Bamboo Bundle Composite Laminated Composites Part I.
3-Dimesional Stability in Response to Corrugating Effect

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Abstract

A novel bamboo bundle laminated composite with a corrugated structure, called BCLC was developed. This series of publications is related to the design, processing, and physical and mechanical properties of the BCLC. The objective of this part of the work was to investigate how the 3-D shrinkage and swelling properties are affected by the shape of the composites. Three types of stacking sequences were designed and their shrinkage and swelling performances were compared. A shaped parameter, K, was used to quantify the corrugated effect on the shrinkage or swelling in three directions. The shrinkage ratio, difference in shrinkage (D), drying coefficient (DC), swelling ratio, difference in swelling (S), apparent density (AD), porosity ratio (PR), and water absorption (WA) were determined. It was found that the dimensional stability of the BCLC was significantly different among the 3 directions of the composites, and it was affected by the stacking sequence of the bamboo bundles. Shrinkage ratio, swelling ratio, and drying coefficient were significantly greater in the thickness direction compared to those in the length or width directions. The shape parameter was largest in the length direction and the smallest in the thickness direction, K_L > K_W > K_T. The corrugated effect of BCLC was more pronounced with swelling than with shrinkage. The correlations of PR vs. AD was determined as r=-0.930, and that of WA vs. AD was determined as r=-0.940, with both being negative. The correlation of WA vs. PR was positive (r=0.997). The synergistic effect of stacking sequence accounted for 11.3%, 9.2%, and 0.6% of the total correlation above. A good linear relationship was found between WA and AD, and between WA and AD.

Key words: Bamboo, Corrugated structure, 3-D Shrinkage and Swelling, Shaped Parameters, Synergistic Effect

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Introduction

Plant based fibers are renewable, biodegradable, and environmental-friendly (John and Thomas 2008; Wang et al. 2011). Bamboo has provided abundant and high-quality cellulose fibers for centuries, becoming a primary feedstock for the weaving, pulp and paper, and fiber-based composite industries in China (Scurlocka 2000; Chen et al. 2011). Bamboo presents excellent mechanical properties, e.g. the tension module of an individual bamboo fiber is 26GPa (Wang et al. 2011; Yuet al. 2011). During the past 20 years, research activities concerning bamboo fiber-reinforced composites (BFRC) have been dedicated to developing economical and lightweight composites for structural applications (Shin and Yipp 1989; Jain et al. 1993; Okubo et al. 2009).

Product performance is not only related to the material properties themselves, but also to the structure design of the composites. Corrugated structure has long been valued as a good engineering design that can be tailored to a variety of applications, such as shipping containers transported by rail, truck, sea, or air (Briassoulis 1986; Thorpe and Choi 1992; Duong et al. 2010). The advantages of a corrugation structure design include: 1) high energy absorption at impact (Torre and Kenny 2000); 2) anisotropic nature, which is flexible in the corrugation direction and stiff in the transverse direction (Yokozeki et al. 2006); and 3) light-weight (Guo et al. 2010, 2011).

Renewable biomass, e.g. wood, bamboo, and rattan, are typically heterogeneous, anisotropic, viscoelastic, and hydrophilic, and are considerably sensitive to ambient moisture and temperature. The properties of the corrugated composite structure are basically homogeneous along the thickness direction, but vary for the corrugated laminates in 3-D. The shape of the corrugated design of the composites may increase the anisotropic nature compared to that of planar composites (Kress and Winkler 2011). Furthermore, the hygroscopic characteristics of cellulosic fibers from bamboo used for the BCLC will lead to dimensional instability, such as swelling and shrinkage, which will reduce the mechanical properties of the composites. (Moe and Kin 2002; Moe and Kin 2003; Hyo and Do 2006).

Currently, limited published experimental data is available on the manufacturing of bamboo fiber-enhanced composites with a corrugated structure. Cruz (2007) fabricated corrugated roof panels using high-density polyethylene (HDPE) reinforced with wood fibers prepared from urban waste materials and found that with a 60% wood fiber content, the mechanical properties decrease as the particle size is reduced, additionally, more processing conditions and rheological tests were required to obtain the best processing conditions to reach a high mechanical performance. Hunt (2007) used the finite element analysis (FEA) method to investigate the constitutive behaviors of 3D engineered fiberboard, and indicated that linear-elastic isotropic material properties in combination with simplified engineering equations could be used for an initial evaluation of corrugated panels. As a structure’s geometry becomes complicated, however, it becomes necessary to use more sophisticated
models to handle more detailed constitutive properties of the material. The overall goal of this project was to investigate the feasibility of manufacturing BCLC from bamboo bundles and UF resin, and to evaluate the 3-D shrinkage and swelling properties as affected by the shape of the composite structure.

The specific objectives were: 1. To explore the technical feasibility of manufacturing BCLC; 2. To investigate the 3-D shrinkage and swelling behaviors of BCLC; 3. To develop an empirical shaped parameter K used for shrinkage and swelling processes from which the parameter can be used to quantify the corrugated effect in 3-D; and 4. To quantitatively evaluate the synergistic effect of stacking sequence on the correlation of apparent density(AD), porosity ratio(PR), and water absorption(WA).

**Materials And Methods**

**Preparation of Bamboo Bundle**

Three-year-old Cizhu bamboo (*Neosinocalamus affinis*) was obtained from Changning, Yibin, Sichuan Province, China. The bamboo material had an initial moisture content (MC) of about 65%. For the material preparation, the bamboo tubes were first split into four pieces of approximately the same size. The bamboo joints were removed using a hatchet. An untwining machine was designed for brooming and rolling the bamboo.

The untwining machine was made up of three main sections: a drive unit(to provide power), idler wheels(to broom the bamboo), and an adjustment device(to regulate the pressure between the idler wheels). The idler wheel was 16cm in diameter with halve-trapezoid shaped cutter teeth. The length, width, inter-tooth spacing, and inclination angle of the teeth were designed as 1, 1.5, 2.3,mm and 45°, respectively. By adjusting the distance of the upper and lower pressure rollers, the teeth could realize different brooming and discongesting effects during the bamboo feeding process. The schematic for the brooming, rolling, and compression processes are shown in Fig. 1.

![Bamboo untwining](Image1)

*Fig. 1.* Brooming, rolling, and compression process

Because of the high MC of the inner portion of bamboo, the bamboo bundles were easily tangled up on rollers due to the high plasticity of the material. At a low MC (<10%), the bamboo joint becomes too brittle which may lead to the separation of the bamboo bundle sheet. Based on the results of the initial testing, an ideal brooming effect was found when the MC of the bamboo was controlled between 24 and 30%.
During the brooming process, the bamboo chips were first flattened using a relatively greater gap between the upper and lower rollers: 3 to 4 mm for the 1\textsuperscript{st} roller set, 2.5 to 3.5 mm for the 2\textsuperscript{nd}, 2 to 2.7 mm for the 3\textsuperscript{rd}, and 2 to 2.7 mm for the 4\textsuperscript{th}. For the subsequent brooming process, the gap for the third and fourth roller sets was reduced to 0.75 to 1 mm. After repeating the process five times, the bamboo strips were rolled, knead, and flattened into a loosely laminated reticulate sheet. The laminated sheet was cross linked together in the width direction with no fracture along the length direction, and was nearly uniform in thickness, maintaining the original bamboo fiber arrangement. The bamboo bundle sheets were finally cut into pieces of 300 mm in length, and then air-dried to a MC between 8 to 12\%. This brooming process produces greater than a 90\% bamboo yield.

**Preparation of BCLC**

A commercial phenol formaldehyde (PF) resin obtained from Taier Corporation (4 West Road, Dahongmeng, Fengtai District, Beijing, China) was used for the composites fabrication. The PF resin was diluted with water to a solid content of 15\%. The bamboo bundles were immersed in the PF resin for 8 minutes and then dried to a MC between 10\% and 12\% under an ambient environment. A 300 mm×300 mm CARVER Auto M-3895 hot press with a Press MAN control system (Carver Inc. USA) and a custom designed corrugated mold was used to press the BCLC at a platen temperature of 160\°C. The dimensions of the BCLC were 300 mm (length) by 150 mm (width) by 8 mm (thickness). The target density was set as 0.88 g/cm\(^3\). The “cold-cold” process was used to ensure a complete curing of the resin. The hot press time was 30 minutes (10 minutes for press closing, 10 minutes for the pressure maintained at the target thickness, and 10 minutes for press opening). Three types of stacking sequences were designed: 1) bamboo fibers were aligned along the corrugated wave direction (I-type), 2) bamboo fibers were aligned perpendicular to the corrugated wave direction (II-type), and 3) bamboo fibers were cross laminated [0/90/0] (III-type). Composites with ramie woven fabrics bonded with the MDI resin were also fabricated and used as controls. Three replicates were made for each condition.

**Methods**

**3-Dimensional shrinkage and swelling testing**

The following properties of the BCLC were tested in accordance with the standard procedures described in GBT 7019(1997), China: Shrinkage ratios (\(\beta_L, \beta_W, \beta_T\)), shrinkage difference (D), drying coefficient (DC), swelling ratios (\(\gamma_L, \gamma_W\), and \(\gamma_T\)), swelling difference (S), apparent density (AD), porosity ratio (PR), and water absorption (WA). The WA and swelling ratio were measured after a 24-h immersion in distilled water at 20\°C. Two types of shrinkage and swelling were designed to analyze the 3-D changes of BCLC: 1) Shrinkage: air dry to oven dry, air dry to saturation then to oven dry; 2) Swelling: air dry to saturation, oven dry to saturation.

(1) The shrinkage ratio and swelling ratio, the percent of hygroscopic dimensional change or volume change, were calculated using the following equations:
where $\beta$ is the shrinkage ratio (%) and $\gamma$ is the swelling ratio (%); $l_A$ and $l_0$ are the specimen sizes (mm) in an air-dry state and an oven dry at 60°C, respectively; $l_w$ and $l_1$ are the specimen dimensions (mm) after the water immersion at 5°C for 24 h and after oven drying at 103°C for 24 h, respectively.

(2) The shrinkage difference (and swelling difference) represents the ratio of a tangential shrinkage (or swelling) of wood to its radial shrinkage (or swelling). Different shrinkage/swelling ratios are used to describe the dimensional stability of wood. Shrinkage/swelling ratio differences were calculated based on the following equations (Guan et al. 2009):

$$D = \frac{\beta_T}{\beta_W}, \quad S = \frac{\gamma_T}{\gamma_W}. \tag{2}$$

where $\beta_T$ and $\gamma_T$ are the shrinkage ratio and swelling ratio along the thickness direction, respectively, and $\beta_W$ and $\gamma_W$ are the shrinkage ratio and swelling ratio in the width direction, respectively.

(3) The drying coefficient is the shrinkage ratio after 1% change in MC and calculated using the following equation

$$K_{L,W,T} = \beta / (W_1 - W_2) \tag{3}$$

where $K_{L,W,T}$ represents the drying coefficient in length, width, and thickness respectively; and $W_1$ and $W_2$ are the initial and final MC, %.

(4) The shaped parameter was calculated in order to quantify the corrugation effect on the shrinkage or swelling in 3 directions. The shaped factor was determined by subtracting the shrinkage ratio or swelling ratio from the shrinkage ratio or swelling ratio along the corrugated direction (having the material and shaped combining effect) from that perpendicular to corrugation (with the material effect only). The following formulae were used to estimate the actual efficiency of corrugated structure for shrinkage or swelling in 3-D:

$$K_L = \beta_{\text{I-type}} - \beta_{\text{II-type}} \quad \text{or} \quad \gamma_{\text{I-type}} - \gamma_{\text{II-type}} \tag{4}$$

$$K_W = \beta_{\text{I-type}} - \beta_{\text{II-type}} \quad \text{or} \quad \gamma_{\text{II-type}} - \gamma_{\text{I-type}} \tag{5}$$

$$K_T = \beta_{\text{II-type}} - \beta_{\text{I-type}} \quad \text{or} \quad \gamma_{\text{II-type}} - \gamma_{\text{I-type}} \tag{6}$$

where $K_L$, $K_W$, $K_T$ are the factors for length, width, and thickness, respectively after air dry to oven dry or air dry to saturation.

**Water Absorption Measurements**

The water absorption rate (WA), apparent density (AD), and porosity ratio (PR) of BCLC can be determined using the following equations:
\[ \text{WA(\%)} = \frac{m_2 - m_1}{m_1} \times 100 \]  

---(7)

\[ AD = \frac{m_3 \times p_0}{m_1 - m_3} \]  

---(8)

\[ \text{PR(\%)} = \frac{m_2 - m_1}{m_3 - m_1} \times 100 \]  

---(9)

where \( m_1 \) is the weight of the oven dry specimen (g), \( m_2 \) isthe wet specimen weight in water after immersed in water for 24h (g), \( m_3 \)isthe wet specimen weight in air after immersed in water for 24h(g), and \( p_0 \) is the water density (g/cm\(^3\)).

Three replicates were used. SPSS 12.0 and Origin 8.0 were used for the statistical analysis with a significance level of alpha=0.05.

**Results And Discussion**

**3-D Shrinkage and Swelling**

The effects of the corrugated structure on the 3-D shrinkage and swelling properties of BCLC are shown in Tables 1 and 2. Figure 2 reveals the 3-D drying coefficient (DC) from air dried to oven dried process.

<table>
<thead>
<tr>
<th>Item</th>
<th>Air dry-absolute dry</th>
<th>Air dry-Saturation-absolute dry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \beta ) ( % )</td>
<td>( \beta_W ) ( % )</td>
</tr>
<tr>
<td>I-type</td>
<td>0.38a</td>
<td>0.91a</td>
</tr>
<tr>
<td>II-type</td>
<td>0.98a</td>
<td>0.20a</td>
</tr>
<tr>
<td>III-type</td>
<td>1.50a</td>
<td>0.32a</td>
</tr>
<tr>
<td>Control</td>
<td>0.27a</td>
<td>0.22a</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Air dry-Saturation</th>
<th>Absolute dry-Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \gamma_L ) ( % )</td>
<td>( \gamma_W ) ( % )</td>
</tr>
<tr>
<td>I-type</td>
<td>0.84c</td>
<td>1.29c</td>
</tr>
<tr>
<td>II-type</td>
<td>1.43c</td>
<td>0.25c</td>
</tr>
<tr>
<td>III-type</td>
<td>1.37c</td>
<td>0.26c</td>
</tr>
<tr>
<td>Control</td>
<td>0.50c</td>
<td>0.22c</td>
</tr>
</tbody>
</table>

In general, the shrinkage and swelling properties of 3-D shrinkage ratio (\( \beta_T \)), swelling ratio (\( \gamma_T \)), and DC were significantly greater along the thickness direction than in the length and
width directions. The ANOVA test also confirms the observation at the 95% confidential level (Tables 1 and 2 and Fig. 2). Bamboo is a viscoelastic material having both elastic and plastic behaviors. During hot-pressing, bamboo bundles were bent passively by the combined effects of pressure, temperature, and corrugated molding. During the initial stage of hot-pressing, the temperature was much higher at the surface than that at the core; therefore, the surface bundles softened, leading to a greater compression rate. As the resin continued to cure, the bamboo initially began to experience plastic deformation and become consolidated. The core layer was therefore not easily compressed resulting in a lower compression rate, which caused an uneven density distribution along the thickness direction and a high inter-laminar stress in the composites. In addition, the corrugated structure accelerated the fiber deformation or fracture under the effect of the bending wave. These deformed fibers that arranged along the corrugated wave direction will have a trend towards recovering their original shape when absorbing water; however, bamboo bundles can’t stretch freely due to the limitation of their corrugated shape. Under the hydrothermal effects, partial stresses will be released from other unconstrained directions leading to a much higher degree of variation in 3-D.

As shown in Tables 1 and 2, the 3-D shrinkage and swelling performance of BCLC were quite different for different stacking sequences. For the I-type stacking sequence, the shrinkage ratio ($\beta_L$), DC, and swelling ratio ($\gamma_L$) were lower in the length direction, but higher in the width direction than that for the II-type and III-type. Additionally, the D and S for the I-type were also the lowest compared with that for the II-type and III-type. These results indicated that the I-type composites had a relatively better stability in the direction parallel to the corrugated wave compared with that of the II-type and III-type composites, whereas it has an inferior resistance against shrinkage or swelling in the transverse direction to the corrugation. Contrarily, the II-type composites (bamboo fiber orientation vertical to the corrugation direction) represented an overall stability along the transverse direction of the corrugated wave as compared to that in the parallel direction. As shown in Tables 1 and 2 and Fig. 2, lower values of shrinkage ratio ($\beta_w$), DC, and swelling ratio ($\gamma_w$) were observed in the width direction than that in the length direction. III-type BCLC showed intermediate values of...
shrinkage ratio ($\beta_L$ and $\beta_w$) and swelling ratio ($\gamma_L$ and $\gamma_w$) in the length and width directions. The stacking sequence showed no effect on shrinkage and swelling behaviors along the thickness direction. Modified by the stacking sequence, the variability of BCLC for 3-D stability could be mainly due to the difference in bamboo fibers’ shrinkage or swelling properties in 3-D. The shrinkage or swelling in the length direction of the fiber is much smaller compared to that in the transverse direction. As a result, the dimensional stability in the length direction (corrugated wave direction) showed a better performance than that in the width direction when the fiber’s direction is parallel to the corrugated wave (I-type). Bamboo bundles, however, arranged along the transverse direction to corrugation (II-type), BCLC exhibited an optimum dimensional stability in the width direction (vertical direction to corrugated wave).

In comparison with the ramie woven control specimen, a lower dimensional stability was observed for BCLC, where the values of shrinkage ratio, shrinkage difference, swelling ratio, and swelling difference were generally larger than those of the control specimen. A better dimensional stability of ramie woven corrugated panel could be mainly contributed to the interweave structure. Further study would need to be conducted to optimize the untwining degree of the bamboo bundle sheet, and to modify the hot-pressing parameters and the corrugated structure in order to improve the performance of BCLC.

**Shaped effect in 3-D**

As mentioned in the previous section, the corrugated shape has a certain effect on the shrinkage and swelling properties in 3-D. The degree of shaped effect in regard to the corrugated structure could be quantitatively characterized by subtracting the value of shrinkage ratio or swelling ratio in the direction parallel to the corrugation of I-type (with both material and structure effect) from that perpendicular to the corrugation of II-type (only material effect), as shown in Equation (4)-(6).
and 0.595, 0.145, and 0.041 for swelling. It is seen that \( K_L > K_W > K_T \), where \( K_L \), \( K_W \), and \( K_T \) are the shaped parameter for the length, width, and thickness directions. This result indicates that the largest shaped effect for both shrinkage and swelling was in the length direction, followed by width and then thickness. The dimensional variability was probably due to the biggest deformation along the bamboo fiber’s direction caused by the effects of bending, compressing, and folding during hot-pressing to form the corrugated shape. The following order regarding shape changes were transverse direction of the bamboo bundle. In addition, the sum of \( K_L \), \( K_W \), and \( K_T \) calculated for swelling (0.780) was greatly higher than that for shrinkage (0.336), demonstrating that a shaped effect in response to swelling was much larger than that for shrinkage. When the BCLC is in contact with water, the hydrophilic groups of the bamboo fibers will attract the water molecules. Then, water molecules continually step into a micro capillary system, filling the gaps between the fibers and the matrix resulting in cell wall swelling and localized yielding along with micro crack growth (Sandeep and Lopez-Anido 2011). As a result, the interfacial bonding strength of BCLC decreases, leading to reduced dimensional stability as compared to shrinkage.

**Correlation of Physical Properties to Water Absorption**

BCLC is a porous material with diverse mechanical properties for different AD or PR. In order to quantitatively investigate the linear relationship between AD and WA and between PR and WA with the synergistic effect of stacking sequence, Pearson correlation analysis was performed. A partial correlation analysis was also conducted for different stacking sequences.

**Table 3. Bivariate and Partial Correlation Analysis by SPASS**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Apparent Density</th>
<th>Porosity Factor</th>
<th>Water Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation Coefficient</td>
<td>1</td>
<td>-0.926**(-0.863)</td>
<td>-0.936**(-0.885**)</td>
</tr>
<tr>
<td>Significance(2-tailed)</td>
<td>&lt;0.001(0.01)</td>
<td></td>
<td>&lt;0.001(&lt;0.001)</td>
</tr>
<tr>
<td>Degree of Freedom</td>
<td>0</td>
<td>10(9)</td>
<td>10(9)</td>
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**Porosity ratio**

<table>
<thead>
<tr>
<th></th>
<th>Pearson Correlation</th>
<th>Significance(2-tailed)</th>
<th>Degree of Freedom</th>
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<tr>
<td>Correlation Coefficient</td>
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<td>Degree of Freedom</td>
<td>10(9)</td>
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**Water absorption**

<table>
<thead>
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</tr>
<tr>
<td>Degree of Freedom</td>
<td>10(9)</td>
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</table>

Notes: **correlation is significant at the 0.01 level (2-tailed), and the numbers in parentheses represent the partial correlation analysis’ results.
The Pearson’s correlation coefficients between AD and WA, and between PR and WA were -0.936 and 0.997 (p<0.01), respectively while the corresponding slopes were -95.978 (decreasing) and 1.729 (increasing) when not controlled for stacking sequence, as shown in Table 3 and Figs. 4 and 5. When controlled for stacking sequence, the Pearson’s correlation coefficients between AD and WA, and between PR and WA decreased to -0.863 and 0.997 (p<0.01), respectively, as shown in Table 3. There were 9.287% and 0.597% degree of linear correlations between AD and WA, and between PR and WA, respectively, during the water absorption process, which was determined by synergism of the stacking sequence. Unexpectedly, the synergistic effect of the stacking sequence for the linear relationship between AD and PR was the largest at 11.271%. Calculations of the degree of linear correlation for the water adsorption process are shown below.

between AD and WA: 9.287% = (-0.936)² - (-0.885)², between PR and WA: 0.597% = (0.997)² - (0.994)², and between AD and PR: 11.271% = (-0.926)² - (-0.863)²

AD and PR are key parameters in characterizing the physical properties of corrugated composites so therefore, AD and PR were used to describe how the physical properties affect the water absorption (see Figs. 4 and 5). It is shown in Figs. 4 and 5 that linear relationships exist between AD and WA, and between PA and WA. The relationships were established as:

WA = 112.56 - 95.98AD, R² = 0.87; WA = -12.75 + 1.73PR, R² = 0.99.

**Conclusions**

1. Shrinkage and swelling properties were significantly different in 3-D. The shrinkage ratio, swell ratio, and DC were greatest in the thickness direction. The I-type stacking sequence exhibited a better dimensional stability in the direction parallel to the corrugated wave, while the II-type represented an optimized stability along the transverse direction of the corrugation.
2. The shaped parameter $K$ provided a quantitative characterization for the corrugated effect on shrinkage and swelling in 3-D. For both shrinkage and swelling, it showed that $K_L > K_W > K_T$. The corrugated effect in response to swelling was larger than that of shrinkage.

3. Strong linear relationships were found between AD and WA, and between PA and WA. The degrees of linear correlation determined by synergism of stacking sequence were 9.29% and 0.60%, respectively.

Acknowledgements

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References