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Experimental and Finite Element Analysis of Shear Strength in Melunak and Mengkulang Glulam Using Shear Block Test

Nor Jihan Abd Malek[1]*, Rohana Hassan[2], Mohd Nizam Shakimon[3], Nurharniza Abdul Rahman[1], Nazrul Azmi Ahmad Zamri[1], and Khaled M. H. Alreqeb[4]

[1]*Faculty of Engineering and Quantity Surveying (FEQS), INTI International University, Persiaran Perdana BBN, Putra Nilai, 71800 Nilai, Negeri Sembilan, Malaysia*

[2]*Institute for Infrastructure Engineering and Sustainable Management (IIESM), Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*

[3]*Faculty of Engineering, Science and Technology, Kuala Lumpur University Science and Technology, Jalan Ikram-UNITEN, 43000 Kajang, Selangor, Malaysia*

[4]*Faculty of Engineering, Built Environment and Information Technology, SEGi University, Kota Damansara, 47810 Petaling Jaya, Selangor, Malaysia*

ABSTRACT

This study investigates the shear strength parallel to the grain of glued laminated timber (glulam) produced from two Malaysian tropical hardwoods, Melunak (SG5) and Mengkulang (SG5), bonded with a phenol-resorcinol-formaldehyde (PRF) adhesive. The study aimed to determine the shear strength and compare the percentages of wood and glue failures. Twenty block specimens (10 Melunak and 10 Mengkulang), each measuring 50 × 50 × 50 mm, were tested using a universal testing machine. Shear block testing and shear strength evaluation were conducted in accordance with MS 758:2001 and EN 392:1995. Mengkulang recorded a higher average shear strength than Melunak by approximately 2.03 N/mm²; the mean values were 12.9847 N/mm² for Mengkulang and 10.9482 N/mm² for Melunak. Both species exceeded the minimum shear strength requirement of approximately 6 N/mm² specified in MS 758:2001. Post-test observations showed that failure occurred predominantly in the wood rather than along the glue line, indicating strong adhesive bonding. Finite element analysis was also conducted using Abaqus CAE. A three-dimensional model incorporated the specimen geometry, mesh, boundary conditions, material properties, and loading conditions used in the experimental programme. The simulated shear-strength response was close to the experimental results, with a difference of approximately 3%. The combined experimental and numerical

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E-mail addresses:
norjihan.amalek@newinti.edu.my (Nor Jihan Abd Malek)
rohan742@uitm.edu.my (Rohana Hassan)
nizam@klust.edu.my (Mohd Nizam Shakimon)
nurharniza.rahman@newinti.edu.my (Nurharniza Abdul Rahman)
nazrulazmi.zamri@newinti.edu.my (Nazrul Azmi Ahmad Zamri)
khaled012618@gmail.com (Khaled M.H. Alreqeb)
* Corresponding author

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findings demonstrate the shear-strength characteristics and bonding performance of Melunak and Mengkulang glulam.

Keywords: Bonding performance, finite element method, glued laminated timber, shear block test, shear strength

INTRODUCTION

Timber has been significant in environmental interactions and developmental advancements (Buchanan, 2015). Its superior strength-to-weight ratio and adaptability in various structural applications, such as beams, roof trusses, and wall cladding, make it a favoured choice among building materials (Kretschmann et al., 2010). Timber is sourced from various tree species, each with distinct growth rates, structural properties, and durability grades (Zobel et al., 1989). Recent innovations in wood research and design have further expanded the potential uses of timber (Davies et al., 2014).

Glued laminated timber is an engineered wood product consisting of bonded timber laminations (Buchanan & Abu, 2017). It can be fabricated in specific sizes and shapes for structural elements like columns and beams (Dinwoodie, 2000). However, the selection of timber species for lamination requires careful consideration of two key characteristics: susceptibility to glue and dimensional stability under varying atmospheric conditions (Gustafsson et al., 2003). Recent studies have highlighted the importance of understanding the factors influencing the glueing quality of solid wood products in timber construction (Hänsel et al., 2022).

Recent studies have investigated the shear properties of structural-size Malaysian tropical timber using torsional testing in accordance with EN 408:2010 (Mohd Puaad, 2021), while a shear or picture-frame method has also been proposed for determining shear modulus and shear strength (Krüger et al., 2018).

This study addresses this issue by examining the shear strength of two types of Malaysian tropical hardwood: Melunak and Mengkulang. The goal is to determine their shear strength values and compare the percentages of wood and glue failure. The outcomes of this study could offer valuable insights into the performance of these species in glued laminated timber applications, potentially guiding future material selection decisions and aligning with recent efforts by start-ups to make sustainable timber a reality (Xiao, 2007).

LITERATURE REVIEW

Shear strength is an essential property of timber, particularly in structural applications such as glued-laminated timber. Several methods have been proposed and applied to assess and determine the shear strength of various timber species and products.

One method is based on torsional tests, which measure the shear stress and strain in a circular cross-section of timber under torsion. This method is in accordance with the European standard EN 408:2010 (European Committee for Standardisation, 2010). A study utilising this method on selected Malaysian tropical timber revealed that small clear specimens exhibited higher shear strength than structural-size specimens (Mohd Puaad, 2021). This finding suggests that defects such as knots, splits, and checks in larger specimens influence timber's shear strength. Furthermore, the study indicated that the current European standard may not fully accommodate tropical timber species due to their high density and variability (Mohd Puaad, 2021). In addition to these factors, the moisture content of timber also impacts its shear strength. A study by Ravenshorst et al. (2016) determined the shear strength of tropical hardwood timber and found that high-density tropical hardwoods have significantly lower shear strength values compared to softwoods, according to European strength class tables.

Another method is based on shear or picture-frame tests, which measure the shear modulus and shear strength of a rectangular timber cross-section under shear (Krüger et al., 2018). This method is a straightforward way to determine the shear properties of wood, thereby reducing testing time and cost compared to other methods that require separate tests for each property. The method also allows for a more uniform stress distribution in the specimen, which could improve the accuracy and reliability of the results.

Adhesive bonds also influence the shear strength of glued-laminated timber products. Sikora et al. (2018) conducted shear strength and durability testing of adhesive bonds in CLT using two types of adhesives: polyurethane (PUR) and phenol- resorcinol-formaldehyde (PRF). It was found that while PUR specimens had higher shear strength values, PRF specimens demonstrated superior durability in delamination tests, indicating that the choice of adhesive for cross-laminated timber depends on the intended service conditions and performance requirements. The study also highlights the need for further research on the influence of moisture content, temperature, and loading duration on the shear strength and durability of adhesive bonds in cross-laminated timber.

Recent research has also focused on the bending, shear, and compressive properties of cross-laminated timber (CLT) fabricated from black spruce. The study found that increasing CLT thickness while maintaining the same span-to-thickness ratio can slightly reduce the characteristic bending strength of black spruce CLT. For the CLT shear panels, results show that increasing the CLT thickness while maintaining identical span-to-thickness ratios has little enhancement on their characteristic shear strength (He et al., 2020).

In addition, analytical models have also been developed to calculate the shear strength of wood based on its microstructure and fracture mechanics. A study published in Wood Science and Technology (van de Kuilen & Leijten, 2006) discussed the appropriateness of these models and compared them with experimental results. The study found that they

could accurately predict only the shear strength of wood, indicating that there are still gaps in understanding the complex mechanisms underlying wood failure under shear stress. The study also suggests that more experimental data and advanced numerical methods are needed to improve the accuracy and applicability of analytical models for wood shear strength.

The finite element method (FEM) is a numerical technique for simulating the mechanical behaviour of complex structures under various loading conditions. FEM has been widely applied in timber analysis, as it can overcome some of the challenges and limitations of experimental methods, such as the high cost of preparing timber samples, the variability of material properties, and the difficulty of measuring stress and strain distributions. One of the main advantages of FEM over other numerical methods, such as finite-difference or boundary-element methods, is its ability to handle complex geometries and arbitrary boundary and initial conditions (Zienkiewicz et al., 2013). FEM divides the structure into smaller elements with simple shapes, such as triangles or quadrilaterals, and approximates the solution at each element node using interpolation functions.

The global solution is then obtained by assembling all the elements and applying the boundary and initial conditions. This approach allows FEM to capture the detailed features and nonlinearities of timber structures, such as cracks, defects, joints, and anisotropy. However, FEM also has some limitations that must be addressed to ensure its reliability and validity. One of the main challenges is achieving convergence, meaning the solution remains largely unchanged as the mesh is refined or the element size decreases (Bathe, 2014). Convergence is affected by various factors, such as the model's complexity, mesh size, mesh type and shape, material properties, and analysis technique (Monteiro et al., 2020). For example, different mesh sizes can produce significantly different results and stress-strain curves (Chen et al., 2010b). Smaller mesh sizes can improve accuracy but increase computation time (Chen et al., 2010b). Larger mesh sizes can reduce computation time but introduce errors (Chen et al., 2010b). Moreover, some mesh shapes, such as quadrilateral elements, may cause convergence errors due to distortion or singularity (Aicher et al., 2005; Chen et al., 2010b). Therefore, choosing an appropriate mesh size and shape for each problem is crucial.

Another challenge is to select suitable material models and failure criteria for timber structures. Timber is a natural material that exhibits different mechanical behaviours in different loading directions. It is usually ductile in compression and brittle in tension and shear (He et al., 2004). Therefore, most FEM models adopt an orthotropic elasto-plastic behaviour in compression and a brittle elastic behaviour in tension and shear (Ahmad, 2010; Aicher & Dill-Langer, 2003; Aicher & Dill-Langer, 2004; Brandon, 2015; Ceccotti et al., 2002b; He et al., 2004; Shakimon et al., 2016). Some models also assume linear-elastic,

perfectly plastic behaviour in compression (Brandon, 2015). However, these models may only capture some of the nonlinearities and complexities of timber structures. For instance, some models neglect the influence of moisture content, temperature, loading rate, grain angle, or defects on timber properties. Some models also ignore size or scale effects on timber strength (Aicher et al., 2005).

Furthermore, different failure criteria have been proposed for timber structures based on different yield theories or fracture mechanics. For example, some models use the Hill yield criterion (Monteiro et al., 2020), a generalisation of the von Mises yield criterion that accounts for anisotropy (Chen et al., 2010b). Some models use the Hoffman yield criterion (Chen et al., 2010b), based on a quadratic function of stress components (Chen et al., 2010b). However, these criteria may suit only certain timber structures or loading conditions. Therefore, using experimental data, it is necessary to compare and validate different material models and failure criteria for timber structures.

FEM has been applied to various timber structures, such as beams, columns, frames, joints, connections, panels, floors, walls, roofs, bridges, and buildings (Aicher et al., 2005). The structural performance of glued laminated timber beams with round holes has also been investigated experimentally (Okamoto et al., 2021). One specific application is to simulate the shear strength of glulam when loaded parallel or perpendicular to the grain. For example, Ceccotti et al. (2002b) used a three-dimensional solid element model to analyse the shear behaviour of glulam loaded parallel to the grain. The model considered the orthotropic elasto-plastic behaviour of wood and the contact interaction between the laminations. The model was validated by comparing the results with experimental data from Ceccotti et al. (2002a). The model agreed well with the experimental data on load-displacement curves and failure modes. The model also revealed the stress distribution and deformation pattern in the glulam. Aicher and Dill-Langer (2003) used a two-dimensional plane strain element model to analyse the shear behaviour of glulam loaded perpendicular to the grain. The model considered the orthotropic elastic behaviour of wood and the frictional contact between the laminations. The model was validated by comparing the results with experimental data from Aicher and Dill-Langer (2004). The model agreed reasonably with the experimental data regarding load-displacement curves and failure modes.

Therefore, FEM is a valuable and powerful tool for analysing the shear strength of glulam loaded parallel or perpendicular to the grain. However, FEM also has some limitations that must be overcome to improve its accuracy and applicability. Future research should focus on developing more realistic and reliable material models and failure criteria for timber structures and optimising the mesh size and shape for convergence studies. Moreover, more experimental data are needed to validate and calibrate the FEM models for different types of timber structures and loading conditions.

MATERIALS AND METHODS

Experimental Setup

In this study, the Melunak and Mengkulang species were selected as specimens for glued-laminated timber (glulam). These timbers are naturally moderately durable (Ross, 2010), untreated, and suitable for outdoor environmental conditions. Melunak and Mengkulang are hardwoods, with Melunak classified as a light hardwood and Mengkulang as a medium hardwood. General structural use of timber is addressed in MS 544: Part 1: 2001 (Department of Standards Malaysia, 2001b). The glulam specimens were fabricated in accordance with the guidelines provided in MS 758:2001 (Department of Standards Malaysia, 2001a). A total of 20 specimens, 10 each of Melunak and Mengkulang, were prepared to the required dimensions of 50 × 50 × 50mm. This size was based on the minimum requirement stipulated in EN 392:1995 (European Committee for Standardisation, 1995) and BS EN 14080:2013 (British Standards Institution, 2013). The prepared specimens are shown in Figure 1, and a side view of the bonded timber block is shown in Figure 2. To determine the shear block performance on the glue line of each species, a shear block jig and a universal testing machine were used by Davies et al. (2014). The shear block specimens were cut from a glulam beam using a band saw to achieve the required dimensions. The timber specimens were marked on the timber block prior to cutting and placed under the band saw blade for cutting. These timber specimens were preassembled in the UiTM laboratory. The shear block test was performed in accordance with EN 392. (1995), which provided adequate measurements for width > 40 mm to 50 mm and thickness > 40 mm to 50 mm.

The shear block testing equipment is shown in Figure 3. The testing machine was set to apply a load at 9.8 kN/min, ensuring failure would occur within 20 s. Generally, it is anticipated



Figure 1. 50 × 50 × 50mm specimens

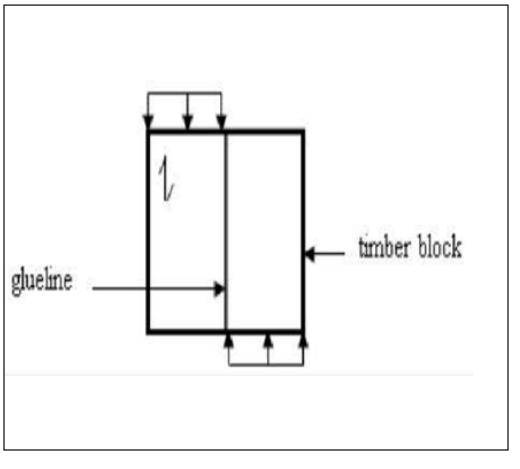

Figure 2. Side view of timber block with glue

that the specimen will fail when the machine applies approximately 15% to 85% of its loading capacity at this calibrated rate, used to determine the appropriate setting. The maximum shear strength (f_V) will be calculated using Equation 1 provided below, with the result rounded to two significant figures.



Figure 3. Shear block equipment

$$f_v = k\frac{F_u}{A}\ (\mathrm{N/mm^2}) \qquad [1]$$

where.

F_u is the ultimate load, in Newton.
A is the sheared area (for a test bar A = bt, and for a drill core A = lt) k is a modification factor (k = 0.78 + 0.0044 t)
It is the thickness, in millimetres.

In addition to shear strength, it is crucial to determine the percentage of wood failure to assess bond quality. This is typically measured through visual examination. If the sheared area is not a simple rectangle, divide it into smaller, measurable shapes (rectangles or squares), calculate the area of each, and sum them. However, it is important to note that the average or individual wood failure percentage of the specimen should not exceed the minimum wood failure percentage as stipulated by EN 392. (1995).

Finite Element Modelling Framework

The finite element model (FEM) of the glulam timber block was meticulously developed using the Abaqus interface. This comprehensive process involved defining the sample geometry, which formed the basis for the model database (.cae file) and an input file. The input file contained the geometry of the glulam timber block sample within its assembly, as shown in Figure 4.

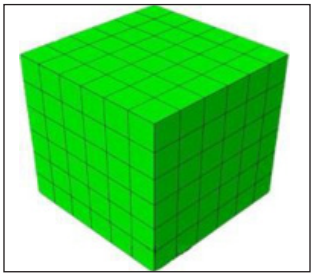

Figure 4. Typical FEM model of the glulam timber block

Material properties were then specified, with the glulam timber block sample defined as an orthotropic material, adhering to Cartesian coordinates with three mutually perpendicular axes of elastic symmetry at each point. A total of nine independent engineering constants were defined, that is, modulus of elasticity E, Poisson's ratio (v) and shear modulus (G) for three orthotropic axes 1(X), 2(Y) and 3(Z) with the value of E1 (10600 N/mm^2) based on MS 544: Part 2: 2001 (Department of Standards Malaysia, 2001c) for glulam timber Mengkulang and Melunak. The values of the independent engineering constants: E2, E3, v21, v31, v32, G12, G23, and G31 were determined from ratios reported by Ahmad (2010) and Green et al. (1999), as shown in Equations 2, 3, and 4 and in Table 1.

$$\frac{E_1}{E_2} = 11.5 \quad [2]$$

$$\frac{E_1}{G_{12}} = 16 \quad [3]$$

$$\frac{V_{12}}{E_1} = \frac{V_{21}}{E_2} \quad [4]$$

Table 1
Values of independent elastic constants for both species

E1 (N/mm^2)	E2 (N/mm^2)	E3 (N/mm^2)	v12 (N/mm^2)	v13 (N/mm^2)	v23 (N/mm^2)	G12 (N/mm^2)	G13 (N/mm^2)	G23 (N/mm^2)
10600	848	922	0.015	0.35	0.015	662.5	66.2	441.7

The timber grain directions parallel to the loading direction were modelled by creating material property orientations with the element's stacking direction isoparametric to 1, thereby aligning the timber grain direction with the vertical load direction. The average density of 530 kg/m^3 for both timbers, as it is categorised under the same strength-group block models used. To simplify FEM modelling, the general contact interaction with the selected surface pairs option was used to laminate two timber blocks forming the glulam contact surface, preventing them from intersecting. Four inputs were created to simulate the lamination: tangential behaviour, normal behaviour, cohesive behaviour, and damage. In the tangential behaviour, a friction coefficient of 0.3 was used in the penalty feature to simulate the friction at the timber contact surface. In normal operation, the hard-contact feature was selected to prevent the contact surfaces of the timber blocks from intersecting. The cohesive behaviour was created to simulate the PRF glue used to bond the timber blocks. The stiffness coefficients were specified under uncoupled conditions (to allow only one deformation in one direction) using the stiffness values for a traction (stress) separation

curve in cohesive elements, namely K_{nn}, K_{ss}, and K_{tt}. They represent the traction required to separate two surfaces in normal (nn) and tangential (ss and tt) directions and are calculated using Equations 5 and 6.

$$K_{nn} = \frac{E}{t} \quad [5]$$

$$K_{ss} = \frac{G}{t} = K_{tt} \quad [6]$$

Where;
E is the modulus of elasticity of the cohesive element
G is the shear modulus of the cohesive element
t is the thickness of the cohesive element applied on the contact surfaces

The damage in the contact surface of both sample species was modelled considering the normal strength (T_n) of 7MPa, and shear strength (T_s) of 12MPa from the experimental results. The fixed boundary conditions were applied to the half-bottom surface of the glulam timber block and were partially fixed along the sides of the blocks, with translation in the vertical direction allowed. Shearing under pressure with automatic incrementation was applied to the half-top surface of the glulam timber block to enable the FEM model to be tested until failure. To avoid errors when submitting the FEM model to the Abaqus solver for analysis, small increment sizes of 0.1, 0.1×10^-10, and 0.3 were defined as the initial, minimum, and maximum increment sizes, respectively. The mesh was controlled by specifying global mesh constraints for the two parts of the timber model. An element size of 8 is controlled by setting the global element size for each part based on its overall dimensions. The element type DC3D8R, an 8-node linear hexahedron for 3D stress analysis, was used in the generated meshes. This rigorous process ensures a comprehensive and accurate representation of the glulam timber block samples, facilitating precise analysis and reliable results.

RESULTS AND DISCUSSIONS

The average shear strength value is derived from the shear strength values of 10 test specimens. As depicted in Figure 5, Mengkulang exhibits a higher average shear strength than Melunak, approximately 2.0364 N/mm^2. Furthermore, Melunak's average shear strength is 10.9482 N/mm^2 with a standard deviation of 4.11 and a coefficient of variation of 26.58%, while Mengkulang's average shear strength is determined to be 12.9847 N/mm^2 with a standard deviation of 3.03 and a coefficient of variation of 42.7%. Two types of failure

modes were identified: wood failure and glue failure. Wood failure, which accounted for 100% of the failure surface for both timbers, is shown in Figure 6. However, as shown in Figure 7, Melunak and Mengkulang block specimens exhibited 95% wood failure, with the remaining 5% failing at the glue line. Both types of failures were determined through visual inspections using the proportional method as applied by Zobel et al. (1989). The timber specimen was divided into four quadrants to determine the percentage of failure in either the wood or the glue, with each quadrant representing 25% of the total sheared area. Wood failure was indicated by a brown surface on the timber and a less appealing appearance.

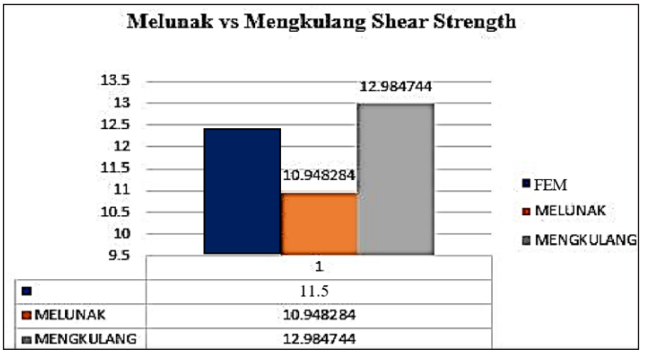

Figure 5. Percentage difference of shear strength of Melunak, Mengkulang, and FEM



Figure 6. Wood failure at 100% for melunak (left), mengkulang (middle) and FEM (right)



Figure 7. Wood failure at 95% and 5% glue failure for Melunak and Mengkulang

CONCLUSION

This research investigated the shear strength of glulam made from two Malaysian wood species: Melunak and Mengkulang. These timbers are naturally durable (Shakimon et al., 2016), untreated, and suitable for outdoor environmental conditions. Melunak and Mengkulang are hardwoods, with Melunak classified as a light hardwood and Mengkulang as a medium hardwood. General structural use of timber is addressed in MS 544: Part 1: 2001 (Department of Standards Malaysia, 2001b). The research objectives were to determine the shear strength values and the wood failure percentages of Melunak and Mengkulang glulam specimens under different loading conditions. The glulam specimens were fabricated in accordance with EN 392:1995 (European Committee for Standardisation, 1995). A total of 20 specimens, 10 each of Melunak and Mengkulang, were prepared to the required dimensions of 50 × 50 × 50mm. This size was based on the minimum requirement stipulated in the guidelines. The shear strength of both specimens was determined in accordance with EN 392:1995 (European Committee for Standardisation, 1995) using a universal testing machine. The average shear strength values were calculated for Melunak and Mengkulang glulam specimens. The results showed that Mengkulang glulam specimens had higher average shear strength than Melunak glulam specimens, approximately 2.0364 N/mm^2. Furthermore, Melunak's average shear strength was 10.9482 N/mm^2 with a standard deviation of 4.11 and a coefficient of variation of 26.58%, while Mengkulang's average shear strength was determined to be 12.9847 N/mm^2 with a standard deviation of 3.03 and a coefficient of variation of 42.7%. Both specimens reached the minimum shear strength of about 6 N/mm^2 specified in MS 758:2001 (Department of Standards Malaysia, 2001a). The results also indicated that both specimens exhibited wood failure rather than glue failure. Wood failure accounted for 100% of the failure surface for both timbers, as shown in Fig. 5. However, as shown in Fig. 6, some specimens exhibited 95% wood failure and 5% glue failure. Both types of failures were determined through visual inspections using the proportional method as assessed in accordance with MS 758:2001 (Department of Standards Malaysia, 2001a). The timber specimen was divided into four quadrants to determine the percentage of failure in either the wood or the glue, with each quadrant representing 25% of the total sheared area. Wood failure was indicated by a brown surface on the timber and a less appealing appearance. The research findings validated the objectives set in this study. They also confirmed the previous studies that conducted similar tests on glulam specimens (Aicher & Dill-Langer, 2003; Ceccotti et al., 2002a). The results demonstrated that the adhesive bond performed excellently against shear loading, allowing the wood to reach its shear strength limit. However, Mengkulang showed a higher average shear strength than Melunak due to its differences in density and grain patterns. The higher density resulted in stronger wood with fewer failures, while the lower density resulted in weaker wood with more failures. Therefore, it can be concluded that to utilise

the full-strength capacity of wood under load and reduce failure in wood, the glue bond should have higher shear stress resistance than wood. Due to strong adhesive bonding, shear failure occurred primarily in the wood rather than at the glue line, indicating good bonding performance of both Melunak and Mengkulang wood species with glue.

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