Comparing the Effects of Fiber Orientation on Flexural Response in Unidirectional Carbon Fiber Composites

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Abstract

The orientation of fibers within fiber-reinforced composites are theorized to contribute greatly to flexural strength. With unidirectional carbon fiber, the effect of the direction of the fibers relative to the direction of the loading instrument can be experimentally observed and recorded using a three-point flexure test. While unidirectional carbon fiber is not often used in industrial and civilian applications, the principal mechanism behind flexural strength can be clearly determined as there are fewer directional variables to consider. Once the principal mechanism is determined, it may be extrapolated to other types of carbon fiber in industrial and civilian environments where strong and lightweight material is required. After testing, it was determined that the strongest composites have fibers aligned perpendicular to the line of contact between the loading instrument and the sample, while the weakest composites have fibers aligned parallel to the line of contact. This illustrates the relationship between flexural strength of a fiber-reinforced composite and the direction of the fibers relative to the load.

Introduction

The flexural properties of carbon fiber composites can vary widely depending on the fiber arrangement and the orientation of the fiber arrangement relative to the applied load. Possible fiber arrangements include bidirectional weaves and unidirectional sheets, and loads can be applied to these fiber arrangements at different angles. In applications such as aerospace and Formula One racing car frames, carbon fiber is frequently used as a component in structures to create a strong, lightweight material, but the loading of these environments is extremely inconsistent. Additionally, the arrangement of the carbon fibers may also vary between different applications. Unidirectional fiber sheets allow the angle of the load to be clearly oriented relative to the load. The matrix of composites is non-directional by nature and likely does not influence composite strength under different orientations.

Flexure tests are a style of test used to measure the flexural behavior when a material is bent by a load. In a three-point flexure test, an object is placed over two supports and under a single wedge-shaped loader in the center.

The objective of this laboratory experiment was to create a measurably consistent environment by using a three-point flexure test on carbon fiber composite samples with a unidirectional fiber arrangement to directly test flexural response in different fiber orientations. Three orientations were used in the flexure tests: fibers running parallel, diagonal, and perpendicular to the line of contact between the loading wedge and sample.

The purpose of measuring the flexural response is to use the correlations revealed in this experiment to influence our understanding of carbon fiber in industry, where lightweight and strong materials are required. A fibrous material observed to fail under one orientation may not fail when placed under the same load in a different orientation.

Materials and Methods

- Unidirectional carbon fabric, 12 in × 3 yd roll (Fiber Glast Development Co.)
- Super-hard epoxy resin, 1.25 quart kit (TAP Plastics)
- Press machine with 3-point flexural test attachments (Instron)

The carbon fiber sheet was cut into squares measuring approximately 15 cm × 15 cm. The squares were then stacked on top of one another, with epoxy resin brushed onto each layer of the stack throughout the whole stacking process. The squares were layered until the stack reached a height of approximately 0.8 cm, and the stack was left under a fume hood to cure.

Afterward, the stack was cut into ten cuboid-shaped samples, each measuring approximately 10 cm × 1.2 cm × 0.5 cm and each having a different fiber orientation, illustrated in Figure 1. When placed under flexural load, four of the ten samples would have fibers running parallel to the line of contact created between the loading wedge and the sample (one of these samples was discarded prior to testing). Another four samples would have fibers running diagonal (about 45°) to the line of contact (one of these samples was discarded prior to testing). Two samples would have fibers running perpendicular to the line of contact (neither of these samples were discarded). Ideally, at least three samples of each orientation would have been obtained for a total of nine usable samples. In reality, eight usable samples were obtained, but this number did not prevent the flexural response of carbon fiber from being adequately studied.

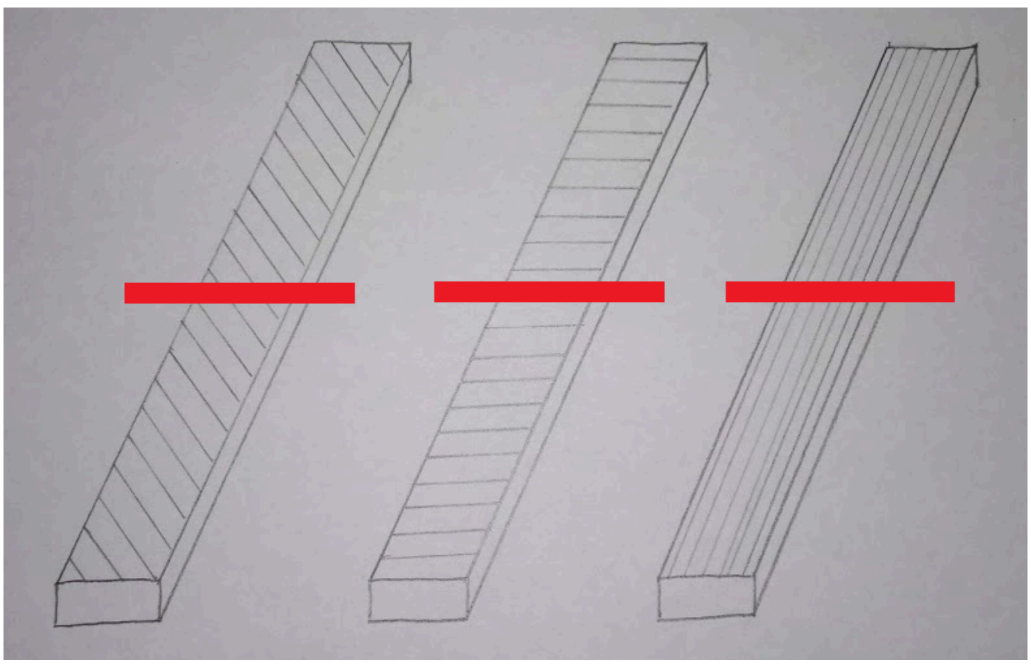


Figure 1. The three sample types each had fibers running in a different direction relative to the line of contact (red line) created between the loading wedge and the sample. The left diagram shows fibers running diagonal to the line of contact (representing samples 3, 4, 5), the middle diagram shows fibers running parallel (samples 6, 7, 8), and the right sample shows fibers running perpendicular (samples 1, 2).

Each sample was placed under the press to test the three-point flexural response. The span between the two supports was set at 9.0 cm for each sample. In accordance with ASTM D790, this span length is over 15 times the height of the samples, ensuring internal shears do not interfere with flexure measurements. During each test, flexural stress-strain behavior was recorded and compiled. Load was applied to cause a displacement of 0.2 cm per minute. Limit states were set as maximum possible of 50 kN, maximum displacement of 2.0 cm, or a 20% decrease in measured stress (indicating crack propagation).

Safety Analysis

Carbon fiber is slightly hazardous, as stray fibers can cause irritation to skin. When handling the carbon fiber, gloves and safety goggles were worn at all times to prevent contact with the fibers. This is especially important after the flexure test is completed, as samples may have small, loosened fibers along their surface.

Epoxy resin is also hazardous when handled improperly. Gloves and safety goggles were worn at all times to prevent skin contact, which could cause minor irritation. In an enclosed space, epoxy resin fumes can cause respiratory irritation, so the application of the epoxy resin took place entirely under a fume hood to prevent significant inhalation of resin-related particles.

When using the press machine, all standard safety precautions, including keeping limbs out of active loading zones and closing the protective screen door, were followed. During testing this turned out to be an important safety precaution, as an experimental error caused a sample to eject from the loading zone at high speed, posing a projectile threat.

Results

Eight samples total were tested. Samples 1 and 2 had fibers aligned perpendicular to the loading wedge. Samples 3, 4, and 5 had fibers aligned diagonal (about 45°) to the loading wedge. Samples 6, 7, and 8 had fibers aligned parallel to the loading wedge (Figure 1).

Samples 1 and 2 were the samples with fibers aligned perpendicular to the loading wedge and were by far the strongest and toughest samples. Both had a preliminary failure at about 35 MPa, but continue to endure stress up to about 500 MPa before continuing to deform. Toughness could not be measured as there was no ultimate point of failure.

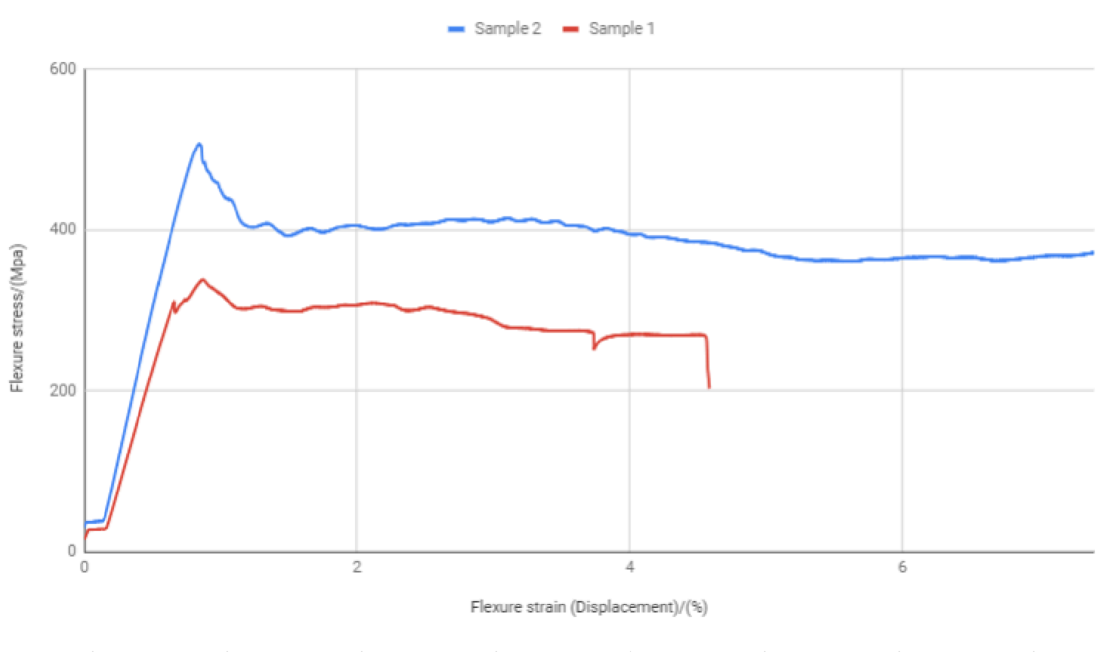


Figure 2. Samples with fibers running perpendicular to the loading wedge demonstrated large flexural strength. Testing of Sample 2 (red) ceased due to experimental error and did not fail. Testing of sample 1 (blue) ceased once maximum load was reached and did not fail. Wave-like behavior can be observed after the stress peak.

As demonstrated in Figure 2, sample 1 never failed but underwent a large amount of deformation (Figure 3), at about 20 mm from its original position. Elastic deformation also occurred but was not measured.

Figure 3. Sample 1 post-test did not reach failure, but underwent significant plastic deformation in the form of compression (top face), tension (bottom face), and bulging.

Samples 3, 4, and 5 were the samples with fibers aligned diagonal to the loading wedge and were far weaker than the perpendicular fiber samples, enduring a flexure stress of about 60 MPa. A preliminary failure still occurred at approximately 35 MPa. Another thing to note is that the samples failed on the side that was in tension (bottom) before the side that was in compression (top).

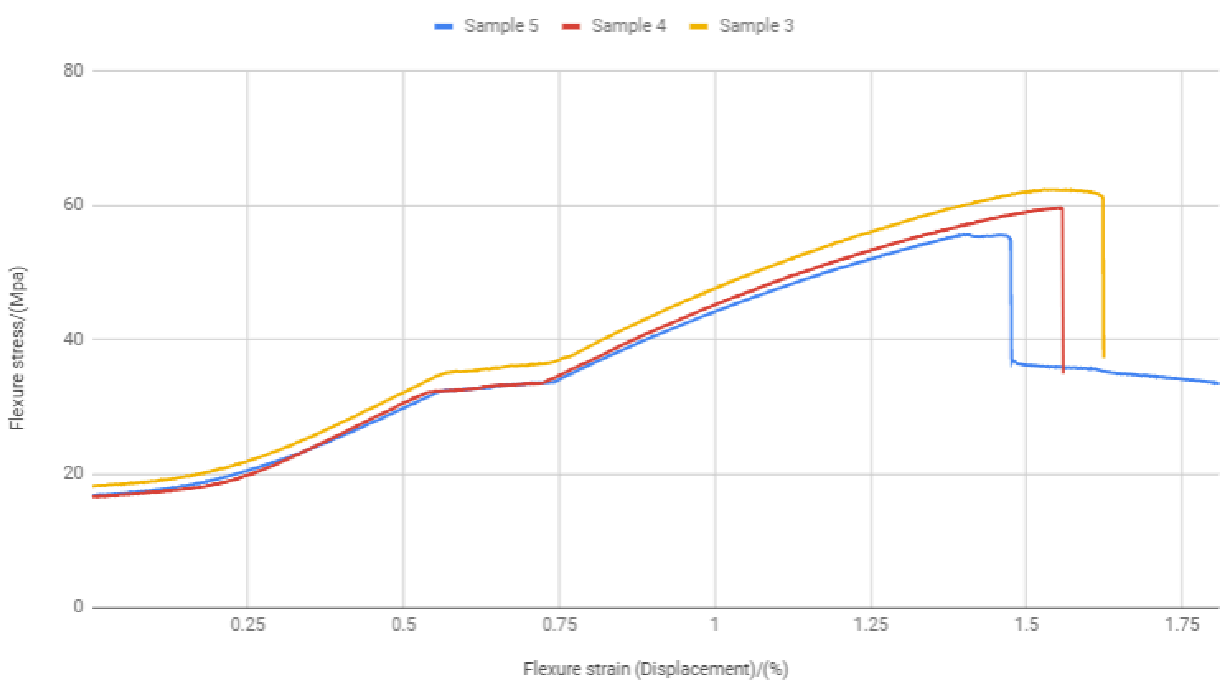


Figure 4. Samples with fibers running diagonal to the loading wedge demonstrated weak flexural strength. A preliminary failure occurred at approximately 35 MPa, while complete failure occurred at approximately 60 MPa.

Figure 5. Sample 4 post-test shows small amounts of plastic deformation and less visually obvious crack propagation.

Samples 6, 7, and 8 had their fibers oriented perpendicular to the load and failed at about 50 MPa as seen in figure 6. Failure of the epoxy can also be seen in the graph at 35 MPa. The deformation that occurred at failure was minimal and can not be seen (figure 7).

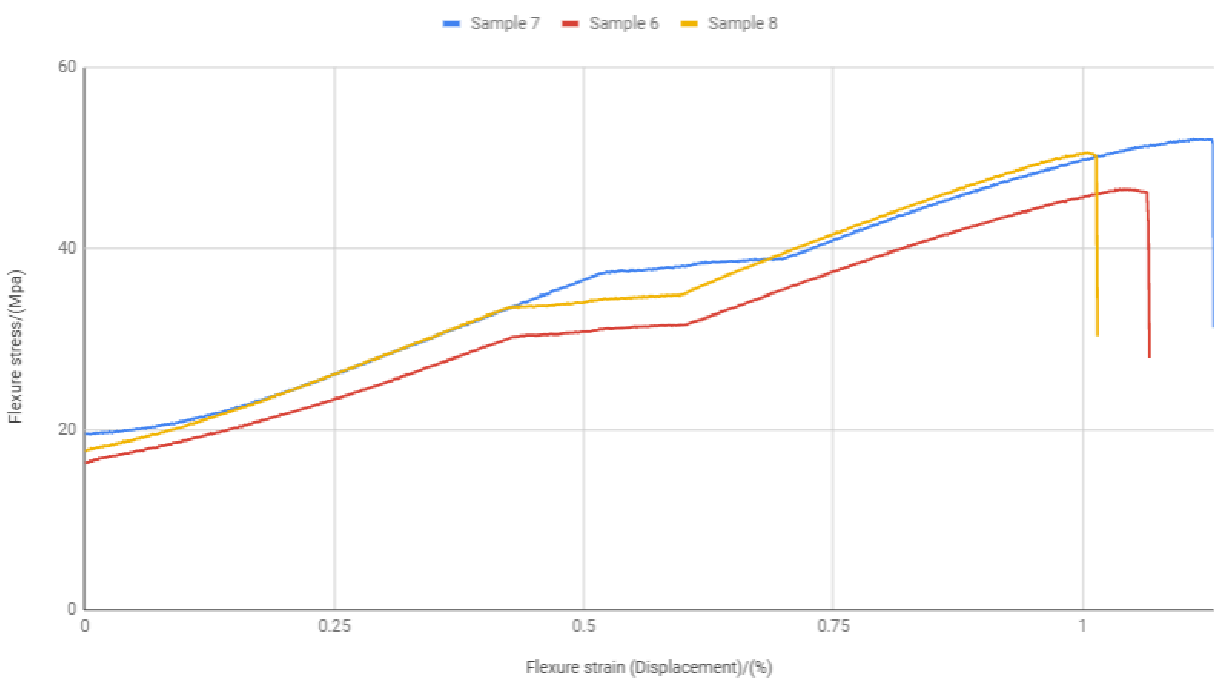


Figure 6. Samples with fibers running parallel to the loading wedge demonstrated the weakest flexural strength. A preliminary failure occurred at approximately 35 MPa, while complete failure occurred at approximately 50 MPa.

Figure 7. Sample 8 post-test shows no plastic deformation and no visual cues that crack propagation has occurred.

According to the superimposed data (Figure 8), there are consistent failures occurring at 35 MPa. It is clear from the data that the perpendicular samples are 10 times stronger than all other samples.

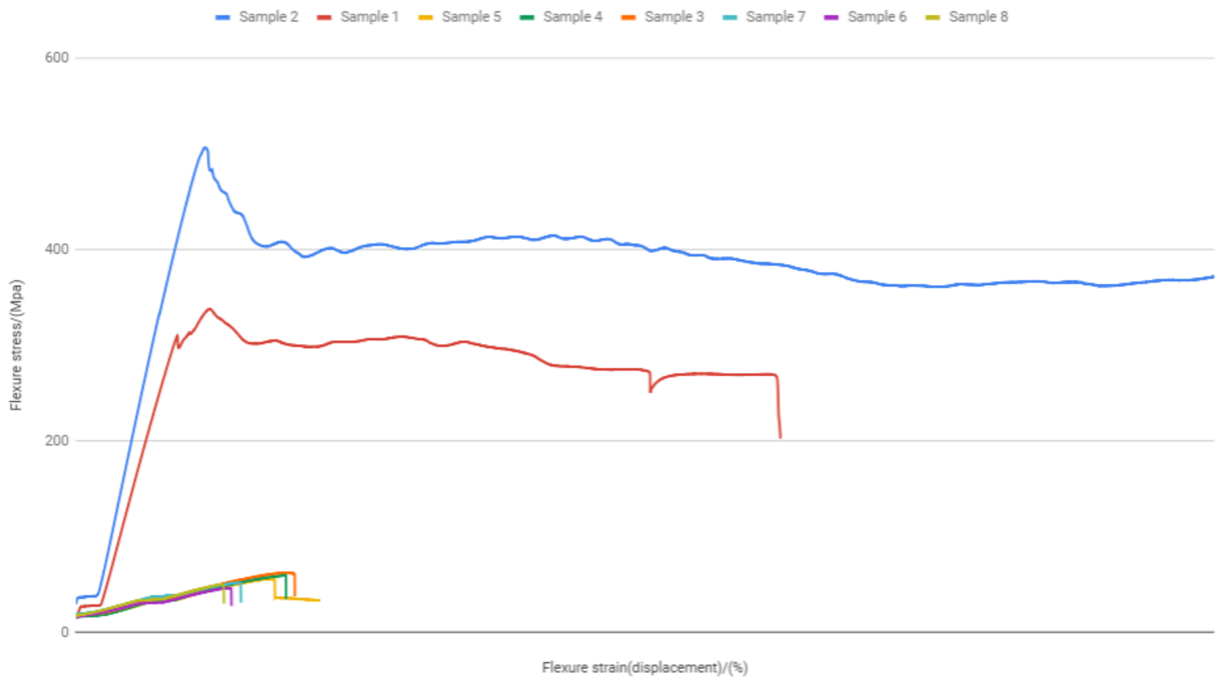


Figure 8. When superimposed, the data for all samples illustrates the vast difference in flexural strength between the samples with perpendicular fibers compared to the other fiber orientations. Preliminary failure at 35 MPa is consistent for all fiber orientations.

Discussion

From the recorded data, it can be ascertained that fiber orientation contributes a significant and variable role in the flexural strength of carbon fiber composites, while the epoxy resin contributes a small and consistent role.

All samples regardless of fiber orientation demonstrated a stress plateau at about 35 MPa. This is due to the epoxy resin failure, since the resin had no changeable orientation between each sample type. The epoxy is considered to be brittle but as illustrated in the data the cracks in the epoxy take some time to propagate.

The parallel and diagonal fiber samples all had cracks in the epoxy quickly appear along the same direction as the fibers of the carbon fiber. After the initial failure of the epoxy at 35 MPa, more stress was applied before complete failure occurred. This is possible because the composite still has small amounts of fibers not perfectly oriented in unison with other fibers, creating a small but present construct that must be overcome before failure. Upon failure, these fibers failed in a brittle manner, viewable in Figure 7. Crack propagation in any other direction is not feasible because at any other angle, the crack would run against the fibers and each individual fiber would have to be fail to increase the crack length.

The perpendicular fiber samples had cracks appear much later in testing in a somewhat different fashion than the other two sample types. Epoxy resin cracks propagated slowly as the carbon fibers continued to bend. In contrast to the other two sample types, the perpendicular fiber samples behaved in a more ductile manner. This is due to the loading wedge applying most load across each individual fiber, as opposed to the loading wedge applying most load to the resin only. Because each individual fiber resists a portion of the load, the total strength of the composite is greatly increased. For failure to occur the load would have to break all of the individual layer of the carbon fiber. In our test only about half of the layers broke and then proceeded to bulge out as the next layer was broken. This process of slowly breaking every layer can be seen in the data of Figure 2 as the stress-strain curve oscillates after the stress peak. It gives the impression that the material is ductile. However, had the load been tensile pulling rather than flexural bending, the fibers would have behaved in a very brittle manner rather than ductile fashion (Farahikia et al.).

The lump created at the center of the perpendicular fiber samples is due to internal compression along the top face of the sample and internal tension along the bottom face of the sample. Cracks propagate from the bottom up, as tension causes the epoxy resin, and later the fibers, to be pulled apart. In Figure 9 below, exaggerated crack propagation from flexural stress is demonstrated on a sample parallel fiber sample.

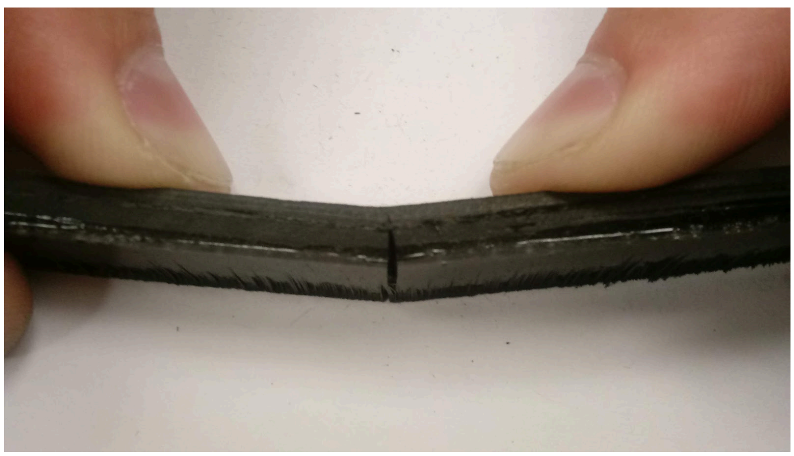


Figure 9. A parallel fiber sample illustrates cracks propagating from tension in the bottom face.

The wave-like behavior observed in the perpendicular fiber samples (Figure 2) is caused by the individual layers of carbon fiber sheets failing one after another. Stress is relieved once a sheet fails and then increases again as the next sheet starts absorbing the load. Had the loading continued beyond the limit states set before testing, the last sheet of carbon fiber would have to fail before total failure of the sample would occur.

The experimental error noted in sample 1 was due to improper stabilization of the two supports that hold the sample up. While the supports were correctly set at a span of 9.0 cm, they were not screwed down. During the test, the stress within the sample became so great that it was able to push the supports apart. The sample launched from the loading zone and data recording ceased. Because press machine's the safety door was closed no injuries occurred. Despite this error, the data clearly shows that fibers oriented perpendicular to the loading wedge have the greatest flexural strength when compared to the other two orientations.

Other less notable errors may have occurred during the process of sample creation. Small air bubbles may have remained between some of the carbon fiber layers, creating voids in the composite. These voids would allow cracks to propagate with greater ease, thus lowering the load needed to cause failure in the sample. Once the sample hardened, it had to be pried off of the surface it was on, as the epoxy adhered to the sheets we pushed together in order to form a good sample. In the process of removing the sheets the sample sheet (prior to being cut out) was bent to get it free of the sheets. Also, if the flexural press was not set to be in contact with the sample prior to loading, the data may be initially inaccurate.

Conclusions

Under three-point flexural loading, unidirectional carbon fiber composite samples each have different toughnesses almost entirely dependent upon fiber orientation relative to the line of contact between the loading wedge and the sample. Samples with fibers running parallel to the line of contact had the lowest toughness; samples with fibers running diagonal (about 45°) to the line of contact were slightly tougher; and samples with fibers running perpendicular to the line of contact had the greatest toughness by a wide margin.

In the samples with the parallel fibers, the strain is only imparted to the resin and the bonds that hold the fibers together, and the fiber orientation prevents the fibers from absorbing any significant amount of load. In the samples with diagonal fibers, the resin still takes the majority of the load, while some of it is imparted onto the fibers themselves. In the samples with perpendicular fibers, the fibers have nearly all the load imparted onto them, resulting in a much higher toughness. When the load is parallel to the fibers and the resin breaks, the only support remains the bonds between the fibers. This is analogous to the intermolecular bonds in polymers. The bonds within a polymer chain are incredibly strong, but the bonds between the chains are relatively very weak. The same concept applies with the unidirectional carbon fiber used in this test, thus why the samples did not fail as soon as the resin failed, but were much weaker than the perpendicular samples.

From the data, it is concluded that the greater the angle between the direction of the fibers and the direction of the loading wedge, the greater the ductile behavior of the composite sample. The samples with fibers running parallel to the loading wedge behaved most brittly, and the samples with the fibers running diagonal to the loading wedge behave slightly less brittly. In contrast, the samples with the fiber running perpendicular to the loading wedge behaved in a highly ductile manner, providing great flexural strength before failure could ever occur.

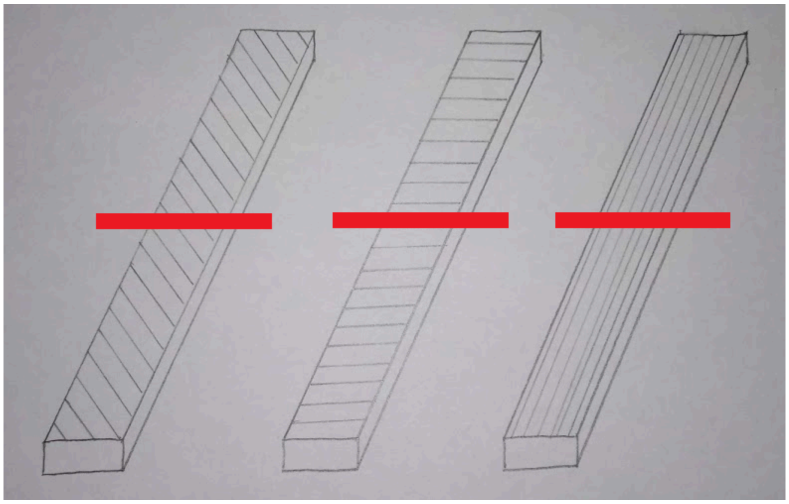
From the trends observed in this experiment, it is conclusive that to have reasonable strength against applied loads, the fibers within a carbon fiber composite must be oriented in a direction different than the direction of the loading instrument (with fibers being perpendicular to the loading instrument creating the greatest strength). In industrial and civilian environments, the direction of the fibers relative to the load cannot usually be controlled, greatly limiting the feasibility of unidirectional carbon fiber composites. To remedy this limitation, composites should contain bidirectional carbon fiber weaves, allowing the composites to receive loads from many different angles while still retaining flexural strength. Another experiment may be designed to test the limitations of bidirectional carbon fiber composites.

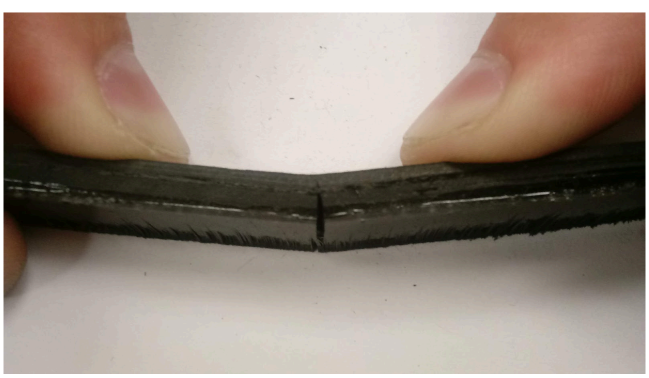
References

1. Farahikia, Mahdi, et al. “Evaluating the Mechanical Properties of Carbon Fiber Reinforced Polymer Matrix Composite Materials at Room and Elevated Temperatures.” *Design, Materials and Manufacturing, Parts A, B, and C*, vol. 3, 9 Nov. 2012, pp. 1151–1158., doi:10.1115/imece2012-85671.

Appendices

Jackson Bauer





Connor Lemmon

Flexure strain (D (%)	Flexure stress Sample 2	Flexure stress Sample 1	Flexure stress Sample 5	Flexure stress Sample 4	Flexure stress Sample 3	Flexure stress Sample 7	Flexure stress Sample 6	Flexure stress Sample 8
0	30.2498	15.0426	16.8162	16.5516	18.0848	19.441	16.2103	17.5448
0.0004	30.3883	15.1314	16.7629	16.6304	18.1486	19.4659	16.2809	17.5787
0.0019	31.1696	15.6211	16.7407	16.5728	18.1488	19.4803	16.3202	17.6878
0.0036	32.2119	16.1896	16.7506	16.6082	18.189	19.4718	16.3274	17.7596
0.005	33.0638	16.6775	16.7862	16.6447	18.1851	19.4459	16.4956	17.7482
0.0061	33.8612	17.0616	16.8382	16.5949	18.2219	19.455	16.4687	17.8967
0.0074	34.588	17.6207	16.8421	16.528	18.1967	19.5119	16.4838	17.8094
0.0086	35.2453	18.025	16.8349	16.5665	18.2367	19.5554	16.6299	17.8735
0.0098	35.9053	18.5236	16.8097	16.6726	18.2693	19.4931	16.6106	17.9028
0.0111	36.1214	19.039	16.8928	16.6138	18.2076	19.6055	16.6839	17.9659
0.0124	36.2586	19.4916	16.794	16.6684	18.2326	19.5242	16.6169	18.014
0.0136	36.4314	19.9795	16.8413	16.6558	18.2445	19.571	16.788	17.9805
0.0149	36.5491	20.5938	16.9076	16.6385	18.2546	19.5956	16.7607	18.0829
0.016	36.624	21.078	16.8618	16.6728	18.273	19.6393	16.8025	18.0673
0.0172	36.6633	21.5854	16.8593	16.6785	18.2171	19.5471	16.8185	18.0513
0.0185	36.6091	22.1217	16.8716	16.5821	18.248	19.6578	16.8415	18.1806
0.0197	36.6884	22.5914	16.8918	16.6683	18.3034	19.6002	16.8336	18.1264
0.021	36.7382	23.1224	16.9122	16.7117	18.3454	19.6402	16.8969	18.1596
0.0223	36.7069	23.6655	16.8756	16.7146	18.3178	19.6078	16.9256	18.1833
0.0234	36.6567	24.1069	16.9574	16.6503	18.358	19.743	17.0163	18.1544
0.0247	36.6899	24.7689	16.9316	16.7483	18.3905	19.6511	16.9677	18.2823
0.0259	36.7666	25.3045	16.9235	16.7256	18.3485	19.5836	17.0218	18.3515
0.0272	36.7204	25.7809	16.9614	16.7326	18.3549	19.681	17.051	18.2541
0.0284	36.7325	26.3501	16.9674	16.7105	18.381	19.7259	17.0225	18.3176
0.0296	36.8349	26.745	16.9768	16.7194	18.3789	19.6913	17.0529	18.4114
0.0309	36.8194	26.8906	16.9801	16.756	18.398	19.7957	17.0923	18.3819
0.0321	36.8443	27.0589	17.046	16.7029	18.4667	19.7009	17.1589	18.4846
0.0333	36.7904	27.163	17.009	16.7967	18.4524	19.7602	17.1694	18.472
0.0346	36.8336	27.149	16.9601	16.7836	18.4314	19.797	17.1886	18.483
0.0359	36.834	27.1744	16.9708	16.7432	18.3945	19.7617	17.2083	18.559
0.037	36.7857	27.2025	17.0549	16.8312	18.4117	19.8667	17.2722	18.6589
0.0383	36.9025	27.2576	17.0476	16.8464	18.4567	19.9033	17.326	18.5703
0.0394	36.855	27.2911	17.0062	16.8438	18.4697	19.8624	17.3281	18.6563
0.0407	36.8816	27.2123	17.0463	16.8372	18.5001	19.8832	17.3053	18.708
0.042	36.9277	27.2968	17.0642	16.875	18.393	19.9023	17.3441	18.6711
0.0432	36.9454	27.2641	16.9922	16.8877	18.4975	19.9252	17.4438	18.7124

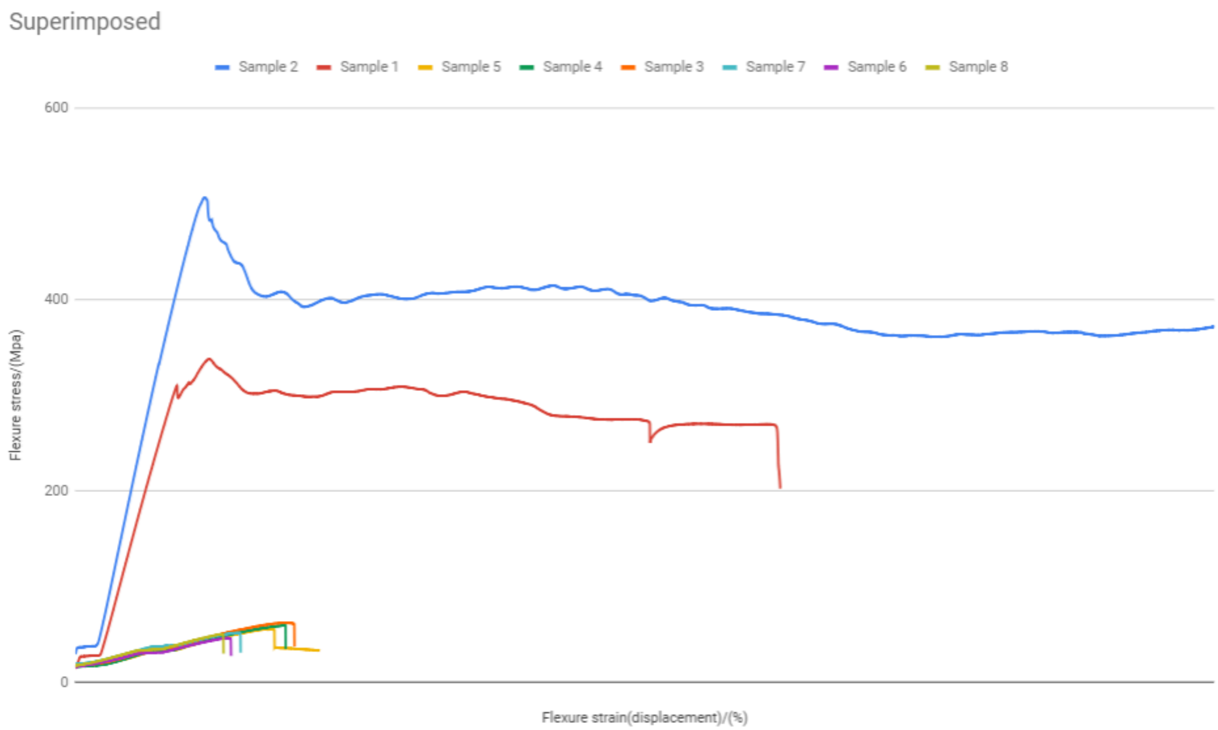


Figure 10. This is the graph of all the data points and it is a good summary of our lab visually.

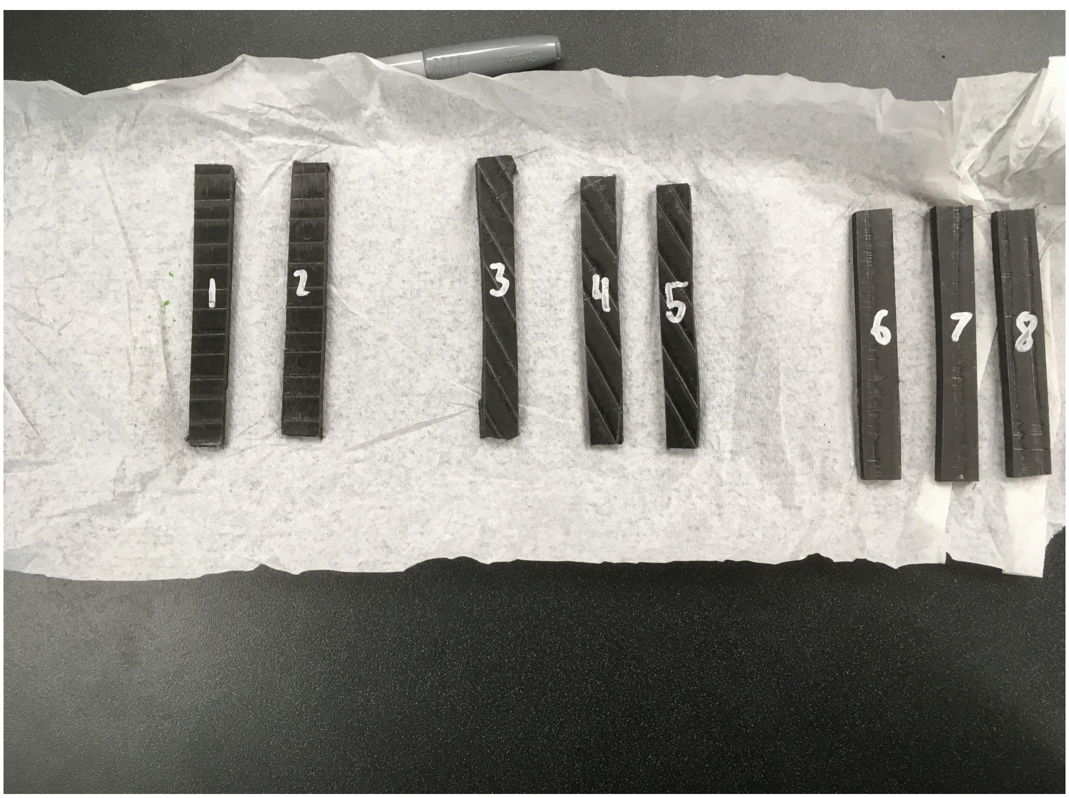


Figure 11. All the samples before they were tested. You can clearly see the fiber directions.

Figure 12. All the samples after their tests. Barely any deformation expect for samples one and two.