_{\max} = 100 \frac{l_{\max.delam}}{2 l_{glue line}} \ (in\,\%) \tag{2}$$

where $l_{tot.delam}$ was the delamination length of all glue lines in the test specimen, $l_{\text{tot.glue line}}$ was the entire length of glue lines on the two end-grain surfaces of each test specimen, $l_{\text{max.delam}}$ was the maximum delamination length of one glue line in the test specimen and $l_{\text{glue line}}$ was the length of one glue line, normally the width.

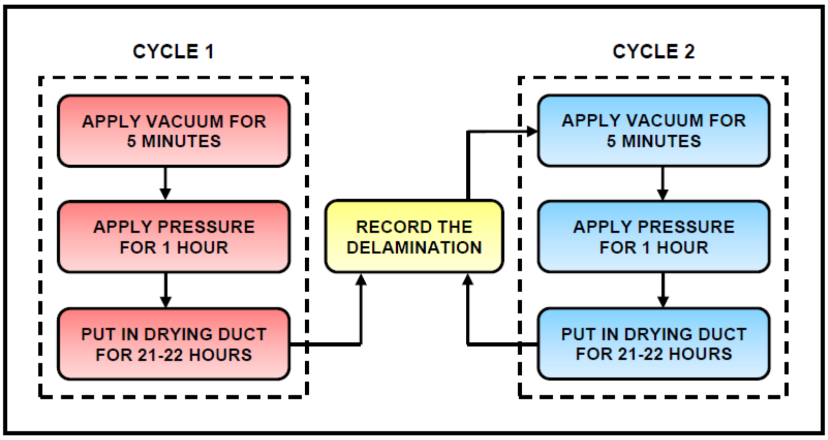

Fig. 2. Delamination test process [17,19]

Afterward, the block shear test would determine the shear strength properties. Using the Universal Testing Machine and shearing tool as shown in Figure 3, the constant load will be applied, and load reading is continuously detected and recorded to the ultimate load or until failure occurs, after no less than 20 seconds.

Fig. 3. Shearing tool with test bar [19]

Later, the average wood failure percentage for all glue lines in a cross-section and any individual value shall exceed the minimum wood failure percentages stated in Table 3. The shear strength f_v shall be determined with two significant digits from Eq. (3) accordance MS 758: 2020 [17].

$$f_v = k_v \frac{F_u}{A} \tag{3}$$

where A was the sheared area (for a test bar A = *bt*, and for a drill core A = l*t*), k was a modification factor (*k* = 0.78 + 0.0044*t*) and *t* was the thickness, in millimetres. The factor *k* modifies the shear strength for test specimens where the thickness in the grain direction of the sheared area is less than 50 mm. The average shear strength of all glue lines in a cross-section shall be at least 6.0 N/mm². A shear strength of 4.0 N/mm² shall be regarded as acceptable if the wood failure percentage is 100%.

Table 3
Minimum wood failure percentage relating to the shear strength [17]

	Average			Individual values		
Shear strength f_v in N/mm^2	6	8	$f_v \geq 11$	$4 \leq f_v < 6$	6	$f_v \geq 10$
Minimum wood failure percentage in %*	90	72	45	100	74	20

Linear interpolation shall be used

* For average values, the minimum wood percentage is: 144-(9f_v). For the individual values, the minimum wood failure percentage for the shear strength $f_v \geq 6$ N/mm^2 is: 153.3 (13.3 f_v)

In the last phase, the bonding quality data were analyzed and evaluated based on the requirement stated in MS 758:2020 [17]. Response surface methodology (RSM) was used in order to obtain the optimum glued spread and press pressure for the Laran glulam beam. RSM allows for the creation of mathematical models that represent the relationship between the input variables (adhesive spread rate and press pressure) and the response (bonding quality). This modelling facilitates the identification of optimal settings for the variables, ensuring that the desired response is achieved while minimizing trial and error. The software used for this method was Design Expert Software Version 11 as shown in Figure 4.

Fig. 4. Design Expert Software Version 11

To evaluate the moisture content, the specimens were split into 3 mid-span sections at the end of the test. The timber moisture content is calculated as a percentage of its oven-dry weight. Oven drying is the most popular and well-known method for measuring a timber’s moisture content. Once the sample cutting is done, each test piece's weight is recorded before it is placed in the oven. According to MS 837:2006 [20], the oven's temperature must be kept constant at 103±2°C. The samples were removed from the oven after a 24-hour time had reached, and the cubes were weighed separately. The samples were then reweighted and sent to the oven for 2-hour intervals until no more weight loss was recorded. The weight was recorded, and the calculation for moisture contents was calculated using Eq. (4).

$$Moisture\,content = \frac{Weight\,at\,test - Oven\,dry\,test}{Oven\,dry\,test} x100\ (\%) \tag{4}$$

Prior to the moisture content test, the weight and volume of each specimen were measured. The density of the specimens then will be determined using the Eq. (5).

$$Density, \rho = \frac{Mass}{Volume}\ (kg/m^3) \tag{5}$$

3. Results

Table 4 summarises the delamination, shear strength, wood failure percentage, moisture content and density in average value for Laran glulam using Phenol-Resorcinol Formaldehyde (PRF) glue with various glue spread rates (200 g/m^2, 250 g/m^2, 350 g/m^2 and 400 g/m^2) and different press pressures (0.7 MPa, 1.0 MPa and 1.4 MPa).

Table 4
Delamination, shear strength, wood failure percentage, moisture content and density

Glue spread (g/m^2)	Press pressure (MPa)	Moisture content (%)	Density (kg/m^3)	Total delamination (%)	Maximum delamination (%)	Shear strength (N/mm^2)	Wood failure percentage (%)
200	0.7	12.9	365.7	8.2	11.5	5.29	95.75
200	1.0	11.1	454.3	25.6	24.5	6.41	96.58
200	1.4	11.6	447.8	83.1	50.0	1.54	77.92
250	0.7	12.5	418.1	4.3	5.7	6.12	93.75
250	1.0	12.2	437.9	17.8	24.7	7.48	98.67
250	1.4	11.8	470.6	30.8	29.1	6.07	91.50
350	0.7	11.7	472.1	2.2	2.8	7.48	93.42
350	1.0	11.7	458.6	3.5	6.3	8.69	99.42
350	1.4	12.6	445.5	14.6	16.7	7.43	95.83
400	0.7	12.1	458.0	1.2	2.1	6.31	97.50
400	1.0	11.8	424.7	1.1	1.7	8.68	98.75
400	1.4	12.3	470.0	1.9	2.7	8.99	99.42

Note: Bold values means that more than one specimen presented delamination higher than the respective limit. Underlined values means that one specimen had delamination higher than established limits.

Firstly, delamination tests were performed on eight different glulam samples with two glue lines per each glue spread and press pressure. Delamination happens when gaps exist between laminations at a glue line instead of in the wood fibre. Delamination occurs when the adhesive bond is not strong enough to withstand moisture cycling. Insufficient adhesive bonding can result in openings that can be seen as separations in the surface of the smooth timber. Table 4 shows the average percentage of total delamination and maximum delamination of the sample. From the test result, the average percentage of total delamination for 8 samples of Laran glulam achieved the requirement value of less than 10%. An increase in the adhesive caused different performances for various pressure levels. The three pressure was observed where the delamination value decreased with the increase of the glue spread.

However, the sample with glue spread (400 g/m^2) and press pressure (1.0 MPa) has the lowest average percentage that requirement with a value maximum of 20% in maximum delamination of a single glue line. This can be explained by the fact that increasing pressure (from 0.7 to 1.0 MPa) also causes a decrease in delamination when comparing specimens with the same amount of glue spread. Still at 1.4 MPa, an increase in delamination was seen with the same glue spread of 400 g/m^2. The maximum delamination of the sample with glue spread (200 g/m^2 and 250 g/m^2) and press pressure (1.4 MPa) has the highest percentage average that exceeded the required maximum value of 20%.

Next, the shear strength for most of the specimens in various glue spread and press pressure are above 6 N/mm^2 except for glue spread for 200 g/m^2 with press pressure of 0.7 MPa and 1.4 MPa. These results indicate the bonding quality of glue line for glue spread of 200 g/m^2 is only suitable for the press pressure of 1.0 MPa only. In Table 4, there are an increasing pattern of mean shear strength due to increasing of glue spread for all press pressure except for press pressure 0.7 MPa. The mean shear strength is slightly lower for the glue spread of 400 g/m^2 (6.44 N/mm^2) compared to glue spread of 350 g/m^2 (7.62 N/mm^2). In general, the average shear strength for pressure 1.0 MPa with glue spread rates of 200 g/m^2, 250 g/m^2, 350 g/m^2 and 400 g/m^2, shows a good performance in shear strength with average values 6.54 N/mm^2, 7.63 N/mm^2, 8.82 N/mm^2 and 8.85 N/mm^2 respectively.

According to Serrano *et al.,* [21], describes when different timber densities combined with low adhesive spread rates and lack of pressure can lead to weak and undesirable bonds. The Laran glulam for pressure 1.0 MPa shows the highest values of wood failure percentage with 98% than pressure 0.7 MPa (95%) and 1.4 MPa (91%). It shows that the adhesive-wood bond was stronger where the timber fibre is visually more. This statement can be support from the standard Malaysian Timber Industry Board (MTIB) with the density is about 370-465 kg/m^3. In Malaysia, Laran timber falls under Light Hardwood [22]. According to Vick (1999), lamina thickness, pressure application, and wood species all impacted the adhesion quality [23].

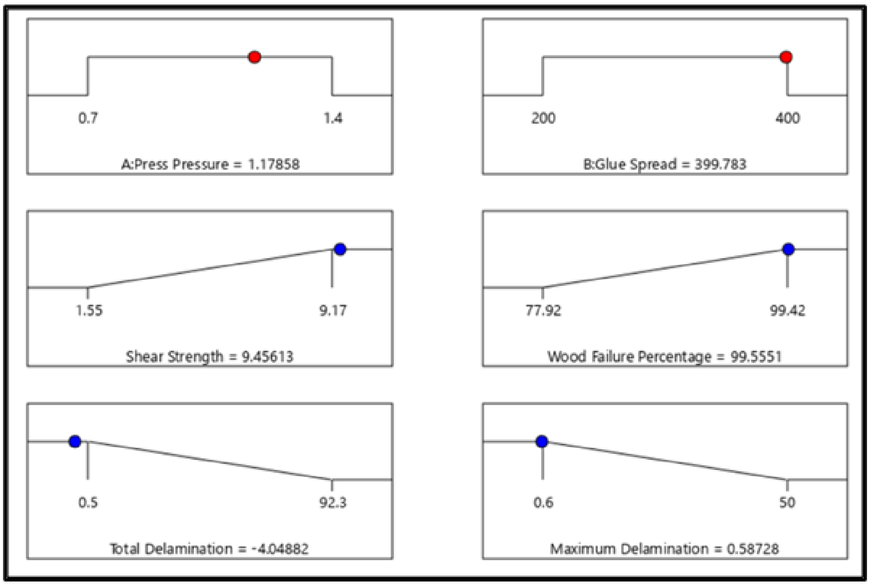

Fig. 5. Result from Design Expert software version 11 with RSM method

Finally, the response surface methodology (RSM) has been used to obtain the optimal response utilizing Design Expert software, version 11. The most crucial component of RSM is experiment design. The RSM seeks to choose the most optimal and satisfies where the response should provide an estimation of the relationship between the input and output [24,25]. Based on Figure 5, show the optimum glue spread and press pressure for the Laran glulam beam using the data in Table 4. The data shows that the optimum press pressure was 1.18 MPa and the glue spread was 399.78 g/m^2.

Meanwhile, regarding shear strength and wood failure percentage, the highest value was 9.5 N/mm^2 and 99.6%. However, the total delamination and maximum delamination data show that the lowest values were 0.4% and 0.5%. Thus, the value from the actual study obtains were 1.0 MPa and 400 g/m^2 while the RSM data were 1.18 MPa and 399.78 g/m^2. This indicates a slightly different press pressure and glue spread (0.17 MPa and 0.22 g/m^2), which are considered that the RSM method are more precise and accurate in find the exact value [26]. Hence, the RSM data can be regarded as optimal glue spread and press pressure for the Laran glulam beam.

4. Conclusions

In conclusion, this paper presents the outcomes of an extensive bonding investigation during the glulam manufacturing process, employing Phenol-Resorcinol Formaldehyde (PRF) adhesive with varying levels of glue spread and press pressure. The primary objective of this study was to ascertain the bonding quality in the fabrication of glulam using Laran plantation wood, and to identify the optimal adhesive spread rate and press pressure for Laran glulam.

The findings indicate that alterations in glue spread and press pressure had negligible impact on the physical characteristics of Laran glulam. Nonetheless, noteworthy distinctions were noted in certain bonding properties under scrutiny, specifically delamination and shear strength. Notably, the total and maximum delamination across three pressure tiers decreased as the glue spread rate increased, concurrently improving when the pressure approached 1.0 MPa. Importantly, a mean pressure of 1.0 MPa for all glue spreads met the prerequisites for both shear strength and wood failure percentage. The highest average shear strength value recorded was 9.17 N/mm^2, observed at a glue spread of 400 g/m^2 and a pressure of 1.4 MPa.

In light of these findings, it can be deduced that a glue spread of 400 g/m^2 and a pressure of 1.0 MPa should be employed, as these parameters represent the optimum levels at which all produced Laran glulam adheres to the prescribed technical specifications. Furthermore, a comprehensive statistical analysis was conducted utilizing response surface methodology (RSM) to precisely determine the ideal glue spread and press pressure values. Consequently, considering the array of bonding properties, it is recommended that a glue spread of 399.78 g/m^2 and a press pressure of 1.18 MPa be adopted as the favoured parameters for Laran glulam manufacturing endeavours.

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