E-ISSN: 2829-7687
Journal of Fibers and Polymer Composites
Vol. 4 No. 1 (2025): 68-80

Tailored Fiber Alignment in Holed Bamboo Fiber Reinforced Plates

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Abstract. *Natural fiber composites have proven elusive to large scale use in industry due to their lower mechanical properties than glass or carbon fibers despite their low cost, natural availability, and sustainable sourcing. A method to overcome this obstacle is by placing the fibers in the optimum orientation to best resist the stresses the component is subjected to. This is achieved through a simple analysis of the part's stress distribution and then using the Tailor Fiber Placement (TFP) process to orient the fibers to optimally resist these stresses. In this study holed Bamboo-Polyester Composite Plates (BPCP) were made using Vacuum Assisted Resin Transfer Molding (VARTM), compression molding and TFP processes. Different fiber orientations and crack resistance patterns were devised to compare the performance of the natural fibers to drilled Fiber Glass Chopped Strand Matts (FGCSM). The study showed that for a tensile test of a rectangular composite plate with a fiber content of 25% Volume, the holed BPCP exhibited a 65 MPa tensile strength and 1.75% strain, which is 172% and 145% of that of a comparable drilled FGCSM plate with the same fiber volume fraction respectively.*
Keywords: *Natural Fiber Composite; Tailor Fiber Placement; Bamboo Natural Fiber.*

Type of the Paper: Regular Article.

1. Introduction

Light-weighting is one of the primary goals in vehicle design and manufacturing. However, this practice was not considered from the lens of sustainability until recent decades [1]. OEMs and third tier manufacturers are now seeking methods to reduce the weight of their parts and overall final products in an effort to conserve the materials used, the amount of energy expended in processing and manufacturing those parts. Companies also have a vested interest in reducing the weight of their vehicles, in an effort to reduce the per mile fuel consumption and increases the range of those vehicles. All of these issues, along with the environmental impacts associated with the sourcing of the materials used in structural components in vehicles have become front and center in the strategic plans for automotive corporations [2,3]. Accordingly, composite parts that are lightweight, have a relative high stiffness and are sustainably sourced are growing to be the prime candidates to replace metallic and weighty polymeric components in vehicles [3,4].

With regards to the sourcing of the fiber component in the composite, improvement efforts for greater sustainability involve replacing the synthetic fibers, such as Glass Fiber (GF) or Carbon

https://doi.org/10.55043/jfpc.v4i1.238
Received February 8, 2025; Received in revised form March 27, 2025; Accepted March 27, 2025; Published March 29, 2025
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Fiber (CF), with natural fibers sourced from plants [5]. This not only offers the opportunity for sourcing the fiber component in a sustainable way, but also works toward actively removing carbon dioxide from the atmosphere. In opposition to synthetic fibers, natural fibers act as carbon sinks, as they capture carbon in the plant material during their life cycle, ultimately trapping it in the fibers, which are later used to create the composite material [6,7].

Natural plant fibers have not experienced widespread adoption in industry due to supply chain concerns, as well as concerns over the extent of processing the fibers would need to undergo before they are ready to be optimally used as reinforcing components in composites [8]. More crucially however, is the concern over the mechanical strength and performance of the natural fibers compared to synthetic ones, where GF usually has a tensile strength of 3.5 GPa and a modulus of 70 GPa, with composites made from chopped GF strand mat reinforced thermosets routinely reaching tensile strengths of 100-250 MPa and moduli of 325-3000 MPa. CF usually exceeds these limits with tensile strengths of 4 GPa and a modulus of 230 GPa while in fiber format [9–11]. On the other hand, Natural fibers such as those sourced from bamboo, cotton, or hemp exhibit tensile strengths that range from 287-1110 MPa and moduli ranging from 5-70 GPa [9,12,13], with their composite forms experiencing an even further reduction in strength depending on the matrix material used. This disparity between the performance of traditional natural and synthetic fibers can present a significant barrier to adopting natural fibers on a large scale in the industry, especially in fields where even fractional differences in the mechanical performance of components can cause have a large impact on the overall performance of the greater assembly, such as in the fields of automotive and aerospace [14,15].

Regardless of the disparity in performance, plant fibers are still actively being used as substitutes for synthetic materials in the automotive market by global leaders such as Ford, Mitsubishi, and Mercedes in interior applications and door panels [16]. However, components made from natural fiber composites are commonly manufactured utilizing the same process as their synthetic fiber counterparts resulting in the finished product having a lower-strength [17]. This reduction in strength is considered as an acceptable trade off given the increase in sustainability, which as mentioned, has become a more central goal for automotive manufacturers [18,19].

Natural fibers however need not compete with synthetic fibers in the applications where a high strength to weight ratio is critical. Instead, there are several areas in automotive manufacturing where composite materials of medium strength are widely used, such as in panelling, fenders and outer body structures [20,21]. These areas routinely use chopped strand mats that are made with hand layups and are infused with resin by simply pouring and dousing the mats with the resin prior and after laying them in place [22,23]. This method of manufacturing creates components with low fiber volume fractions and it is understood that the failure regimes in these parts would originate in the resin rich areas in the matrix [24].

Bamboo is a natural composite which is comprised of cellulose fibers held together by a lignin and hemicellulose matrix, with The cellulose fibers are the load-bearing component in this composite [25]. In bamboo, thousands of cellulose fibers run along the entire length of the bamboo culm which can be as long as 40 m [25,26]. Additionally, a higher concentration of cellulose fibers near the outer wall improves the stem's flexural rigidity [27]. Bamboo fiber is a commonly produced and used in the textile industry and is coveted for its smoothness and ease of production. The bamboo plant is native to every continent containing tropical and subtropical regions and is famous for its rapid growth which can be up to 30 cm per day for some species [28]. Accordingly, the sourcing of the bamboo fibers can be industrially scaled with little concerns of the depletion of its supply [29].

Joining of composite components by attaching metallic brackets to bear the joining loads caused by the threads of fasteners or in riveting, as machining operations such as drilling and milling, can cause defects such as delamination, to arise in the machined area, which further compromises the strength of the component [30,31]. A solution to this is to create the composite layup with the holed area for joining readily vacant. This can be achieved through the process known as Tailored Fiber Placement (TFP), which is an optimization technique that gives designers the ability to specify the direction, length, and orientation of fibers (straight or curved) on multiple layers within a composite material [32]. When properly placed, this process allows for stronger and lighter composites compared to short fiber composites or even conventional continuous straight fiber composites by capitalizing on the fiber's anisotropic properties [33,34]. This is primarily done by utilizing a tow-steered embroidery machine that lays and stitches the fiber according to a blueprint input onto a sheet of fabric to maintain the desired orientation of fiber throughout the layup [32]. This offers an automated process that is quick and repeatable [35] while also being highly efficient as there is minimal post-processing after the fibers have been laid [36]. The real benefit of utilizing TFP comes from understanding the proposed part's load path. Through this understanding, the fibers can be placed along these load paths which maximizes the overall efficiency of material use in the part. Composites with fibers stitched around the holed area can withstand up to 180% the loads of a similar drilled composite part [37]. This becomes of greater relevance when it comes to joining the composite components made with chopped strand mats, as drilling can cause significant damage due to load-carrying fibers being cut during the drilling process [36].

In this study we focus on the production and placement of bamboo fibers, as the reinforcing element in fiber reinforced composite plates. The goal is to investigate the extent in which the use of the TFP technique can improve the performance of holed strand mat composites created from bamboo fibers reinforcing a polyester matrix and bridge the gap between the performance of the natural fiber and synthetic fibers. A comparison is made using glass fiber chopped strand mats to form the baseline for the standard behavior of synthetic fiber strand mats. This will help highlight a wider scope of behavior for the fibers in both their drilled and intact states, in terms of their performance within the composite matrix. Different types of bamboo fibers were used and tested to showcase a wider variety in scope and behavior of bamboo fiber reinforced thermoset composites, which will also highlight the extent to which different processing methods of the fiber can influence the overall behavior.

2. Materials and methods

2.1. Fibers Used

Various types of composite samples were created to establish a proper comparative analysis, which includes, Chopped Strand Glass Fiber (GF), Chopped Strand Bamboo Fiber sourced using three different techniques, mechanically (MBF), by combing of bamboo top, producing Viscose Bamboo Top (VBF) and through a Chemical delignification process producing Chemically delignified Bamboo Fiber (CBF), as shown in Fig. 1.

Fig. 1. Different types of bamboo fiber used in study, with a) being the VBF, b) being showing the MBF and c) showing the CBF

2.1.1. Glass fiber

The GF was acquired from Fiber Glast (TM) in mat form with an average fiber length of 1 in, and had an area density of 1.5 oz/ft2.ˆ

2.1.2. Viscose Bamboo Fiber

VBF shown in Fig. 1-a is created using commercial textile manufacturing techniques accordingly, they were acquired form Hearthside Fibers. The fibers were then cut to a the length of 2 in.

2.1.3. Mechanical Bamboo Fiber

MBF were created mechanically by separating the culm into narrow sections along the circumference. The fibers in each section were frayed apart by crushing the laterally crushing the segments and manually extracting individual fibers. This produced fiber bundles that varied in length and diameter, as shown in Fig. 1-b. This variance is common for bamboo fiber produced utilizing this method, however, these effects were exaggerated for this test due to them being hand produced. The average fiber length was between 3-5 in.

2.1.4. Chemical Bamboo Fiber

CBF shown in Fig.1-c was created using a similar delignification technique as that used in [12]. The bamboo stalk was chopped down into thin strips, which were randomly oriented to allow for the production of randomly oriented fiber mats upon the completion of the reaction. A higher concentration of peroxyformic acid was used (90% wt), which caused the eruption of a highly exothermic reaction. The products of the reaction were cellulose macro fibers, along with lignin which were manually separable as shown in Fig. 2-a. The final fibers could be compressed into randomly oriented mats which are then used for resin infusion, as shown in Fig. 2-b.

a)  b) 

Fig. 2. a) Lignin manually removed from CBF produced by chemical delignification process b) CBF matts created by the chemical delignification and compaction.

2.2. Sample Preparation

Samples of GF and Bamboo were prepared to match the parameters outlined in ASTM D3039 and ASTM D5677. In order to minimize the potential for inconsistency in behavior, which may arise from random defects during infusion, the Vacuum Assisted Resin Transfer Molding (VARTM) process was utilized to ensure the resin transfer process was as consistent as possible. Due to disparity in fiber compaction, fiber size and bulk fiber behavior, the infusion process yielded parts with varying dimensions and fiber-matrix volume fractions. Two resin systems were used, SC-15 from Kaneka, which is an Epoxy Infusion resin and ENVIREZ™ MR 56301 from INEOS, which is a Recycled Content Polyester Resin.

Table 1. VARTM Samples Fiber Volume fraction

Fiber Type	Fiber Volume Fraction (%)
GF	55
MBF	15
CBF	26
VBF	29

Due to differences in dry fiber compaction levels pre-infusion, a notable disparity in the fiber volume fraction was measured in the plates made from the different types of fiber using VARTM, as shown in Table 1. Accordingly, in order to ensure that the consolidation levels were similar across the different fiber types, a different process was used for the creation of samples, where the fibers were first mixed with the resin by hand and then were consolidated into a 10x10" plate using a compression platen and a picture frame mold. At the high pressures of the compression mold (CM), the excess resin oozes out, ensuring that the fiber to resin ratios remain comparable across different composite mixtures which averaged around

Due to the difficulty of creating a fiber tow of consistent quality for TFP using either the mechanical or chemical processes, the use of the MBF and CBF was discontinued for the TFP portion of the study.

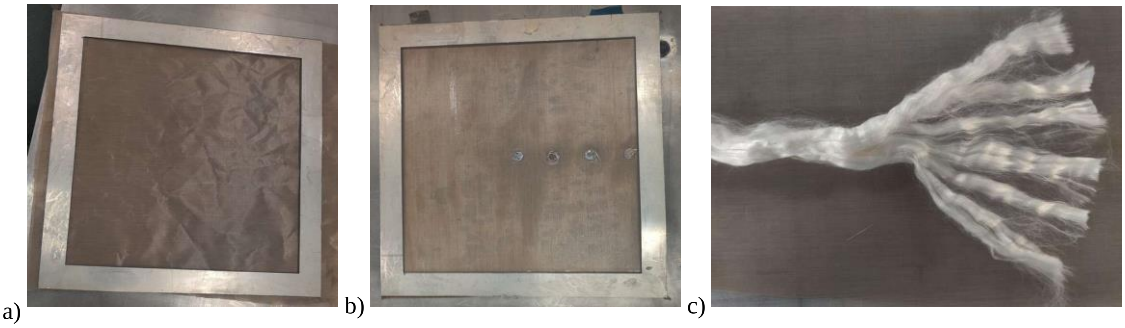

Fig. 3. a) Flat picture frame mold with no pegs, b) Mold with pegs wrapped in teflon tape to hold inserts in place and maintain dimensional consistency of holes and c) showing initial tow which is then separated into smaller tows that can be used in the TFP process.

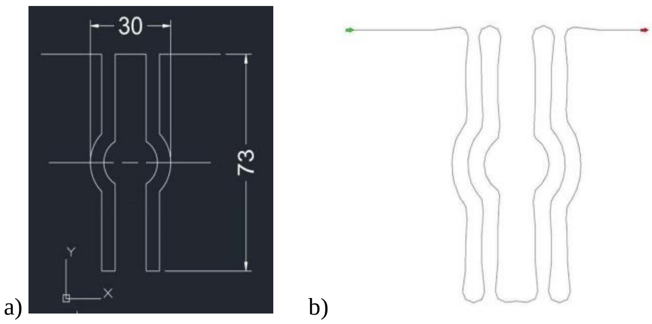

Fig. 4. a) showing Autocad drawing of pattern with 2 tows for reinforcement b) showing Edopath pathway for TFP stitching for 3 tows of reinforcement.

For the manufacturing process in the compression platen, two types of picture frame molds were made, one of which was used for the manufacturing of samples for the standards ASTM D3039 and ASTM D5677 and another mold for the samples that contain the TFP reinforcing insert made from the Bamboo Tow, as shown in Fig. 3-a and b. The tow that was used in the TFP machine was mas made by separating the large tow received from the supplier into smaller tows of suitable dimension to pass through the guide as shown in Fig. 3-c.

The TFP process was planned by first creating a digital twin on ABAQUS CAE and investigating the size of the area affected by the stress concentration that will occur around the hole. The problem was defined as a plane stress problem and a finer mesh was given to the area surrounding the hole for greater accuracy. The material behavior was considered homogeneous given the random distribution of fiber expected in chopped strand mats. Upon initial testing of the samples, it was observed that the failure was not consistently occurring in the region surrounding the hole, but rather in other solid areas of the gauge, which can be attributed to the presence of resin rich areas. To mitigate this effect, 10 mm holes were drilled into the samples instead of the standard specified 6 mm to further augment the stress concentration that the holed area experiences. A pattern for the TFP reinforcement which will be used to reinforce the affected area was created on AutoCad and the TFP process was planned using EDOpath software as shown in Fig. 4. The pattern was then stitched using the Laystitch Machine and consisted of a single layer, which extracted, each creating a single insert. Each sample contained three layers of the reinforcement inserts, which accounted for the entirety of the gauge length. The fibers were however frayed at the ends to insure a smooth transition of stress from the TFP fibers to the rest of the fibers in the samples, leading to an effective reinforced region extending to around 60% of the gauge length, as shown in Fig. 5-a-c. Given that the resulting strength were not up to desired levels, the old pattern with two tows of fiber per side was replaced with a new pattern with three tows of fiber per side.

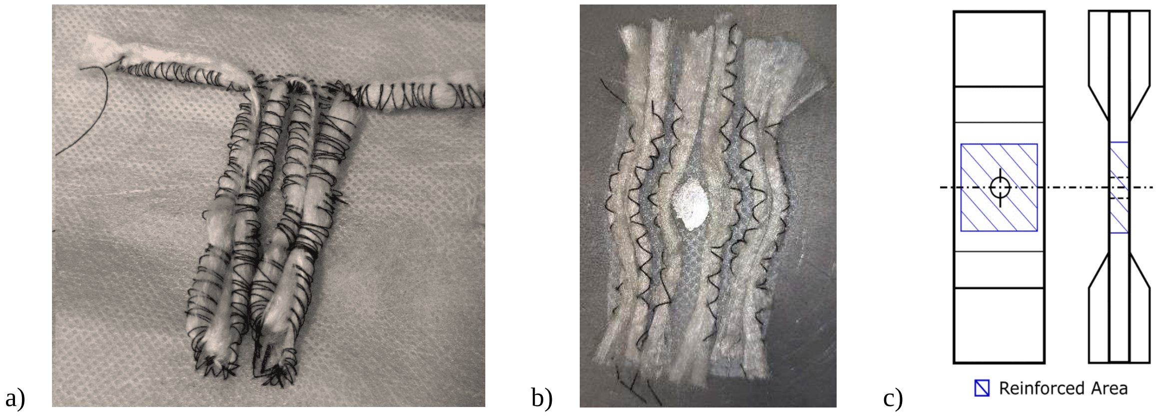

Fig. 5. a)Showing bamboo fiber path prepared by TFP machine, b) showing inserts used in molds, c) showing the region covered by the reinforcing insert

Due to the now increased fiber density from the TFP patterns, the interface between the reinforcing fibers and the chopped fibers was too sudden, causing a loss in strength, as it produced a resin rich area. Accordingly, a different pattern was created where the reinforcement fibers spanned 100% of the sample, now denoted FULL TFP as shown in Fig. 6-a and b.

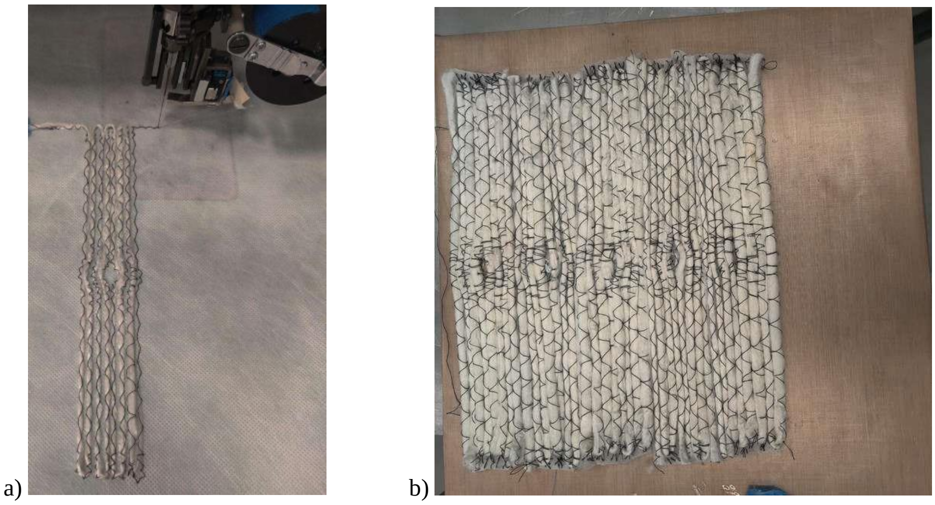

Fig. 6. a) showing FULL TFP pattern as made in the Laystitch machine b) showing FULL TFP samples placed in mold.

3. Results and Discussion

3.1. Fiber Properties

The first set of results that came from the VARTM prepared samples showed a wide variation in behavior between GF and the different varieties of bamboo fiber plates. It is important to note that this was expected given the large difference in fiber/resin volume fractions between the different plates. However, by adjusting for this using the rule of mixtures and normalizing the moduli value of original glass fiber, we are able to deduce the predicted moduli of the different variations of bamboo fiber and as it shows that in-fact bamboo fibers have a relatively equivalent modulus to that of the GF as shown in Table 2.

Table 2. Fiber Moduli

Fiber Type	Resin Modulus (GPa)	Fiber Volume Fraction(%)	Normalized Composite Modulus (GPa)	Fiber Modulus (GPa)
GF	3.25	55	41	72
MBF	2	15	18	80
CBF	3.25	26	22	68
VBF	3.25	29	17.5	50

The remainder of the tensile tests throughout this study were performed on the samples prepared with the compression mold.

In order to determine whether natural fiber composites with TFP reinforcement can compete with traditional chopped-strand glass fiber composites after both materials have been drilled, it was imperative to understand the mechanical properties of the various natural fiber in their pristine states. As shown in Fig. 7 GF plates exhibit a behavior with relatively higher mechanical strength and stiffness than those prepared with the different types of bamboo fiber. The preliminary tests showed that CBF and MBF had higher elastic modulii than VBA with CBF being the highest of the three. MBF held the highest strain (%) of the natural fibers; which given the pristine nature of the fiber can be attributed to the lack of damage in the individual fibrils from processing, meaning that a greater percent of the damage sustained in the fiber is mechanically driven relative to the other forms of fiber, which leads to higher overall toughness level in the fiber. VBF had the least favorable mechanical properties of all the natural fiber forms which can be understood in light of the higher levels of damage the fibrils sustain during their mechanical processing.

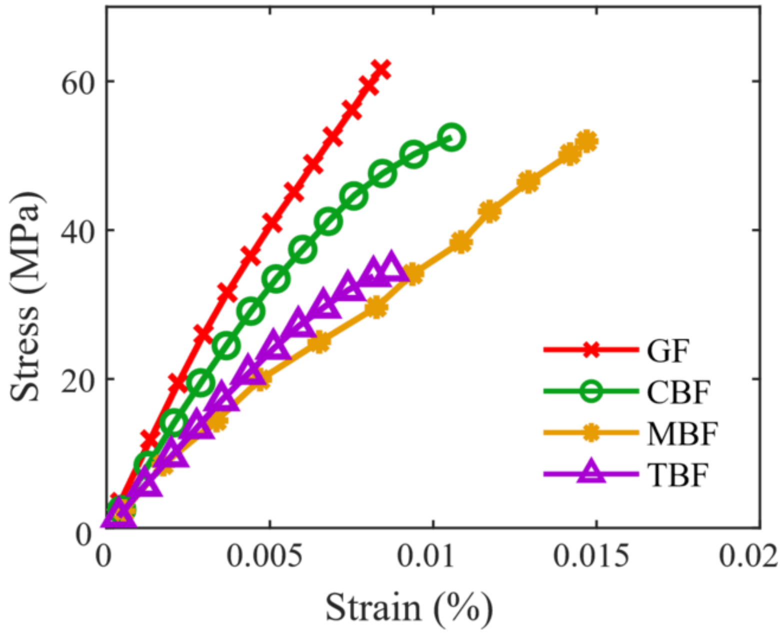

Fig. 7. Showing a comparison of tensile behavior of GF to VBF samples prepared by both VARTM and CM

3.2. Machining Damage Response

After the investigation into the pristine behavior of the composites has been concluded, we are able to proceed with studying their behavior after being compromised by the machining operation of drilling. This provides a more elaborate understanding of the resilience of the fiber types and how they respond to damage withing their respective composite systems. As shown in Fig. 8, the drilling of a hole into all of these various composite material types reduces their mechanical performance, with the highest reduction in strength exhibited by GF and the lowest by VBF. This can be understood in light of the effects caused by the additional stress concentrations introduced by the hole. The reduction in strength caused by the hole for each material can be seen in Table 3.

Table 3. Geometry of Samples

Fiber type	Reduction in strength (%)
GF	39.5
CBF	29.75
MBF	23.33
VBF	13.8

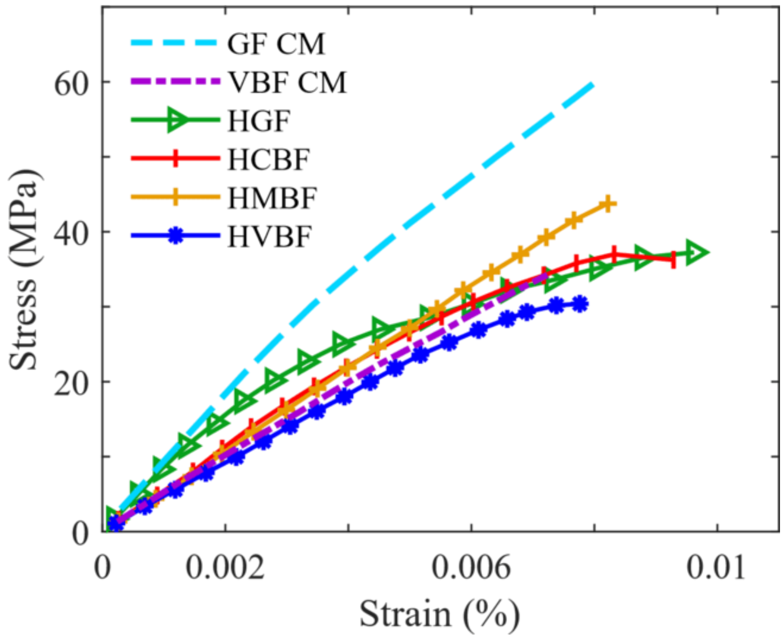

Fig. 8. Showing a comparison of the tensile behavior of pristine samples to those with drilled holes denoted H(fiber type).

3.3. Tailor Fiber Placement Reinforcement

By introducing TFP reinforcement the stress concentrations around the holed area were indeed reduced, as there was no interruption of the flow of stress around the holes and failure in the samples occurred outside of the stress affected region. However even with the use of the three tow per side pattern, the samples were still compromised by the transition area between the TFP reinforcement and chopped fiber, due to the abrupt change in fiber distribution and alignment. A fact which prevented the samples from regaining the strength lost as a result of the drilling process. By replacing the reinforcement pattern with one that extended the entire length of the sample (TFP FULL), the VBF sample not only regained it's original pre-drilling strength, but also surpassed it and that of the pristine GF sample for the same fiber volume fraction across the different configurations. With an increase in ultimate strength of over 112% and in ultimate strain of 126%. The stiffness of the composite expressed in it's modulus remained practically constant, as VBF has a higher level of elasticity and toughness compared to GF as demonstrated in Fig. 9.

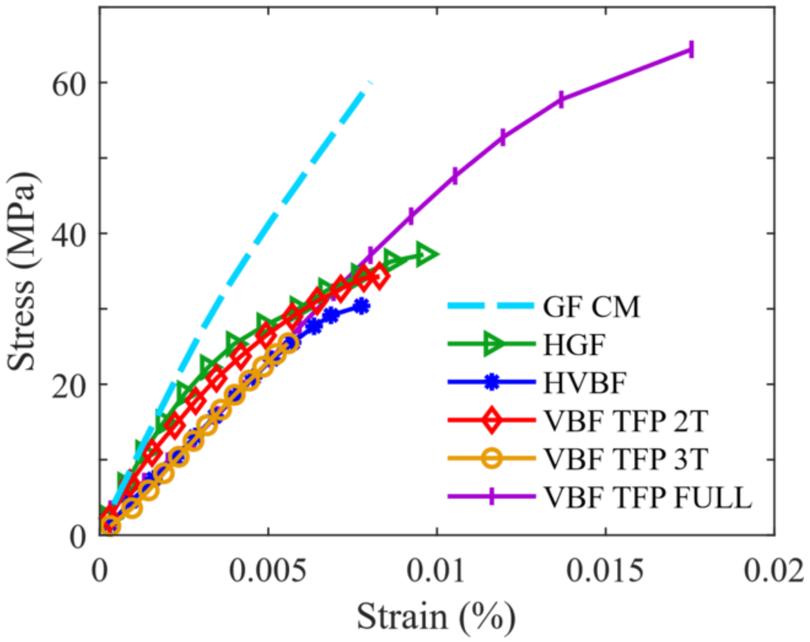

Fig. 9. Showing a comparison between the tensile properties of the GF samples vs that of TFP reinforced VBF samples.

4. Conclusions

Through this study it can be concluded that even though natural fibers may not have comparable strength levels to synthetic fibers, especially when synthetic fibers are in their typical consolidation levels when produced at an industrial scale. Natural fibers have many qualities that allow them to even surpass the properties of synthetic fibers when appropriately processed and manufactured. It has been shown that even while using the format of bamboo fibers with the lowest tensile strength, it is possible to extend its mechanical properties beyond that of GF using TFP, and incorporating it into the final sample manufacturing and preparation. This study also shows that when it comes to the use of natural fibers, the behavior is fairly similar to synthetic fibers when compared in their "non-ideal" environments, such as in compression molding, hand layups and open air laminating techniques. This is in large due to the matrix dominated properties these manufacturing methods produce, which can be compromised just as much by the defects caused by manufacturing, as much as those which originate from machining and post processing.

Acknowledgement

We would like to acknowledge the composite vehicle research center at MSU for its contribution to the research effort conducted in this study through equipment and materials.

We would also like to acknowledge the contributions of Garret Colasinski in aiding with fiber preparation and lamination efforts.

References

[1] Faruk O, Bledzki AK, Fink H-P, Sain M. Progress Report on Natural Fiber Reinforced Composites. Macromol Mater Eng 2014;299:9–26. https://doi.org/10.1002/mame.201300008.

[2] Lau K, Hung P, Zhu M-H, Hui D. Properties of natural fibre composites for structural engineering applications. Compos B Eng 2018;136:222–33. https://doi.org/10.1016/j.compositesb.2017.10.038.

[3] Chauhan V, Kärki T, Varis J. Review of natural fiber-reinforced engineering plastic composites, their applications in the transportation sector and processing techniques. Journal of Thermoplastic Composite Materials 2022;35:1169–209. https://doi.org/10.1177/0892705719889095.

[4] Verma D, Sharma S. Green Biocomposites: A Prospective Utilization in Automobile Industry, 2017, p. 167–91. https://doi.org/10.1007/978-3-319-49382-4_8.

[5] Saheb DN, Jog JP. Natural fiber polymer composites: A review. Advances in Polymer Technology 1999;18:351–63.

[6] Sanjay MR, Arpitha GR, Naik LL, Gopalakrishna K, Yogesha B. Applications of Natural Fibers and Its Composites: An Overview. Natural Resources 2016;07:108–14. https://doi.org/10.4236/nr.2016.73011.

[7] Girijappa YGT, Rangappa SM, Parameswaranpillai J, Siengchin S. Natural Fibers as Sustainable and Renewable Resource for Development of Eco-Friendly Composites: A Comprehensive Review. Front Mater 2019;6. https://doi.org/10.3389/fmats.2019.00226.

[8] Fuqua MA, Huo S, Ulven CA. Natural Fiber Reinforced Composites. Polymer Reviews 2012;52:259–320. https://doi.org/10.1080/15583724.2012.705409.

[9] Rahman R, Putra SZFS. Tensile properties of natural and synthetic fiber-reinforced polymer composites. Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites, Elsevier; 2019, p. 81–102. https://doi.org/10.1016/B978-0-08-102292-4.00005-9.

[10] Jagannatha TD, Harish G. Mechanical properties of carbon/glass fiber reinforced epoxy hybrid polymer composites. Int J Mech Eng & Rob Res 2015;4:131–7.

[11] Fu SY, Lauke B, Mäder E, Yue CY, Hu X. Tensile properties of short-glass-fiber- and short-carbon-fiber-reinforced polypropylene composites. Compos Part A Appl Sci Manuf 2000;31:1117–25. https://doi.org/10.1016/S1359-835X(00)00068-3.

[12] Li Z, Chen C, Xie H, Yao Y, Zhang X, Brozena A, et al. Sustainable high-strength macrofibres extracted from natural bamboo. Nat Sustain 2021;5:235–44. https://doi.org/10.1038/s41893-021-00831-2.

[13] Liu D, Song J, Anderson DP, Chang PR, Hua Y. Bamboo fiber and its reinforced composites: structure and properties. Cellulose 2012;19:1449–80. https://doi.org/10.1007/s10570-012-9741-1.

[14] Holbery J, Houston D. Natural-fiber-reinforced polymer composites in automotive applications. JOM 2006;58:80–6. https://doi.org/10.1007/s11837-006-0234-2.

[15] Mrazova M. Advanced composite materials of the future in aerospace industry. INCAS BULLETIN 2013;5:139–50. https://doi.org/10.13111/2066-8201.2013.5.3.14.

[16] Hoque ME, Rayhan AM, Shaily SI. Natural Fiber-based Green Composites: Processing, Properties and Biomedical Applications. Applied Science and Engineering Progress 2021. https://doi.org/10.14416/j.asep.2021.09.005.

[17] Lokesh P, Kumari TSAS, Gopi R, Loganathan GB. A study on mechanical properties of bamboo fiber reinforced polymer composite. Mater Today Proc 2020;22:897–903. https://doi.org/10.1016/j.matpr.2019.11.100.

[18] Mayyas A, Qattawi A, Omar M, Shan D. Design for sustainability in automotive industry: A comprehensive review. Renewable and Sustainable Energy Reviews 2012;16:1845–62. https://doi.org/10.1016/j.rser.2012.01.012.

[19] Szász L, Csíki O, Rácz B-G. Sustainability management in the global automotive industry: A theoretical model and survey study. Int J Prod Econ 2021;235:108085. https://doi.org/10.1016/j.ijpe.2021.108085.

[20] Koronis G, Silva A, Fontul M. Green composites: A review of adequate materials for automotive applications. Compos B Eng 2013;44:120–7. https://doi.org/10.1016/j.compositesb.2012.07.004.
[21] Akampumuza O, Wambua PM, Ahmed A, Li W, Qin X. Review of the applications of biocomposites in the automotive industry. Polym Compos 2017;38:2553–69. https://doi.org/10.1002/pc.23847.
[22] Caprino G. Short-fibre thermoset composites. Fatigue in Composites: Science and Technology of the Fatigue Response of Fibre-Reinforced Plastics, 2003, p. 269.
[23] Mariatti M, Chum PK. Effect of Laminate Configuration on the Properties of Glass Fiber-reinforced Plastics (GFRPs) Mixed Composites. Journal of Reinforced Plastics and Composites 2005;24:1713–21. https://doi.org/10.1177/0731684405051654.
[24] Harris B. Fatigue in composites: science and technology of the fatigue response of fibre-reinforced plastics. Woodhead Publishing; 2003.
[25] Lakkad SC, Patel JM. Mechanical properties of bamboo, a natural composite. Fibre Science and Technology 1981;14:319–22. https://doi.org/10.1016/0015-0568(81)90023-3.
[26] Kozlowski R, Wladyka-Przybylak M. Uses of Natural Fiber Reinforced Plastics. Natural Fibers, Plastics and Composites, Boston, MA: Springer US; 2004, p. 249–74. https://doi.org/10.1007/978-1-4419-9050-1_14.
[27] Mbuge DO. Mechanical properties of bamboo (Bambusa vulgaris) grown in Muguga, Kenya. University of Nairobi, 2000.
[28] Kleinhenz V, Midmore DJ. Aspects of bamboo agronomy, 2001, p. 99–153. https://doi.org/10.1016/S0065-2113(01)74032-1.
[29] Qisheng Z, Shenxue J, Yongyu T. Industrial utilization on bamboo. International network for bamboo and rattan, 2002.
[30] Kobayashi A. Machining of plastics. RE Krieger Publishing Company; 1981.
[31] Belingardi G, Koricho EG, Beyene AT. Characterization and damage analysis of notched cross-ply and angle-ply fabric GFRP composite material. Compos Struct 2013;102:237–49. https://doi.org/10.1016/j.compstruct.2013.03.006.
[32] Mattheij P, Gliesche K, Feltin D. Tailored Fiber Placement-Mechanical Properties and Applications. Journal of Reinforced Plastics and Composites 1998;17:774–86. https://doi.org/10.1177/073168449801700901.
[33] Spickenheuer A, Schulz M, Gliesche K, Heinrich G. Using tailored fibre placement technology for stress adapted design of composite structures. Plastics, Rubber and Composites 2008;37:227–32. https://doi.org/10.1179/174328908X309448.
[34] Brooks TR, Martins JRRA, Kennedy GJ. High-fidelity aerostructural optimization of tow-steered composite wings. J Fluids Struct 2019;88:122–47. https://doi.org/10.1016/j.jfluidstructs.2019.04.005.
[35] Crosky A, Grant C, Kelly D, Legrand X, Pearce G. Fibre placement processes for composites manufacture. Advances in Composites Manufacturing and Process Design, Elsevier; 2015, p. 79–92. https://doi.org/10.1016/B978-1-78242-307-2.00004-X.
[36] Koricho EG, Khomenko A, Fristedt T, Haq M. Innovative tailored fiber placement technique for enhanced damage resistance in notched composite laminate. Compos Struct 2015;120:378–85. https://doi.org/10.1016/j.compstruct.2014.10.016.
[37] Khaliulin VI, Khilov PA, Toroptsova DM. Prospects of applying the tailored fiber placement (TFP) technology for manufacture of composite aircraft parts. Russian Aeronautics (Iz VUZ) 2015;58:495–500. https://doi.org/10.3103/S1068799815040236.