

Effect of Defects on Mechanical Properties of Composites: Undergraduate Research on Materials

Mir M. Atiqullah

Department of Mechanical Engineering Technology
Southern Polytechnic State University
1100 South Marietta Parkway, Marietta GA 30060
matiqull@spsu.edu

Abstract

Undergraduate research in engineering and technology is gaining popularity as an added opportunity of learning and a gateway to advanced studies. Many students find undergraduate research as a tryout for potential graduate studies, as well as a way to establish relationship with research faculty. Albeit new in our Mechanical Engineering Technology department, two students were selected to participate in a research involving defects in composite materials. These students did have minimal background in composites from the general Engineering Materials course. These minority students were supported by summer scholarships from Peach State Louis Stokes Alliance for Minority Participation (PSLSAMP). The issue of defects and their effect on the mechanical properties of composites is of great concern among high end users. A limited set of experimental investigation with defective composite flat panels was selected for investigation. One of our adjunct faculty offered access to his fabrication facility and guidance to the students for fabricating these ‘defective’ panels. Three types of defects were incorporated: hole as a discontinuity, edge groove simulating transverse crack, and Teflon interlayer simulating delamination. Once the panels were fabricated, strips were cut out for testing. Students also learned special processes for cutting and drilling composites. Aluminum tabs were glued to the ends of the composite strips to facilitate gripping by tensile tester. Two main testing methods were employed: tensile and 3-point bending. Unique failure modes of these specimens provided a lot of excitement as well as exposure regarding the mechanical behavior of composite materials containing defects. Certain correlations were observed between defects and resulting properties. Testing and results are far from complete. This endeavor provided great enthusiasm for engineering materials among the students. Other students have shown interest for continuing research on these and other materials projects.

Background

Composite materials are manufactured from 2 or more materials to take advantage of desirable characteristics of the components. A composite material, in mechanics sense, is a structure with the ingredients as element transferring forces to adjacent members. The advance in design and application of composites has accelerated in the past decade especially in the aeronautics, defense, and space industries. Commercial applications are also increasing as products needing challenging materials properties are increasing in demand. To fill the ever increasing demand for composites engineers the engineering and technology graduates need to be knowledgeable in the field, if not develop some level of expertise, before they graduate from college. Traditional materials science/engineering course can accommodate only an overview of composites. In the absence of a dedicated composites course a special project course or a research project on composites could be a supplement to the standard materials course. During the summer of 2007, two minority students were awarded scholarships from Peach State Louis Stokes Alliance for Minority Participation (PSLSAMP) to do undergraduate research. These students already completed their regular engineering materials course and were assigned to the project of performing an experimental investigation of failure modes of composite materials. While it was somewhat challenging,

the students took special interest in learning the fundamentals of composite materials, their mechanical properties as well as their failure characteristics in the presence of defects. Small amount of funds were available to purchase raw materials for fabrication of composite panels. Some special tools were also purchased to cut specimens and render damages to the specimens, albeit intentionally. The fabrication of the flat panels were done off campus at the invitation of an adjunct professor at his facility. Details of fabrication and specimen preparation are described later in this paper. In fact, the experience gained by the students in composite fabrication was as much of an interest, if not more, as the experimental failure tests originally targeted. Both theoretical and experimental studies were limited to polymer matrix composites. Furthermore the students were to use a hydraulic Satec/Instron universal testing machine with computer control and data acquisition. To be able to use the tester the students had to learn to operate the tester, familiarize with the control software and finally calibrate the displacement LVDT using a height gage as a standard. This calibration task was also a significant learning experience for the participating students.

Composite materials and testing

Composites belong to one of the four categories of structural materials. The other three are metals and alloys, polymers, and ceramics. In fact composites are not a different category material but various combinations of 2 or more of the latter 3 categories. This combination is at macroscopic level such that individual components retain their mechanical properties contributing towards those of the composite. On the other hand combination at the microscopic level, such as alloys and solid solutions (at the atomic level) are not considered composites. Composites, although more expensive than their counterpart materials, can demonstrate rather unusual combination of property values which is difficult, if not impossible, to achieve in any one standard material. It is not a random but careful and calculated combination of materials that leads to a composite that exhibit superior properties than any one ingredient alone.

While composites can be made out of a number of components, most composites are made of just two. One of them is known as matrix phase which is continuous and surrounds the other one known as dispersed phase. Mechanical properties of composites are a function of those of the ingredients, as well as their relative fraction amounts, and how the dispersed phase is distributed. The distribution is characterized by type/shape of the dispersed phase particles, size of the particles, as well orientation and distribution.

Distribution of fibers in fiber-reinforced composites is varied as per the application or load to be carried. These types are (1) continuous fiber composite, (2) woven composite, (3) chopped fiber (whisker) composite and (4) hybrid composite.

A classification¹ of composite is according to dispersed phase and geometry of bulk composites as shown in figure 1. Continuous fiber composites are used aligned along the application of load. A laminate formed by bonding continuous fibers with matrix material is again bonded together with other laminae to gain thickness and strength. The probability of separation of these laminae from each other is always a possibility since it depends on the strength of the matrix holding them. Chopped fiber composites are relatively inexpensive but suffer from poor mechanical properties. The sandwich structure is constructed of high strength outer laminae bonded to lightweight foam or honeycomb structure. Due to its extremely high strength in bending load and light weight, sandwich structures are extensively used in aerospace structural applications.

Fibers^{2,3} in fiber-reinforced composites are made of glass, graphite or carbon, Kevlar (Aramid polymer), Boron (as coating on carbon, tungsten etc.), silicon carbide (SiC), etc. Particulate composites could also be made with these as well as other materials. These are not elaborated any further here.

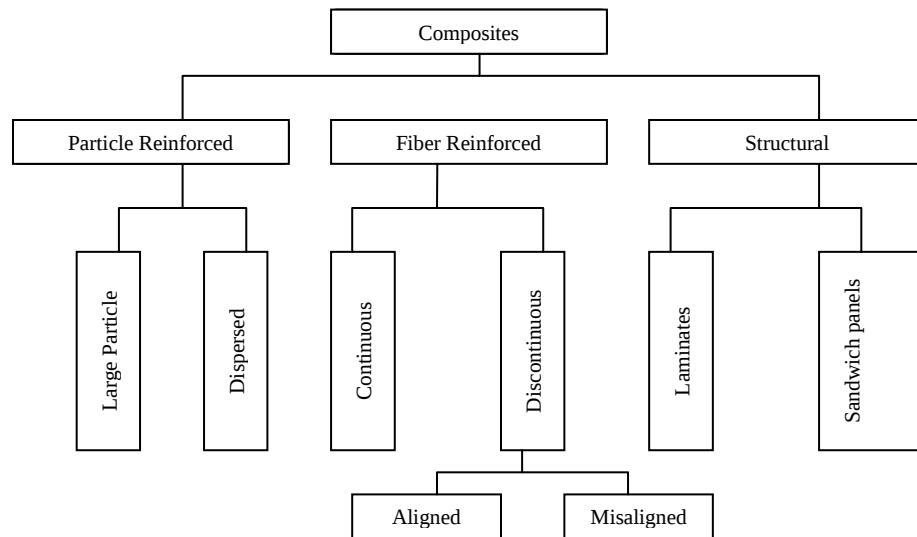


Fig. 1: Classification of composite types.

The matrix holds the fibers in place, and helps transmit internal forces between the fibers. The matrix also imparts some mechanical properties to the composite such as ductility, toughness, corrosion protection etc. Matrix is generally made of polymers but other also gaining popularity including epoxy, metals, and ceramics. There is another component to the composite materials, the filler material. These are additives to enhance and/or change some physical properties of composites. These modifications include weight reduction, UV protection, flame suppression, cost reduction etc.

Composite ingredients and manufacturing processes.

The knowledge of how composites are manufactured or processed is vital for the knowledge of how they may fail, since manufacturing is targeted towards achieving a specific structure. It is interesting to note that each type of composite, classified by its structure, is fabricated¹ using a set of unique processes.

Metal Matrix Composites (MMC) are fabricated using 2 steps: Consolidation followed by shaping. Discontinuous or whisker reinforced MMCs can be shaped using various metal forming processes such as forging, rolling etc.

Ceramic matrix composites (CMC) may be fabricated using various controlled pressing and heating sequences such as hot pressing, isostatic pressing and liquid phase sintering. Often ceramic matrix composites are toughened by adding ceramic whiskers such as SiC, Si₃N₄ etc. Ceramic matrix composites manufactured using increased fiber content gains strength and fracture toughness. CMCs have better high-temperature creep and thermal shock resisting characteristics.

Carbon-carbon composite manufacturing is complex and expensive and involves many steps performed very carefully. Starting with polymer matrix and carbon fiber, the composite is laid down in desired shape. Then the layup is heated in an inert atmosphere which ‘pyrolyzes’ the resin of the matrix, meaning turns into large carbon chain molecules. Further heat treatment at elevated temperature makes the carbon chain matrix more dense and strong. Original carbon fibers remain chemically unchanged within the dense carbon matrix.

Hybrid composites are made by utilizing two or more types of fibers within the same matrix. By judicious selection of fiber types, hybrid composites may have better overall mechanical properties. Most common hybrid is made of carbon and glass fibers in resin matrix. Glass-carbon composites are stronger, have higher impact resistance and toughness, and cost less than single fiber counterparts.

The largest bulk quantity of composites produced is of the type glass fiber-reinforced polymer. This type has several very important characteristics that make it most popular. The tensile properties may be seriously compromised if the surface of a fiber reinforced polymer is damaged. Close attention must be paid to coat newly drawn fibers as soon as it is produced. This coat is removed during manufacturing of composite parts. This group of composites includes carbon fiber-reinforced polymer composites, and Aramid fiber-reinforced polymer composites.

Polymer is the most commonly used composite matrix material. Matrix choice most commonly determines the maximum operating temperature. High temperature causes the matrix to soften, melt, or otherwise degrade beyond usability. Polyesters and vinyl esters are the most commonly used polymers as matrix. Epoxy is a better choice for matrix albeit for a higher cost. Epoxies are choice materials for matrix and have better mechanical properties and are resistant to moisture.

Composite characteristics

Characteristics⁴ of a composite material may differ from those predicted from the properties of the ingredients. This is due to manufacturing irregularity, reaction kinetics, and thermal expansion. Basic properties of composites include density, fiber volume fraction, voids, thermal expansion, tensile properties, and transverse properties. The summer research students⁷ mostly utilized the tensile properties as failure criteria under bending and tensile loading. As part of becoming familiar with composite materials testing, students calibrated the Universal testing machine and practiced operating the tester using the control and data collection software which was developed in-house earlier using Labview software package. Several straight specimens were tested under tensile loading upto fracture. It was visibly and audibly clear that composites fail much more abruptly as compared to ductile metals such as aluminum and steels.

Failure mechanisms

Composite failure^{4,5} is a cumulative process preceded by a succession of various inters damage under load. Micromechanical level failure mechanisms are primarily 3:

1. Fiber breaking
2. Matrix cracking and
3. Interface (between fiber and matrix) debonding.

These mechanisms vary with the type of loading, and mechanical properties of the constituents. Failure mechanisms are same in most composites but their mode of occurrence vary with type of loading and properties of the constituents. Uniformly distributed micro damages coalesce to form larger cracks leading to failure. It is the shear stress at the fiber-matrix interface that is responsible for transferring stress from matrix to the fiber. Stronger interfaces facilitate higher strength and stiffness albeit at the expense of fracture toughness. Similarly weak interfaces help deflection of matrix cracks along the interface resulting in a lower strength and stiffness and higher fracture toughness. The shear strength at the fiber matrix interface is important in determining the various failure mechanisms. The strength of the fibers dictates the strength of the composite, which is an anisotropic property. Failure can be predicted for ductile materials, such as steels, Aluminum alloys, using maximum Shear Stress Theory (MSST).

Distortion energy theory can also be used for ductile materials. Unfortunately composite materials are brittle and various empirical theories of failure^{4,5} have been proposed. These are:

1. Maximum stress theory
2. Maximum strain theory
3. Tsai-Wu failure theory

Under longitudinal tensile loading the average longitudinal stress σ_1 is applied on the overall composite. Considering equilibrium under tensile loading force on the composite is the sum of the forces in matrix and the fiber.

$$\sigma_1 A = \sigma_f A_f + \sigma_m A_m$$

where f stands for fiber and m for matrix and $A = A_f + A_m$

Therefore, dividing by A on both sides, we get:

$$\sigma_1 = \sigma_f V_f + \sigma_m V_m$$

Where V_f and V_m are volume ratios for fiber and matrix materials respectively. Uniform distribution of strength in fiber and matrix assumed, which is not always correct. However, in fiber matrix composites two different scenarios of failure are possible. In one the ultimate tensile strain is lower than that of the fiber such as in ductile matrix composites. In the second one, the ultimate tensile strain of the matrix is less than that of the fiber. This phenomenon is evident in the failure of brittle matrix composites.

The mechanical properties of common composite materials are available from standard hand books and various sources. The central theme of this research project was to determine the adverse effect of existing defects in composite materials' properties. Table 1 lists some common metals, alloys, and few common composites along with their properties for comparison purposes.

Table 1: Mechanical Properties of Some Selected alloys and composites.
(note: yield only applies to alloys)

Materials	Specific Gravity	Modulus (GPa)	Tensile Strength (MPa)	Ratio of Modulus to Weight (10^6 m)	Ratio Tensile to Weight (10^3 m)	Yield Strength (MPa)
SAE1010 Steel (cold worked)	7.87	207	365	2.68	4.72	303
AISI 4340 Steel	7.87	207	1722	2.68	2.30	1515
AL 6061-T6 Al Alloy	2.70	68.9	310	2.60	11.7	276
Ti-6Al-4v Titanium Alloy	4.43	110	1171	2.53	26.9	1068
17-7PH Stainless Steel	7.87	196	1619	2.54	31.0	1515
High strength carbon fiber-epoxy (unidirectional)	1.55	137.8	1550	9.06	101.9	
High modulus carbon fiber-epoxy(unidirectional)	1.63	215	1240	13.44	77.5	
E glass fiber-epoxy (unidirectional)	1.89	39.3	965	2.16	53.2	
Kevlar 49 fiber epoxy – (unidirectional)	1.38	75.8	1378	5.60	101.8	
Carbon fiber- epoxy quasi-isotropic	1.55	45.5	579	2.99	38	

For the current phase of the experimental study, a limited set of defects and their effects on the mechanical properties of composites were selected. Defects could be generally divided into two categories;

1. External/through. (e.g. edge groove, through hole)
2. Internal. (e.g. delamination)

Furthermore, composite materials could sustain other physical damages such as surface damage near high heat zone, corrosion and degradation by harsh chemicals, surface damage by sharp object, superficial fiber damage, and warped the panel due to curing or heat treatment. It was decided to perform a limited set of experimental study within the time available. This project is to continue in the future where other standard as well as unusual failures⁸⁻¹⁶ are covered.

Fabrication and testing

Carbon reinforced composites were selected as they can tolerate considerably higher temperatures. For fabrication of the panels, following equipment and tooling were utilized:

1. Autoclave
2. Pressure Gages
3. Vacuum Bags
4. Vacuum Pump
5. Layout instruments
6. Band Saw
7. Vertical Milling Machine
8. High Temperature Curing Adhesive
9. High Temperature Heat Resistant Tape
10. High Speed Circular Saw (Diamond cutter)
11. High Temperature Teflon Film

Raw materials used was unidirectional carbon fiber cloth and 2024 aluminum used as the tabbing material for gripping the specimens at ends to avoid damaging the test pieces by the tester grips. For the sake of uniformity of the specimens, several square flat panels were manufactured simultaneously. Their construction consisted of:

- Lay up: 12 plies @ (0/90°) (i.e. alternate bidirectional)
- Fiber % volume: 53.3%
- Fiber density: 1.77 g/cm³
- Resin % volume: 37 %
- Resin density: 1.219 g/cm³

The panels were laid up making sure that the straight edges are parallel to each other. All panels were laid up with fiber direction towards the same direction resulting in a unidirectional, anisotropic material. The layup process continued until a desirable thickness was achieved. Then the panels were debulked to help in better adhesion as well as gas expulsion from in between the layups. Then the panels were bagged and heated in the autoclave for six hours. The panels were trimmed around the edges to produce clean specimens and tabbed using the aluminum strips on both sides and both ends using a high temperature curing adhesive. Curing took about 4 hours. Next the panels were cut using standard wet tile saw with diamond cutter disks. These resulted in strips with the aluminum tabs at the ends for gripping as shown in figure 2. The resulting panels and cut up strips are shown in figure 3.

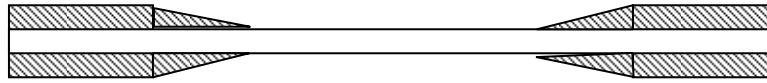


Figure 2: Schematic of tensile specimen tabbed at the ends.

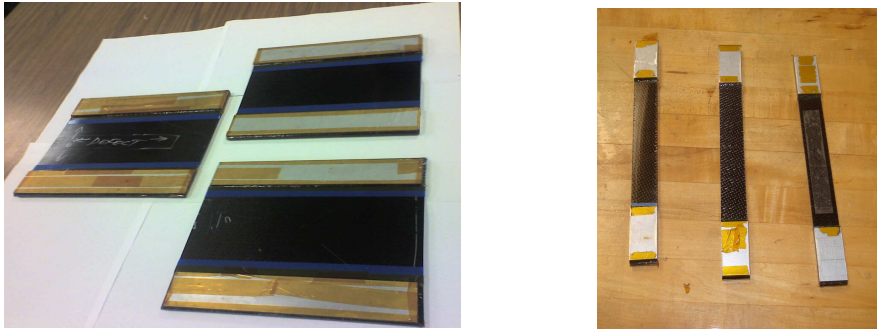


Figure 3: Left- Square composite panels with aluminum tab at ends. Right- 1 inch wide test strips cut from the panels. A wet tile cutter with diamond disk proved useful.

Test setup

The central goal of this project was to experimentally determine the effects of various defects on the mechanical properties of the composite materials. As such fiber reinforced composite panels were fabricated with internal defects caused by Teflon insert in between carbon laminates. Furthermore holes were drilled on the edge as well as at the center of selected test panels to simulate trough defects. Two drill sizes were used; 0.25 inch and 0.125 inch. Edge defect was generated using the 0.25 inch drill. These drills were special ones with a single cutting edge. The set of defects are not complete by any means. The research would continue to investigate other surface and internal defects and their effects. Test panels without any defects (not intentional) were used as control for comparing test data.

Results

Both tensile and 3-point bending tests were performed on the specimens.

The test data for specimens with through hole and edge groove were comparatively more consistent. The summary of average tensile test results is shown in table 2. Both the defective specimens demonstrated about 50% in strength reduction, with insignificant difference between them.

Table 2: Fracture strengths of defective specimens as compared to control

Specimen type	Strength (ksi)	Failure mode
Control	120	Brittle fracture – shattered into 3 pieces simultaneously
Central hole	57	Fractured into 2 pieces
Edge groove	61	Fractured into 2 pieces

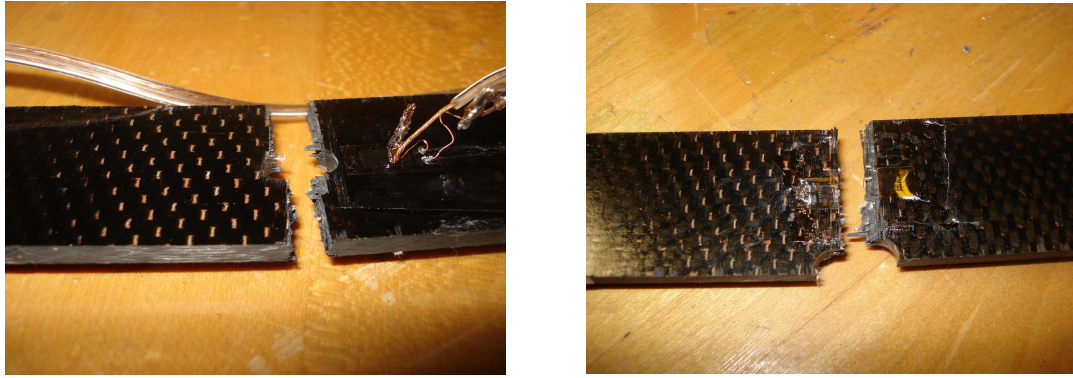


Figure 4: Failed specimens with through defects simulated by central hole and edge cutout.

Internal defect was simulated by inserting a layer of Teflon in the specimen during fabrication. This would prevent interlayer bonding at the central region. This is shown in Figure 5.

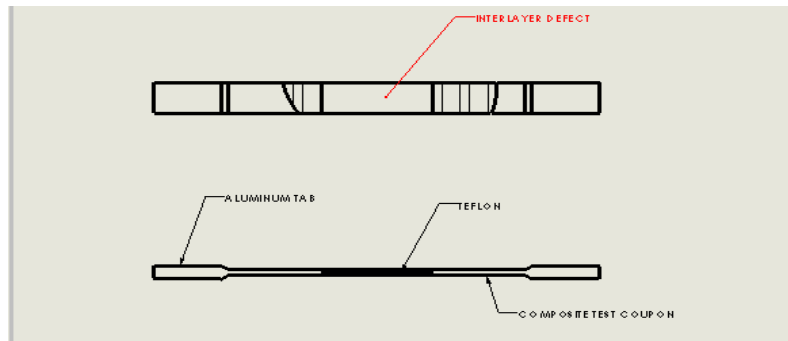


Figure 5: CAD model of specimen strip showing aluminum tab and interlayer defect (Teflon insert)

Internally defective specimens were tested in both tensile and bending mode. In tensile test, the specimens demonstrated almost no significant difference with the control. However in bending the defective specimen was about 15% weaker. Theoretically if the layers were completely separate, the stiffness would have been reduced by 75%. However that did not happen as the layers were firmly bonded at the ends. Moreover the only partial length of the test piece was defective, meaning the Teflon layer did not separate the layers all the length of the gage length. The results are shown Table 3.

Table 3: Flexural strength of interlayer defective composite specimen.

Specimen	Cross section area (in ²)	Failure bending stress (ksi)
Control	0.14204	142
Inter-layer defective	0.139	121

Analysis and Discussion

The experience of composite fabrication and specimen preparation was as rewarding to the students as the final testing and getting results. The range of tests performed was limited and covered just few types

(interlayer, edge, central) of defects. At this time the testing remains far from complete. However limited inferences could be made based on available test data. The specimens behaved in a very brittle manner without exhibiting much ductility, as expected. Although ultimate strength values were different, the elasticity measured from the slopes of the plots, were about same for all types of defective specimens. Control specimen without any defect shattered into 3 pieces during the test while defective specimens broke into two pieces through the defective region. Although the fracture happened without any visible indication of yield or deformation, it is obvious that stress concentration at the hole and notch caused first fracture that propagated through the specimen width.

The results of testing internally defective specimens were more predictable. Although the specimen was not completely separated by the Teflon separator, the specimen showed the significant reduction in flexural strength. No correlation can be made until more testing is done focusing on interlayer defects and their types and magnitudes.

Conclusion

The project was undertaken to introduce the students to composite materials, their characteristics and effect of defects on the mechanical properties of such materials. The uniqueness of composite materials and their responses to various loading and defect conditions were key features of this endeavor. The experience in calibrating a tester was bonus learning for the students, although it appeared frustrating at the beginning. The student researchers remained quite interested in the project and both of them eventually accepted engineering positions in the composites industry. They attributed this project as the motivator for them as well the employers for their employment. Mistakes were done and then many things were learned in the areas of fabrication as well as testing. It is hoped that more students would take up continuation of this project in the future and incorporate further variety of defects as well testing modes into the research.

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Author Biography

Mir M. Atiqullah is an Associate Professor in the Department of Mechanical Engineering Technology at Southern Polytechnic State University, Marietta, Georgia. He has a BSME degree from Bangladesh University of Engineering and Technology and MS and PhD degrees in mechanical engineering from Purdue University, West Lafayette, Indiana. His research interests include mechanical design, computational optimization, supercomputing, optical sensors and materials testing. He has been teaching engineering and technology since 1996. His teaching areas include engineering materials, engineering mechanics, machine design and capstone design. He is a member of ASEE and ASME.