Bending properties of Mengkulang Glued laminated (glulam) timber and laminated veneer lumber (LVL)

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Abstract-- This paper presents the investigation of mechanical properties of glued-laminated timber (glulam) and laminated veneer lumber (LVL) manufactured from a tropical medium hardwood, Mengkulang (Heritiera s.p). The properties included the bending stiffness; local and global modulus of elasticity (MOE local, \( E_{\text{m,l}} \) and MOE global, \( E_{\text{m,g}} \)) and the strength (bending strength parallel to grain, \( f_{\text{m}1} \)). Three samples comprising 7 glulam beams, 7 nos. of LVL flatwise beams (for bending flatwise) and 6 nos. LVL edgewise beams (for bending edgewise), were subjected to four-point loading procedures according to Eurocode standards. Results specified Mengkulang glulam had the highest strength and stiffness among the others. The MOE global was higher than MOE local as discovered in the glulam sample, mainly due to the presence of the weak zone at the low bending stiffness. The LVL edgewise sample was proved to have greater values of stiffness and strength than that of the LVL flatwise. The LVL edgewise fracture beam could be observed as grain deviation at the tension zone whereas LVL flatwise exhibited horizontal shear failure. The glulam sample passed the requirement of delamination percentage and the shear strength according to MS 758. The results from experimental also showed that the bending strength and stiffness of glulam and LVL, manufactured from medium hardwood of Mengkulang species (strength group S.G.5) could be improved to the equivalent strength of heavy hardwood.

Index Term-- ETP, glulam, LVL, Mechanical properties, Mengkulang

1.0 Introduction

The structural application of engineered timber products (ETP, Fig 1) in Malaysia is now increasing since the first glulam building, Masjid FRIM, was constructed in 1977. Nevertheless, the MTIB Exhibition Centre (Galeri Glulam) in Johor Baharu (Fig 2) that was completed in 2012 has given a positive impact on the development of the ETP usage. The building was constructed using tropical hardwood glued laminated timber (glulam) manufactured from Resak and Keruing species as the main structures (Smedley et al., 2012). After the successful of the project, several building namely Crops for the future building in Semenyih, Malaysian Pavilion Expo Milano 2015, Walkway Taman Negara, Pulau Kukup, and Multipurpose Hall, TLDM Lumut were also constructed using tropical hardwood glulam. (Fig 2). Despite the constructions mentioned above, there are on-going studies undertaken by educational institutions and government bodies such as the MTIB, JKR and CIDB to develop data related to the properties of these products. The fact is, the mechanical properties required for the design are still inadequate and unstandardized, thus resulting in lack of interest and familiarity amongst designers and architects to understand the behaviour of these products (Ahmad, 2013). Other factors include the cost of products which are not as competitive to other materials such as lightweight steel and concrete whereby to some extent will affect the demand in our local building construction. To expedite more usage of ETPs namely glulam and LVL, more data related to these materials properties need to be prepared and disseminated to the industry.

Reference to design (glulam) and laminated veneer lumber (LVL) structure is based on MS 544: Part 3: 2001 and MS 544: Part 12: 2006, respectively. However, the grade stresses used for LVL and glulam refer to solid timbers' values as stated in MS 544: Part 2, previous studies demonstrated that glulam and other ETPs possess higher strength than its parent material (Wan Mohamad et al., 2011, Burdurlu et al., 2007, H'ng, 2003, Kretschmann et al, 1993 and Abbot & Whale, 1987). For bending member that have higher stress on the top due to compression, and bottom member due to tension, glulam beam can be manufactured by laminating the higher strength of other timber species at the top and bottom layer, and this can enhance its strength and load capacity (Ismail, 2015). Thus, the requirement for actual characteristic strength is very crucial for designers to attain economic and optimum design whilst avoiding inaccuracies and over-designing structural members.

Present Malaysian standards adopted the BS 5268 that is referred to the permissible stress utilizing mechanical testing on small clear defects free specimens. Whereas, the Eurocode standard, EN 1995 approach the limit state design with the strength and stiffness of timbers based on tests on the structural sizes. Normally, structural size specimens exhibit higher results than small clear specimens due to presence of defects which can affect the strength (Puad et.al,2016). Therefore, this research work aims to investigate the bending bending strength and stiffness of Mengkulang glulam and LVL according to BS EN 408: 2010 +A1: 2012.

The experimental works of this research primarily include a series of bending tests to determine the local and global moduli of elasticity, and the bending strength parallel to grain (formerly known as modulus of rupture). The respective tests were conducted according to Clause
9.0, 10.0, and 19.0. The difference between the MOE local and MOE global is basically the bending behaviour since MOE local represent a pure bending deflection without shear, torsional or axial forces, while MOE global are incorporated with a combination of shear and bending deflection. Previous research conducted by Solli (2000) on over 200 numbers of samples demonstrated that there were good correlations between this two-stiffness modulus.

However, the tension cross-sectional area of a beam is reported to have a significant effect on the value of MOE global. (Sousa, Branco, & Lourenco, 2014).

This research also involved the quality control tests for Mengkulang glulam that includes delamination test and shear strength test according to MS 758.

**Fig. 1.** (a) Glued laminated (glulam) timber, (b) Laminated Veneer Lumber (LVL)
2.0 EXPERIMENTAL

2.1 Material

The species used to manufacture the beam specimen is Mengkulang (Heritiera sp.), a medium hardwood from the strength group of S.G.5. (Table 3, MS 544:2:2001). The timber can be visually identified by its colour of red-brown to dark red-brown. Its density is approximately 800 kg/m$^3$ at 19% moisture content and the specific gravity is 0.55. For most cases, timbers from the S.G.5 group are not intended for structural purposes (Muhammad, 2015). Nevertheless, there were several studies on the mechanical properties of ETPs manufactured from the S.G.5 group strength involving timber species such as Bintangor, Kedondong and Keruing in order to investigate their performance as structural members (Wan Mohamad et al., 2011 and Ahmad, 2013). The findings indicated those timbers have good bending strength in meeting the standard requirement, and their bending properties were also influenced by the density of timber.

A local plywood factory manufactured the Mengkulang LVL based on the manufacturer’s specification for wood-based panel products. The product was the LVL board panels of about 50 mm thick x 1200 mm width x 2440 mm long. Each panel composed of thirty-three plies of 1.6 mm thick veneers with five cross lamination in-between that were glued together using weather boil proof type phenolic resin, namely Phenol Resorcinol Formaldehyde (PRF). This type of laminations can provide better dimensional stability than solid timber (H’ng, Ahmad & Tahir, 2012). Mengkulang glulam samples were produced by another commercial sawmill company to a required size of 85 mm width x 90 mm depth of beam member. PRF adhesive was used in joining three 30 mm thick lamination to form the 90 mm beam depth. All glulam and LVL samples were taken from one production source to ensure the uniformity of testing results.

2.2 Specimen Preparation

Glulam and LVL beam specimens were prepared in accordance to MS758:2001. The LVL panels were cut into specimen sizes using a table saw machine. Table 1 shows the specimen detail prepared for the test. All the specimens were conditioned at room temperature (27±2) °C with 55% relative humidity. This condition was not in accordance to the Eurocode, which specifies (20±2) °C, and (65±5) % humidity since it would be difficult to achieve the standard environment in a tropical country. The samples were stored in the laboratory as they would not be affected by climate changes.
Table I
Samples numbers and dimension

<table>
<thead>
<tr>
<th></th>
<th>Mengkulant LVL (flatwise loading)</th>
<th>Mengkulant LVL (edgewise loading)</th>
<th>Mengkulant Glulam</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of samples</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Cross sectional dimension, b (mm) x h (mm)</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td>50 x 100</td>
<td>100 x 50</td>
<td>85 x 90</td>
</tr>
<tr>
<td>Total length</td>
<td>1900</td>
<td>950</td>
<td>1710</td>
</tr>
<tr>
<td>Span length, l = 18h</td>
<td>1800</td>
<td>900</td>
<td>1620</td>
</tr>
</tbody>
</table>

2.3 Apparatus and procedures

2.3.1 Bending Test

A two-point load method, where the standard prescribed as 4-point bending with a simple supported beam and a centre-to-centre span as shown in Fig 3 and 4 was configured and applied to all beam specimens according to BS EN 408:2010+A1:2012. The apparatus consists of a test machine, reaction-bearing plates, load bearing plates and two linear variable differential transformers (LVDTs) for measuring the vertical displacement. The lateral restraint was provided to prevent lateral buckling. The load on the beam was applied through a uniform displacement of the loading pistons at a rate not greater than (0.003 x h) mm/s. The maximum applied load should not exceed 40% of the estimated failure load, $F_{\text{max,est}}$ for determination of local and global modulus. This estimated maximum load was obtained from preliminary tests carried out on the same species. However, as the bending strength parallel to grain is to be investigated in this research, the applied loading was increased until the failure of the beam occurred within $(300 \pm 120)$ s.

During the test, LVDTs were connected to a data logger in which the readings were recorded by MEAS data file software installed in a computer. Data including loading time, load increment and displacements (w) was measured for both local and global MOE were then automatically converted into a Microsoft Excel spreadsheet file. The interpretation of results involved the plotting of load deformation graph for each specimen for the corresponded MOEs.

![Diagram](image4.png)

Fig. 3. Bending test set-up for local modulus of elasticity
The section of the graph between 0.1 \( F_{\text{max, est}} \) and 0.4 \( F_{\text{max, est}} \) would be analysed with regression analysis. If the section obtained a correlation coefficient of 0.99 or higher, then the gradient for linear graph plotted would be taken to calculate \( E_{m,l} \) and \( E_{m,g} \). The formulas provided in the standard for calculating the output parameters refer to the total loading force (F), which equals \( F/2 \) when applying at the 1/3 span points. The calculation of global modulus of elasticity the shear modulus was considered as infinity.

The local and global modulus of elasticity (\( E_{m,l} \) and \( E_{m,g} \)), bending strength parallel to grain (\( f_m \)) were determined using the respective equations below:

\[
E_{m,l} = \frac{a l_1^2 (F_2 - F_1)}{16 l (W_2 - W_1)} (1)
\]

\[
E_{m,g} = \frac{3 a l^2 - 4 a^3}{2 b h^3 (w_2 - w_1 - \frac{6a}{5gbh})} (2)
\]

\[
f_m = \frac{3F a}{b h^2} (3)
\]

Where:
- \( E_{m,l} \) = Local modulus of elasticity (N/mm\(^2\))
- \( E_{m,g} \) = Global modulus of elasticity (N/mm\(^2\))
- \( f_m \) = Bending strength parallel to grain (N/mm\(^2\))
- \( F_2 - F_1 \) = The increment of load on the regression line with a correlation coefficient of 0.99 or better (N)
- \( W_2 - W_1 \) = The increment of deformation corresponding to \( F_2 - F_1 \) (mm)
- \( a \) = Distance between a loading position and the nearest support (mm)
- \( l \) = Second moment of area (mm\(^4\))
- \( b \) = Width of the cross section, or the smaller dimension (mm)
- \( h \) = Depth of the cross section, or the larger dimension (mm)
- \( F_{\text{max}} \) = Maximum load (N)
- \( G \) = Shear modulus determined by method given in Clause 11.1 or 11.2 of the code, or shall be taken as infinite (N/mm\(^2\))

2.3.2 Moisture content and density

After the specimen were tested until failure, two test pieces of approximately 30 mm thick were cut from each of the specimen for the determination of moisture content and density. The methods for determining the moisture content conformed to BS EN 13183-1 and EN 323 using the Equation (4) stated below. The density is calculated by dividing the weight by the test piece volume. Reference was made to BS EN 322 for the density of LVL as well.

\[
H = \frac{m_H - m_0}{m_0} \times 100 (4)
\]

Where
\[ m_H = \text{Initial mass of the test piece (g)} \]
\[ m_0 = \text{The mass of the test piece after drying at (103 \pm 2) °C} \]

2.3.3 Delamination Test of Glulam Specimen

For the delamination test, specimens with dimension of 75 mm in length, 85 mm in width and 90 mm in depth were immersed in water with a drawn vacuum of 70 kPa to 85 kPa for 5 minutes, followed by applied pressure of 500 kPa to 600 kPa for an hour. The vacuum pressure was repeated to make it a two-cycle procedure with a total time of 130 minutes. This test was conducted according to MS758:2001 which is similar to procedures adopted from the BS EN391:1995, but with adjustments made to meet the Malaysian requirements. Fig 5 shows the preparation of the test vessel in the laboratory. The test specimens were dried at temperature range from 60°C to 70°C with a relative humidity less than 15% for approximately 21 hours to 22 hours. At the end of the drying period, the lengths of open glue lines on end grain surfaces of each test specimens were measured, and the total percentage of delamination is calculated using equations below:

\[
\text{Total delamination percentage} = 100 \times \left( \frac{l_{\text{tot delam}}}{l_{\text{tot glueline}}} \right)
\]

Where,
\[ l_{\text{tot delam}} = \text{Delamination length of all glue lines in test piece (mm)} \]
\[ l_{\text{tot glueline}} = \text{Centre length of glue line on the two end-grain surfaces of each test piece (mm)} \]

\[
\text{Maximum delamination percentage} = 100 \times \left( \frac{l_{\text{max delam}}}{l_{\text{glueline}}} \right)
\]

Where,
\[ l_{\text{max delam}} = \text{Maximum delamination length of one glue line in the test piece (mm)} \]
\[ l_{\text{glueline}} = \text{Length of one glue line, normally the width, b of the test specimen (mm)} \]

Fig. 5. Test Preparation for the delamination test

2.3.4 Shear Test on Glue Lines

The shear strength of glue line parallel to the grain direction were determined in accordance with the MS 758:2001 and BS EN 392: 1995, but with necessary amendments to comply with the Malaysian requirements. All two glue lines of the three laminations were tested. The test pieces were cut from the bending test beam samples as shown in Fig 6. A total number of 20 specimens were prepared with dimensions of 50 mm in width, depth and length. The test piece was subjected to a constant rate 0.01 mm/s to obtain a maximum load within or at least 20 seconds. (Fig 7). Percentages of the timber failure should be estimated immediately after the test and the shear stress strength was calculated using equation below:
Where,
\[ f_v = k \frac{F_u}{A} \]  \hspace{1cm} (7)

\[ f_v \] = shear strength
\[ F_u \] = ultimate load
\[ A \] = sheared area \( (A = b \times t) \)
\[ k \] = modification factor, ie. \( k = 0.78 + 0.044t \), \( t \) = thickness

It should be noted that the \( k \) factor was not considered in this calculation because the thickness in the grain direction of the sheared area is 50 mm.

\[ \text{Fig. 6. Typical sample cuttings} \]

\[ \text{Fig. 7. Test setup for Block Shear test} \]

3.0 RESULT AND DISCUSSION

3.1 Bending strength and stiffness of glulam and LVL

The results of the maximum load of each beam, modulus elasticity and bending strength are tabulated in Table 2. Clause 5.4.3.3, BS EN 384: 2010 specifies that the values of bending strength for glulam should be adjusted to 150 mm depth or width by multiplying by the factor, \( k_h \) as shown in Equation 8, with \( h \) defined as a beam depth during the bending test. Similarly, the value of bending strength for individual LVL edgewise specimen should be multiplied by the factor, \( k_m \) cor., as in Equation 9 (BS EN 14374:2004).

\[ k_h = \left( \frac{150}{h} \right)^{0.2} \]  \hspace{1cm} (8)
\[ k_{m,\text{corr.}} = \left( \frac{b}{300} \right)^s \]  

(9)

Where,

\( b \) = Width of the tested specimen (mm) = height of beam, \( h \)

\( s \) = Size effect parameter, i.e. \( s = 2v - 0.05 \), \( v \) is the coefficient of variation of test results

**Table II**

Summary of bending properties for Mengkulang Glulam and LVL

<table>
<thead>
<tr>
<th>Modulus of Elasticity</th>
<th>Bending strength parallel to grain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Max Load (kN)</td>
</tr>
<tr>
<td>GLULAM</td>
<td>35.00</td>
</tr>
<tr>
<td></td>
<td>22.96</td>
</tr>
<tr>
<td></td>
<td>25.09</td>
</tr>
<tr>
<td></td>
<td>30.09</td>
</tr>
<tr>
<td></td>
<td>28.17</td>
</tr>
<tr>
<td>Mean</td>
<td>28.26</td>
</tr>
<tr>
<td>COV (%)</td>
<td>16.5</td>
</tr>
<tr>
<td>LVL/FLATWISE</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>13.69</td>
</tr>
<tr>
<td></td>
<td>10.71</td>
</tr>
<tr>
<td></td>
<td>11.34</td>
</tr>
<tr>
<td></td>
<td>13.74</td>
</tr>
<tr>
<td>Mean</td>
<td>12.87</td>
</tr>
<tr>
<td>COV (%)</td>
<td>13.1</td>
</tr>
<tr>
<td>LVL/EDGEWISE</td>
<td>21.52</td>
</tr>
<tr>
<td></td>
<td>22.00</td>
</tr>
<tr>
<td></td>
<td>20.98</td>
</tr>
<tr>
<td></td>
<td>16.62</td>
</tr>
<tr>
<td></td>
<td>19.65</td>
</tr>
<tr>
<td></td>
<td>19.79</td>
</tr>
<tr>
<td>Mean</td>
<td>20.09</td>
</tr>
<tr>
<td>COV (%)</td>
<td>9.7</td>
</tr>
</tbody>
</table>

Note: **1**: invalid specimen due to \( R^2<0.99 \), **2**: invalid specimen due to test error

*: values given have been multiplied by either \( k_h \) or \( k_{m,\text{corr}} \)

**Table III**

Mean values of density and moisture content

<table>
<thead>
<tr>
<th>Mengkulang samples</th>
<th>Density (kg/m(^3))</th>
<th>Moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glulam</td>
<td>714</td>
<td>13.0</td>
</tr>
<tr>
<td>LVL flatwise</td>
<td>584</td>
<td>13.6</td>
</tr>
<tr>
<td>LVL edgewise</td>
<td>674</td>
<td>12.8</td>
</tr>
</tbody>
</table>

From the Table 2 and bar charts as shown in Fig 8 and 9, it can be observed that Mengkulang glulam obtained the highest value for both modulus of elasticity (MOE) and the bending strength parallel to grain followed by the LVL Edgewise. The mean value of density and moisture content for each sample tabulated in Table 3 give similar results whereby the glulam exhibited the highest density among the three samples, while LVL flatwise had lesser density
than that of the edgewise bending. This indicates that the density influences the bending performance of Mengkula glulam and LVL. Although the samples are manufactured from the same species, bending properties of LVL flatwise and edgewise are much lower. The range is between 9000 to 20,000 N/mm² for MOE global, 12,000 to 20,000 N/mm² for MOE local, and 38 to 100 N/mm² for bending strength. The significant differences are mainly due to the manufacturing process, whereby the Mengkula glulam specimen is consisted of three layers of thick laminates bonded together to become a beam size of 85 mm wide and 90 mm thick. Whereas, the beam from timber LVL was made of 33 layers of thin veneers glued and compressed together into a timber panel which is then cut into the beam size required. Thus, the presence of more lumen volumes is found in Mengkula LVL rather than in Mengkula glulam, resulting in less dense and lighter material. However, there are no significant difference between the two samples of LVL as they were made from the same source of production, regardless of random selections were made for testing the specimens.

H’ng, Ahmad and M.Tahir (H’ng, Ahmad & Tahir, 2012) discussed the influence of timber density on bending properties. The report states that LVL for high-density tropical timbers, as they have thicker cell walls and less lumen volume, it can influence the amount of adhesive penetrations resulted in insufficient bonding of the veneers, and subsequently lead to lower flexural capacity of the beam. The study also suggested tropical timbers of density less than 600 kg/m³ would produce the optimum bending properties values as observed in LVLs made from Keruing, Kedondong and Bintangor species.

The coefficient of variations (COV) was determined and the results are as shown in Table 2. Higher variability was observed in bending strength for all samples instead of in MOE local and MOE global. The difference can be explained as the ultimate or maximum load governs the bending strength whereas MOE is dependent on the proportion of stress and strain limit. Furthermore, different mode of failures in the test specimens could also be considered in contributing to the load carrying capacity of the beams. Although the COV percentage of the MOE and bending strength in Mengkula glulam ranged from 11 to 15%, the variability is still not exceeding 20%, thus can be considered acceptable according to BS EN 384: 2010.

Further analysis from this research, indicated the ratio of MOE local/MOE global for LVL flatwise and LVL edgewise were 1.29 and 1.18 respectively, which is in good agreement with the ratio of 1.17 reported by Ravenshorst and Van de Kuilen (2010) when the test conducted over the softwoods, temperate hardwoods, and tropical hardwoods. Higher ratio found in the LVL flatwise than in LVL edgewise was related to the variability (COV) of the test results. However, the ratio of MOE local and MOE global was less than 1.0, because of the occurrence of a zone with a low bending stiffness within the MOE local area (Ravenshorst et al, 2014) apart of the large variability of the test results.

Statistical analysis of the two means of MOE local and MOE global are also represented by the error bars in Fig 6 which equals to standard deviation (s) divided by the square root of number of measurements that made up the mean. The overlapped SE between the MOE global and MOE local for Mengkula glulam sample specified that the difference was not statistically significant. The sample also had the largest error bars amongst the samples for both bending strength and stiffness, while the t-test analysis for paired two samples lead to the following results: The p-value for LVL flatwise and LVL edgewise are 0.008 and 0.00006 which are less than p-value of 0.005 (at confidence level of 95%). Hence, the difference between MOE local and MOE global for both the LVL samples were significant. However, the p-value for glulam sample was 0.34 that is greater than 0.05, therefore the difference was not significant.
Load versus displacement graphs were plotted and shown in Fig 10 and 11, representing samples with almost similar results to the mean values. When the load applied was increased up to 40% of the estimated load, the displacement linearly proportion to the load. This explained the elastic behaviour of the orthotropic material. Only one specimen of LVL flatwise failed to give regression of 0.99 when plotting the linear graph of 0.1F to 0.4F and was thus discarded. A slight decrease of displacement was detected in some of the specimens after initial cracking or the first sound of breaking occurred, but it continued to the linear ramps increment, indicating the adequacy of ductility in the tension zone. When the load reached to the ultimate capacity and sudden failure occurred, the specimens have fractured in a brittle manner.

The graphs from Figure 8 also indicated Mengkulang glulam is the stiffest amongst the samples, while LVL edgewise was found to be stiffer than LVL flatwise.

Theoretically, different values between the local and global modulus of elasticity obtained from the bending test are most probably resulted from the shear deformation in
the side parts of the beam and the zone with lower bending stiffness or is called a weak zone (Ravenshorst et al. 2014). This condition was discovered in the Mengkulang glulam samples when three specimens out of five being tested showed higher values of MOE local than MOE global. The existence of finger joints at the bottom layer near the midspan of the glulam beam contributed to this type of failure (refer Fig 12 (a)). Besides that, shear failure at the horizontal plane can be seen in the mode of LVL flatwise as in Fig 13(a). This type of failure might also be due to insufficient and incomplete bonding of veneers that already existed in the specimen that must be investigated further. The grain deviation is one of the well-known stiffness reduction factors for most tropical hardwood (Ravenshorst et al, 2014). It is generally known that performance of glulam and LVL are affected by many factors namely lamella thickness lamella joints, lathe checks, loading direction and glue bond strength (Ahmad, 2013). For edgewise bending, the fracture of LVL was observed in the deviation of fibre grains at the tension zone of the maximum deflected area as in Fig 14 (a). Similar failure was found for the glulam specimen as in Fig 14 (b). However, there was also shear failure noticed at the edgewise specimen in which it might be due to the bonding performance of the veneers.

The glulam specimens in this study remained intact as one piece after reaching the maximum load showing the ability to absorb a certain amount of load in post-failure stage. At this stage, the laminations process significantly showed the brittle behaviour after ductile behaviour. Besides that, this process prevents the excessive tension cracks along the line.

According to MS544:2:2001 (Table 4), comparison of the grade stresses for various strength groups of timber, glulam and LVL species Mengkulang can be made, as stated that the bending parallel to grain for SG5 is between 6.8 to 12.1 N/mm² (wet and dry condition) and modulus of elasticity are 6100 to 9100 N/mm² (mean and minimum). Thus, based on the bending strength and modulus of elasticity of both glulam and LVL could be categorised as group SG1 and SG2 respectively. The strengths of glulam and LVL for this study are 3 times higher than the solid timber.
Fig. 12. (a)-(b) Failure of Glulam beam

Fig. 13. (a)–(c) Failure of Mengkulang LVL Flatwise beam
3.2 Delamination of glulam

Delamination, known as accelerated ageing test is used to proof the resistance against the climate exposure during lifetime of the glulam structural member. Test method A was selected to conduct the accelerated ageing test. According to MS758:2001, delamination test method A is a qualification test for glulam beams under class 1 for interior application and type 1 adhesive, phenol resorcinol being used during manufacturing of glulam member. This test method measures the openings of glue lines known as a delamination right after an accelerated ageing process in which the test specimens was submerged in water with vacuum and pressure, followed by fast drying at high temperature (Fig 5). This accelerated ageing process causes stresses in wood perpendicular to the glue line, thus putting a strain on the joint. This strain on the joint will result in failure of the glue line that in turn would cause either delamination or creates cracks in the timber. The glulam beams are intended to be used as a roof truss member and could be categorized as an interior application. According to this standard, for method A, the total delamination percentage after treatment should be less than 5% of initial 2 cycles and less than 10% for extra cycles.

For these glulam beams, 20 specimens were subjected to accelerated ageing process. The results of the total delamination percentage of test specimens for glulam species Mengkulang after 3 cycles are shown in Figure 15. Out of 20 specimens, only nine specimens exceed 10% of total delamination percentage. Glulam specimen species Mengkulang meet the requirement for the applications as interior members.
3.3 Shear strength of glue lines

The second test required for quality control of glulam is shear test of the glue line loaded in longitudinal direction. In addition to the delamination test, shear tests were carried out for specimens taken from the same Mengkulang glulam sample. Twenty specimens were prepared for test. The strength of glue lines in glulam is determined by shear test. According to MS758: 2001 requirement, the shear strength of glue line shall be at least 6.0 N/mm² with 90% of minimum wood failure. The result of shear strength of glue line for glulam is tabulated in Table 4. All shear strength was higher than 6.0 N/mm² with estimated wood failure more than 90%, thus indicated that the glulam sample used in this research is valid for quality control and meets the requirements in MS 758:2001.

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Shear Strength (N/mm²)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.80</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>13.58</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>14.78</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>17.58</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>17.68</td>
<td>16.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shear Strength (N/mm²) [**]</th>
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<tbody>
<tr>
<td>Resak (SG4)</td>
</tr>
<tr>
<td>14.76</td>
</tr>
</tbody>
</table>

[**] Wan Mohamad et al, 2011

Based on the comparisons of the test results with report from Wan Mohamad et al. (2011) as presented in Table 4 and 5, it can be observed that there are no significant differences in the shear strength of glulam specimen. However, glulam from Mengkulang showed highest values of 16.08 N/mm², followed by Merpauh,
Resak and Bintangor. Kapur showed the lowest value of 13.82 N/mm². Although Resak, Kapur and Merpauh are categorised in the same strength group, the shear strength of Kapur are much lower. Mengkulang contains relatively smaller pores and extractive content compared to Merpauh, Resak, Bintangor and Kapur has further restricted the penetration of the adhesives to the centre of the glulam. Moreover, the shear strength was not affected by the density of timber; as it depends on the ability of laminations bonding. The performance of adhesive being used in the fabrication of glulam was observed and evaluated by means of shear test according to MS758:2001. A comparison with shear strength of LVL cannot documented due to absence of data for LVL.

The results of shear strength tests shown in Fig 16.

4.0 Conclusion

This paper presented a research on the bending properties of Mengkulang glulam and Mengkulang LVL (flatwise and edgewise bending). The bending tests were carried out according to BS EN 408: 2010+A1 clauses 10.0, 11.0 and 19.0 which is to determine the respective stiffness (ie. local modulus of elasticity, Eₘₐₖ and global modulus of elasticity, Eₘₙ), and bending strength parallel to grain (ie. modulus of rupture, fₘ). Besides, quality tests of delamination and shear strength test were also conducted for the glulam sample. The results obtained that:

a. From the three Mengkulang samples of glulam, LVL flatwise and LVL edgewise, Mengkulang glulam exhibited the highest bending strength and stiffness.

b. Values of MOE local and MOE global for LVL edgewise were greater than that of LVL flatwise. The MOE local for both LVL flatwise and edgewise was also greater than MOE global.

c. The failure of Mengkulang glulam was due to the weak zone resulted from the presence of the finger joints near the mid span of the beam. The fracture observed also indicated failure of the grain deviation due to stresses at the tension zone.

d. For LVL flatwise, the fracture was mainly due to horizontal shear, while for LVL edgewise, the main failure was a tension failure.

e. Mengkulang glulam met the requirement for delamination test for bonding quality according to MS 758: 2001.

f. The shear strength of Mengkulang glulam is in compliance with MS 758: 2001.

g. Due to absence of data for the delamination test of Mengkulang LVL, the bonding quality was not discussed in this research. Further research should be considered in future.

h. Future research should emphasize on increasing the number of specimens to the required sampling
numbers in order to obtain more reliable data for subsequent development of characteristic strength of the ETPs manufactured from tropical hardwood.

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