The Effect of Lamina Configurations of Glued-Laminated Timber on the Modulus of Elasticity and the Modulus of Rupture

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Abstract

In a sustainable construction, each material must be used effectively. Glued-laminated timber (glulam) is one of the engineered wood products that can be formed by gluing wood laminae together with the proper adhesive. Due to the orthotropic nature of wood, the orientation of each lamina may affect the mechanical properties of the glulam. In this paper, the effect of lamina configurations of glulam beams made of meranti (shorea) on the static bending modulus of elasticity (MoE) and the modulus of rupture (MoR) have been studied both experimentally and numerically. Several lamina configurations have been considered, namely vertically laminated beam, horizontally laminated beam, and mixed laminated beam. Each configuration uses four laminae of the same dimensions (50 mm x 100 mm x 1800 mm). The adhesive used for gluing the laminae was polyvinyl acetate. Each simple beam specimen was loaded statically at midspan and the maximum deflection at midspan was measured. The results show that the vertically laminated glulam is the most effective configuration because it gives the highest both the static bending modulus of elasticity and the modulus of rupture. The least modulus of elasticity and modulus of rupture have been obtained from the horizontally laminated glulam. This conclusion is also supported by finite element analysis considering the orthotropic nature of the material.

Keywords lamina configuration, glulam, orthotropic, static bending modulus of elasticity, modulus of rupture
Introduction

The use of solid sawn lumber in structural applications are decreasing today. On the other hand, the use of glued-laminated timber (glulam) is increasing. The advantages of the use of glulam are among others the size capabilities and environmentally friendly (Moody et.al 1999). Based on the orientation of the plane of the laminae, glulam beam can be classified as vertically laminated beam (all vertical configuration), horizontally laminated beam (all horizontal configuration), and mixed laminated beam (Bodig and Jayne 1993). Combining various grades of laminae in a glulam is commonly refereed to as glulam combination. To optimize bending strength and stiffness in horizontally laminated glulam combination, it is common to use lower quality laminae in center portion and higher quality laminae on the outside faces of the glulam combination (American Plywood Association 2003). Herawati et.al (2010) studied the performance of glulam beams of various types of lamina configuration made from two different species, namely African wood and mangium. For the same amount of material of the same quality, it is interesting to study which laminae configuration gives the highest strength and stiffness.

In this paper, the effect of laminae configurations of glued-laminated timber on the modulus of elasticity and the modulus of rupture are studied both experimentally and numerically. Experimental studies were carried out by loading a few glulam beams at midspan. Numerical studies were performed utilizing finite element analyses.

Experimental Procedures

Materials

Thirty two meranti (shorea) laminae of the size 50 mm by 100 mm by 1800 mm (see Figure 1) were air dried until the moisture content approximately reached 15%. The actual moisture content of all laminae varied from 14% to 18%. Although all laminae are of the same species, the specific gravity of all laminae varied from 0.36 to 0.52.

Polyvinyl acetate (PVA), commercially known as carpenter’s glue, was prepared as adhesive of the laminae. PVA is suitable as adhesives for porous materials such as wood (AITC 2007).

For clamping the laminae after gluing them, four steel clamps for each glulam beam were used. These clamps were removed after the glue dried and hence the laminae could act as a glulam beam.

Methods

Productions of Glulam Beams

To study experimentally the effect of lamina orientation of glulam beams on the strength (as represented by modulus of rupture) and stiffness (as represented by modulus of elasticity), eight glulam beams were made. Three glulam beams had laminae with vertical configuration, three glulam beams had laminae with horizontal configuration, and two
glulam beams had mixed configuration (see the cross sections of the glulam beams in Figure 2). As seen in the figure, each glulam beam consists of four meranti laminae. Glue was applied on each interface between laminae. As seen in Figure 3, four steel clamps were used to give enough pressure between each lamina. The minimum pressure to produce a glulam is 0.7 MPa (Thelandersson and Larsen 2003).

**Figure 1. Dimensions of each lamina.**

![Dimensions of each lamina](image1)

**Figure 2. Cross sections of glulam beams: (a) all laminae are vertical, (b) all laminae are horizontal, (c) two laminae are vertical and the other two are horizontal (mixed).**

![Cross sections of glulam beams](image2)

**Figure 3. Clamping glulam beams to give pressure on each lamina interface.**
Static Bending Tests
To estimate the modulus of elasticity MoE and the modulus of rupture MoR of each glulam beam, destructive static bending tests were performed. Each beam was simply supported with a beam span of 1600 mm. A Universal Testing Machine (UTM) with a loading capacity of 500 kN as seen in Figure 4 was used. As seen in the figure, the displacement was applied at midspan. Both load and midspan displacement were recorded directly into the computer attached to the machine. The rate of displacement chosen was 2 mm/minute. The displacement was increased until the load decreased significantly indicating the significant loss in stiffness and strength of the beam. The load versus displacement curves for each beam is shown in Figure 5, 6, and 7. As seen in the figures, all beams cease behave elastically at much lower load level than the maximum load. Another feature in the load versus midspan deflection curves is that the beam stiffness degradation increases as displacement increases. This indicates the increase in failed material in the beam. Figure 8 and 9 show examples of failure mode of the beams tested.

Figure 4. Universal Testing Machine for static bending test.
Figure 5. Load (N) versus midspan deflection (mm) of glulam beams with all horizontal laminae.

Figure 6. Load (N) versus midspan deflection (mm) of glulam beams with mixed orientation laminae.
Figure 7. Load (N) versus midspan deflection (mm) of glulam beams with mixed orientation laminae.

Figure 8. Failure mode of glulam with all vertical configuration (specimen All_Vert_1).

Figure 9. Failure mode of glulam with all horizontal configuration (specimen All_Hor_3).
Modulus of elasticity MoE is computed using elementary formula assuming the material is homogenous, elastic, and isotropic, i.e.

$$MoE = \frac{P_{\text{elastic}} L^3}{4 \Delta_{\text{elastic}} bd^3} \quad (1)$$

where $P_{\text{elastic}}$ = load in the elastic stage (N), $\Delta_{\text{elastic}}$ = deflection (mm) at load level of $P_{\text{elastic}}$, $b$ = beam width (100 mm), $d$ = beam depth (200 mm), $L$ = beam span (1600 mm), MoE = static bending modulus of elasticity (MPa). MoE for each glulam beam and the average MoE for each lamina configuration obtained experimentally is shown in Table 1.

**Table 1. Comparison between Modulus of Elasticity (MoE) of each specimen tested and that obtained from finite element analysis (FEA).**

<table>
<thead>
<tr>
<th>Beam Designation</th>
<th>Experimental MoE (MPa)</th>
<th>Average Experimental MoE (MPa)</th>
<th>MoE from FEA (MPa)</th>
<th>Percentage of MoE difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All_Hor_1</td>
<td>2374</td>
<td>2005</td>
<td>759</td>
<td>164</td>
</tr>
<tr>
<td>All_Hor_2</td>
<td>2475</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All_Hor_3</td>
<td>1167</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed_1</td>
<td>2970</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed_2</td>
<td>1664</td>
<td>2023</td>
<td>1146</td>
<td>76</td>
</tr>
<tr>
<td>Mixed_3</td>
<td>1436</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All_Vert_1</td>
<td>1885</td>
<td>2093</td>
<td>4444</td>
<td>-53</td>
</tr>
<tr>
<td>All_Vert_2</td>
<td>2301</td>
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</tbody>
</table>

**Table 2. Modulus of Rupture MoR for each glulam orientation.**

<table>
<thead>
<tr>
<th>Beam Designation</th>
<th>Maximum Load $P_{\text{max}}$ (N)</th>
<th>Average Maximum Load (N)</th>
<th>MoR (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All_Hor_1</td>
<td>21675</td>
<td>23135</td>
<td>13.88</td>
</tr>
<tr>
<td>All_Hor_2</td>
<td>31754</td>
<td>23135</td>
<td></td>
</tr>
<tr>
<td>All_Hor_3</td>
<td>15117</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed_1</td>
<td>30828</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed_2</td>
<td>20464</td>
<td>24610</td>
<td>14.77</td>
</tr>
<tr>
<td>Mixed_3</td>
<td>22539</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All_Vert_1</td>
<td>23573</td>
<td>27036</td>
<td>16.22</td>
</tr>
<tr>
<td>All_Vert_2</td>
<td>30499</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
As widely used by many researches, the modulus of rupture MoR (MPa) is computed using

\[ MoR = \frac{3P_{\text{max}}L}{2bd^2} \]  \hspace{1cm} (2)

where \( P_{\text{max}} \) = maximum load from load versus displacement curve (N). It should be noted that Equation (2) is an approximation because it is derived using elastic, homogenous, and isotropic assumption, while \( P_{\text{max}} \) is actually much beyond the elastic limit, wood is actually not an isotropic material, and glulam is actually not homogenous. MoR for each glulam beam tested in this research is shown in Table 2.

**Finite Element Analysis**

**Finite Element Model**

Assuming wood as an orthotropic and elastic material with three mutually perpendicular material principal axes (longitudinal, radial, and tangential), nine elastic properties are required in the three dimensional finite element analysis. For meranti, the properties are \( E_L = 5529 \) MPa, \( E_R = 851 \) MPa, \( E_T = 453 \) MPa, \( \mu_{LR} = 0.35 \), \( \mu_{LT} = 0.45 \), \( \mu_{RT} = 0.56 \), \( G_{LT} = 275 \) MPa, \( G_{LR} = 303 \) MPa, and \( G_{RT} = 71 \) MPa. These properties are taken from Suryoatmono and Tjondro (2008).

In the three dimensional finite element analysis, the type of element used is 8-node solid element with three translational degrees of freedom at each node. Undeformed finite element mesh of the beam analyzed in this study is shown in Figure 10. The longitudinal axes of the laminae (the fiber direction) is assumed to coincide with the longitudinal direction of the glued beam. The lamina plane is regarded as the longitudinal-tangential plane of the material, and hence the thickness direction of the lamina coincides with the radial axis of the material. Compatibility between each lamina is assumed to be perfect, i.e. no slip occurs between laminae.

![Three dimensional finite element model of glulam beam.](image-url)
The analysis was performed for glulam beams with all vertical, all horizontal, and mixed configurations. Elastic midspan deflection due to concentrated load of 10 kN for each beam is shown in Table 3. As seen in the experimental results in Figure 5, 6, and 7, this level of load is still in the elastic range.

<table>
<thead>
<tr>
<th>Beam Designation</th>
<th>Midspan deflection $\Delta_{\text{elastic}}$ (mm)</th>
<th>Ratio of midspan deflection and span (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All horizontal</td>
<td>16.87</td>
<td>1.05</td>
</tr>
<tr>
<td>Mixed</td>
<td>11.16</td>
<td>0.70</td>
</tr>
<tr>
<td>All Vertical</td>
<td>2.88</td>
<td>0.18</td>
</tr>
</tbody>
</table>

### Discussion

#### Modulus of Elasticity

Using elastic load $P_{\text{elastic}}$ and elastic deflection $\Delta_{\text{elastic}}$ obtained from finite element analysis, the modulus of elasticity $\text{MoE}$ for each lamina configuration can be computed using Equation (1) as shown in Table 1. The experimental and finite element analysis results show that the highest and lowest $\text{MoE}$ are for all vertical and all horizontal configurations, respectively. As seen in the finite element results in Table 1, $\text{MoE}$ of mixed configuration glulam beam is approximately 1.5 times $\text{MoE}$ of all horizontal configuration glulam beam, while $\text{MoE}$ for all vertical configuration glulam beam is approximately 5.8 times $\text{MoE}$ of all horizontal configuration glulam beam.

#### Modulus of Rupture

Although the difference is not much, the modulus of rupture of all vertical configuration glulam beam is the highest and the modulus of rupture of all horizontal configuration glulam beam is the lowest, as obtained from the experimental study. Finite element analysis for predicting modulus of rupture was not performed because the necessary non linear capability such as modeling crack is not available in the finite element software.

### Conclusions

It is important to consider lamina orientation in order to produce the highest possible of stiffness and strength. In producing glulam beam using lamina having the longitudinal-tangential plane, the highest strength (as represented by modulus of rupture MoR) and stiffness (as represented by modulus of elasticity MoE) can be obtained if all laminae are parallel so that all laminae are bent with respect to the radial axis.
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References


