Fibers and Polymers 2022, Vol.23, No.1, 155-163
DOI 10.1007/s12221-021-0982-1
ISSN 1229-9197 (print version)
ISSN 1875-0052 (electronic version)

The Natural Fiber Reinforced Thermoplastic Composite Made of Woven Bamboo Fiber and Polypropylene

Bo-Jyun Wang and Wen-Bin Young*

Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 70101, Taiwan, ROC
(Received August 18, 2020; Revised September 29, 2020; Accepted October 6, 2020)

Abstract: The aim of this study was to study the mechanical properties of woven bamboo fiber (WBF) reinforced polypropylene (PP) composites. The bamboo fiber mat was constructed manually by hand. The WBF/PP composites were fabricated by thermoforming process. The basic characteristics of the bamboo strips, such as density, cross section, and tensile properties were measured first. The strengths of the bamboo strip in different sizes were measured, and they were around 400 MPa after 5 wt% alkali treatment. The WBF/PP composite with alkali treated bamboo fibers had better tensile strength than that with untreated bamboo fibers. The strength and modulus are about two times larger in longitudinal direction, while they are about the same in the transverse direction. For the hygrothermal aging test, the composites were highly sensitive to moisture, which could degrade the composites mechanical properties. In the bamboo fiber preforming process, the moisture can enhance the formability of the woven bamboo fiber mat and prevent the bamboo fiber to spring back after forming. The experimental results implied that the preforming of the woven bamboo fiber mat into complex shape is feasible under the wet condition.

Keywords: Woven bamboo fiber, Bamboo fiber composite, Hygrothermal aging, Bamboo fiber preform

Introduction

In recent years, polymer composite is one of the popular materials in current industry. The applications include aerospace, automobiles, ships, or even the needs of people's livelihood. Composites have excellent characteristics as: lower density, high chemical resistance, higher specific strength and modulus. However, composites tend to aggravate the pollution to the environment due to the usage of inorganic fibers. People began to pay attention to this issue, leading to the development of nature fibers reinforced composites. In 2003, the European composite material industry used 43,000 tons of bio-fibers for composite materials. By 2010, the use of bio-fibers had increased to 315,000 tons, accounting for 13 % of the entire composite material industry [1-3]. Most natural fibers used plant fibers, such as bananas, coconuts, sisal, jute, bamboo, etc. [4-6], because plant fibers have the advantages of high strength, low density, low energy consumption and biodegradability [7-9].

Bamboo fiber is a popular material among natural fibers. Its specific strength is almost comparable to that of glass fiber. Not only the bamboo grows fast, but also it can reach the best strength in 3 years, and its mechanical properties are also superior to other natural fibers. Therefore, the bamboo is a suitable choice for the development of natural fiber composites. The chemical composition of bamboo is composed of cellulose, hemicellulose, and lignin. The lignin and hemicellulose can be dissolved in sodium hydroxide (NaOH) [10].

*Corresponding author: youngwb@mail.ncku.edu.tw

The mechanical properties of bamboo fibers are important for being the reinforcement of composites. Das *et al*. [10] reported that the bamboo strips have the highest density with the treatment of NaOH in 5 % concentration. Because the alkali will remove hemicellulose and lignin, but it will also form new hydrogen bonds, causing the fiber to aggregate. Amada *et al*. [11] reported that there are more fibers near the bamboo skin, so the outer portion of the bamboo culm has a better strength. The alkali treatment of the bamboo fibers was reported to increase the mechanical properties of the bamboo fiber composites [12-16]. Ochi [15] reported that the heating temperature of bamboo fiber cannot exceed 160 °C. When heated above 160 °C, the strength will decrease slightly due to thermal degradation. Takagi and Ichihara [17] reported that the surface of bamboo fiber becomes rough after alkali treatment. It can effectively increase the adhesion between the matrix and fiber, which will enhance the mechanical properties of the bamboo composites.

Composite materials are often exposed to the moisture environments during the application. Natural fibers are easy to absorb moisture, which causes weakening of the bonding force between fibers. In additions, water molecules may also interact with polymers (hydrolysis), which reduces the mechanical properties of the composite [18,19]. For natural fiber reinforced composite, it is necessary to explore the effect of hygrothermal aging.

During the applications, composite materials are often designed in many complicated structures in the automobile or aerospace industry. In the compression forming process, the fiber mat must be preformed into a complicated shape before forming of the composites. In the preforming of natural fibers, the fibers are easily affected by moisture and temperature, which causes the expansion and softening [20]. After soaking the bamboo in the water, the glass transition temperature of lignin, cellulose, and hemicellulose can be reduced, leading to softening of the bamboo, so that it can withstand the deformation during the process of forming into a complex shape. Hao and Liu [21] indicated that the softening of bamboo strips was an important step in forming into different shapes. Softening can increase the shaping ability of bamboo strips.

The woven bamboo fiber reinforced PP composite can be used in several areas as automobile, construction, and appliance, etc. In this study, the woven bamboo fiber (WBF) mat was constructed and combined with the polypropylene (PP) to form a composite by the thermoforming process. The strengths of the bamboo strip in different sizes were measured. The strength and modulus of WBF/PP composite are tested in both the longitudinal and transverse directions. The hygrothermal aging tests of the composites were also conducted to study the effect of moisture on the WBF/PP composite. The bamboo fiber preforming in a hemisphere shape was also performed to study the formability of the woven bamboo fiber mat.

Experimental

Materials

The mechanical method was used to extract the bamboo strips from thorny bamboo culm which grown in Taiwan. Firstly, a bamboo culm section was cut without node portions and barks were removed from the bamboo culm. Secondly, the bamboo culm was cut into slices with a thickness of 0.7 mm by a cutting machine as shown in Figure 1(a). Finally, the bamboo slice was cut into bamboo strips along the fiber direction. The bamboo strips used in this study had a dimension of $0.7\times4\times160$ mm^3, as shown in Figure 1(b). All the bamboo strips were dried in the oven at 80 ^{o}C for 5 hours to remove the moisture. Polypropylene film (Nan Ya Plastic, Taiwan) was used as the matrix for the WBF/PP composites. In this study, the bamboo strip was referred as the bamboo fiber instead of the actual the micro bamboo fibers.

Alkali Treatment

For the alkaline treatment, the bamboo strips were soaked with 5 wt% NaOH solution at room temperature for 2 h while the NaOH solution was stirred every 30 min. This alkali treatment are selected based on the optimized conditions in the literature [22]. The weight ratio of bamboo fibers and NaOH solution is 1:30. After that, alkali-treated bamboo strips were washed with water, and then placed in an oven for drying out under the temperature of 80 °C for 8 hours. After alkali treatment, the volume of the BF can be measured by the water displacement method, which can be used to calculate the cross section area of the BF with the known fiber length.

Woven Bamboo Fiber Preparation

The bamboo strips of $0.7\times4\times200$ mm^3 were used for the weaving. All the bamboo strips were treated by NaOH solution first. After that, the strips were woven into bamboo fiber mats manually by hand. The woven mats were soaked in the water for 30 s. Then, the wet woven mats were covered with release films on both sides and compacted at 140 °C for 10 minutes on a hot press. The compaction under the wet condition help to fix the woven shape and reduce the waviness of the BF. The release film was made of Teflon to prevent form burning of the BF during the heat compaction.

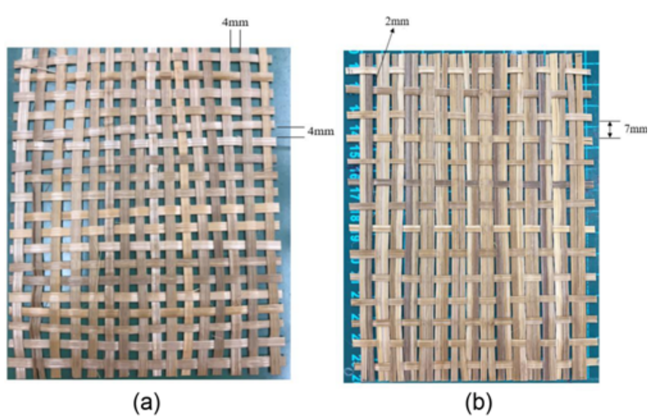

Figure 2. (a) plain woven bamboo mat (b) twill woven bamboo mat.

Figure 1. (a) Bamboo slices (b) bamboo strips in $0.7\times4\times160$ mm^3.

The woven fiber mat was cut into the size of 160×120 mm^2. The woven bamboo fiber mats have two types: one is plain weave, and the other is twill weave (type 2×1) as shown in Figure 2. The space between BFs in plain weave is about 4 mm in both directions. For the twill weave mat, the space between longitudinal BFs is 2 mm and 7 mm between transvers BFs.

WBF/PP Composites

The twill or plain weave WBF/PP composites were fabricated by the thermoforming process. The bamboo mat was placed in an oven at 80 °C for 1 hour to remove the moisture. Bamboo fiber mats and PP film were alternatively laid together and placed in the mold cavity (160×125×2 mm^3). For the case of plain weave composites, the laminate includes two plain weave mats with one PP film on the top and bottom sides, and two PP films in the middle between the weave mats. For the case of twill weave composites, one has the same assembly as the plain weave laminate, and the other has the assembly double the arrangement of the previous laminates.

The laminate was covered by a vacuum bag and was drawn a vacuum for 30 min to remove the air inside the assembly. After that, a caul plate of aluminum block was placed on top of the laminate and heated to 160 ^{o}C for 45 min on a hot press machine. During this stage, the PP film will melt, and the thickness of the laminate may decrease. Therefore, the hot press must be adjusted to have the laminate to touch the hot plates for heating. After the PP film was changed to molten phase, a compression pressure of 1.7 MPa was employed to compact the laminate. Finally, the laminate inside the mold was cooled down naturally for 12 h on the hot press. The plain weave composite has a final thickness of 2.2 mm. The twill weave composite has the thickness of 2.2 mm and 4 mm.

The density of the alkali treated BF can be measured with the water displacement method, and the resulting averaging value is 1.052 g/cm^3 (ρ_f). The density of PP is about 0.91 g/cm^3 (ρ_r). With known weight and density of the BF and PP, the fiber volume fractions of the composites can be estimated as:

$$V_f = \frac{m_f / \rho_f}{m_f / \rho_f + m_r / \rho_r} \tag{1}$$

where V_f is the BF volume fraction, m_f and m_r are the weight of the BF and PP in the BF/PP composite.

Notice that, the void was ignored in this estimation. The fiber volume fractions of fabricated WBF/PP composites are listed in Table 1. A little bit higher fiber volume fraction was noticed in the 4-layer twill composite. This may be due to the more loss of melt PP flowing out the laminate along the sides for the thicker laminate in the compaction process.

Table 1. Fiber volume fractions of WBF/PP composites

WBF/PP composite			
Type	Fiber layers	PP layers	Fiber volume fraction (%)
Plain	2	4	41.7
Twill	2	4	50.88
Twill	4	8	51.51

Tensile of Bamboo Strip

The BF and ALK-BF were cut into a length of 40 mm and attached to a paper on each end with epoxy adhesive. The paper was used to increase the friction force between the clamp and BF. Then, samples were dried at 80 °C for 5 hours to cure the epoxy adhesive and further dry the fiber. Finally, the tensile strength of the fibers was measured using a home-made micro-stretcher with a pulling speed of 3 mm/min and a 1100 N loadcell (WMC-1100N, Interface).

Tensile Test and Flexural Test

A universal material testing machine (AG-250/300KNX, Shimadzu corporation, Japan) was used for the tensile tests of the WBF/PP composites. The tensile test samples have two different dimensions. They were cut directly form a rectangular composite plate with different dimensions in longitudinal and transvers directions (160×120 mm^2). For the longitudinal direction, the sample has the dimension of 160×12 mm^2 while it is 120×12 mm^2 in the transverse direction. A 4 mm tabs were glued on both ends of the tensile test sample to protect it from damage during gripping. Each sample was installed a strain gauge (gauge length=5 mm) and connected to the strain indicator (Intertechnology Inc.) before tensile test. The tensile tests were conducted at tensile speed of 0.3 mm/min. A low tensile rate was selected in order to minimize any occurrence of the dynamic effect during the tests.

Three-point bend test was performed on alkali treated twill and plain weave composite samples of dimensions 160×12 mm^2 in the longitudinal direction, and 120×12 mm^2 in the transverse direction. The flexural properties of the composite samples were obtained using the mini testing machine with a 1100 N loading capacity. The loading span was set at 60 mm and the crosshead speed was 3 mm/min.

Hygrothermal Aging Test

In order to understand the moisture absorption of WBF/PP composites and the effect of humidity on the mechanical strength, hygrothermal aging test was performed. The alkali treated twill WBF/PP samples was submerged in the boiling water for the times of 1 hour, 2 hours, 3 hours, or 4 hours, respectively. In order to evaluate the weight change of the composite after water absorption, the weight of dry specimen, W_0, and the weight after water absorption, W_1,

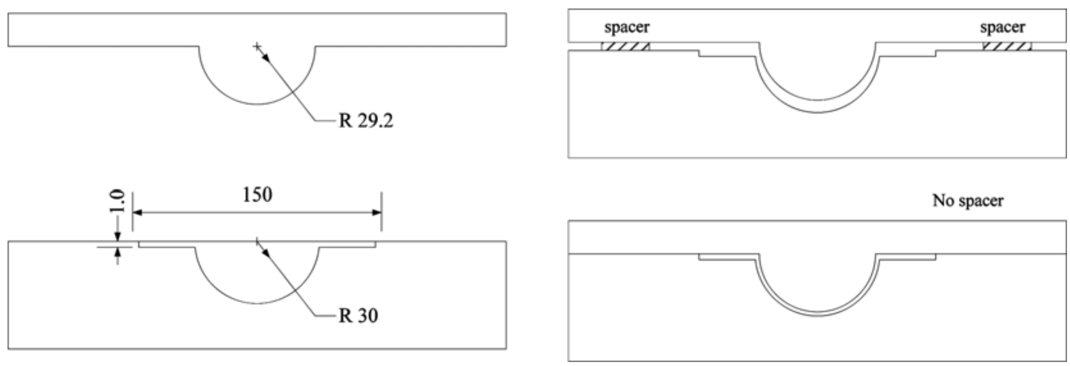

Figure 3. Cylindrical shape fiber preform mold (unit: mm).

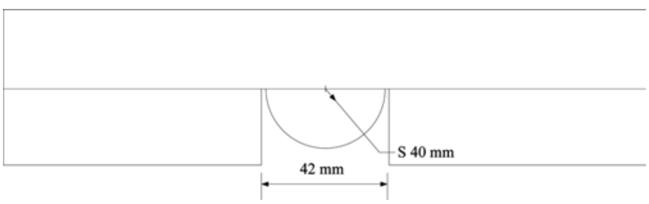

Figure 4. Spherical shape fiber preform mold.

were measured for each specimen. The following equation was used to calculate the moisture content, W_c, of a composite:

$$W_c = (W_1 - W_0)/W_0 \tag{2}$$

Tensile tests were also conducted for samples with different submerging time.

Bamboo Fiber Mat Preforming

In order to understand the feasibility of forming the woven bamboo mat into the complex geometric shape, two practices were conducted to forming the woven mat to cylindrical and spherical shapes. Water was sprayed onto the bamboo mats for 60 s by a sprayer to increase its moisture content. After that, the moisture content of the bamboo fiber mat could reach about 50 %. For forming into a cylindrical shape, the wet bamboo fiber mat was placed into the mold cavity (150×125×1 mm^3) as shown in Figure 3, and were heated up to 140 $^{\circ}$C for the forming process of 30 s. Spacers may be installed between the upper and lower molds as in Figure 3 to control the forming distance and radius of the preform. The photographs of the preforms were taken after cooled down for 1 min. The preform images were imported into the computer to measure the radius of curvature of the preforms.

For the spherical shape preforming, a semi-spherical shape mold head with a radius of 40 mm was attached to the upper mold, and a cylindrical hole of radius of 42 mm was drilled on the lower mold, as shown in Figure 4.

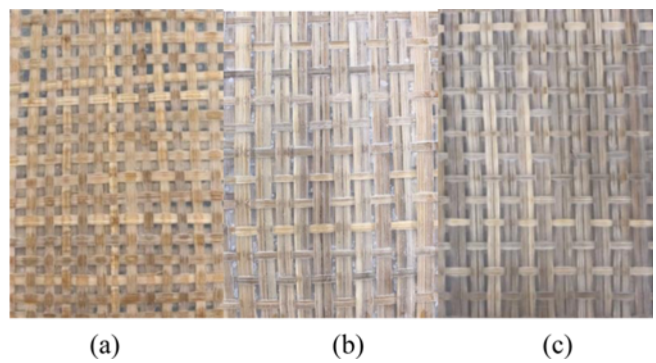

Figure 5. WBF/PP (a) plain, (b) twill (2-layer bamboo), and (c) twill (4-layer bamboo) composites.

Results and Discussion

Tensile Properties of Bamboo Strips

Three WBF/PP composites were fabricated by the thermoforming process. The resulting composites are shown in Figure 5 for plain weave and twill weave bamboo composites. The twill weave composites have two different thicknesses: one has 2 layers of woven bamboo fiber and the other has 4 layers of bamboo fiber. Since the woven bamboo fiber has large space between fibers, there is some resin reach areas in the composite located at the fiber intersection regions. More layers of woven bamboo fiber in the composite can reduce through thickness resin reach areas.

In order to understand the size effect of the bamboo strip on the mechanical property, bamboo strip was cut in five different widths from 1 to 6 mm (1, 2, 4, 6 mm). Figure 6 shows the strengths of untreated and alkali treated bamboo strips in different sizes. It can be found that the tensile strength of the bamboo strip will increase with the width of bamboo strips for the range from 1 to 6 mm. On the other hand, the smaller size of untreated bamboo strip shows higher tensile strength. For bamboo strip with a width of 1 mm, the strength of alkali treatment bamboo strips is lower

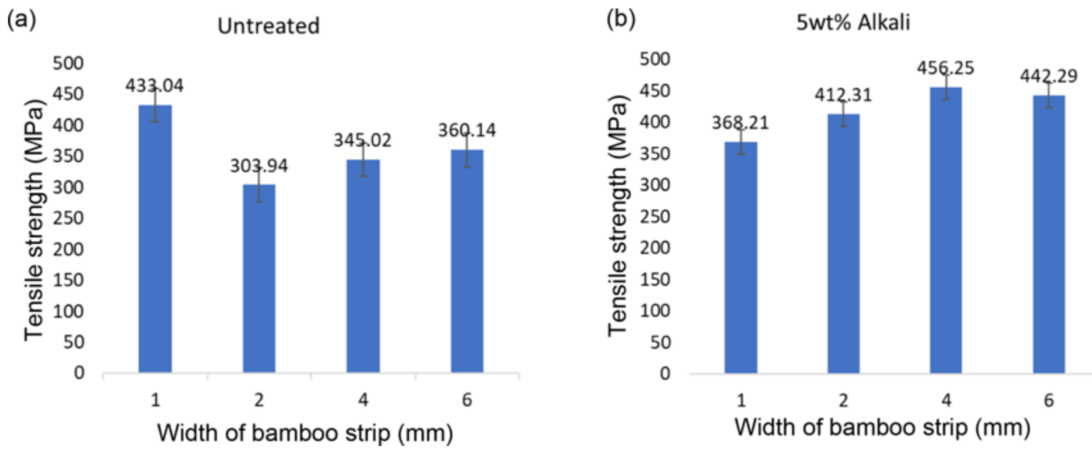

Figure 6. Strength of (a) untreated and (b) alkali treated bamboo strips.

than untreated bamboo strips. This result met with the report of the literatures. For thinner bamboo strip, the treatment tended to damage the integrality of the entire bamboo strip and decrease its strength.

For bamboo strip with a width larger than 2 mm, the strength of alkali treatment bamboo strips is stronger than untreated bamboo strips. The possible reason is that the width of the bamboo strip is too large for alkali to penetrate inside. Alkali only removes low-strength substances from the surface of bamboo strips. There are large areas inside the bamboo strip which is not affected by the alkali and retains much integrality and strength of the bamboo structure.

Tensile and Flexural Test of WBF/PP Composites

Figure 7 shows the tensile strength and modulus of alkali treated and untreated WBF/PP composites. In 0-degree direction (warp direction), the tensile strength increases 58 % from 31.56 MPa to 49.92 MPa, and the Young's modulus increases 62 % from 4.77 GPa to 7.74 GPa for composites with alkali treated bamboo fibers. In 90-degree direction (weft direction), the tensile strength increases 73 % from 32.06 MPa to 55.92 MPa, the Young's modulus increases 122 % from 4 GPa to 9.44 GPa with alkali treated bamboo fibers. The results met with literature that the alkali treatment of bamboo fibers can enhance the tensile properties of the composites. It is because of that, after the alkaline treatment, the surface of bamboo strips become rough, which can enhance the adhesion with the polypropylene. Moreover, the lignin and hemicellulose are removed and fiber active sites increase by mercerization process and allow better fiber wetting. Therefore, the following study will focus on the composites with alkali treated bamboo strips.

The tensile properties of plain and twill weave WBF/PP composites are shown in Figure 8. All composites have larger strength and modulus as compared to the neat PP, showing good reinforcing effect of the bamboo fibers. For the woven bamboo fiber composites, the tensile properties

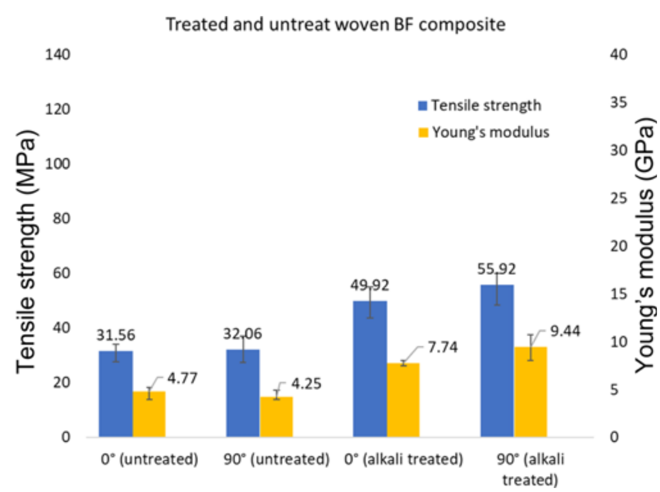

Figure 7. Tensile strength and modulus of treated and untreated WBF/PP composites.

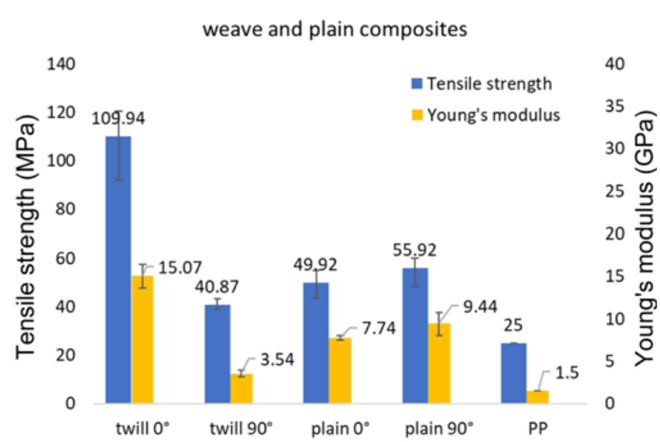

Figure 8. Tensile strength and modulus of plain and twill weave WBF/PP composites.

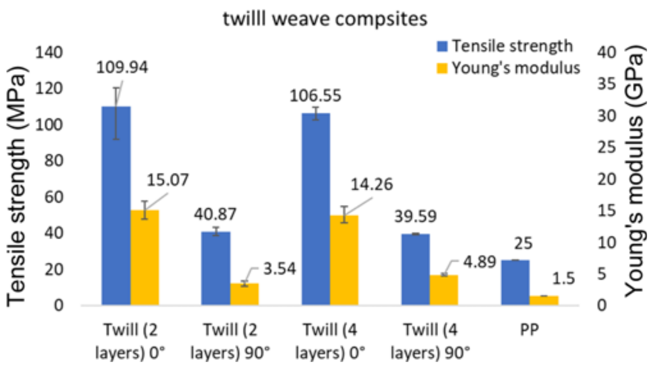

Figure 9. Tensile properties of twill weave WBF/PP composites with different number of woven bamboo layers.

have gained reinforcement as compared the neat PP. The twill weave composite has gained larger strength long the 0-dgree direction while has less reinforcing effect in the 90-degree direction. However, it still has comparable strength in the 90-degree direction as compared with that of the plain weave composite.

In 0-degree direction, the tensile strength and modulus of the twill weave WBF/PP composites increase 120 % and 94 % as compared to the plain weave WBF/PP composites, respectively. This larger strength and modulus are due to the twice number of bamboo strips of the twill woven mat as compared to the plain-woven mat along the 0-degree direction. In 90-degree direction, the tensile strength and modulus of the twill woven WBF/PP composites decreases 27 % and 62.5 % as compared to the plain-woven WBF/PP composites, respectively. The decrease of the tensile properties of the composite for twill weave composites was due to the less bamboo strips and larger space in 90-degree direction than plain weave mat.

Figure 9 shows the tensile properties of twill weave WBF/PP composites with different number of woven bamboo layers. The composite with 4 layers of woven bamboo fiber has twice thickness as the composite with 2 layers of woven bamboo fiber. Due to the forming process as mentioned earlier, the thicker composite has a slight larger fiber volume fraction. However, the tensile property for both composites in different thicknesses are about at the same level.

The comparison of the current data for woven bamboo fiber composites with other bamboo composites in literatures is shown in Figure 10. Point A, B are the strengths of WBF/PP composites by current study. Point C is long bamboo fiber reinforced PP composites by Jain *et al.* [23]. Point D, D1, E, E1 are long bamboo fiber reinforced epoxy composites by Chiu [22]. Point H, I are short bamboo fiber reinforced PP composites by Samal *et al.* [24] and Okubo *et al.* [25] respectively. For the thermoplastic matrix composites, the strength of unidirectional bamboo fiber composite is better than that of woven bamboo fiber or short bamboo fiber composite. Although the unidirectional bamboo fiber composite has the better strength, it has no reinforcement in the transverse direction. This study demonstrates that the bamboo fiber can be woven in different forms to enhance the strength in specific directions while keep certain strength at the transverse direction. For the thermoset composite, the strength of bamboo/epoxy composite is higher than that of Bamboo/PP composites shown in the figure. This might be due to the higher strength of the thermoset epoxy resin. In general, continuous bamboo fiber provides more reinforcement effect than the short fiber as expected. The bamboo strip

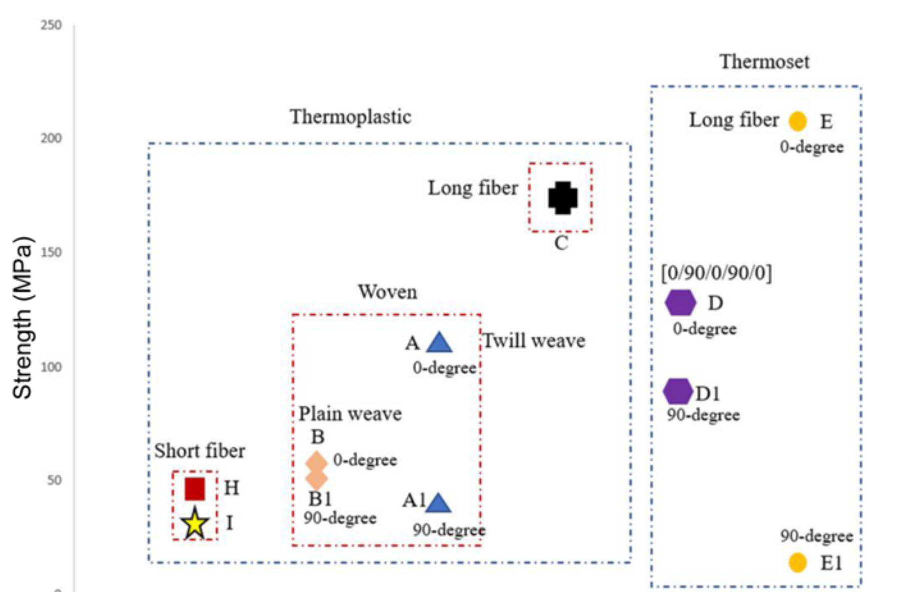

Figure 10. Current study and compared with the literature; A, A1, B, B1 are the current WBF/PP composites; C is from Jain [23]; H and I are from Samal [24] and Okubo [25]; D, D1, E and E1 are from Chiu [22].

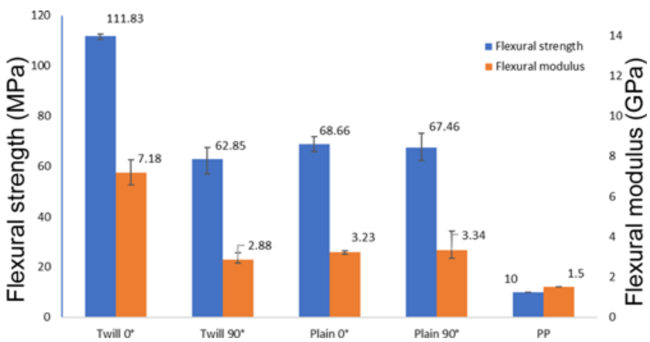

Figure 11. Flexure strength and modulus of the WBF/PP composite.

used as the fiber in this study has successful reinforcing effect on the PP matrix as compared to the composites reported in literatures.

The flexural strength and modulus of WBF/PP composite are shown in Figure 11. The twill weave WBF/PP composite has higher flexural strength and modulus than the plain weave WBF/PP composite in the 0-degree direction. For twill weave composite, the flexure strength increases 62.8 % from 68.88 MPa to 111.83 MPa, and the flexure modulus increases 122.3 % from 3.23 GPa to 7.18 GPa as compared to the plain weave WBF/PP composite. In the 90-degree direction, the flexural strength and modulus are compatible for both type of composites. For twill weave composite, the flexure strength is less 6.83 %, and the flexure modulus is less 13.77 % as compared to the plain weave composite. The general trend is the same for the tensile properties of the plain and twill weave composites. The twill weave composite has twice number of bamboo strips in 0-degree direction, and it has less number of bamboo strips and larger space as compared to the plain weave composite in 90-degree direction.

Hygrothermal Aging Test

The mechanical properties of natural fiber (such as flax, hemp and sisal.) reinforced composites can decrease considerably when they are exposed to moisture [26-28]. In this study, the moisture absorption test of the twill weave WBF/PP composite in boiling water is shown in Figure 12. The moisture absorption of bamboo composite is significant, which agrees with the literature [29]. As bamboo composites are soaked in the boiling water for 30 minutes, the moisture content of the composites reaches about 10 %. After one hour, the absorption rate decreases gradually. When the soaking time is up to 4 hours, the moisture content of composite is about to level off. This also suggests that the minimum soaking time to derive a maximum wet bamboo composite is about 4 hours. Notice that the wetting process was conducted under the boiling water.

The moisture content of WBF/PP composite increases quickly with the duration of soaking in boiling water as shown in Figure 12. For about 4 hours, the moisture content of the WBF/PP composite reaches the saturation about 21.3 %. Figure 13 shows tensile strength and modulus of the twill weave WBF/PP composite along the 0-degree direction. We can see that the strength and modulus decrease with the increase of the moisture content of the composites. The moisture absorption has a great influence on the tensile properties of the WBF/PP composites. About 40 % of the strength of the composite was retained after 3 hours of soaking in boiling water.

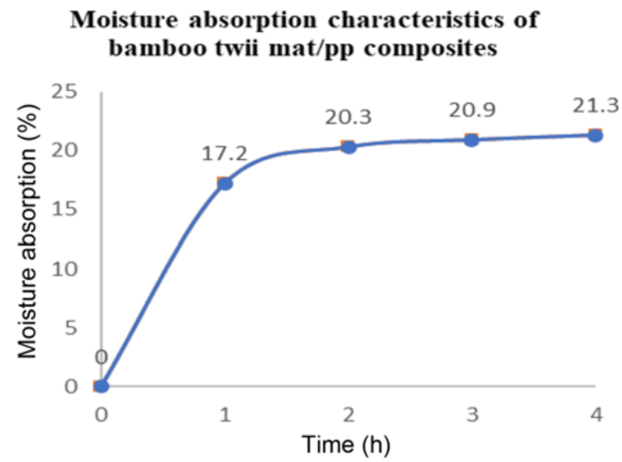

Figure 12. Moisture absorption of twill WBF/PP composites.

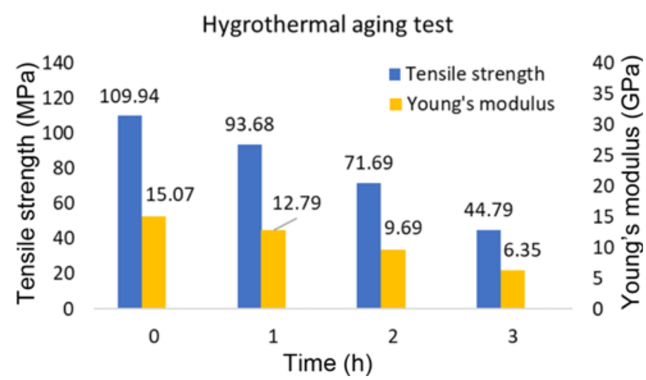

Figure 13. Changes in tensile properties of twill weave WBF/PP composites in 0-degree direction as soaking in the boiling water.

Woven Bamboo Fiber Preform and Composite

The twill weave bamboo fiber was formed into a cylindrical shape with a tool shown in Figure 3 with or without spacers. For the dry WBF, large spring back was noticed as the radius of curvature was about 60 mm as compared to the radius of curvature of 30 mm at the mold. As water was sprayed on the woven fiber for about 60 s, the moisture can reach 50 %, and the resulted preform had a radius of curvature of 30 mm which is the same as that of the

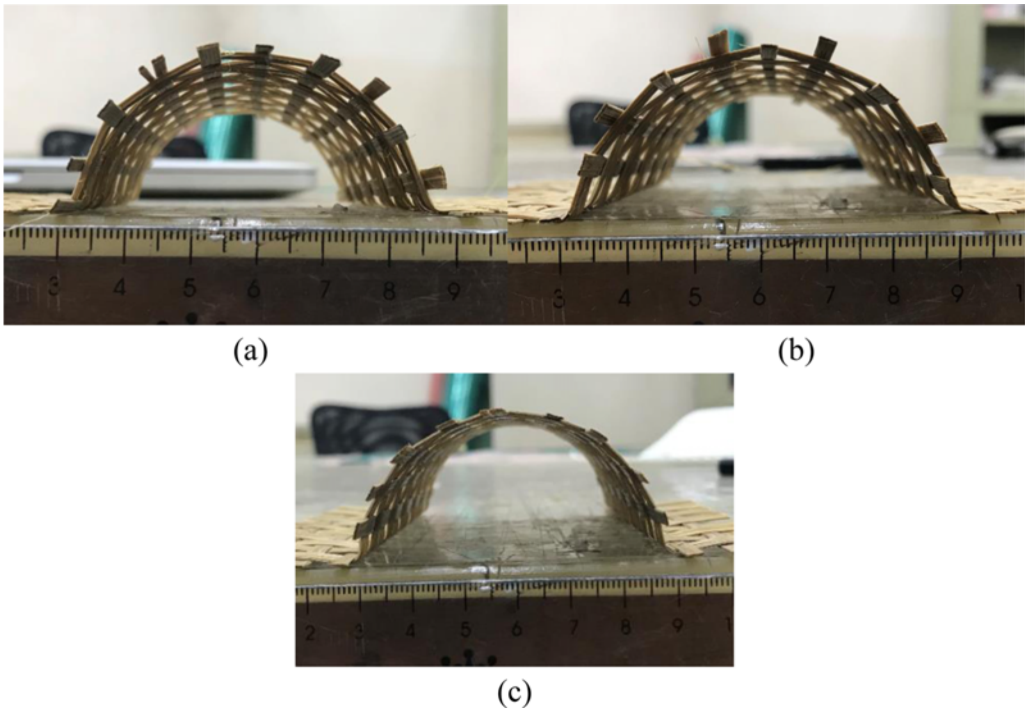

Figure 14. Radius of curvature of the preforms using (a) 3 mm, (b) 6 mm, and (c) no spacers.

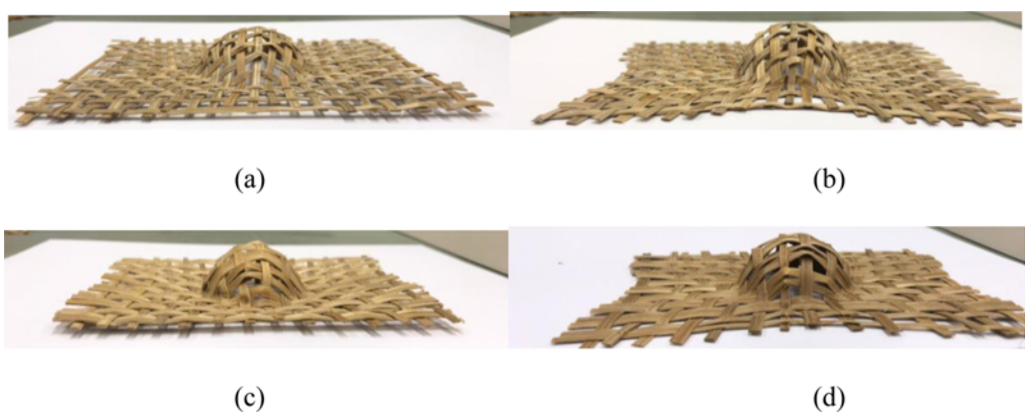

Figure 15. Bamboo preform after forming (a) dry plain weave bamboo mat, (b) wet plain weave bamboo mat, (c) dry twill weave bamboo mat, and (d) wet twill weave bamboo mat.

mold. It was concluded that the WBF can be preformed perfectly at the current shape under the moisture condition of 50 %. To further vilify the process, the WFM was formed with spacers (3 or 6 mm in thickness) between the upper and lower mold half. The resulting preforms are shown in Figure 14 together with the preform without using spacers. The radii of curvature of the preform are about 30.5, 31.0, and 30 mm respectively for 3 mm, 6 mm, and no spacers. No obvious spring back was observed in the preform.

Figure 15 shows the photographs of the twill and plain weave bamboo mats after preforming under the dry (a, c) or wet (b, d) condition. The results show that the radius of curvature of dry bamboo preform is larger than wet bamboo mats and confirm to the tool shape. The dry bamboo preform shows some spring back after forming. This further demonstrates that it is possible to form the woven bamboo fibers into shape with double curvatures. Moisture can soften the bamboo strips in the woven bamboo mat and make it possible to form the bamboo mat into a complex geometric shape. It is noticed that there are certain areas where shows buckling of the bamboo strips. Since the preform mold is one side instead of a matched mold, the bamboo cannot sustain compression stress. Further study is necessary to characterize the preforming process for woven

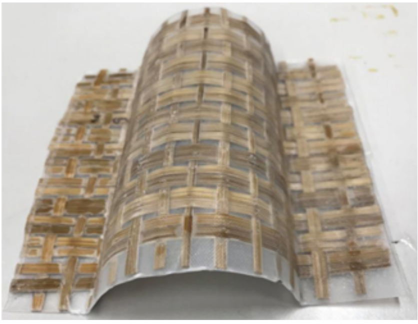

Figure 16. Bamboo fiber composite in cylindrical shape.

bamboo fibers with a matched mold.

A cylindrical woven bamboo fiber composite was fabricated using the thermoforming and bamboo preform as shown Figure 16. This demonstrates the practice of composite fabrication using the bamboo preform and PP in a non-planar component shape.

Conclusion

The woven bamboo fiber reinforced PP composites were investigated in this study. For the bamboo strip, the tensile properties do not vary much in a width from 1 to 6 mm with a thickness around 0.6 mm (after alkali treatment). The bamboo strips with 4 mm in width was used to construct the woven bamboo fiber in both plain and twill types. A thermoforming process was successfully used to fabricate woven bamboo fiber composites. The woven bamboo fiber composites show about the same tensile properties in both the directions. The twill weave composite has higher tensile properties along the 0-degree direction due to the more fibers along this direction.

The WBF/PP composites are sensitive to the moisture, which will degrade mechanical property. On the other hand, the wet bamboo is necessary in the preforming process in order to enhance the deformation of the bamboo fibers. Composite fabrication using the bamboo preform and PP in a non-planar component shape was also successfully practiced. The woven bamboo fiber preforms in both the cylindrical and spherical shapes were made by thermoforming in the wet condition.

Acknowledgement

The authors would like to thank for the financial support from Ministry of Science and Technology in Taiwan under the contract number of MOST 108-2221-E-006-068.

References

1. J. Hobson and M. Carus, *JEC*, Paris, France: JEC Composite, **63**, 31 (2011).
2. Q. Liu, T. Stuart, M. Hughes, H. Sharma, and G. Lyons, *Compos. Part A: Appl. Sci. Manuf.*, **38**, 1403 (2007).
3. L. Yan, N. Chouw, and K. Jayaraman, *Compos. Part B: Eng.*, **56**, 296 (2014).
4. S. Chakraborty, S. P. Kundu, A. Roy, B. Adhikari, and S. Majumder, *Constr. Build. Mater.*, **49**, 214 (2013).
5. S. M. Islam, R. R. Hussain, and M. A. Z. Morshed, *J. Compos. Mater.*, **46**, 111 (2012).
6. M. Mansur and M. Aziz, *International Journal of Cement Composites and Lightweight Concrete*, **4**, 75 (1982).
7. X. Li, Y. Li, Z. Zhong, D. Wang, J. A. Ratto, K. Sheng, and X. S. Sun, *Bioresour. Technol.*, **100**, 3556 (2009).
8. E. C. Ramires, J. D. Megiatto Jr, C. Gardrat, A. Castellan, and E. Frollini, *Bioresour. Technol.*, **101**, 1998 (2010).
9. N. Reddy and Y. Yang, *Bioresour. Technol.*, **100**, 3563 (2009).
10. M. Das and D. Chakraborty, *J. Appl. Polym. Sci.,* **107**, 522 (2008).
11. S. Amada, Y. Ichikawa, T. Munekata, Y. Nagase, and H. Shimizu, *Compos. Part B: Eng.*, **28**, 13 (1997).
12. W.-B. Young and Y.-C. Tsao, *J. Compos. Mater.*, **49**, 2803 (2015).
13. T.-N. Chou and W.-B. Young, *J. Aeronaut. Astronaut. Aviat.*, **50**, 237 (2018).
14. J.-K. Huang and W.-B. Young, *Compos. Part B: Eng.*, **166**, 272 (2019).
15. S. Ochi, *Int. J. Compos. Mater.*, **2**, 1 (2012).
16. R. Sukmawan, H. Takagi, and A. N. Nakagaito, *Compos. Part B: Eng.*, **84**, 9 (2016).
17. H. Takagi and Y. Ichihara, *JSME Int. J. Series A Solid Mech. Mater. Eng.*, **47**, 551 (2004).
18. A. Karmaker, *J. Mater. Sci. Lett.*, **16**, 462 (1997).
19. M. M. Thwe and K. Liao, *Compos. Sci. Technol.*, **63**, 375 (2003).
20. R. S. Mbakop, G. Lebrun, and F. Brouillette, *Compos. Part A: Appl. Sci. Manuf.*, **109**, 604 (2018).
21. R. Hao and W. Liu, *Furniture & Interior Design*, **4**, 13 (2014).
22. H.-H. Chiu and W.-B. Young, *Fiber. Polym*., **21**, 2938 (2020).
23. S. Jain, R. Kumar, and U. Jindal, *J. Mater. Sci.*, **27**, 4598 (1992).
24. S. K. Samal, S. Mohanty, and S. K. Nayak, *J. Reinf. Plast. Compos.*, **28**, 2729 (2009).
25. K. Okubo, T. Fujii, and Y. Yamamoto, *Compos. Part A: Appl. Sci. Manuf.*, **35**, 377 (2004).
26. A. K. Bledzki and J. Gassan, *Prog. Polym. Sci.*, **24**, 221 (1999).
27. H. N. Dhakal, Z. Y. Zhang, and M. O. W. Richardson, *Compos. Sci. Technol.*, **67**, 1674 (2007).
28. A. Stamboulis, C. A. Baillie, and T. Peijs, *Compos. Part A: Appl. Sci. Manuf.*, **32**, 1105 (2001).
29. W. Chunhong, L. Shengkai, and Y. Zhanglong, *J. Reinf. Plast. Compos.*, **35**, 1062 (2016).