Development of layered laminate bamboo composite and their mechanical properties

C.S. Verma, V.M. Chariar
AICTE, Chanderlok Building, Janpath, New Delhi, India

ABSTRACT

Dry bamboo culms of Dendrocalamus strictus were processed into thin laminas and cold pressed using epoxy resin to produce layered bamboo epoxy composite laminates. Mechanical properties of layered bamboo–epoxy composite laminates including tensile strength, compressive strength, flexural strength and screw holding capability have been evaluated. Mode of failure were identified at macroscopic level as suggested in ASTM standard and their mechanism were examined at microscopic level using SEM analysis of fractured surfaces under different type of tests.

Keywords:
A. Laminate
A. Wood
B. Mechanical properties

1. Introduction

Bamboo is fast becoming a promising wood substitute and one of the chief reasons for this is that as usable bamboo can be harvested in 3–4 years from the time of plantation as opposed to timber which takes decades [1,2]. While there are several publications on characterization of bamboo composites based on bamboo fibers in polymeric matrix [3–10] very few reports on evaluation of bamboo composites based on laminas exist in the literature [11,12]. The tensile and compressive properties such as strength and modulus of fibrous composites decreases with increase of angle of fibers from 0° [13]. The modified epoxy was prepared to get improved impact and adhesive properties by different techniques [14,15]. Conventional screw yielded the maximum screw withdrawal resistance in Oak, followed by stone pine, black pine and fir [16,17]. Mechanical and physical properties of woods such as teak, deodar, and kail are good for structural purposes [18–24]. Mechanical properties of bamboo based laminates need to be investigated thoroughly so that the full potential of bamboo as a functionally graded composite could be utilized. This publication reports the mechanical properties evaluation of 5-layered bamboo epoxy laminates.

2. Materials and methods

2.1. Fabrication of LLBCs

Four year old green bamboo (Dendrocalamus strictus species) culms were obtained from TERI Gram (Tata Energy and Research Institute), District Gurgaon (Haryana), India. Moisture content of green bamboo collected were 37% at the time of felling (Digital moisture meter model MD-4G). Moisture content is then reduced to 10–12% by sundry. This was done to ensure better adhesion between bamboo laminae and the epoxy resin. A full length bamboo culm was cut length-wise into six slats using radial hydraulic splitting machine. Each slat was sliced using sliver cutting machine for getting slivers from outer, middle and inner regions as shown in Fig. 1. Slivers prepared from outer regions were processed on two side planning machine to remove some amount of outer skin which is weak in adhesion. Lamina specimens were prepared from outer slivers only for fabricating layered laminate bamboo composites (LLBCs). It is noted that width of laminas comes out from bamboo culms were generally less due to circular cross section. Therefore laminas were butt joined using adhesive to make laminates/plies with larger width. The liquid diglycidyl ether of bisphenol–A type (Araldite LY 556) with curing agent/hardener triethylene tetramine (TETA, HY 951) was used as adhesive. Density and curing time at room temperature of adhesive are 1.3 g/cm3 and 24 h respectively. The suggested ratio of araldite and hardener used are 100:23 by weight. The said adhesive will provide a low-viscosity, solvent free room temperature curing laminating system. Due to the very low cure shrinkage, Araldite LY 556 with hardener HY 951 based laminates will be dimensionally stable, free from internal stresses and excellent water resistance [14,15]. Tensile, compressive and flexural strength of Araldite given in Huntsman parts manufacturing selector guide are 30–35 MPa, 110–120 MPa and 85–90 MPa respectively and their modulus are 3–10 GPa, 2.5–2.8 GPa and 3 GPa respectively. The laminae were butt joined using said adhesive to make one laminate
of larger width. To make first layer of laminate, laminae were arranged systematically and placed over on die cavity of 250 mm × 100 mm × 15 mm (Fig. 2) using adhesive for butt joined. One piece of lamina (rectangular light thick surface shown in Fig. 5, which is microscopic image) is butted against another and affixed with adhesive (rectangular dark thin surface shown in Fig. 5, which is microscopic image). To avoid adhesion between epoxy and die, polyesters sheet were used. Top surface of first layer of laminate was then coated with adhesive for interfacial bonding. Then other laminas were placed over on first laminate to make another layer of laminate. In this manner five layers of laminate/ply were stacked together to form one sample of unidirectional LLBCs. This laminate was then sandwiched between the plates of die set by applying pressure of 10 kg/cm² (2.5 T) using UTM (100 T). This ensured that the slivers were straight during solidification of adhesive and the excess adhesive was squeezed out. The sample was left for 24 h at room temperature for cross linking of epoxy. Surfaces of specimens were cleaned with acetone. The sample obtained was subjected to sand grinding from all sides so as to obtain smooth surfaces as shown in Fig. 3. Using said suggested methods, following types of samples with different lamina configurations/angles have also been prepared.

1. Sample A [0°/0°/0°/0°/0°]. 2. Sample B [0°/45°/0°/45°/0°]. 3. Sample C [0°/90°/0°/90°/0°].

Five test specimens were prepared from each type of LLBCs samples respectively using cross cutting and grinding as per ASTM standards D3039M and D7264 for tensile and flexural testing respectively where specimens were in the form of constant rectangular cross section of 250 mm overall length, 16 mm wide with a
thickness of 10 mm where thickness of laminas were 2 mm each as shown in Fig. 4A and C respectively. To ensure that the failure should not occur in or near the grip region during testing, the thickness of laminate sample specimens was increased near the ends by using small tabs which were made from a bamboo itself and attached at the ends of the laminate specimens by using araldite as an adhesive. Tabs were 50 mm long, 16 mm wide and thickness of 5 mm with 1 mm lamina thickness as shown in Fig. 5. Cross sectional image of LLBCs cube.

Further another specimens of LLBCs were prepared for evaluating screw holding capability for different lamina configuration as per IS:1708(P-15)-86 guidelines as shown in Fig. 4D. The screws were installed according to IS:1708(P-15)-86 guidelines. The shape of laminates was made uniform by using medium fine sandpaper (grade 180) where sanding motion was ±45°.

### 2.2. Equation to determine amount of adhesive required and fabrication cost of LLBCs

The empirical equation derived for determining volume (Ve) of adhesives required (trial and error method) during fabrication of LLBCs is given below:

\[ Ve = (n + 1) \times L_p \times B_p \times T_e + n(B_p/B_s) \times L_p \times T_s \times T_e \]

where \( n \) is the number of layers, \( L_p \) is the length of ply, \( B_p \) width of ply, \( T_e \) thickness of adhesive coated, \( B_s \) and \( T_s \) width and thickness of laminae respectively. Five layers laminates has six lap surfaces out of which four are interfacial and two are free surfaces i.e. top and bottom surfaces. Top and bottom surfaces should coat with adhesive to prevent shrinkage, borer attack and to make water-proof. Five layer laminas has approximately thirty abutting surfaces. Here abutting surfaces dimensions was 250 mm × 2 mm for single laminae. Then total volume of adhesive required for a sample of dimension of 250 mm × 100 mm × 10 mm when single lamina thickness was 2 mm will be approximately 33,000 mm³. Thickness of adhesive is 0.19–0.23 mm. Thicknesses of adhesive used in LLBCs have been seen (as shown in Fig. 5) from Nikon Microscope. Thicknesses of adhesive were measured with the help of image J software. Thus total amount of adhesive required will be less than 60 g (density 1.3 g/cm³). This amount of adhesive have also been confirmed by experiments. Thickness of adhesive coated can be reduced which will reduce the cost of LLBCs.

Cost of bamboo culms, epoxy and hardener used were $0.094/kg (Rs.1 = $0.02352), $3.53/kg and $1.42/kg respectively Then approximate cost calculated for fabrication of LLBCs was $23.68 per cubic foot (except labor and machining cost). Labor and machining cost for one sample is supposed to be $3.528. Then total cost of LLBCs will be $27.22 per cubic foot.

### 3. Testing

Five specimens for all type of laminate configuration/angles of LLBCs as shown in Fig. 4A–D were tested to evaluate their tensile, compressive, and flexural properties in addition to screw holding power.

<table>
<thead>
<tr>
<th>Lamina configuration</th>
<th>Tensile</th>
<th>Compressive</th>
<th>Flexural</th>
<th>Screw holding power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. stress (MPa)</td>
<td>Max. modulus (GPa)</td>
<td>Max. stress (MPa)</td>
<td>Max. modulus (GPa)</td>
</tr>
<tr>
<td>Sample A [0°/0°/0°]</td>
<td>Max. 240</td>
<td>17.2</td>
<td>82.5</td>
<td>17.1</td>
</tr>
<tr>
<td></td>
<td>Min. 191</td>
<td>14.3</td>
<td>78</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Mean 205</td>
<td>16</td>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>S.D. 19.85</td>
<td>1.28</td>
<td>1.84</td>
<td>2.17</td>
</tr>
<tr>
<td>Sample B [0°/45°/0°]</td>
<td>Max. 232</td>
<td>17</td>
<td>71.9</td>
<td>15.2</td>
</tr>
<tr>
<td></td>
<td>Min. 175</td>
<td>13</td>
<td>48.6</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>Mean 188</td>
<td>14.5</td>
<td>55</td>
<td>13.2</td>
</tr>
<tr>
<td></td>
<td>S.D. 24.66</td>
<td>2.46</td>
<td>9.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Sample C [0°/90°/0°]</td>
<td>Max. 188</td>
<td>16</td>
<td>78.9</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>Min. 160</td>
<td>12</td>
<td>49.5</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td>Mean 169</td>
<td>14.3</td>
<td>66</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>S.D. 11.26</td>
<td>1.52</td>
<td>11.90</td>
<td>2.05</td>
</tr>
<tr>
<td>Average of samples A, B and C</td>
<td>Max. 187.3</td>
<td>14.9</td>
<td>67</td>
<td>14.06</td>
</tr>
</tbody>
</table>
For tensile and compressive tests, the specimens were carefully positioned at the center of the cross-head with its end faces exactly perpendicular to the longitudinal axis to get the more accuracy. For flexural strength test, support span to thickness ratio was taken as 20:1 so that failure occurs at the outer surface of the specimen, due only to the bending moment. Loading nose and supports were aligned and finally, the three point bend tests were performed. Mechanical properties and their stress–strain curves were obtained from the automatic computerized chart recorder with the help of software called testXpert software inbuilt in UTM machines for above said tests.

For measuring screw holding capability, conventional screw was driven into the LLBC specimens, perpendicular to the material surfaces (Fig. 4D). Load was applied to pull the screw with the help of UTM. Loads were measured with the help of dial indicator in built in machine.

The summarized tests results of above mechanical properties in addition to screw holding capability of LLBCs are presented in Table 2. Typical stress–strain curves for LLBCs under tensile, compressive and flexural loading are shown in Fig. 6A–C respectively.

**4. Results and discussion**

Fig. 6A shows that tensile stress increased linearly with increase in strain until point of ultimate load under tensile loading. Above this point, the stress–strain curve showed sharp, staggered decreases in load and brittle fracture. Laminate under a tensile loading, a kink is observed in the stress–strain graph, indicating the FPF load and the curve continues with increasing load, but with a smaller slope, signifying a reduced stiffness in the direction of the load. Tensile fracture of unidirectional LLBC is mainly longitudinal cracking of fibers. In some specimens, partial damage occurred when the tensile stress reached 80% of ultimate stress. The material of LLBCs is not homogenous but has an orthotropic property due to which fibers are pulled out from the matrix.

Fig. 6B shows that compressive stress increased almost linear with increase in strain until point of ultimate stress under compressive loading. Above this point, the stress–strain curve showed non-linear segments. During fracture, compressive stress of LLBCs rapidly decreased with buckling of specimens.

The stress–strain curves under tensile and compressive loading are regular up to ultimate point where strength of sample A is greater than sample B and of sample B than sample C because in sample A, all fibers of laminas are in unidirectional and cross linking of the polymer is continuous whereas in samples B and C, all fibers are not unidirectional and cross linking is not continuous. Thus it is concluded that strength and modulus of LLBCs decreases with increase in lamina angle under tensile as well as compressive loading.
loading. According to the Tsai–Hill criteria [13], the tensile and compressive properties of composites continuously decrease as the angle of orientation of the fibers increases from 0°. In this report, fibers direction in all laminas are same i.e. unidirectional but laminas angle are different in all type of LLBCs samples. Tensile and compressive strength is less in sample C than sample B and is less in sample B than sample A due to increase in orientation of middle layers fibers from 0°. The tensile strength is three times than compressive strength along fiber direction but modulus is nearly same. Fig. 6C shows flexural stress–strain curves for sample type A, B and C under flexural loading which indicate that the nature of curve is similar for samples A and C where flexural strength of sample A is greater than sample C and of sample C is greater than sample B but sample B predicts more toughness compare to sample A and sample C on flexural stress–strain curve. From the curves it is observed that behavior of the samples A and C composites is close to linear segment and above ultimate stress an irregular, staggered decrease in stress was observed. Bending fractures concentrated near the middle of the test specimen where load was applied and bending fracture was brittle.

Screw holding capability of LLBCs on their edge decreases with increase in lamina angles as the number of fibers to hold screw decreases from sample A to sample C but on face, sample B predicts
more screw holding capability than samples A and C. Average screw holding power on face was significantly larger than that of edge. As a result, fastening is not normally recommended for edge but for some purposes edge fastening may be necessary.

Some fractured specimens of tensile, compressive and flexural tests are shown in Figs. 7–9 respectively. Under tensile loading, it was observed that some specimens start to fail at edge, some at grips and some at multimode. For all layer of laminate, first matrix (bamboo as well as adhesive) failure occurs followed by fibers failure with metallic sound where fracture propagates spontaneously and the first layer breaks. Further it is observed that among five layers, any one layer first break then propagates to other layers (Fig. 7). The SEM photographs (Fig. 10A and B) of fractured lateral surface shows the source of the cracks and their subsequently propagation and enlargement. The fiber pull out indicate that there were perfect bonding between bamboo and adhesive.

Compressive failure was attributed by microbuckling surrounded by delamination. The delaminated portions spread to the undamaged areas of the laminate by a combination of delamination buckling and growth, the buckling further enhancing the growth of damaged area. The culmination of this last event is the complete loss of stiffness of specimens (Fig. 8). The SEM photographs (Fig. 11A and B) of fractured lateral surface shows the

source of the cracks and their subsequent propagation and enlargement.

Flexural failure on the tension surface of specimens was due to matrix and fiber breakage while on the compressive surface was due to buckling of specimens. In some fractured specimens, delaminations were also observed in fractured specimens due to fracture of resin during bending (Fig. 9). The SEM photographs (Fig. 12A and B) of fractured lateral surface of specimens tested in flexure shows delamination along with tension and compression in the upper and lower portions respectively.

Failure modes of fractured specimens of LLBCs have been identified using a standard failure identification codes (three parts) used in ASTM standards. The summarized identification of failure modes under different loading conditions are presented in Table 3.

5. Comparison and advantages

Comparison of LLBCs with teak wood on the basis of mechanical properties and cost incurred are presented in Table 4 where properties of LLBCs are as par of teak wood and even fabrication cost is less
than that of teak wood. As compared to naturally provided bamboo culms, LLBCs is more usable in terms of building and general purpose material because there is possibility to increase the volume of LLBCs in all direction as shown in Fig. 13 by increasing number of layers using suitable equipments which is in solid form like woods. Further thickness and shape of the LLBCs can be tailored during fabrication to meet specific requirement. Use of bamboo as structural purposes in place of wood could also help in prevention of deforestation because bamboo is useful in 3–4 years inspite of 30–40 years in case of wood such as kail, deodar and teak. Deforestation of wood causes serious local environmental problem and possibly relates to the climate change in the world. Like teak wood, surface of LLBCs could be smooth for esthetic purposes by surface sanding, polishing and finally by ultraviolet finishing. Furthermore, use of bamboo and technology for fabrication of LLBCs could help to improve economy of rural people.

6. Conclusions

1. Laminas can be used for fabrication of LLBCs of different lamina configurations using adhesion. An empirical expression is derived and used for determining amount of adhesive required per sample of LLBCs which is verified by experiments.

2. Tensile and compressive properties of LLBCs decreases with increase in lamina angle. A combination of different factors could be used to decide the application of bamboo laminates because mechanical properties were affected by the lamina configuration.

3. The mechanical properties evaluated of the LLBCs are resembling with the properties of the teak wood. A comparative cost and mechanical properties analysis of LLBCs with teak wood timber indicates that LLBCs could be used as building and general purposes material like, furniture, beam and column, etc., because there is possibility to increase the volume in any shape and in any direction by increasing number of layers where the thickness and shape of composite can be tailored during fabrication to meet specific requirement. Furthermore use of more bamboo and technology for fabrication of LLBCs could help to improve economy of rural people.

Acknowledgments

We are grateful to the Laboratory in charge of Stress Analysis Lab, Numerical Computation Lab and strength of material Lab of IIT Delhi and lab in charge, Material Testing Lab and central workshop, NSIT, New Delhi, Delhi test house, Azadpur, New Delhi, Polymer Science Lab of IIT Delhi (SEM analysis) for assistance rendered in testing.

References