Structural Performance of Glued Laminated Bamboo Beams

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Abstract: This paper presents a study aimed to characterize the structural performance of laminated bamboo lumber (LBL) and bamboo glulam beams (BGBs) as a first step to evaluate their potential application as a structural material. LBL was tested to determine their flexural, tensile, and shear properties, whereas BGBs were tested for their flexural, shear, and compressive properties. The BGBs were fabricated using two different adhesives: isocyanate resin (ISO) and phenol-resorcinol formaldehyde (PRF). BGBs with ISO performed better in bending strength, whereas the stiffness of glulums with both glue types was equivalent. Irrespective of the glue type, failure modes and shear test data showed BGB bending strength was limited by interlaminar shear in the LBL used in BGB fabrication. From the experimental study, it is concluded that the LBL does possess higher allowable and average strength values in tension and bending and comparable stiffness values, with much less variability to a commonly used structural species of wood, Douglas fir. The potential of using LBL in framing applications exists. However, certain impediments need to be addressed and researched before acceptance of LBL and BGB in the construction marketplace. DOI: 10.1061/(ASCE)ST.1943-541X.0000807. © 2013 American Society of Civil Engineers.

Author keywords: Bamboo; Laminated bamboo lumber; Structural composite lumber; Bamboo glulams; Engineered wood; Engineered lumber; Glued laminated lumber; Glulams; Wood structures.

Introduction

Bamboo has gained popularity in the green building community because it is a renewable, natural, and biodegradable material (Bonilla et al. 2010). Moreover, it is fast growing, has lower embodied energy than timber, steel, and concrete while creating less pollution in production than steel or concrete (van der Lugt et al. 2003, 2006; Lee et al. 1994; Rittironk and Elnieiri 2007; Nath et al. 2009). Not considering the environmental impacts of transportation of bamboo from where it is abundantly available to the western world, studies compared bamboo to timber and concluded bamboo to be more sustainable than timber in various metrics (van der Lugt et al. 2003).

Of several hundred species of bamboo, one of the most commonly used species is Moso bamboo (Phyllostachys pubescens Mazel ex J. Houz). The modulus of rupture (MOR) for Moso bamboo ranges between 97.9 and 137.9 MPa, and the corresponding modulus of elasticity (MOE) range is 9.0–20.7 GPa (Lee et al. 1994; Madhavi et al. 2011). As the numbers suggest, bamboo is a strong and stiff material. Bamboo in its natural form is a hollow tubular structure and thus highly efficient in resisting bending forces. However, this structure is the largest impediment in use of bamboo in engineered construction because of the difficulty of making connections. Moreover, because the bamboo stem is hollow and small in diameter relative to trees, larger rectangular pieces of dimension lumber cannot be sawn out of a piece of bamboo. Bamboo’s round shape sometimes leads to inefficient utilization of space and is hardly used where flat surfaces are required.

To mitigate these challenges, laminated bamboo lumber (LBL) was introduced. LBL (Fig. 1) resolves the identified deficiencies in the natural shape of bamboo because it is formed in rectangular sections that are more suitable for use in traditional structural applications. The result is a composite rectangular structural member, fabricated by using a renewable material that makes it competitive, in this regard, with commonly used building materials. LBL is made by gluing together strands of bamboo to form rectangular cross sections similar in shape and size to conventional lumber [Fig. 1(a)]. Multiple studies have described the need and processing of LBL (Lee et al. 1998; Nugroho and Ando 2001; Rittironk and Elnieiri 2007; Sulastiningsih and Nurwati 2009). Recently, Madhavi et al. (2011) comprehensively reviewed the manufacturing process and mechanical properties of LBL. A brief description of LBL manufacturing is provided in “Materials.”

With respect to structural properties, tests show Moso LBL has an average MOR of 107.2 MPa, with coefficient of variation (COV) of 10% (Yü et al. 2008; Aschheim et al. 2010; Madhavi et al. 2011) and a MOE of 10 GPa with a COV of 11.7% (Lee et al. 1998; Aschheim et al. 2010). These well exceed the lengthwise MOR and MOE of competing timber products, making it possible to lower the amount of material needed to produce something of equal stiffness and strength to a similar functioning wood product.

Bamboo products are being utilized in composite materials to reduce mass and maintain structural integrity. This includes panel products like plywood, I-joists (Aschheim et al. 2010), and wind turbines (Platts 2008). Although bamboo has been used in a broad range of applications, it has not been utilized as a structural material in common load-bearing applications despite research by Nugroho and Ando (2001), Lee et al. (1998), and Sulastiningsih and Nurwati (2009), characterizing LBL bending properties. This research showed LBL MOR varied from 74 to 107 MPa, depending on the specific species and processing type, with a corresponding range in MOE of 8–14 GPa.

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**Research Need**

LBL have found limited use in structural applications, such as glued laminated beams (a.k.a., glulams). Characterization of mechanical properties of LBL glulams [Fig. 1(b)] is needed to gain confidence in the material, develop characteristic values, establish engineering properties, and assess the feasibility of their use in typical glulam applications.

**Research Objective**

The primary objective of this study was to characterize the structural properties of LBL and bamboo glulam beams (BGBs), and compare these properties to typical softwood lumber and softwood glulam beams. A secondary objective was to assess influence of glue type on BGB mechanical properties.

**Materials**

**Laminated Bamboo Lumber**

Laminated bamboo lumber (LBL) is made by gluing together strands of bamboo to form rectangular cross sections similar in shape and size to conventional lumber [Fig. 1(a)]. This is accomplished in four steps. First, tubular bamboo sections are ripped through the length to form strands, which are then passed through a planer. The strands are then edge glued into small rectangular sections called slats [Fig. 1(a)] of dimension $6.4 \times 19 \times 2,464$ mm using emulsion polymer isocyanate (EPI). Slats are then laminated either horizontally or vertically to form a row. A majority of the manufacturers laminate the slats vertically, and therefore, the dimension and orientation are the same relative to tangential and radial direction of bamboo. When laminated vertically, 23 bamboo slats are used to form a row. Finally, two rows are laminated together to form a $38 \times 142.5 \times 2,464$ mm LBL (nominal 2- by 6-in. LBL) void of end joints. The finished LBL was procured from a manufacturer in China.

**Bamboo Glulam Beams**

Five pieces of LBL were laminated together by a beam manufacturer in Eugene, Oregon, to produce each bamboo glulam beam (BGB). Ten beams were fabricated using phenol-resorcinol formaldehyde (PRF) (5210J resin with 6310L hardener produced by Momentive Glue Company), whereas an additional 10 were assembled using a formaldehyde-free isocyanate (GT20 with a GT205 hardener produced by Purbond, Bridgewater, New Jersey). A static clamping pressure of 690 kPa was applied for 6 h, after which beams were planed to dimensions of $133.5 \times 190 \times 2,464$ mm (5.25 × 7.44 × 97 in.) as shown in Fig. 1(b). Because BGBs were equal in length to the LBLs, no end joints were required in BGB production.

**Methods**

**Experimental Design**

The experimental design in Table 1 identifies the number of specimens for each test and each type of BGB. Moreover, the dimension of specimens and other important testing parameters are also listed.

![Fig. 1. Laminated bamboo lumber and bamboo glulam beams details: (a) various features of a laminated bamboo lumber (LBL); (b) cross section of a bamboo glulam beam (BGB) made by laminating together flatwise five LBLs](image_url)

<table>
<thead>
<tr>
<th>Material</th>
<th>B × D × L (mm)</th>
<th>Span (mm)</th>
<th>Sample</th>
<th>Bondline area (mm × mm)</th>
<th>Sample</th>
<th>B × D × L (mm)</th>
<th>Cp, Cpara</th>
<th>B × D × L (mm)</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBL (edgewise)</td>
<td>38 × 142.5 × 2464</td>
<td>2,388</td>
<td>12</td>
<td>44.5 × 70</td>
<td>16</td>
<td>38 × 142.5 × 2464</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBL NDE</td>
<td>38 × 142.5 × 2464</td>
<td>2,388</td>
<td>32</td>
<td>63.5 × 76</td>
<td>20</td>
<td>50 × 50 × 100</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>BGB PRF</td>
<td>133.5 × 190 × 2464</td>
<td>2,388</td>
<td>10</td>
<td>63.5 × 76</td>
<td>20</td>
<td>50 × 50 × 100</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>BGB Iso</td>
<td>133.5 × 190 × 2464</td>
<td>2,388</td>
<td>10</td>
<td>63.5 × 76</td>
<td>20</td>
<td>50 × 50 × 100</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Note: LBL = laminated bamboo lumber; BGB = bamboo glulam beam; Iso (glue type) = isocyanate; PRF (glue type) = phenol resorcinol formaldehyde; and NDE = nondestructive evaluation.
This experimental plan did not record the MOE of each LBL and then use that data to model BGB properties using transformed section. The study was designed to find mechanical properties of LBL and probable use of LBLs in BGBs. Moreover, no effort was directed to use higher grade materials in the outer laminations of BGBs. All LBLs used in this study had similar properties with a fairly low variability (as discussed in “Results”). LBLs were randomly selected to form layups for BGBs.

**Specimen Conditioning**

All specimens before testing were conditioned in a conditioning chamber maintained at a constant temperature and relative humidity (RH) of 20°C and 65%, respectively. After testing, their moisture content was determined using ASTM D4442 Method A (ASTM 2010a).

**Nondestructive Bending Tests**

Thirty-two pieces of LBL were tested flatwise using a Metriguard Model 340 E-Computer. The device was calibrated using a 3.6-kg mass and the system’s calibration function. The specimen rested on a load cell at one end and a rigid support on the other with a 2,388-mm span [Fig. 2(c)]. Excitation occurred by knocking on the center of the specimen. Each specimen was excited twice to ensure excitation reproducibility. The E-computer uses the following formula to calculate MOE:

\[
\text{MOE} = f_n^2 wL^3 / (k b h^2)
\]

where \( w = \) mass; \( k = \) adjustment constant with units dependent on other equation variables; \( L = \) total span; \( f_n = \) undamped natural frequency; \( b = \) specimen width; and \( h = \) specimen thickness.

**Static Bending Tests**

Twelve pieces (boards) of LBL (edgewise) and 18 BGBs (flatwise) were tested to failure in bending under a third point loading following ASTM D198 (2010d). A 220 kN StrainSert universal load cell calibrated to ±1% accuracy was used to measure load. The shear-free span and distance between the reaction bearing plates and load applicators was 795 mm for a total span of 2,388 mm. This resulted in a span-to-depth ratio of 12.6:1 for glulam beams and 16.75:1 for LBL. The loading head was equipped with a load-eaver and both reaction-bearing plates were able to pivot.

For BGBs, a yoke deflectometer equipped with an LVDT calibrated to ±1% accuracy was used to measure the midspan deflection [Fig. 2(a)]. The deflection measuring apparatus differed from the LBL’s because of the need for lateral support [Fig. 2(b)], instead using a string LVDT deflectometer.

BGBs were loaded at a constant rate of 6.5 mm/min and LBL at 13 mm/min to achieve an average time to failure of 7 min. Average moisture contents of both glulams and LBL were 6.5%.

For both flatwise bending of BGBs and edgewise bending of LBLs, the modulus of elasticity (MOE) and the modulus of rupture (MOR) were calculated using Eqs. (2) and (3), respectively

\[
\text{MOE} = k a (3L^2 - 4a^2) / (24l)
\]

\[
\text{MOR} = P_{\text{max}} L / (bd^2)
\]

**Fig. 2.** Various test setups: (a) yoke deflectometer apparatus used in flexure test of BGB; (b) LBL edgewise bending set up using a third-point loading method; (c) nondestructive MOE determination using a Metriguard 340 E-Computer; (d) tension testing apparatus; (e) tension strain measurement device with a gauge length of 914 mm using an LVDT; (f) shear-block specimen from a BGB; (g) shear block test apparatus; (h) compression test setup using a bearing block to minimize initial alignment
where \( k \) = slope within proportional limit from load versus deflection graphs; \( I \) = moment of inertia; \( a \) = distance between loading support and loading points; \( L \) = total span; \( P_{\text{max}} \) = maximum bending load; \( b \) = specimen thickness; and \( d \) = specimen depth.

**Tension Tests**

LBL specimens were tested in tension parallel to the grain in accordance with ASTM D198 (2010d). Distance between grips averaged 1,980 mm [Fig. 2(d)]. The extension was measured using an extensometer with a gauge length of 914 mm and an accuracy of \( \pm 1\% \) [Fig. 2(e)]. Load was applied at a constant rate of 6 mm/min with an average time to failure of 8 min. The load apparatus consisted of one stationary grip and one grip attached to a 900-kN capacity cylinder. Both grips were self-aligning. Grips were preloaded using pneumatic air bags to aid in the gripping process. Significant crushing from the grips was not observed. Ultimate tensile stress (\( \sigma_T \)) and modulus of elasticity in tension were calculated as follows:

\[
\sigma_T = \frac{P_{\text{max}}}{a}
\]

(4)

\[
\text{MOE} = \frac{\sigma_T}{\varepsilon}
\]

(5)

where \( P_{\text{max}} \) = maximum axial load; \( a \) = cross-sectional area; \( \varepsilon \) = equal to \( \Delta L/L \), where \( \Delta L \) is the LVDT reading and \( L \) is LVDT gauge length.

**Shear Tests**

Forty specimens removed from the BGBs and 16 specimens from the LBL boards were tested for bond strength properties using compressive loading following ASTM D905 (2011b) with certain departures from the standard. LBL specimens were prepared with a bond line area of \( 44.5 \times 70 \) mm \((1.75 \times 2.75 \) in.) as opposed to \( 50 \times 50 \) mm specified in the standard. Specimens were cut from the end of the BGB tested in flexure and prepared over the interphase as mentioned in ASTM D905 (2011b). In certain regards, the test specimen was similar to ASTM D143 (ASTM 2010b); and hence, the apparatus specified in ASTM D143 was used for testing the blocks. All bond line areas were measured with digital calipers accurate to \( \pm 0.01 \) mm. Specimens were loaded at a rate of 5 mm/min using a 100-kN load cell with an accuracy of \( \pm 1\% \) with an analytical scale with an accuracy of \( \pm 1 \) mg. Moisture content was determined after measuring density properties by placing the block in a 103°C oven for a period of 24 h.

**Compression Tests**

Specimens of \( 50 \times 50 \times 100 \) mm were tested in compression perpendicular to the grain and compression parallel to the grain following ASTM D143 (2010b). An Instron 5582 UTM equipped with a 100-kN load cell and capable of measuring deflection to 0.02 mm was used to test the specimens in Cperp, whereas another Universal testing machine equipped with 200 kN was used to measure compression parallel. The specimens were conditioned for a period of 14 days before testing, which equilibrated to an average of 7% MC. Load was applied at a constant rate of 5 mm/min for both, compression parallel and perpendicular. The loading apparatus had a 50 mm (2-in.) metal bearing plate, and the specimen rested on a metal bearing plate equipped with a ball bearing to allow adjustment for equal loading and reduce initial alignment [Fig. 2(b)]. Compressive strength was calculated using the methods in ASTM D143 (2010b).

**Density Determination**

One specimen each from 10 different pieces of LBL was cut into approximately \( 38 \times 50 \times 50 \) mm \((1.5 \times 2 \times 2\) in.) blocks and any excess fiber was carefully removed with very fine grit sandpaper. Density was determined by using ASTM D 2395-Method A (2010c). The volume of each block was measured using calipers with an accuracy of \( \pm 0.01 \) mm, and mass was measured using an analytical scale with an accuracy of \( \pm 1 \) mg. Moisture content was determined after measuring density properties by placing the block in a 103°C oven for a period of 24 h.

**Results and Discussions**

**Flexural Strength and Stiffness**

Mean MOR and MOE values for BGBs with both PRF and isocyanate (ISO) adhesives are presented in Table 2. The MOE values are similar for both glue types. The PRF BGB has a slightly higher MOE than BGB ISO, but the difference was statistically not significant (\( p \gg 0.05 \)). However, for MOR, the isocyanate-based glue performed significantly better (\( p = 0.0119 \)) than the BGB PRF—70.13 MPa (BGB ISO) as opposed to 42.16 MPa (BGB PRF). A typical load deflection curve is shown in Fig. 3. The curve shows that both PRF BGB and ISO BGB has similar stiffness as indicated by the linear portion of the load deflection curve. However, the maximum load for BGB ISO is higher than BGB PRF. Although there is a huge variability in the MOR results observed for both the BGBs (Table 2), the coefficient of variation (COV) for BGB ISO is much lower than that of BGB PRF. The span-to-depth

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**Table 2. Summary of Test Results For Bending, Shear, and Compression Tests**

<table>
<thead>
<tr>
<th>Material</th>
<th>MOE (MPa)</th>
<th>COV (%)</th>
<th>MOR (MPa)</th>
<th>COV (%)</th>
<th>Shear stress (MPa)</th>
<th>COV (%)</th>
<th>Deep bamboo failure (%)</th>
<th>Shallow bamboo failure (%)</th>
<th>Adhesive failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGB ISO</td>
<td>22.3</td>
<td>4.7</td>
<td>70.13</td>
<td>27.2</td>
<td>15.67</td>
<td>10.4</td>
<td>77</td>
<td>6.125</td>
<td>22.1</td>
</tr>
<tr>
<td>BGB PRF</td>
<td>22.9</td>
<td>3.6</td>
<td>42.16</td>
<td>59.6</td>
<td>16.43</td>
<td>7.4</td>
<td>90.25</td>
<td>6.125</td>
<td>3.625</td>
</tr>
<tr>
<td>LBL</td>
<td>12.19</td>
<td>14.2</td>
<td>89.2</td>
<td>6.04</td>
<td>9.87</td>
<td>62</td>
<td>49.7</td>
<td>5.6</td>
<td>44.7</td>
</tr>
<tr>
<td>LBL NDE</td>
<td>11.07</td>
<td>4.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: LBL = laminated bamboo lumber; BGB = bamboo glulam beam; ISO (glue type) = isocyanate; PRF (glue type) = phenol resorcinol formaldehyde; and NDE = nondestructive evaluation.

ratio for the flexural tests would induce shear, but it seems unlikely that this was the only reason causing the variability in MOR values. The limiting factor seemed to have been failure in the glue line of LBL beams, which caused separation across the glue line. Across both glue types, 20 beams were tested; 14 of those beams failed because of the glue-line failure in the LBL. The other glue line (e.g., PRF or Isocyanate) did not govern the failure. Three beams failed in tension at a significantly higher MORs than those failing in LBL shear.

The LBL beams were tested edgewise, and the variability in property was much less than that of BGBs. Of the 16 specimens tested, only one glue line separation was observed in the LBL. The majority of the beams failed in tension of the extreme fiber, as expected in a flexural test. The associated COV for LBL is quite low (Table 2). This result was expected because the materials were single-sourced from a manufacturer in China. Properties of bamboo generally vary from location-to-location in the bamboo shoot as well as geographical location of growth (Ahmad 2000). The properties also vary from year to year (Lee et al. 1994). When engineered composites are manufactured using highly variable raw materials, the variability in properties goes down significantly. Additionally, sourcing materials from one manufacturer further reduces the observed variability.

The MOR of LBL edgewise was significantly higher than any of the BGBs. The MOR and MOE are comparable to Douglas fir dimension lumber (MOR = 85 MPa; MOE 13.4 GPa). The results compared well with previous studies on laminated bamboo products (Yu et al. 2008; Madhavi et al. 2011). The nondestructive evaluation results of LBLs in flatwise bending are also presented in Table 2. The MOE flatwise of LBL was significantly ($p < 0.05$) lower than that of edgewise MOE calculated for LBL bending tests and also had lower variability. This could be a result of the relative arrangement of the slats to form LBL with respect to tangential and radial directions of the bamboo. Like wood, bamboo is orthotropic in nature and differences in property exist in the radial and tangential directions of bamboo. However, this observation is in contrast with the conclusions of Ahmad (2000), who reported no significant differences in stiffness in radial and tangential directions. Results of this study explain the differences more prominently in compression tests (discussed in “Compression Properties”). Furthermore, the nondestructive evaluation does not take into account the glue line within the LBL pieces (by virtue of its loading), which may explain the more uniform results. Because the LBLs were made with LBL oriented flatwise, mechanical properties of the BGBs may improve by orienting the lams edgewise. Using edgewise also changes the way bamboo fiber is loaded relative to radial or tangential directions of the fiber. For future studies, a testing program is recommended to investigate the mechanical properties of BGBs with lams oriented edgewise.

**Failure Type and Progression**

Four failure types were observed as BGBs were tested in flexure. These four failure types are shown in Fig. 4. Of the four types, three are interlaminar shear failures: interlaminar shear failure in the tension zone [Type 1; Fig. 4(a)], interlaminar shear failure in compression zone [Type 2; Fig. 4(b)], and interlaminar shear failure in the middle of the beam [Type 3; Fig. 4(c)]. The fourth type of failure was tension failure in the extreme fiber of the tension zone of the beam [Type 4; Fig. 4(d)]. For BGB PRF, five beams exhibited a Type 1 failure, one a Type 2 failure, three a Type 3 failure, and one a Type 4 failure. Of the ten ISO BGBs, six exhibited a Type 1 failure, two a Type 2 failure, zero a Type 3 failure, and two a Type 4 failure.

BGB interlaminar shear failures (Types 1, 2, and 3) had similar failure progressions. First, resulting from a combination of high...
shear stress and an inability of the LBL glue type to transfer stress, a crack initiated between the two layers of a single LBL. This crack was generally located between the support and load point (i.e., in the constant shear region). With subsequent loading, the crack propagated in both directions, eventually causing delamination in the LBL.

Looking closely at the failure modes, it is clear that the strength-limiting aspect of the BGBs, irrespective of the glue type (PRF or ISO), was the interlaminar shear in LBL. The LBL was not able to hold up against the structural demands asked of it in glulam applications. The LBL was procured from a manufacturing facility in China, and the glue used was a variant of EPI. It is inconclusive whether the adhesive limited the performance of the LBL or whether other process parameters for bonding the LBL were contributing in LBL not holding up to the structural demands. Unfortunately, details of the glue type formulation and process parameters are unknown. For LBLs to be used in BGBs, more research and quality control on the preparation of LBL needs to be achieved, and the suitability of a glue type for structural application demands should be investigated.

### Tensile Strength and Stiffness

LBL tested in tension had more variability in tensile MOE values than in tensile strength. The average ultimate tensile strength of LBLs was 61 MPa with a COV of 9%, whereas the average tensile stiffness (MOE) was 13.41 GPa with a COV of 24%. The average tensile modulus is significantly higher than the average edgewise bending modulus. However, if the recommendation of Kretschmann (2010) is followed and tensile MOE is estimated from bending MOE by accounting for shear deformation, then the values are identical (12.19 × 1.10 = 13.41 GPa). This further validates the claims of Kretschmann (2010) that Young’s modulus can be calculated accurately for wood from bending stiffness after accounting for shear deflection. Moreover, there is an indication that this might be true for LBLs. However, more tests are required to validate whether a 10% adjustment to bending modulus is reasonable or not. Douglas fir dimension lumber of cross section 38 × 140 mm (2 × 6 in.) No. 2 Grade has an average modulus of elasticity of 13.4 GPa and ultimate tensile strength of 42 MPa at 12% MC (Kretschmann 2010). With an average MOE of 13.41 GPa and average ultimate tensile strength of 61 MPa, LBL appears to have similar stiffness but higher strength than Douglas fir dimension lumber in tension.

The failure in LBLs subjected to tension occurred in different places, depending on the specimen, with minimal crushing at the grips. Brash tensile failure occurred at places where nodes were located. However, it was difficult to determine if there were nodes at the same place further in the LBL. The nodes and the adjacent glue line create potential stress concentrators for tensile loading within the LBL because a stiffness gradient exists between the node and the adjacent material, as well as the node and the glue line.

### Shear Strength and Adhesive Performance

Given the strength-limiting factor of glue type in LBL, it is important to analyze various glue bonds that will impact strength and stiffness properties. Table 2 presents the shear stress required to fail the glue lines and the corresponding coefficient of variation. Table 2 further presents the average visual failure observed in bamboo (deep or shallow) or adhesive. All the test specimens were visually graded using guidelines in ASTM D5266 (2011a).

Shear stress of a PRF bonded bamboo was higher than that of ISO bonded bamboo, but not statistically significant ($p = 0.1$). A glue line was involved in the failure of 22% of the ISO specimens, but in only 3.6% of the PRF samples (Table 2). No clean (100%) glue failures were observed in any of the BGBs laid up with these two glue types. As a result, bonding quality of the two adhesives was considered adequate.

Interlaminar glue line bond quality of the LBL was poor compared with the PRF and isocyanate. This fact is also elucidated in Table 2. The shear strength of the bond using the EPI was 60% that of BGB PRF. Approximately half these specimens failed in the glue line, which was evident when testing the bamboo glulam beams. As a result this glue type may not be adequate for laminating bamboo slats to make LBL for structural use or the bonding process needs to be revisited. Compared with how often PRF failed in the glue line (3.6%), and isocyanate (22%), the LBL material performed much worse with a value of 44.7%. In addition and subsequent use of LBL in structural applications, the performance of LBL will be the limiting factor as demonstrated by the failure in the BGB bending tests in this study.

### Compressive Strength

Both BGBs (ISO and PRF) had similar compression parallel-to-fiber strengths (C-perp) as compiled in Table 2. This was expected because adhesive is not really required to transfer load between layers being pressed together in a direction normal to gluing planes.

Both BGBs (ISO and PRF) also had similar compression perpendicular-to-fiber strengths. This can be attributed to the fact that the ISO and PRF glue planes are not highly stressed when load is uniformly applied parallel to the glue planes. Fig. 5 shows a typical load deflection curve for a compression parallel-to-fiber loading. A yield point is observed in Fig. 5, and this was consistent with all the other samples as was the very linear stiffness up to this yield point. The consistent yield point for all samples might be a result of uniformity and consistent size of limiting defects in the LBL. Qualitatively, the failure of the samples was plastic deformation in an S-shaped buckle. Interestingly, buckling was highly biased toward failure across the 6.4-mm face of the laminated slats. This was the wide axis of the compression block and indicates a significant stiffness differential in radial–tangential properties of the LBL. This should be taken into consideration when using the LBL for different framing applications. The results, however, were
consistent, and variability was significantly less than associated with any wood species. Therefore, with due considerations to limiting features for LBL, it has the potential to be applied to compression dominant applications.

**Comparison to Standard Softwood Materials**

The comparison to conventional framing material has to be on two levels. The first level is comparison of LBL to dimension lumber of a common species; the second level is comparison of BGBs to softwood glulams. The Forest Products Laboratory’s Wood Handbook (Bergman et al. 2010) and the National Design Specification [American Forest and Paper Association (AFPA) 2012] lists selected properties of dimension lumber and glulam beams from different species of wood. The values for commercially available Douglas fir were taken and compared with the selected properties of bamboo glulam beams tested in this study.

**LBL and Douglas Fir 2 × 6**

When tested edgewise, the LBLs had an average value of 89.16 MPa with a standard deviation of 5.39 MPa, whereas the corresponding MOE was 12.19 GPa with a standard deviation of 1.73 GPa (Table 2). Although 12 samples are not enough to derive characteristic and allowable material property value, for the sake of comparison and to get an initial indication on how LBLs fare in the comparison to softwood lumber, it is important to convert the average values to allowable values. There are currently no standards for physical or mechanical properties of bamboo in the United States, so the conversion of material property values to allowable stress values will be done using the method established in ISO 22157 (International Standards Organization 2004a, b) and ISO 22156 (International Standards Organization 2004c) and using the following equations:

\[ R_{ck} = R_{0.05} \times \left[1 - (2.7 s/m) / N^{0.5}\right] \]  

\[ \sigma_{all} = R_{ck} \times G \times D / S \]  

where \( R_{ck} \) = characteristic value; \( R_{0.05} \) = 5th percentile value (i.e., Mean - 2 × standard deviations); \( m \) = mean of all values from test data; \( s \) = the standard deviation; \( N \) = the number of test (10 minimum); \( \sigma_{all} \) = allowable bending stress; \( G \) = the modification factor for difference between laboratory and practice conditions with a default value of 0.5; \( D \) = the modification factor for duration of load (1.0 for permanent loads); and \( S \) = the safety factor with a default value of 2.25.

Using Eq. (6), a characteristic value for bending stress of 74.68 MPa was obtained. Substituting into Eq. (7) yields an allowable stress is 16.60 MPa as presented in Table 3. This compares to an allowable value for bending stress for a nominal 2 × 6 in. Select Structural Douglas fir member of 13.5 MPa (AFPA 2012). The corresponding Douglas fir MOE is 13 GPA (AFPA 2012) as presented in Table 3. The average MOE of LBL obtained from laboratory tests was 12.19 GPa, which is comparable within the experimental limits. Additionally, in tension, the MOE of LBL is comparable to a Douglas fir 2 × 6, whereas the tensile MOR is much higher than Douglas fir. Similarly, the allowable design value for tensile strength of LBL is 10.4 MPa, which is higher than that of the corresponding Douglas fir value of 9 MPa (AFPA 2012).

The COV for MOE and MOR in bending were 14.2 and 6.04%, respectively, for LBL (Table 2), whereas the corresponding average COV of wood is 22 and 16%, respectively (Kretschmann 2010). For tensile strength, the variability observed for LBL was 9% compared with an average of 25% recorded for solid wood (Kretschmann 2010). Less variation in properties of LBL is expected because it is a composite material and was single-sourced. Laminating homogenizes the natural defects in the material and as a result, produces less variability.

Because LBL is an engineered composite, a reasonable comparison will be with other engineered wood composite that LBL might compete against. One such composite is laminated veneer lumber (LVL), which is essentially used as a framing member. Sinha et al. (2011) have extensively studied LVL bending properties, which are listed in Table 3 along with values (range) obtained by Kretschmann et al. (1993). LVL and LBL have comparable MOE, whereas LBL tests resulted in a higher average MOR than LVL (Table 3). The COVs for MOR and MOE of LVL, as observed by Sinha et al. (2011) was higher than LBL, whereas Kretschmann et al. (1993) reported lower variability than LBL.

The MOR for Douglas fir glulams with dimensions similar to the BGBs is reported to be 45 MPa (Bergman et al. 2010). Although the ISO BGB MOR was higher than the reported MOR for Douglas fir glulams, the PRF BGB had a lower MOR. The MOE of Douglas fir glulam was reported by Bergman et al. (2010) to be 13.6 GPa, which is lower than that of both BGBs. Care needs to be taken when comparing commercial grade glulam and BGBs from this study. Generally, end joints in the lamination govern the performance of commercial grade glulams, which were not present in BGBs. Marx and Moody (1981) reported MOR and MOE for six-layer Douglas fir uniform grade glulam beams without edge joints similar to BGBs used in this study to be 48.74 MPa and 15.37 GPa, respectively (Table 3). Hence, the BGBs are stiffer than corresponding Douglas fir glulam beams but have comparable strength properties—strength properties that could be increased by addressing the adhesive used and revisit the fabricating process of the LBL used in the BGBs.

Because of the low COVs for LBL test results, it is expected that the relative COVs for BGB tests will be lower. LBL has bonding problems, which not only limits the performance of LBL but also limits the strength and performance of the manufactured BGBs. Additionally, the apparent bonding problem induces a lot of variability in the BGB test results. Another factor affecting the performance is the orientation of bamboo slats, with respect to radial and tangential directions of the bamboo stem, to form LBL. Results of this study suggest a difference in properties in different direction for bamboo, and this needs to be considered and controlled for while designing composites using bamboo.
Conclusions

In this study, laminated bamboo lumber was shown to possess higher allowable and average strength values in tension and bending than a nominal 2 × 6 in. Select Structural Douglas fir member, although MOE values were found to be comparable. Differences in properties exist in the radial and tangential direction of bamboo. This governs stiffness in different direction and failure patterns in compression-based applications. When manufacturing LBL, the positioning and dimensions of the slats with respect to radial and tangential direction of bamboo need to be considered and specifically engineered for targeted end use.

The bonding between two pieces of LBL to make glulam was not of concern because both adhesives used in this study to bond LBL did not limit assembly bending strength or stiffness. Instead, glulam strength was limited by the adhesive used or other process parameter used to fabricate the LBL used in the glulams.

LBL shows good potential for structural framing. However, this study shows that there are certain impediments that need to be addressed and researched before acceptance of LBL and BGB in the construction marketplace.

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References


Bergman, R., et al. (2010). Wood handbook: Wood as an engineering material, FPL-GTR-190, U.S. Dept. of Agriculture, Forest Service, Madison, WI.


