Damage Tolerant Composites Reinforced with Z-axis Milled Carbon Fiber

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ABSTRACT

Despite having high specific strength and stiffness, carbon fiber composites are prone to brittle and catastrophic failure. This behavior poses challenges when re-designing metal components with light and stiff composites, especially components with thin walls that are common in electronic devices. In this work, thin (~0.8 mm thickness) panels made with 30% Z-axis milled carbon fiber and 70% unidirectional (0°) carbon fiber (tradename: Supercomp™ 1015 Axial) are shown to match the flexural modulus and strength (per ASTM D-790) of 100% unidirectional (0°) carbon fiber panels with similar thickness and weight. Unlike the pure unidirectional fiber laminates, which fail catastrophically, the panels reinforced with Z-axis milled fiber can be loaded again after initial failure and they retain 42% of their original flexural strength. This work demonstrates a new approach to produce damage tolerant composites using Z-axis milled fiber reinforcement and is relevant for light and stiff enclosure designs for electronic devices.

Keywords: Supercomp, Z-axis, Milled Fiber, Damage Tolerant, Electronics
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1. INTRODUCTION

The form and functionality of electronic devices, such as tablets, laptops, and smartphones, are rapidly evolving to meet consumer demands for higher processing capabilities, longer battery life, and lower cost. Many of these demands rely on innovations in processing, connectivity, display, and battery technologies. However, a shared requirement for all electronic devices, especially portable consumer electronics, are stiff, thin, and durable enclosures to package and protect the internal electronics. Today, aluminum is the incumbent material choice for electronic device enclosures, especially in high-end portable electronics.[1]

Thin and light enclosures can increase the volume and weight allowances of the internal electronic components. However, the continued use of aluminum in enclosures with thin walls can lead to design failures, such as the susceptibility of the enclosure to bending during manufacturing or end use by the consumer (**Figure 1**).[2] Materials that have a higher specific stiffness than aluminum are required to maintain the structural stability of thinner and lighter enclosures. The requirement for stiff and light materials is an opportunity for carbon fiber composites to displace metals like aluminum. Unlike most metals which undergo a plastic deformation prior to fracture, conventional carbon fiber composites in thin structures are brittle and catastrophically fail.

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Figure 1. A new high-end tablet with an aluminum enclosure is delivered bent to the consumer[2]

In order to eliminate catastrophic failure in new composite enclosures, manufacturers have utilized a combination of fiberglass and carbon fiber.[3] Fiberglass composites have 40% higher density and 40% lower flexural stiffness than carbon fiber composites.[4] Thus, incorporating fiberglass decreases the risk of catastrophic failure but also dilutes the lightness and stiffness benefits of carbon fiber. Similar techniques are used in many recreational applications where highly oriented polypropylene fibers (tradename: Innegra™) are incorporated with carbon fiber to create a hybrid composite that does not catastrophically fail but it also reduces the flexural stiffness compared to a 100% carbon fiber composite. Boston Materials' Supercomp maintains the high specific flexural stiffness properties of a pure carbon fiber composite and eliminates the risk of catastrophic failure.[4] Therefore, Supercomp is an ideal material to use in thin, light, and damage tolerant composite enclosures for electronic devices.

2. EXPERIMENTATION

2.1 Materials

Braided unidirectional (UD) dry carbon fiber tapes were sourced from A&P Technology (ZERO® Uni-4.0SM). The dry UD tapes were made using Toray standard modulus, PAN-based carbon fiber (T-700). Both the baseline and Supercomp samples utilized the same dry UD tape. Supercomp 1015 Axial Dry was manufactured by Boston Materials by applying Z-axis oriented milled carbon fibers to the dry UD tape. The milled carbon fibers were sourced from Zoltek (PX30 MF150). Using a proprietary technique, the milled fibers are magnetically functionalized and then dispersed in a water-based slurry. The milled carbon fiber slurry is then applied to the dry UD tape and then the milled fibers are oriented in the Z-axis using vertical magnetic fields. After the fiber orientation step, the resultant material is dried, and the Supercomp 1015 Axial Dry material is spooled. This entire process is implemented in a 12"-wide roll-to-roll production process (**Figure 1**).

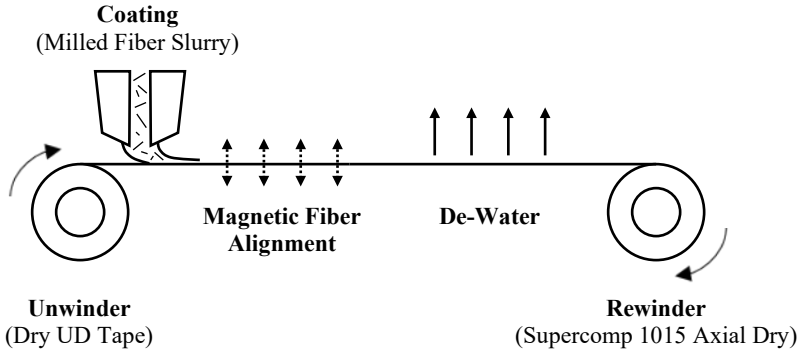


Figure 1. Schematic of the process used to produce Supercomp 1015 Axial Dry

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Both the Supercomp 1015 Axial Dry and the baseline dry UD tape were processed into prepregs by infusing films of 250 °F cure epoxy sourced from Mitsubishi Chemical Carbon Fiber & Composites (Newport 301). The epoxy films are infused into the carbon fiber materials by using a series of heated calender rollers, forming Supercomp 1015 Axial prepreg (**Figure 2**) and the baseline UD prepreg. The film infusion was performed by Aldila Composite Materials.

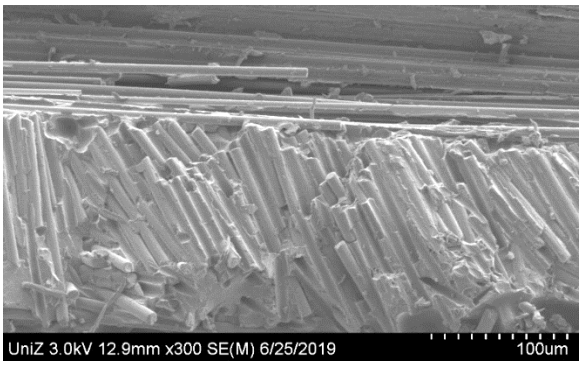


Figure 2. Scanning electron microscope (SEM) cross-section of Supercomp 1015 Axial prepreg

2.2 Coupon Fabrication

The test panels were made by curing laminated prepregs between PTFE release films at 250 °F under 50 psi compaction for one hour using a press (Carver 25 Ton Laboratory Press Model M). The layup schedules and physical properties of the two different types of test panels are shown in **Table 1**. The cured panels were cooled to ambient temperature before removing from the press.

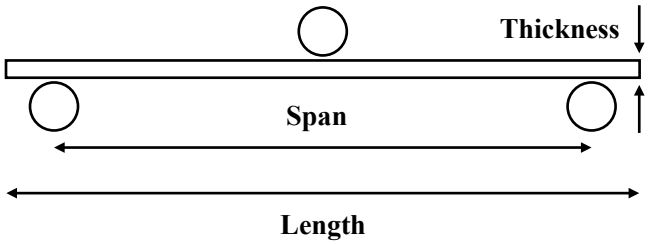
Table 1: Layup schedules and physical properties of the Supercomp and baseline test panels

Panel Type	Layer #	Orientation	Target Thickness (mm)	Target Areal Weight (g/m^2)
Supercomp	4	0°	0.14	145
	3	0° w/ Z-axis fiber ↓	0.28	280
	2	0° w/ Z-axis fiber ↑	0.28	280
	1	0°	0.14	145
TOTAL			**0.84**	**850**
Baseline	6	0°	0.14	145
	5	0°	0.14	145
	4	0°	0.14	145
	3	0°	0.14	145
	2	0°	0.14	145
	1	0°	0.14	145
TOTAL			**0.84**	**870**

The resultant test panels were cut into coupons using an abrasive waterjet (OMAX Protomax). The dimensions of the coupons are shown in **Table 2**. The coupons maintain a span-to-thickness ratio of 32:1, in accordance with the ASTM D790 test standard.[5] The 0° fibers were oriented parallel to the span and length of the coupons.

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Table 2: Coupon dimensions (width is out-of-plane in the schematic)



Coupon #	Width (mm)	Measured Thickness (mm)	Calculated Span (mm)	Length (mm)
Supercomp-1	11.8	0.86	28	33
Supercomp-2	11.8	0.84	27	33
Supercomp-3	11.8	0.81	26	33
Baseline-1	11.8	0.86	28	33
Baseline-2	11.8	0.86	28	33
Baseline-3	11.8	0.87	28	33

2.3 Coupon Testing

The prepared coupons were tested under three-point flexural loading (ASTM D790) to determine 0° flexural strength and modulus using a universal testing system (Instron 3369 with 5 kN load cell). The baseline coupons were subject to an initial loading, after which they failed catastrophically and could not be loaded a second time. Unlike the baseline coupons, the Supercomp coupons had residual flexural strength for a second loading. Strain measurements were taken from crosshead displacement to calculate flexural modulus.

3. RESULTS

The prepared coupons were tested under three-point flexural loading (ASTM D790) to determine 0° flexural strength and modulus. The baseline coupons were subject to an initial loading, after which they failed catastrophically and could not be loaded a second time. Unlike the baseline coupons, the Supercomp coupons had residual flexural strength for a second loading.

Three-point bending was selected for this work to demonstrate the end-use behavior of Supercomp in applications such as electronics enclosures, skis, and hockey sticks. In these applications, manufacturers utilize a three-point or cantilevered deflection test to gauge the stiffness, strength, and failure behavior of the composite part. Accordingly, the three-point bending performed in this work closely matches the testing that component manufacturers use to test their parts.

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3.1 Initial Properties

The initial loading on the baseline and Supercomp coupons showed similar results (within 5%) for both flexural modulus and strength (**Figure 3**). The baseline coupons (n=3) registered 82.03 ± 3.60 GPa and 1680.13 ± 165.96 MPa for flexural modulus and strength, respectively. The Supercomp coupons (n=3) registered 81.54 ± 5.47 GPa and 1606.51 ± 48.98 MPa for flexural modulus and strength, respectively. The initial loading results demonstrate that the innermost plies of a coupon under three-point flexural loading can be replaced with Z-axis milled fiber without a reduction in flexural strength or modulus. This data was not normalized to a target fiber volume.

There was a discrepancy between the flexural strength and modulus reported by Toray for the T-700 carbon fiber cured with epoxy and the coupons that were tested in this work. Toray reports 120 GPa and 1670 MPa for flexural modulus and strength, respectively. However, the data reported by Toray is normalized to 60% fiber volume.[6]

The expected fiber volume for the Supercomp and baseline coupons tested in this work is 55%. Normalizing the flexural strength of the Supercomp and baseline coupon to 60% fiber volume yields similar values to the flexural strength reported by Toray. However, the flexural modulus values are nearly 18% lower than the value reported by Toray, even after normalizing to 60% fiber volume.

The knockdown in the flexural modulus is attributed to the braided unidirectional carbon fiber that is used to produce the Supercomp and baseline coupons. The braiding process does not adequately tension the carbon fibers and allows the fibers to relax. This relaxation is visually apparent as a subtle in-plane distortion of the carbon fiber off the 0° direction. Alternatively, the production process used by Toray, and other prepreggers, applies a high tension on the carbon fibers during the tow spreading process. The spread carbon fiber tows are then immediately captivated by hot-melt epoxy during the prepregging process, which preserves the applied tension on the carbon fibers and holds them uniformly in the 0° direction. Implementing highly oriented carbon fibers in the 0° direction can increase the flexural modulus of the baseline and Supercomp coupons.

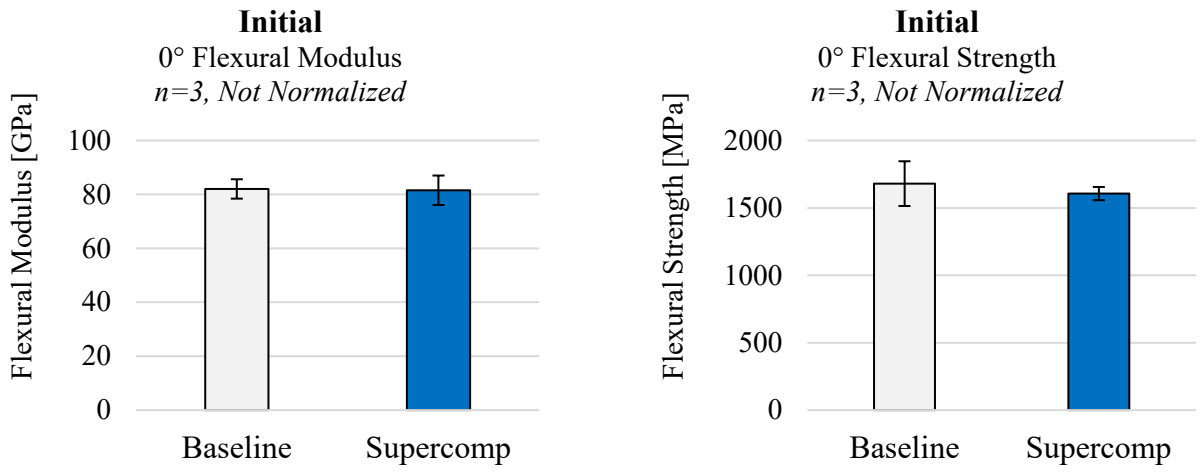


Figure 3. Flexural modulus and strength results after the initial three-point flexural loading

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3.2 Residual Properties

After the initial loading, the baseline coupons catastrophically fractured into two pieces. The Supercomp coupons remained in one piece but had a full fracture of the UD 0° fibers at the top surface of the coupon, which in compression during the three-point flexural loading (**Figure 4**). This local fracture is from buckling of the skin plies during compression, which is like the failure mechanism of a composite sandwich panel under the three-point flexural loading (**Figure 5**).[7]

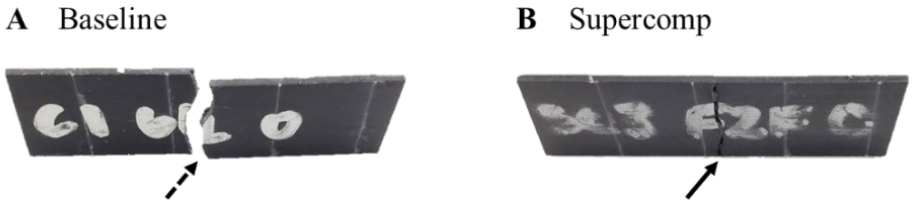


Figure 4. A) The baseline coupon catastrophically failed after the initial loading (dotted arrow) and B) the Supercomp coupon remained intact after the initial loading but had fractured UD 0° fibers at the top surface, which are under compression in three-point flexural loading (solid arrow).



Figure 5. Post-test fracture morphology in the Supercomp coupons after the initial loading. The fracture is caused by buckling of the topmost plies, which are under compression during three-point flexural loading. The baseline coupons fully fractured after the initial loading.

The Supercomp coupons (n=3) demonstrated a residual flexural strength of 677.42 ± 51.35 MPa. The residual flexural strength is 42% of the initial value (**Figure 5**). Residual strength for the baseline coupons could not be collected because the they fully fractured after the initial loading.

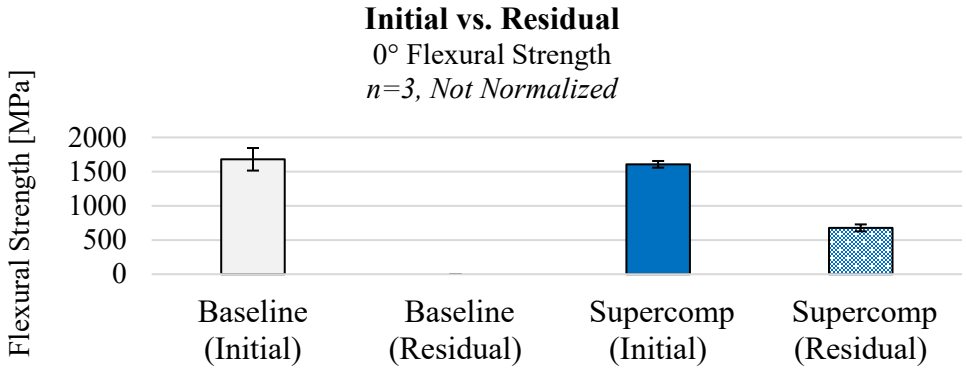


Figure 6. Flexural properties before/after the second loading (Note: residual properties could not be collected for the baseline coupons because they catastrophically failed after the initial loading)

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4. CONCLUSIONS

In this work, it was demonstrated that the innermost plies of a thin (~0.8 mm thick) laminated composite panel with 30% (by weight) Z-axis milled fiber and 70% UD 0° fiber (Supercomp) has comparable flexural strength and modulus as a 100% UD 0° fiber (baseline) panel with similar physical dimensions and weight. This result alone is important for cost optimization since the milled carbon fiber is over 50% lower cost than the continuous fiber used in UD reinforcements.

After the initial three-point flexural loading, coupons cut from the baseline panel failed catastrophically, which is expected. Under similar loadings, the coupons cut from the Supercomp panels remained primarily intact after the initial loading. While there was fractured UD 0° fiber on the topmost skin, which is under compression in three-point flexural loading, the Supercomp coupons could be loaded for a second time and they retained 42% of the initial flexural strength.

In follow-up work, the Z-axis milled fiber reinforcement will be directly applied to off-the-shelf carbon fiber prepreg that has highly oriented fiber in the 0° direction. This process will be implemented by coating a release substrate with the Z-axis milled carbon fiber. The coated substrate will be infused with epoxy, forming a Z-axis milled carbon fiber prepreg. This material will then be transferred to an off-the-shelf carbon fiber prepreg. This process will avoid the flexural stiffness knockdown caused by the braided unidirectional tape.

Additionally, the initial and residual properties of Supercomp panels will be benchmarked against carbon fiber and fiberglass hybrid composite panels that are currently used in consumer electronics applications. The thermal and electrical properties will also be characterized to develop thermal management and electromagnetic shielding functionalities with Supercomp. Lastly, the milled fiber used as the Z-axis reinforcement will be sourced from post-consumer recycled carbon fiber to demonstrate complete circularity for the Supercomp material. Complete circularity is especially important for consumer electronic devices with relatively short lifecycles (which can be as low as 3 years for smartphones) in order to re-capture potential lost value from scrap and reduce reliance on expensive virgin feedstocks.[8]

5. REFERENCES

[1] *Contract consumer electronics, injection molding, enclosure opportunities.* Venture Outsource, 2013.

[2] *Apple says iPad Pros have no design flaw.* TechNewsToday, 2019.

[3] P. Malnati, *Consumer electronics: hybrid composite covers.* CompositesWorld, 2019.

[4] *301 Technical Data Sheet.* Mitsubishi Carbon Fiber and Composites, 2019.

[5] *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials.* ASTM International, 2019.

[6] *Torayca T700S Data Sheet*. Toray, 2019.

[7] *Materials* 2019, 12(18), 2959; https://doi.org/10.3390/ma12182959

[8] A. Holst, *Replacement cycle length of smartphones in the United States 2014-2023, in years.* Statista, 2019.

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