Mechanical Characterization of Bamboo and Glass Fiber Biocomposite Laminates

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ABSTRACT: Single-ply biocomposite laminates were fabricated with two different woven fabrics and a bio-based resin using a wet layup technique at room temperature. A highly elastic, stockinette weave bamboo fiber fabric and a thicker, inelastic plain weave bamboo fabric were both investigated. The elastic fabric was pre-strained at 25% intervals, ranging from 0–100% of its original length. Samples made with E-Glass and S-Glass, two common glass fiber reinforcements, were also fabricated using the bioresin as benchmarks. The ultimate strength and modulus of elasticity characteristics of the composites were determined using the ASTM D3039/D3039M-08 standard test method for determining the tensile properties of polymer matrix composites. The average percent elongation, toughness, and fiber volume ratio of the samples were determined in order to further understand the mechanical response of the composites. The plain weave bamboo fabric laminate had a higher tensile strength and a higher modulus compared to the stockinette weave laminate. Both bamboo laminates had lower strengths and moduli compared to the E-Glass and S-Glass laminates. However, at a pre-strain of 100%, the stockinette weave bamboo laminate exhibited a higher toughness than both the glass fiber laminates and the plain weave bamboo laminate.

KEYWORDS: Bamboo biocomposites, composite, bio-based resin, mechanical strength

1 INTRODUCTION

Natural fibers are beginning to gain popularity as replacements for less sustainable glass fibers as reinforcements in composites. Natural fibers require less energy to produce, exist in fairly abundant supply around the globe, and are recycled much easier than glass fibers. When a glass fiber reinforced polymer (GFRP) is incinerated after disposal, the polymer matrix burns off and emits harmful gasses. The glass fibers have a higher melting temperature than the polymer matrix and do not disintegrate, resulting in waste. Biocomposites consist of natural fibers with more environmentally friendly-based matrix constituents.

Bamboo is a widely abundant material that grows at a rapid rate, making it both sustainable and cost efficient. The widespread abundance of bamboo and the strength that has been associated with it make it a popular choice as a natural fiber. Such bamboo fibers are typically viscose rayon fibers that are made using bamboo as the raw material rather than wood pulp. Bamboo fiber reinforced polymers (BFRPs) have been used as a natural alternative in many structural members in a variety of applications. For example, the stockinette weave fabric used in this testing has already been used as an alternative to glass fibers in surfboard manufacturing.

Bamboo fiber composites have been examined in many other instances. Yong and Yi-qiang have studied the mechanical properties of bamboo fibers using different bioresins and the effect of the fiber volume ratio on these properties [1]. Okubo and colleagues pioneered a method of extracting the fibers from the bamboo stalk in order to obtain the most desirable properties [2]. The strength of composites due to the addition of bamboo micro/nano fibrils mixed in the resin [3], as well as the use of polar maelic anlydride grafter polypropylene (MAPP) in order to increase the interaction between the matrix and the fibers, have been examined by Huang and Netravali, and Samal and colleagues, respectively [4]. Lastly, the effects on the strength and modulus after aging the composite in water [5], and the altering of the amounts of bamboo

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Table 1 Comparison of some of the properties of the bamboo and glass fiber fabrics.

Fiber	Density (g/cm^3)	Weave Pattern	Moisture Regain	Cability to Pre-Strain
Bamboo Fiber	1.25	Stockinette	239%	Yes
Bamboo Fiber	1.13	Plain (90°)	373%	No
E-Glass	2.27	Plain (90°)	66%	No
S-Glass	2.25	Plain (90°)	67%	No

fiber volume ratios as well as the effect of MAPP on these ratios, have been studied by Thwe and Liao [6].

In order to isolate and quantify the mechanical properties of the bamboo biocomposites, single-ply laminates were constructed using a wet layup technique for standardized tensile testing. A pinesap-based bioresin was used as the matrix constituent in order to quantify the influence of the bamboo fiber woven fabrics and the effects of the fabric pre-strain prior to room temperature curing. The material properties of the biocomposites under several different variations were found and compared to traditional E- and S-Glass fiber composites.

2 EXPERIMENTAL METHODS

2.1 Constituent Materials

The matrix material used for all of the composites in this study was a bio-based resin called SUPER SAP® 100/1000, supplied by Entropy Resins. The resin has a typical density ranging between 1.10–1.20 gm/cm^3 measured at 25°C. This pinesap epoxy resin is derived from pine oils sourced as co-products from wood pulp processing and vegetable oil components [7]. Less water is used to produce this particular resin than is used to produce typical polyester resins. The pinesap epoxy resin is also engineered to reduce harmful byproducts, mainly chlorinated hydrocarbons [7].

Two different bamboo fiber woven fabrics were used as the reinforcements. The first fabric is highly elastic (capable of stretching more than twice its original length) and was supplied by Greenlight Surf Supply [8]. This bamboo fabric is an alternative to E-Glass in surfboard shaping, but is typically laid up using polyester resins. Due to its low elasticity, this fabric was used to determine the optimal pre-strain of the fabric before the resin was applied. Little information was provided regarding the origination of these fabrics other than that they are woven in a stockinette weave, which is a common t-shirt weave, allowing them to stretch.

The second fabric is a plain weave bamboo fabric with no chemical additives used in the production process [9]. In comparison to the stockinette weave, this fabric is thicker and does not stretch. The plain weave pattern orients the fibers at right angles to each other. This weave enables the composite to be tested primarily along the direction of the reinforcement fibers. Overall, it is also a more absorbent fabric in terms of moisture regain. Table 1 provides a comparison of some of the properties of the bamboo and glass fiber fabrics.

2.2 Laminate Fabrication and Processing

All laminates were fabricated using a room temperature, non-vacuum wet-layup method. A total of eight unique composite laminates were created and tested. The laminates were fabricated into 300 x 300 mm square sheets and were cured between two thick steel plates in order to apply a small uniform pressure. For the stockinette weave fabric, samples were pre-strained at 0% (secured in place), 25%, 50%, 75%, and 100%, by pulling the fabric the appropriate percentage of its original length and securing it between two aluminum bars held together with spring clamps; 100% pre-strain was close to the maximum possible strain of the weave. The metal plates were wrapped tightly in a release film and an additional loose piece of release film was placed between the composite and the plates in order to allow for the removal of gas bubbles after the resin is applied.

The resin was mixed at the specified 100:48 epoxy to hardener ratio based on measured weights. The resin was stirred for 5 minutes and left to stand for 2 additional minutes in order to remove all gas bubbles. The resin was then spread across the fabric using a tongue depressor and carefully covered in the second layer of the release film. This was done to remove all large gas bubbles and wrinkles in the laminate. A metal plate was placed on top and the entire layup was then flipped and a squeegee process was performed on the other side.

The laminates were cured at room temperature for at least 48 hours. Laminates with excessive wrinkles (due to the release film) or voids (due to trapped gas in the resin) were discarded. All laminates were laid up during a two-week period with an ambient temperature of 20±4°C and a relative humidity of 67±10%.

2.3 Testing Procedures

Samples of the laminates were prepared and tested in accordance with ASTM D3039/D3039M-08 [10]. All laminate sheets were cleaned with isopropyl alcohol and prepared for tensile testing by bonding on 3 mm thick HT G11/FR5 Glass Reinforced Epoxy tabs using 3M Scotch-Weld ™ Epoxy Adhesive 2216 B/A. Once tabbed, the epoxy was allowed at least 48 hours to cure. Samples were then cut into 25.4 mm wide specimens using an MK Diamond 370 EXP wet tile saw. The use of this saw prevented cracks from forming on the outer edges of the samples. Each cut sample was then appropriately labeled with a unique composite identifier and a specimen number.

A minimum of three samples of each laminate were tested until failure under uniaxial tension in an Instron® tensile testing machine. A head displacement of 1.27 mm/min was used. A 25.4-mm extensometer was used to measure strain and stress-strain curves were produced for each specimen. The data gathered from the tensile testing was analyzed in order to determine the ultimate tensile strength, elastic modulus, and toughness of each laminate sample. Toughness represents the amount of energy that the sample can withstand before fracture and is a property that balances both modulus and tensile strength. In order to find the toughness, a third-degree polynomial regression equation was found for each stress-strain curve, and this curve was then integrated along the interval of zero strain to the strain value at which the specimen reached its ultimate strength.

To ensure that all samples did not undergo significant stress due to bending, all of the samples were tested with two 25.4-mm extensometers, one on either side, in a back-to-back formation. No samples showed significant bending (>3%), so all test results were concluded to be representative of tensile mechanical properties. The percent bending was calculated by finding the difference between the percent strain of the back extensometer from the front and dividing by the sum of the front and back strains:

$$B_y = \frac{\left|\varepsilon_f - \varepsilon_b\right|}{\left|\varepsilon_f + \varepsilon_b\right|} \quad (1)$$

where B_y is the percent bending and e_f and e_b are percent strains of the front and back.

The fiber volume ratio for each laminate was found according to ASTM D792-08 [11] and ASTM D3171-11 [12]. Sheets of fabric were submerged into a graduated cylinder in order to find the volume per unit area of the fiber fabrics using water displacement. The volume of the initial size of the bamboo fabric sheet was measured, accounting for the amount of any pre-strain that the fabric received before resin was applied. This volume was then divided by the volume of a cured laminate sample with an equal area according to the following:

$$\textit{Fiber Volume Ratio} = \frac{(\textit{Volume per Area})\, l_f w_f}{lwh} \times 100\% \quad (2)$$

where l_f and w_f are the dimensions of the reinforcement fiber fabric, and l, w, and h are dimensions of the piece of the cured laminate sample. Density of the fabric was found using the volume found by water displacement. The fiber volume properties of each laminate are listed in Tables 2 and 3.

The moisture regain of the different fabrics was found by taking the weight of 300 x 300 mm square sheets of fabric before and after they were submerged in water, using the following formula:

$$\textit{Moisture Regain} = \frac{\textit{wet wt.} - \textit{dry wt.}}{\textit{dry wt.}} \times 100\% \quad (3)$$

The measurements for density and moisture regain of each fabric classification are shown in Table 1. The overall laminate densities of the bamboo samples listed in Tables 2 and 3 initially appear somewhat low compared to the respective fiber densities. However, given the low range of the resin density of 1.10 gm/cm^3, the overall density values of the laminates appear reasonable. The presence of small voids could have further contributed to the low laminate densities, but appeared to be minimal. Laminates with excessive voids were not tested.

Classifications of the tensile test failure mode of each sample are listed in Table 4 according to the codes specified in ASTM 3039/3039M-08. In addition, Table 4 also presents the average, standard deviation and coefficient of variation of the tensile strength, elastic modulus and the percent bending of each of the samples tested.

3 RESULTS AND DISCUSSION

3.1 Comparison of the Bamboo and Glass Fiber Laminates

The maximum ultimate tensile strength of the bamboo laminates was found for the plain weave sample, with a value of 19.24 MPa. This strength is about 68% less

Table 2 Tensile strength, modulus, fiber volume ratio, and elongation percentages data for the strongest bamboo fiber single-ply laminate and the glass fiber laminates.

Fiber	Laminate Density (g/cm³)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Toughness (J/cm³)	Fiber Volume Ratio (%)	Elongation (%)
Plain Weave Bamboo Fiber Laminate	1.15	19.24	1.08	0.39	6.7	3.67
S-Glass Laminate	1.21	60.74	2.99	0.31	5.3	1.62
E-Glass Laminte	1.21	47.23	2.87	0.22	5.7	1.78

Table 3 Tensile strength, modulus, fiber volume ratio, and elongation percentages for the stockinette-weave fiber single-ply bamboo laminates subjected to varying pre-strains.

Pre-Strain (%)	Laminate Density (g/cm³)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Toughness (J/cm³)	Fiber Volume Ratio (%)	Elongation (%)
0	1.17	14.07	0.75	0.45	11.2	4.39
25	1.15	11.86	0.66	0.48	10.0	5.43
50	1.17	17.03	0.88	0.54	7.3	4.47
75	1.17	17.17	0.91	0.50	5.9	4.24
100	1.14	18.06	0.85	0.68	5.1	6.14

than the strength of the S-Glass sample (60.74 MPa) and about 46% less of that for the E-Glass sample (47.23 MPa). The plain weave sample also had the highest modulus of elasticity among the bamboo samples, at 1.08 GPa. It demonstrated highly plastic behavior for nearly the entire loading duration, except for the very beginning due to the resin's relatively high modulus of elasticity (2.62 GPa) [7]. The glass fiber laminates, however, behaved very inelastically up until reaching fracture. The values of the moduli of the S-Glass and E-Glass composites were measured to be 2.99 GPa and 2.87 GPa, respectively. The plain weave bamboo sample, however, did have a slightly higher toughness at 0.39 J/cm³ than S-Glass (0.31 J/cm³) and E-Glass (0.22 J/cm³), meaning that the plain weave bamboo sample required more overall energy to fracture. The stress-strain curves of these laminates are plotted in Figure 1. The testing of the plain weave bamboo, S-Glass, and E-Glass resulted in a narrow range of results having low standard deviations. These values and the measurements from the other bamboo samples are shown in Table 4.

The toughness that was found to be higher in the plain weave bamboo fabric corresponds directly to how much more flexible it is in comparison to the glass fiber fabrics. The percent elongation for the plain weave bamboo laminates reached values of 3.67% of their initial length, while the glass fiber laminates only deformed to 1.62% (S-Glass) and 1.78% (E-Glass). This means that the bamboo fiber laminates were much more ductile than the glass fiber laminates. This is

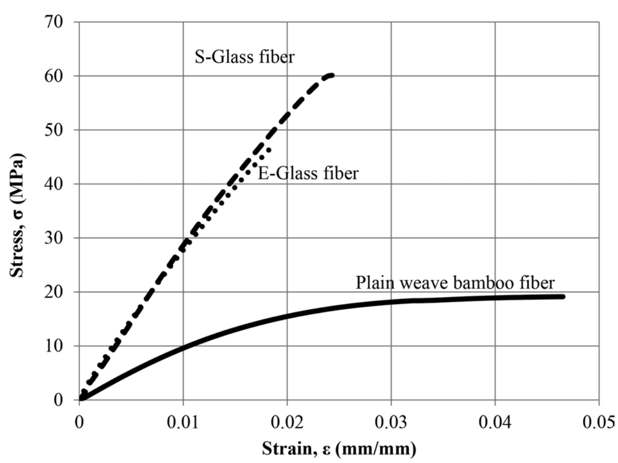

Figure 1 Stress-strain curves for the plain weave bamboo fabric and the glass fiber laminates.

Table 4 Mechanical properties and observed failure modes for all of the tested laminates.

Fiber Type	Average Thickness (mm)	Observed Failure Modes*		Tensile Strength (MPa)	Elastic Modulus (GPa)	Bending (%)
0% pre-strained stockinette weave bamboo	1.63	LWB, LGM, AAB	Average:	14.07	0.75	2.64
			Standard Deviation:	± 0.62	± 0.02	± 0.17
			CV:	5%	3%	6%
25% pre-strained stockinette weave bamboo	1.57	LGM, LGT	Average:	11.86	0.66	1.92
			Standard Deviation:	± 0.48	± 0.09	± 0.39
			CV:	4%	14%	20%
50% pre-strained stockinette weave bamoo	1.75	LWT, AAT	Average:	17.03	0.88	0.71
			Standard Deviation:	± 0.14	± 0.05	± 0.42
			CV:	1%	6%	59%
75% pre-strained stockinette weave bamboo	1.83	LGB, LWB	Average:	17.17	0.91	1.22
			Standard Deviation:	± 0.28	± 0.01	± 0.31
			CV:	2%	0%	25%
100% pre-strained stockinette weave bamboo	1.83	LGM, LGB	Average:	18.06	0.85	1.73
			Standard Deviation:	± 0.07	± 0.09	± 0.26
			CV:	0%	10%	15%
Plain weave bamboo	2.29	LGB, LGT	Average:	19.24	1.08	1.31
			Standard Deviation:	± 0.55	± 0.06	± 0.33
			CV:	3%	5%	26%
E-Glass	0.97	LGT, AGM	Average:	47.23	2.87	2.21
			Standard Deviation:	± 2.14	± 0.12	± 0.27
			CV:	5%	4%	12%
S-Glass	1.04	LGM, LGB	Average:	60.74	2.99	0.48
			Standard Deviation:	± 14.07	± 0.53	± 0.36
			CV:	23%	18%	76%

* As classified in ASTM 3039/3039M-08 [10].

also shown in the difference between the variations of the moduli of the composites mentioned earlier. It is important to note that the average thickness, as shown in Table 4, of the plain weave bamboo laminate (2.29 mm) is significantly higher than that of the E-Glass (0.97 mm) and S-Glass (1.04 mm) laminates. The fiber volume ratios of these samples were fairly consistent, ranging from 6.7% for the plain weave bamboo laminate to 5.3% and 5.7% for the S-Glass and E-Glass laminates, respectively.

The plain weave bamboo and the glass fiber laminates have narrow standard deviations for their tensile stresses and moduli, but not all of the samples have narrow distributions for percent bending. The E-Glass and plain weave samples have bending coefficients of variation of 26% and 12%, but the S-Glass sample has a coefficient of variation of 76%. The cause of this high coefficient of variation is the removal of one of the samples. The third sample tested of E-Glass was improperly loaded and resulted in slippage inside of the grips. This gave very poor data for this sample and it was removed from the test. Since only two samples were tested it made the coefficient of variation greater for this sample.

3.2 Effects of Pre-Strain

Among the samples of the highly elastic, pre-strained stockinette bamboo weave composite, the 100%-strain sample showed the highest ultimate strength of 18.06 MPa. The relationship between pre-strain and ultimate tensile strength, seen in Figure 2, was found to

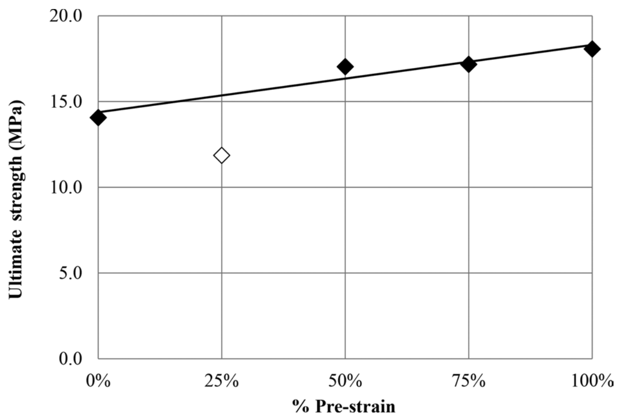

Figure 2 Tensile strength for the stockinette-weave bamboo fabric laminate as a function of the fabric pre-strain. The data point at a percent strain of 25% was considered to be an outlier.

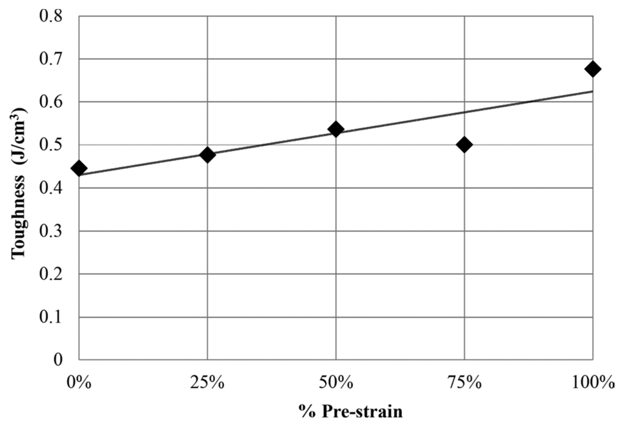

Figure 4 Toughness data for the stockinette-weave bamboo fabric laminate as a function of the fabric pre-strain.

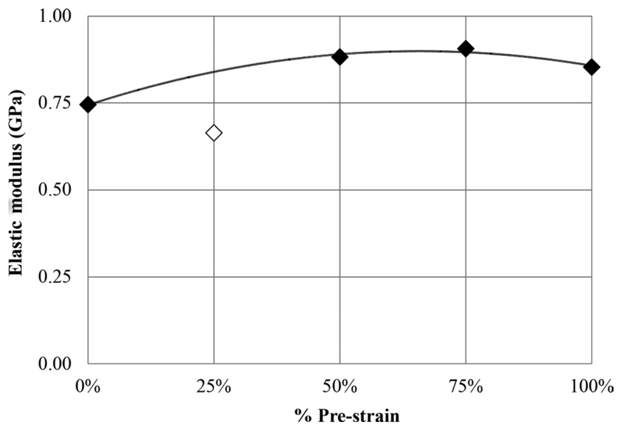

Figure 3 Tensile elastic modulus for the stockinette-weave bamboo fabric laminate as a function of the fabric pre-strain. The data point at a percent strain of 25% was considered to be an outlier.

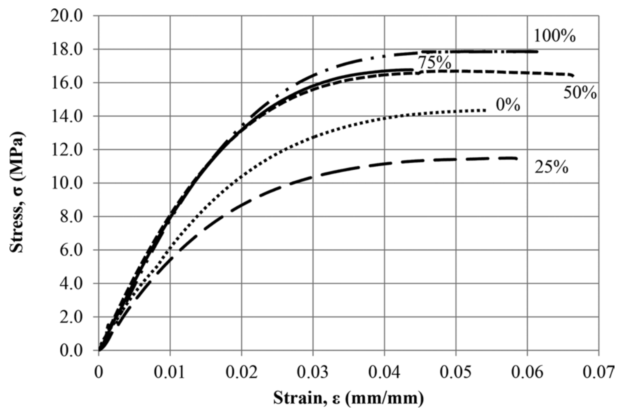

Figure 5 Stress-strain curves for the stockinette-weave bamboo fabric laminate for various fabric pre-strains.

be approximately linear, with the ultimate strength increasing at a rate of about 41 kPa per percent strain from 14.07 MPa at 0%-strain to 18.06 MPa at 100%-strain. An outlier from this trend, as seen in Figure 2, is the 25%-strain sample, which had the lowest strength, at 11.86 MPa.

When modulus data is compared, the 25%-strain sample is again low, but the other four samples follow a parabolic correlation that shows a peak at around 65% pre-strain, as can be seen in Figure 3. This means that to achieve maximum flexibility of the stockinette weave bamboo composites a pre-strain of approximately 65% would need to be applied. The toughness followed a linear relationship with pre-strain, as seen in Figure 4. The maximum toughness value was observed in the 100% pre-strained sample of 0.68 J/cm^3. The stress-strain curves of the five pre-strained samples can be seen in Figure 5. The tensile strength, modulus, fiber volume ratio, and elongation percentages for the different pre-strains are listed in Table 3.

Toughness and percent elongation in the pre-strained samples do not relate as directly as they do in the plain weave and glass fiber laminates. The percent elongation ranged from 4.39% to 6.14% in the 0% and 100% pre-strain samples, respectively. The 25% pre-strain (5.43%) and the 100% pre-strain (6.14%) were the only two samples to have percent elongations higher than 5.0%. This means that these two samples deformed more than the other samples under different amounts of pre-strain.

The average thicknesses of the pre-strained samples varied from 1.57 to 1.83 mm. The cross-sectional area of the laminates was kept as consistent as possible within the tolerance of the lay-up equipment. Since the samples are composites the properties do not scale with laminate thickness. Much thicker samples should show lower strength because the cross-sectional area of the fibers, which bear the majority of the stress, is relatively constant. The tolerance of the sample thickness does not appear to affect the trend in sample strength. The thinnest sample was the 25% pre-strain sample that had a low strength, while the thickest sample was the 100% pre-strain sample that had a higher strength. The thickness depends largely upon how much resin was applied during application, which was monitored and regulated for all the samples. The fiber volume ratios show that as the amount of fiber decreased in the sample, the ultimate strength increased. The 0% pre-strain sample had a fiber volume ratio of 11.2% and an ultimate strength of 14.07 MPa, while the 100% pre-strain sample had an ultimate strength of 18.06 MPa and a fiber volume ratio of 5.1%, as listed in Table 3.

The stockinette weave samples had extremely narrow coefficients of variation for tensile stress and elastic modulus, ranging from 0%–14%. All of the bending coefficients are also in a fairly tight interval (6–25%) except for the 50% pre-strain sample. The 50% pre-strain sample had a bending coefficient of variation of 59%. The high coefficient of variation of the 50% pre-strain samples is due to slight misalignments when connecting the extensometers back-to-back with each other on the sample. This error is recognized in ASTM D3039/D3039M-08 as a common cause of bending when testing composite samples, and that the extensometers need to be realigned if the samples show excessive bending (3–5%) [10]. The misalignments are magnified because only two samples were tested of this composite; both of the samples tested of the 50% pre-strain sample had bending percentages of 1.0 and below.

As the amount of pre-strain increases, the fibers of the stockinette weave fabric become more unidirectionally aligned along the loading direction. This increased directional fiber alignment is optically confirmed in Figure 6 and could potentially account for the linear relationship between the amount of pre-strain and the tensile strength. It has been found that in simple laminates, fiber pre-strain induces compressive stresses in the matrix and helps to suppress damage initiation and growth [13]. For the stockinette weave bamboo composites, maximum tensile strength, toughness, and percent elongation values were reached close to the maximum pre-strain amount, while the maximum tensile modulus appears to occur at 65% pre-strain. Additional research is needed to understand the specific mechanisms responsible for these observations.

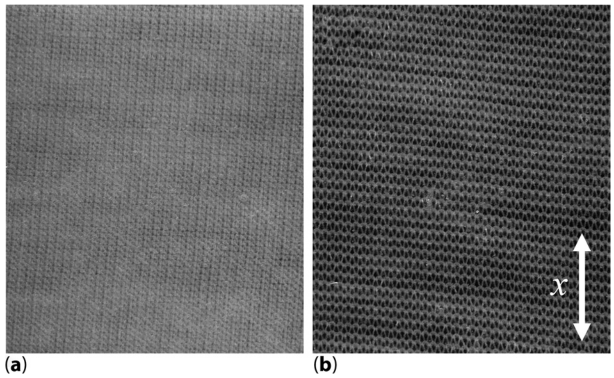

Figure 6 Images of the stockinette-weave bamboo fabric laminate samples with: a) 0% prestrain and b) 100% pre-strain (strain applied along the x-axis direction as shown).

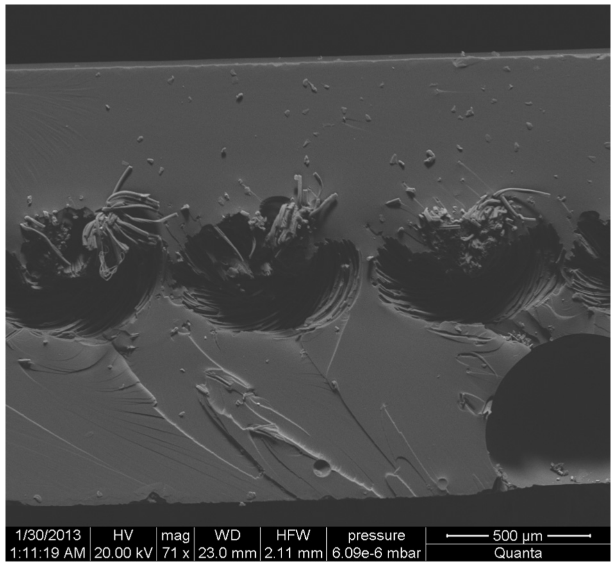

Figure 7 SEM image of the fracture surface of a 25% pre-strained stockinette-weave bamboo fabric laminate, showing poor matrix-to-fiber bonding (71x magnification).

3.3 Analysis of the Fracture Surfaces

The bamboo samples were all examined under a scanning electron microscope (SEM) to observe the fracture surfaces. The most telling images are for the 25% and 100% pre-strained stockinette weave and the plain weave bamboo samples. From these images, the fiber-matrix interface was observed and analyzed. The 25% pre-strain sample, as seen in Figure 7, shows poor bonding of the matrix to the fibers, explaining why this sample was considered as an outlier from the general trend in the pre-strain samples. The visible void between the matrix and fibers, possibly resulting from the processing or curing methods, did not allow the resin to bond well with the bamboo fibers, preventing the sample from acting isotropically. The 100%

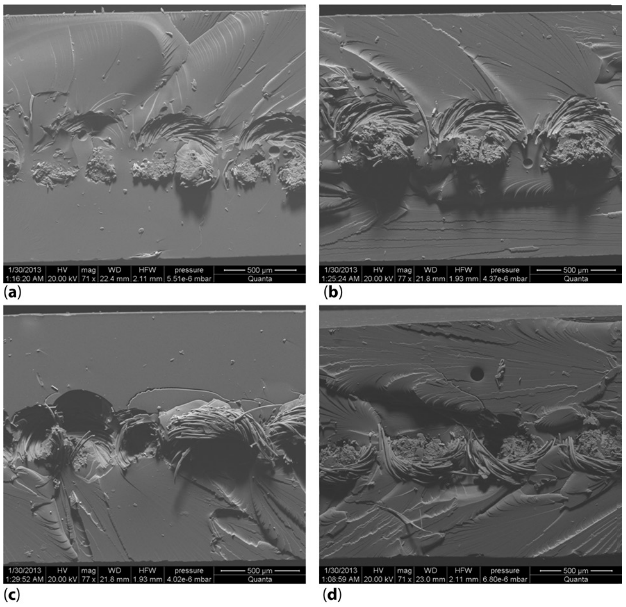

Figure 8 SEM images of the fracture surfaces for stockinette-weave bamboo fabric laminate samples with: a) 0% pre-strain, b) 50% pre-strain, c) 75% pre-strain, and d) 100% pre-strain.

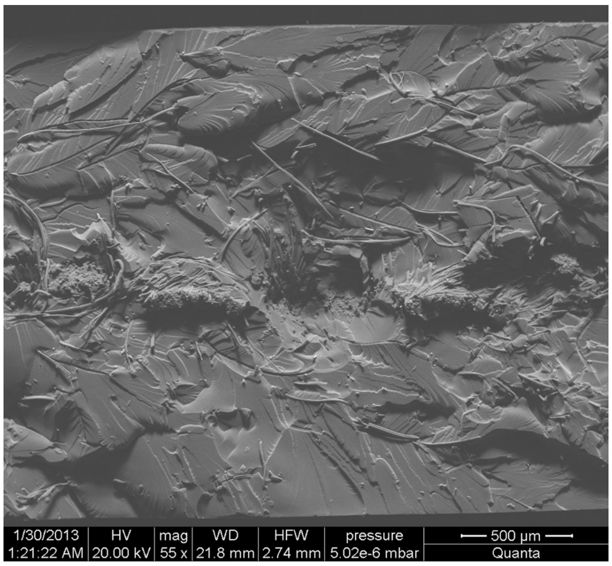

Figure 9 SEM image of fracture surface of a plain weave bamboo fabric laminate sample (55x magnification).

pre-strained stockinette weave bamboo sample, the strongest of the pre-strained samples, shows a well-bonded matrix-to-fiber interface, as do the other pre-strain samples, as seen in Figure 8.

The plain weave sample had an excess of randomly oriented fibers, causing the sample to feel fuzzy. These randomly oriented fibers are seen in Figure 9 and explain why the sample absorbed much more resin than the pre-strained samples. The fracture surface of this sample shows how the excess fibers redirected the fracture crack, resulting in a much rougher fracture surface than those of the pre-strained samples.

4 CONCLUSIONS

Single-ply bamboo fiber laminates were fabricated using a pinesap-based bioresin using a wet layup technique. The mechanical properties, particularly the tensile strength, elastic modulus, percent elongation, and toughness were characterized according to ASTM D3039/D3039M-08 and compared to E- and S-Glass fiber laminates. The fracture surfaces were also investigated using an SEM in order to examine the matrix and fiber interface. The key findings of this study are:

- The ultimate tensile strength of the strongest single-ply bamboo composite was approximately a third of the strength of the glass fiber laminates and approximately a third as stiff, showing that the plain weave bamboo is a less strong, but more flexible alternative to glass fiber laminates.
- The stockinette-weave pre-strained single-ply bamboo composites showed that maximum tensile strength and toughness were reached close to the maximum pre-strain amount, while the maximum tensile modulus appears to occur at 65% pre-strain.
- The ultimate strength of the pre-strain samples increased linearly from 0% to 100%. The 25% pre-strained sample was considered as an outlier to this trend and showed poor fiber-to-matrix bonding on the fracture surface.
- The 100% pre-strain sample was the toughest sample, while the E-Glass laminates were the least tough samples.
- The bamboo fabric laminates had a much lower modulus of elasticity than the glass fiber laminates.

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