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MANUFACTURING, MODELING, AND CHARACTERIZING THERMOPLASTIC COMPOSITES FOR MILITARY VEHICLE APPLICATIONS

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ABSTRACT

This paper focuses on development of methods for manufacturing structural thermoplastic composite materials, characterizing the mechanical properties of such composites, and modeling the static and dynamic performance in relevant military vehicle modeling and simulation environments. A thermoplastic polyethylene terephthalate (PET) / fiberglass composite was selected for this study due to the high specific strength of e-glass fibers, the high toughness of the PET thermoplastic, and relatively low price point, all which make it an attractive candidate for structural lightweighting of vehicles. The raw materials were manufactured into composite laminates using a compression molding process and then the mechanical properties were characterized using experimental test methods. Properties like stiffness, strength, and strain-to-failure of the composite were characterized using standard ASTM methods, and the resulting properties were directly fed into a computational material model. However, in order to characterize more complex material responses, like delamination between layers, a special through thickness butt-joint test was utilized so that the physical properties in the test matched the physics in the modeling and simulation environment. Several lessons were learned throughout the study, which may be useful to engineers and researchers looking to integrate structural thermoplastic composites into future military ground systems.

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1. INTRODUCTION

Defense and commercial automotive industries alike seek out new lightweight material solutions to reduce the weight of vehicle structures. Decreasing weight while maintaining structural integrity leads to a more fuel efficient vehicle that is more mobile than the legacy design. Lightweight composite materials can have strength and stiffness similar to metal alloys, but have lower density and thus can often be used to make lighter structural components. For instance, structural thermoplastic composites have been recently used to make a lightweight tactical cargo shell that was 35% lighter than aluminum [1] and a combat vehicle crew floor that was 56% lighter than a baseline aluminum design [2]. Weight savings was achieved in these ground vehicle applications through a combination of design optimization, low material density of the composite, and high structural performance (*i.e.*, high specific stiffness and strength). In addition to lightweighting benefits, when designed properly, composite materials can provide superior energy absorption due to their complex failure mechanisms. For example, under axial crushing during a vehicle crash event, composite structures can absorb more energy using less mass when compared to sheet metal structures. This trend has been shown to hold true for both thermoset [3, 4] and thermoplastic [5, 6, 7] composites.

A complexity of thermoplastic polymer matrix systems arises as these resin systems can exhibit large variance in material properties due to their manufacturing techniques and thus, must be characterized to their unique manufacturing scheduling (I.E. processing temperatures, heating and cooling rates, consolidation pressures, and time at dwell. These behaviors vary due to the crosslinking nature of the polymer system when undergoing its cooling process.

Thermoplastics can exhibit crystalline or amorphous molecular structures depending on the chemical composition of the polymer, or even the rate of cooling during manufacturing. Specifically, PET is a unique type of polymer system that can exhibit both semi crystalline or amorphous characterizations depending on the manufacturing process. In the case of PET, a fast cooling rate defines more of an amorphous molecular structure where as a slower cooling rate defines a semi crystalline structure. Though manufacturing derived mechanical data can be obtained from a material supplier, it is often unknown which manufacturing scheduling was used to produce the composite used in the characterization process, highlighting the need for a manufacturing specific mechanical characterization.

Adding further complexity, when the matrix system is reinforced with fiber reinforcement, the manufacturing variance only increases. Unidirectional composites carry larger difficulties when manufacturing due to fiber wash, resin rich and resin lean areas within the composite. Fiber wash occurs when the composite reaches melt temperature and consolidated. Any air voids originally in the mold are filled with resin once in its melted state. This carries the fibers and thus, drifts the fibers out of alignment resulting in a “quasi-unidirectional” composite with fiber orientations being a few degrees from true. This phenomenon also can lead to resin rich and lean areas by pinning the fibers in certain areas and allowing the resin to escape and flow toward these voids. Resin can furthermore leak out of the mold and cause further fiber wash.

This paper sets to illustrate the considerations needed to be taken when designing with thermoplastic composites. A characterization process is laid out for a composite ply by ply model to be developed for a PET/GF reinforced polymer unidirectional composite system and discusses the challenges and approaches to solving some of these difficulties.

2. METHODS

2.1. Composite Manufacturing

The manufacturing technique used to consolidate the PET unidirectional plies was utilizing a hydraulic hot press with a square metal mold. The press used was a Grimco

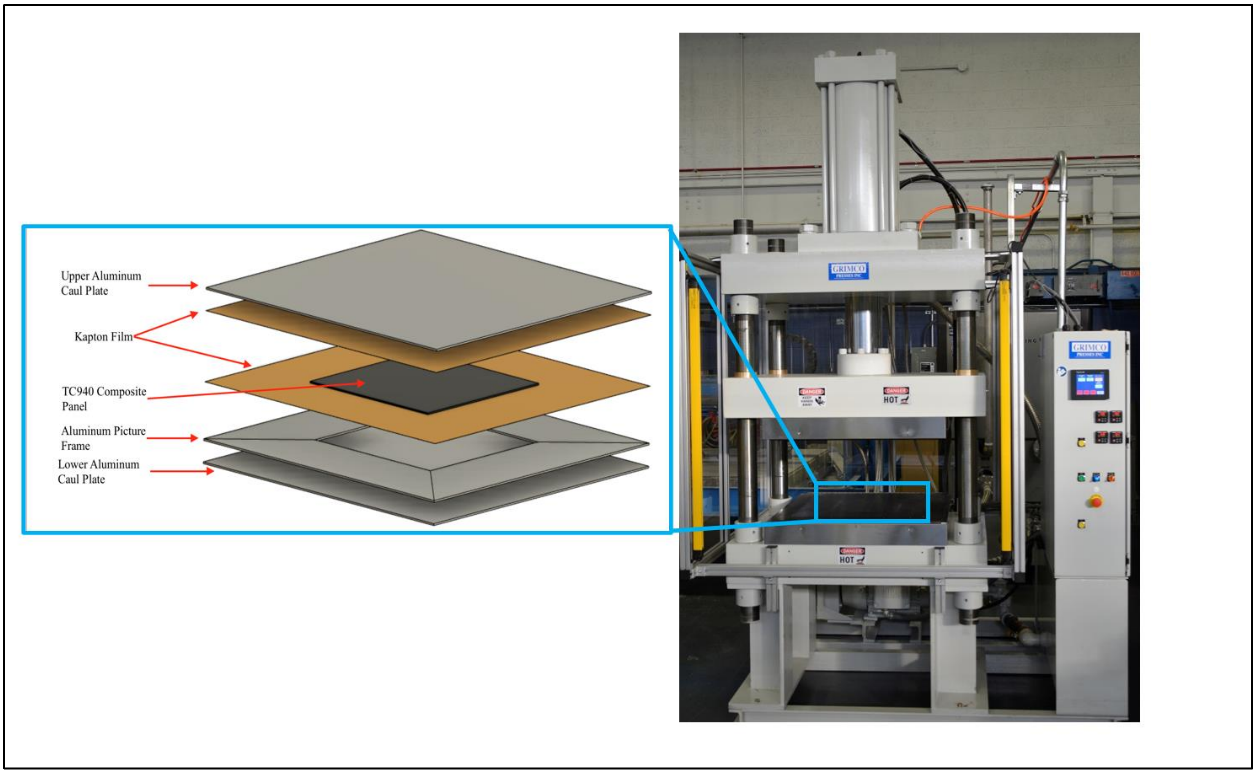

Figure 1: Depiction of tool used to manufacture the thermoplastic composite within a heated hydraulic press

150-ton heated press outfitted with a chilling system to allow for expedited cooling (see Figure 1).

The PET composite was processed with the following manufacturing schedule:

1. Preload at 35-ton force, (0.83MPa)
2. heat to 510°F (maintain 35-ton force),
3. dwell at 510°F for 15 minutes (maintain 35-ton force), and
4. cool to 70°F (maintain 35-ton force until room temperature).

Cooling began at 510°F with air and water cooling to allow platens to cool without over pressurizing from excess water vapor. Pure water was then pumped into the platens at a temperature of 350°F. From this point, a cooling rate of 59°F/min was achieved.

2.2. Mechanical Characterization

The processed PET composite was mechanically characterized for tension, compression, shear, and interlaminar strength properties. These parameters were needed to accurately model the composite material within a finite element simulation with the manufacturing set up specific to that of the experimentally tested composite.

Rectangular bars were manufactured for tensile, shear and interlaminar shear testing (Figure 2). Cylindrical rods were manufactured for compression and normal interlaminar failure stress (Figure 3).

3. RESULTS AND DISCUSSION

3.1. Failure Analysis

The experimentally derived mechanical data is compared against the supplied mechanical data from the manufacturer in Table 1. Note that the tensile and compressive properties in the 90° direction share the highest percent difference than the manufacturing values. It is important to note that in the 90° direction, the fiber has little to no effect and the strength is purely attributed

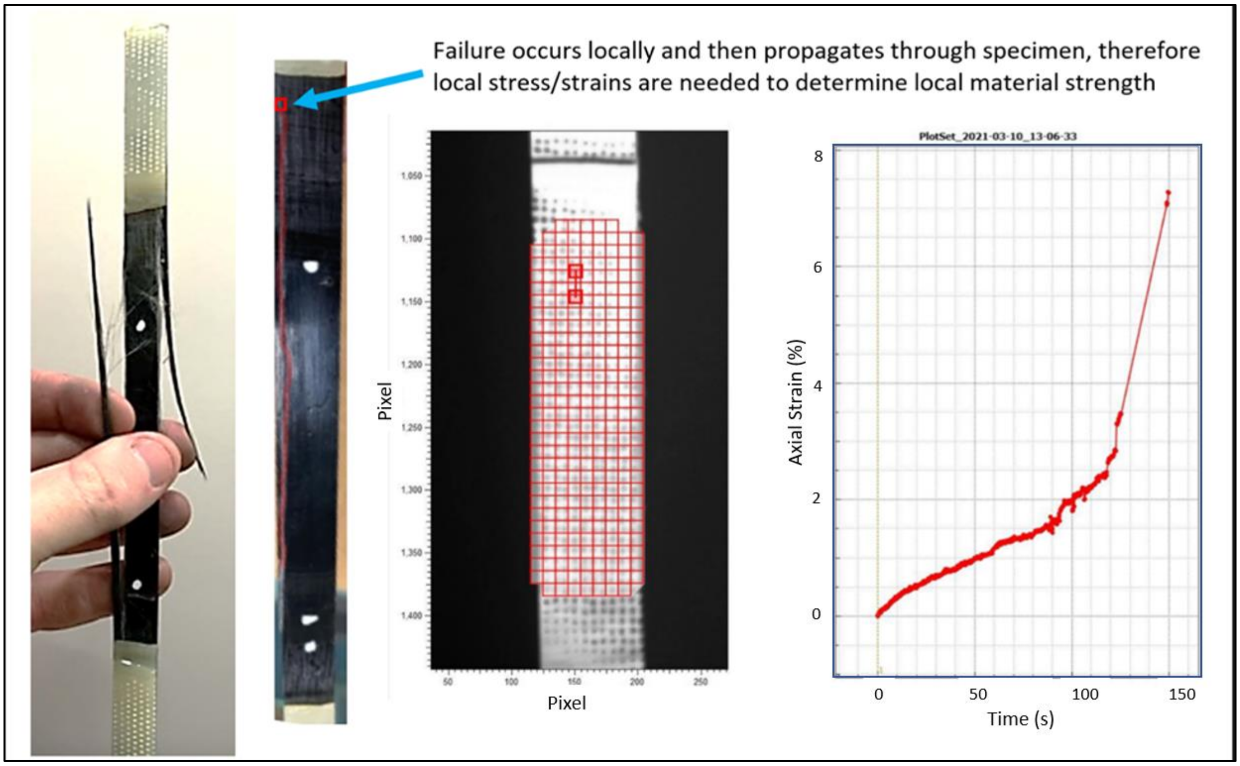

Figure 2: Images of unidirectional tensile specimens showing local failure (left) and digital image correlation graph showing local strains within the specimen.

Figure 3: (Left) Butt joint specimen used for determining through thickness failure strength (Right) lap shear specimen used for determining shear strength between plies.

Table 1. Mechanical Property Data for Unidirectional Composite

Property	Manufacturer	Exp.	Diff.
T-90 Mod	7.05GPa	6.53GPa	7.4%
T-0 Mod	32GPa	35.3GPa	10.3%
$S_{12/13}$ Mod	2.82GPa	2.32Gpa	17.7%
S_{23} Mod	2.58GPa	2.12GPa	17.8%
T-0 Strength	960MPa	960MPa*	N/A
T-90 Strength	68.4MPa	15.4MPa	77.5%
C-90 Strength	54.2MPa	68.2MPa	25.8%
C-0 Strength	329MPa	378MPa	14.9%

to the polymer resin matrix. As mentioned previously, the mechanical properties of the polymer can vary widely depending on the cooling rates so, these results are expected. Unfortunately, the cooling rate of the manufacture derived mechanical data is unknown, but it is fair to assume they are different thus, allowing the PET to exhibit more of a crystalline molecular structure and higher strength values. Microscope images of the PET matrix and glass fibers are shown in Figure 4.

In the fiber direction, the unidirectional nature of the test specimen posed some mechanical characterization issues. Fiber wash led to fiber orientations offset to true 0°. These off-angle fibers cause premature failure within the T-0 strength values as those fibers straightened out to a true 0° first before complete rupturing in a pure tensile behavior. To address this, DIC was used to obtain the local rupture strain at areas where rupture was observed initially. Though premature failure was exhibited in nearly every case, the elastic properties before failure was well captured and used to back calculate the failure stress with the given DIC localized failure strain with the experimentally derived elastic modulus. To characterize the interlaminar properties of the composite, both normal and shear stress at failure was obtained.

3.2. Computational Material Modeling

The finite element model for this particular project implemented MAT_054 which utilizes Chang-Chang failure criterion to indicate element failure. Upon failure, elements strengths are reduced until a strain limit is reached in which the element is completely damaged and eroded from the model (Figure 5). The interlaminar characteristics were captured by implementing nodal ties at each ply interface where the failure was dictated by the normal and shear stresses at the interface with the criterion:

$$\left(\frac{\sigma_n}{NFLS}\right)^2 + \left(\frac{\sigma_s}{SFLS}\right)^2 > 1$$

Where a value larger than one signifies a broken nodal constraint (Figure 6).

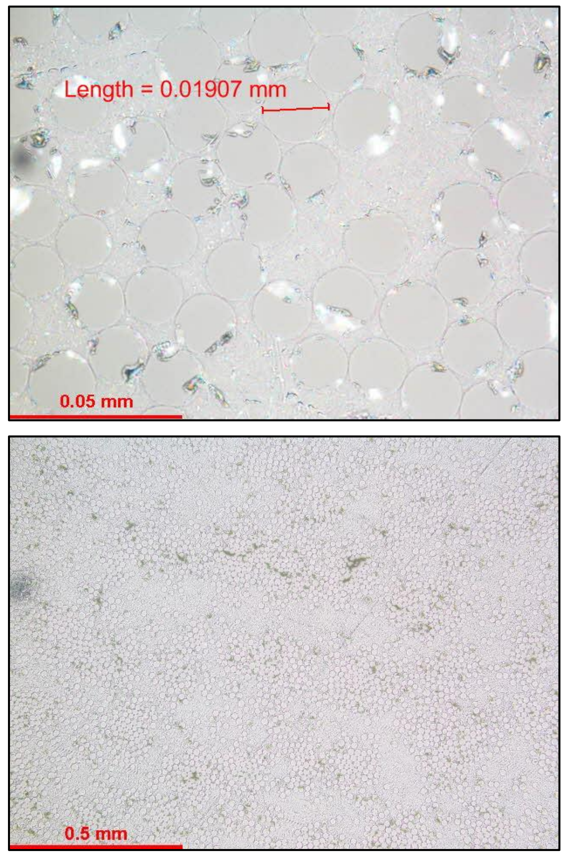

Figure 4: (Top) Macro view of distribution of glass fibers and resin rich areas within the composite (Bottom) Close up view of individual glass fibers.

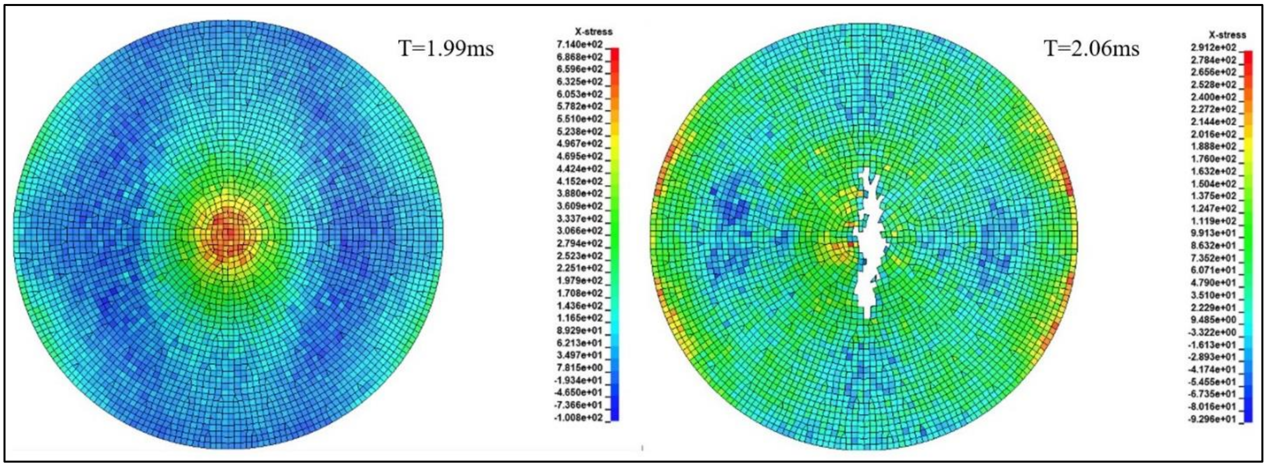

Figure 5: Left: Stress in Fiber Direction Just Prior to Failure. Right: Stress in Fiber Direction Just After Failure and Element Degradation/Erosion

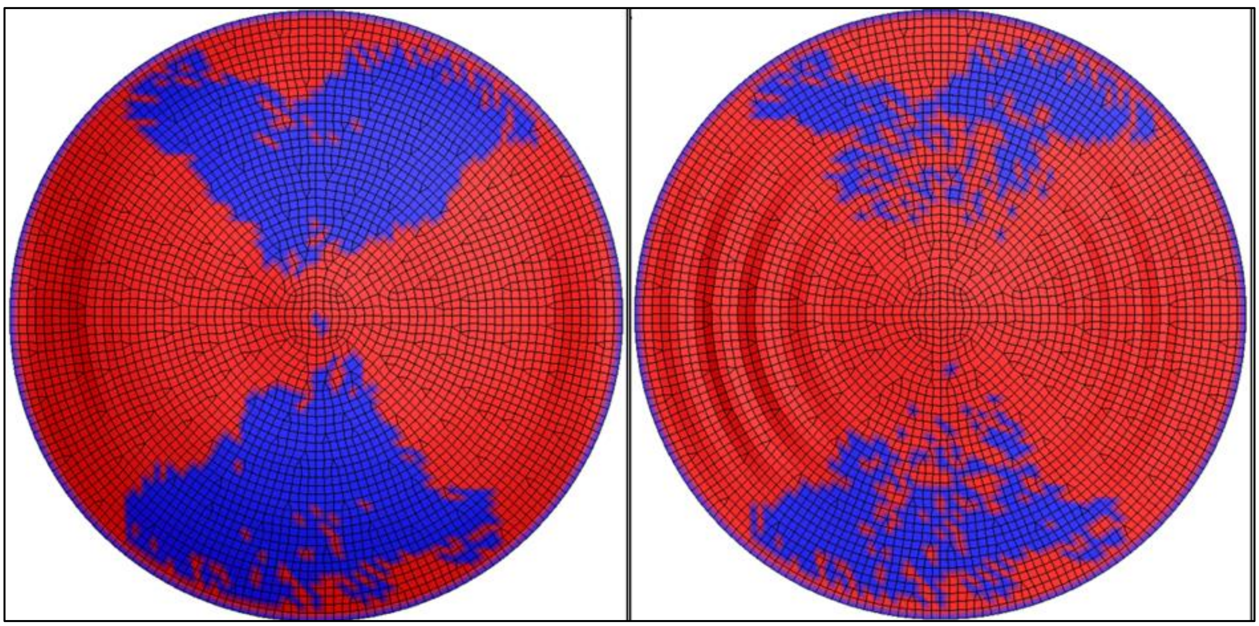

Figure 6: Left: Delamination at Peak Deflection Right: Delamination Post Peak Deflection (Red Indecates Delamination, Blue Indecates Tied Nodal Constratint)

4. CONCLUSIONS

Thermoplastic composites pose great challenges in the manufacturing, characterization, experimentation, and modeling processes. This work sought to bring forth these challenges and address the need to do a full characterization to the specific manufacturing process used for the experimental material structure.

By understanding the entire characterization process, we can more confidently suggest thermoplastic composite integration on ground vehicle systems under given types of loading and instill higher levels of confidence in the finite element models needed to predict performance

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