USING Z-AXIS MILLED FIBERS TO TOUGHEN CARBON FIBER COMPOSITES

Anvesh Gurijala, Robert D. Mone

Boston Materials, Inc.
Boston, MA

Chunzhou Pan, Dr. Randall M. Erb

Northeastern University
Boston, MA

ABSTRACT

Carbon fiber fabrics are surface-coated with Z-axis oriented milled carbon fibers and processed into 3-D reinforced prepregs. These milled carbon fibers provide Z-axis interlaminar reinforcement that increases compressive toughness by over 300% and compressive strength by 35% without any detriment to stiffness. These improvements are important for the construction of light yet durable bicycles that prioritize the safety of cyclists.

1. INTRODUCTION

Since 1999, every single winner of the Tour de France has used a carbon fiber bicycle.[1,2] Bicycle manufacturers rely on carbon fiber composites to deliver light, aerodynamic, and stiff bicycles to professional athletes and fitness hobbyists. These high-end bicycles have thin-wall construction, sub-millimeter thickness in some cases,[3] to reduce weight and drag without sacrificing stiffness in order to offer a competitive edge. Complex geometries coupled with thin-wall construction create stress profiles that put the toughness and durability of composite bicycles at risk.

In recent years, the adoption of carbon fiber composites has trickled into mass-market bicycles and has become available for commuters, leisure cyclists, and adolescents. Unfortunately, the poor toughness of carbon fiber composites remains an unsolved issue leading to unexpected and catastrophic component failures. Despite these material-level challenges, the performance gains provided by carbon fiber bicycles continues to increase the market share even despite the threat of product recalls. For example, in 2018, the United States Consumer Product Safety Commission reported the voluntary recall of 5,550 units (13,000 units worldwide) of a popular carbon fiber bicycle model due to unexpected cracking in the carbon fiber fork that posed a serious crash hazard.[4] A material-level solution to solve this underlying issue is a drastically tougher carbon fiber composite that gives the cyclist the ability to register a change in stiffness before total failure of the bicycle.

SAMPE Conference Proceedings. Charlotte, NC, May 20-23, 2019. Society for the Advancement of Material and Process Engineering – North America.

In this paper, Boston Materials offers a material-level solution for the carbon fiber bicycle market by reinforcing the interlaminar regions of standard carbon fiber composites with Z-axis oriented milled carbon fibers to form a "supercomposite" (**Figure 1**). To dramatically demonstrate the benefit of this approach, compression testing of carbon fiber laminates was conducted. The lack of toughness in carbon fiber laminates is exacerbated under compression, in which planar compressive forces manifest as a buckling load in the continuous carbon fibers, which resolve into Z-axis interlaminar loads, and interlaminar shear. Reinforcing the interlaminar region with Z-axis oriented milled carbon fibers is an effective method to improve the overall toughness of the carbon fiber composite without incurring any penalties to the stiffness or strength.

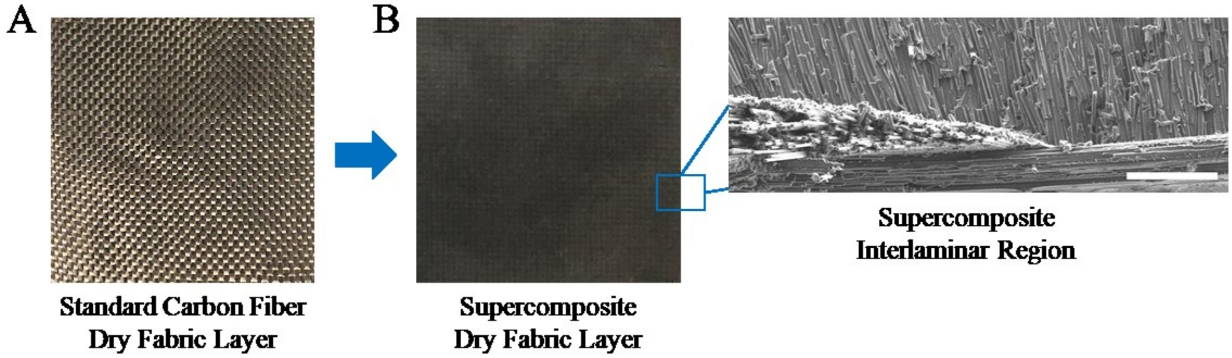

Figure 1. (A) a standard carbon fiber fabric and (B) a layer of supercomposite that features the standard carbon fiber fabric with a surface-coating of Z-axis oriented milled carbon fibers, both prior to epoxy impregnation (Scale bar: 150µm)

2. EXPERIMENTATION

3-D reinforced prepregs that feature Z-axis interlaminar reinforcement (supercomposite) are manufactured by Boston Materials. Commercially available carbon fiber fabrics (3K x 3K, plain weave, standard modulus carbon fiber) are used as a feedstock in a roll-to-roll coating process. In the first step of the process, an aqueous solution of milled carbon fibers (150µm average length, standard modulus carbon fiber) is metered onto the fabric. These milled carbon fibers have a trace sizing (<1% surface coverage) that allows the non-magnetic carbon fibers to elicit a physical response to low energy magnetic fields (<100mT). After the fiber slurry coating step, a vertical magnetic field is applied and the water and sizing is removed, yielding a dry fabric that features a carbon weave with a surface-coating of Z-axis oriented milled carbon fibers. The resultant dry fabric layer is then coated with epoxy (CPD4305, Endurance Technologies) and then B-staged, forming a supercomposite prepreg.

The uncured supercomposite prepreg was cut to 4" x 4" panels and cured using an oven vacuum bag setup. The panels were then water-jet cut into 2" x 1" rectangular samples for testing. The samples were polished after cutting to remove any edge defects that may yield erroneous test results. Supercomposite samples were compared against control samples that feature the same carbon fiber fabrics without Z-axis interlaminar reinforcement, otherwise produced with the same method.

Important in this comparison, both the control samples and the Z-axis interlaminar reinforced samples had similar final cure thickness and weight. To achieve similar thickness and weight, the control samples utilized three layers of carbon fiber fabric, whereas the Z-axis interlaminar reinforced samples only have two layers of fabric with the oriented milled fiber taking up the remaining thickness. As a result, the control samples have more in-plane fiber content. A universal tester was used to compress the prepared samples according to ASTM D3410/D3410M. Fiber volume was calculated by measuring dry fiber mass prior to sample preparation and the weight of the cured sample.

Table 1. Measurements of the samples tested.

Sample Description	**Sample Weight (g)**	**Calculated Fiber Volume (%)**	**Final Cure Thickness (mm)**	**Number of Plies**
Supercomposite 1	1.00	48	0.67	2
Supercomposite 2	1.04	46	0.70	2
Supercomposite 3	1.10	44	0.71	2
Supercomposite 4	1.11	44	0.73	2
Control 1	1.07	45	0.69	3
Control 2	1.07	45	0.71	3
Control 3	1.11	43	0.69	3

3. RESULTS

The results of the compression test are shown in **Figure 2**. Supercomposite samples exhibit noticeably improved compressive strength and toughness while maintaining similar stiffness. The increased compression strength is likely related to the strengthening of the interlaminar region due to the presence of Z-axis oriented milled fibers. The compressive strength of supercomposite samples is 35% higher than the control despite having only two layers of fabric reinforcement (versus the three fabric layers that comprise the control sample). This result indicates that sacrificing some of the planar reinforcement for Z-axis interlaminar reinforcement provides a significant benefit for in-plane compressive properties.

In addition to the enhanced strength, the increased toughness (as measured by the area under the stress-strain curve) is clear with Z-axis interlaminar reinforcement. Supercomposite samples exhibit a toughness of 8.83±2.88 MJ/m^3 compared to the 2.20±0.07 MJ/m^3 of the control suggesting that the Z-axis reinforcement provides an over 300% increase to the toughness. Supercomposite samples with Z-axis interlaminar reinforcement exhibit a unique failure in which a higher strain is reached, and even plastic deformation is possible before fracture. This allows a cyclist the opportunity to register a change in apparent stiffness of a composite bicycle prior to catastrophic failure.

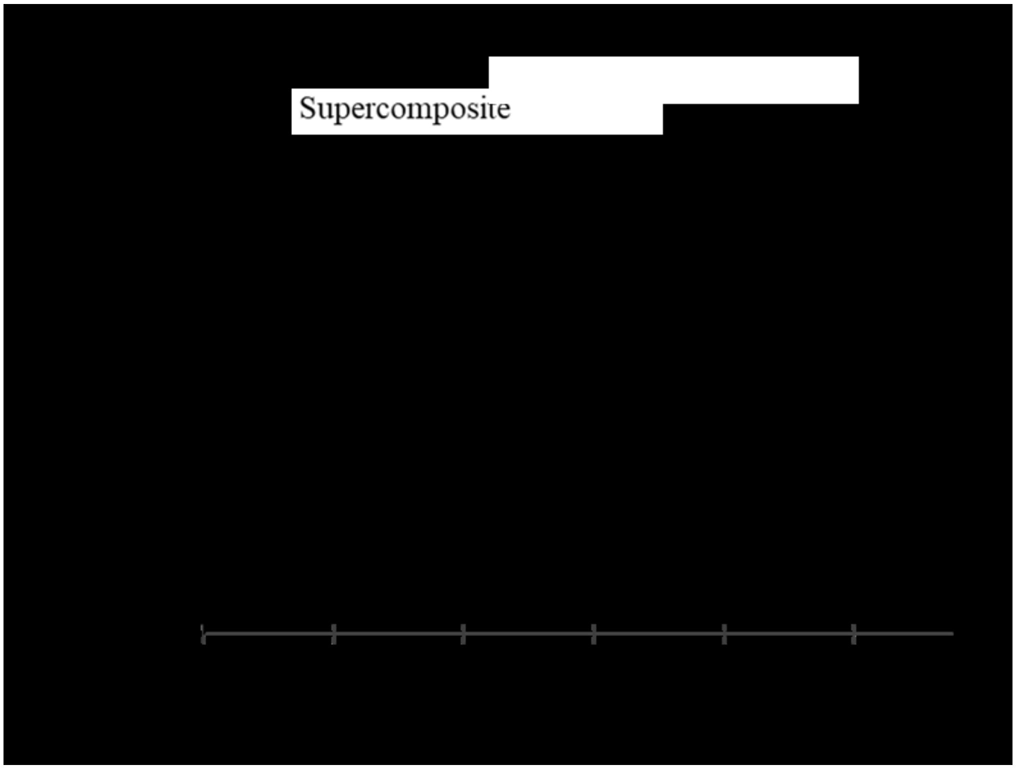

Figure 2. Stress vs. strain relationship of supercomposite in relation to standard carbon fiber composites (control). Three control samples were made from different batches of prepreg produced with a consistent process. Four supercomposite samples were made from different batches of supercomposite prepreg also made with a consistent process.

4. CONCLUSIONS

This work demonstrates that Z-axis reinforcement in the interlaminar region of carbon fiber composites is effective to improve their overall compressive strength and toughness. The ability to increase the compressive strength and toughness of carbon fiber composites without decreasing stiffness makes supercomposite technology ideal for composite bicycles.

In next steps, Boston Materials will investigate the effects of Z-axis milled fiber reinforcement of Mode I fracture, Mode II fracture, and compression after impact. This data will help better understand the full-range of compressive and interlaminar properties of supercomposite laminates. Boston Materials will also test the vibration dampening properties of supercomposite to evaluate shock-absorbing functionality for composite bicycles. Additionally, Boston Materials is launching a pilot production line to manufacture supercomposite with greatly enhanced batch-to-batch consistency.

Boston Materials views this technology as fabric-agnostic; composites made from any fabric reinforcement should benefit from similar increases in strength and toughness without detriment to stiffness. Additionally, supercomposite technology provides an opportunity to increase the usage of milled carbon fibers in high-value applications.

This work was supported in part by NSF grants: CMMI-1536354 and SBIR Phase I 1820051.

5. REFERENCES

1. Jacques Augendre. "Guide Historique 2018." *Le Tour de France.* 2018. 90. Amaury Sports Organisation, France. 29 Jan. 2019 < https://netstorage.lequipe.fr/ASO/cycling_tdf/2018-historical-guide.pdf >.
2. *How carbon fibre revolutionised the Tour de France*. 2007. R-TECH MATERIALS. 29 Jan. 2019 <https://www.r-techmaterials.com/carbon-fibre-revolutionised-tour-de-france/>.
3. Donna Dawson. "Safe cycling: Keys to composite bike design integrity." CompositesWorld. 9 Sept. 2018. Gardner Business Media, Inc., Cincinnati, OH. 27 Jan. 2019 <https://www.compositesworld.com/articles/safe-cycling-keys-to-composite-bike-design-integrity>.
4. *Specialized Bicycle Components Recalls Bicycles Due to Crash Hazard.* 15 Feb. 2018. United States CPSC. 27 Jan. 2019 <https://www.cpsc.gov/Recalls/2018/specialized-bicycle-components-recalls-bicycles-due-to-crash-hazard#>.