8-2019

Terfenol-D Carbon Fiber Reinforced Polymer (CFRP) Embedded Sensing for Early Damage Detection

Brandon Eugene Williams
Clemson University, bew3@g.clemson.edu

Follow this and additional works at: https://tigerprints.clemson.edu/all_theses

Recommended Citation
https://tigerprints.clemson.edu/all_theses/3181

This Thesis is brought to you for free and open access by the Theses at TigerPrints. It has been accepted for inclusion in All Theses by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.
Terfenol-D Carbon Fiber Reinforced Polymer (CFRP) Embedded Sensing for Early Damage Detection

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

by
Brandon Williams
August 2019

Accepted by:
Oliver Myers, Ph.D., Committee Chair
Garret Pataky, Ph.D.
Gang Li, Ph.D.

ARL Mentors:
Asha Hall, Ph.D.
Michael Coatney, M.S.M.E.
Mechanics Division
ABSTRACT

Carbon Fiber Reinforced Polymers (CFRPs) have become an essential part of designing and engineering lightweight rigid bodies; predominantly in the aerospace and automotive industries. Typical epoxy-based CFRPs exhibit virtually no plasticity with minimal strain to failure. Although CFRPs have high specific strengths and elastic moduli, the brittle fracture mechanism presents unique challenges in failure detection for Army’s vertical lift vehicles since failure occurs catastrophically. Current state of the art structural health monitoring (SHM) for aerospace structures are intrusive to the surface of the part and/or requires electrical connectivity. Army uses a “safe-life” interval-based service methodology where components are replaced with regards to a usage spectrum rather than the component’s actual state of structural health. This paper explores a method for solving this problem by investigating the possibility of embedding Terfenol-D (~100 microns in diameter), a magnetostrictive material, into the CFRPs for embedded non-contact structural health monitoring. For baseline results, the change in localized (32 mm² field of view) magnetic flux was only 0.02% for an applied load of 0-100% of the material’s ultimate tensile strength (UTS). For quasi-static testing procedure of specimen 5714 (15 wt.% Terfenol-D embedded CFRP) on a 0-40% loading interval of the material’s UTS, there was an observed localized (32 mm² field of view) magnetic flux gradient of more than 5 mT (4%) with a reversible flux of 100%. For quasi-static testing procedure of specimen 5714 (15 wt.% Terfenol-D embedded CFRP) on a 0-70% loading interval of the material’s UTS, there was an observed localized (32 mm² field of view)
magnetic flux gradient of more than 3 mT (2%) with a reversible flux of only 25%.

Terfenol-D embedded CRFPs have shown promising results for detecting instantaneous levels of degradation. Acoustic emission (AE), X-ray computed tomography (CT) scanning, Finite Element Analysis (FEA) and analytical modeling were used to validate the observed results.
ACKNOWLEDGMENTS

I have contributed to this project, however, none of this would have been possible without the help from the following:

I am highly thankful for the Clemson University in Clemson, SC, and the Army Research Lab at Aberdeen Proving Grounds, MD. Without the support of these two institutions the completion of my research would not be possible. I would also like to thank my incredible and supportive advisor Dr. Myers and mentors Dr. Asha Hall, Mr. Michael Coatney; as well as the staff and faculty at the Vehicle Technology Directorate (VTD) of ARL for their mentorship and inspiration in my endeavors.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE PAGE</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. EXPERIMENTAL PROCEDURE</td>
<td>7</td>
</tr>
<tr>
<td>Baseline Samples</td>
<td>7</td>
</tr>
<tr>
<td>Terfenol-D embedded CFRP Fabrication</td>
<td>7</td>
</tr>
<tr>
<td>Mechanical Testing Equipment</td>
<td>8</td>
</tr>
<tr>
<td>3. RESULTS</td>
<td>17</td>
</tr>
<tr>
<td>Baseline Testing Results</td>
<td>17</td>
</tr>
<tr>
<td>15 Weight Percent Terfenol-D Results</td>
<td>20</td>
</tr>
<tr>
<td>Acoustic Emission (AE) Data Correlation</td>
<td>30</td>
</tr>
<tr>
<td>X-Ray Computed Tomography (CT) Image</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. MATHEMATICAL DESCRIPTION OF TERFENOL-D (CFRP) ........................................39

5. FEA OF TERFENOL-D EMBEDDED CFRP .................................44
   FEA Method..............................................................................44
   Fabrication Solution.................................................................47

6. CONCLUSIONS ........................................................................49

7. REFERENCES ...........................................................................53
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Test Specimens Specifications</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Helmholtz Coils Specification</td>
<td>8</td>
</tr>
<tr>
<td>2.3 Permanent Magnet Specification</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Gauss/Tesla Meter Specifications</td>
<td>13</td>
</tr>
<tr>
<td>2.5 DIC Specifications</td>
<td>14</td>
</tr>
<tr>
<td>2.6 MTS Specifications</td>
<td>16</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Helmholtz Coils testing setup</td>
<td>9</td>
</tr>
<tr>
<td>2.</td>
<td>Permanent Magnet Testing Diagram</td>
<td>12</td>
</tr>
<tr>
<td>3.</td>
<td>Gauss/Tesla Meter</td>
<td>13</td>
</tr>
<tr>
<td>4.</td>
<td>Parallel (Axial) Field Probe Diagram</td>
<td>14</td>
</tr>
<tr>
<td>5.</td>
<td>Parallel (Axial) Field Probe</td>
<td>14</td>
</tr>
<tr>
<td>6.</td>
<td>DIC post-processing example</td>
<td>15</td>
</tr>
<tr>
<td>7.</td>
<td>Fractured Sample</td>
<td>16</td>
</tr>
<tr>
<td>8.</td>
<td>Baseline Stress vs Magnetic Flux vs Strain</td>
<td>18</td>
</tr>
<tr>
<td>9.</td>
<td>Baseline Stress vs Strain</td>
<td>20</td>
</tr>
<tr>
<td>10.</td>
<td>15 wt.% Stress vs Strain</td>
<td>22</td>
</tr>
<tr>
<td>11.</td>
<td>15 wt.% Stress vs Strain</td>
<td>23</td>
</tr>
<tr>
<td>12.</td>
<td>5417-1 Magnetic Flux vs Normalized Stress vs Index; precursor marked (0-40 % UTS)</td>
<td>25</td>
</tr>
<tr>
<td>13.</td>
<td>5417-1 Magnetic Flux vs Normalized Stress vs Index; reversible flux marked (0-40 % UTS)</td>
<td>27</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

14. 5417-1 Magnetic Flux vs Normalized Stress vs Index; reversible flux marked (0-70 % UTS)…………………………….29

15. 5417-1 Magnetic Flux vs AE Peak dB vs Normalized Stress (0-40 % UTS)………………………………………………32

16. 5417-1 Magnetic Flux vs AE Peak dB vs Normalized Stress (0-70 % UTS)………………………………………………34

17. Micro X-Ray CT scan of 5417-1 after 0-70 % UTS mechanical testing………………………………………………36

18. Nominal Actual Comparison Micro X-Ray CT scan of 5417-1 after 0-70 % UTS mechanical testing…………………………37

19. Micro X-Ray CT scan of distribution embedded particles……………………………………………………………………38

20. 2-D schematic of Terfenol-D embedded CFRP……………………………………………………………………………………39

21. Strain versus magnetic field [11, 18]………………………………………………………………………………………………41

22. k_{33} and d_{33} versus applied stress [11, 18]………………………………………………………………………………………42
List of Figures (Continued)

Page

23. 2-D Multiphysics FEA model of

Pristine Terfenol-D embedded CFRP .........................47

24. Von Mises Stress FEA model of

Pristine Terfenol-D embedded CFRP .........................48
1. INTRODUCTION

As the demand for lightweight high strength composite structures increases in the aerospace and automotive industries, it is paramount for designers and engineers to understand how the materials that compose the structures will perform in extreme conditions; specifically for the Army the conditions experienced in high stress flight regimes. Polymeric composites, such as carbon fiber reinforced polymers (CFRPs), have many advantages including high rigidity, high specific strength, directional strength properties, corrosion resistance, high fatigue strength, low thermal expansion, and shock absorption [1, 3, 11, 14, 20].

Although there are many benefits to using CFRPs in design and engineering, there are some characteristics of CFRPs that arise concerns regarding the long-term durability of these composites; especially when it comes to performances under critical loading and carrying conditions [5, 11]. Although CFRP has high specific strength and elastic modulus, the brittle fracture mechanics present unique challenges in failure detection since failure occurs catastrophically.

The Army’s vertical lift vehicles currently are subject to “safe-life” interval-based service methodology [2] where components are replaced with regards to a usage spectrum rather than the component’s actual state of structural health. This maintenance methodology is not only time consuming but is also very costly for multiple reasons such as:

- Inspection and maintenance require the aircraft to be landed and shut down; loss of operation time.
• Appropriate personnel must be hired to perform the inspection; which costs money and time along with the integrated risk of human error.

• Inaccurate analysis of aircraft structures could lead to the disposal of fully operational component; which is extremely cost inefficient.

• Inaccurate analysis of aircraft structures could lead to operation of a failure prone component; which could lead to catastrophic failure of component as well as the entire aircraft.

Structural health monitoring (SHM) is a valuable solution in assessing the internal damage of CFRP components; however, there are currently no real-time, non-contact, non-destructive evaluation (NDE) techniques available. Current state of the art structural health monitoring (SHM) for aerospace structures are intrusive to the surface of the part and requires electrical connectivity [9]. There are efforts in embedded sensing for SMH such as well-connected Nano-fillers, which detect damages by changes in the material’s conductivity [26]. Although there are other efforts in SHM, this research has created a new, real-time, non-contact NDE technique for the use of the Army for their vertical lift vehicles. Knowing the instantaneous state of health in CFRPs would dramatically reduce cost and repair-time for operation and maintenance of the Army’s vertical lift vehicles.

Terfenol-D is a magnetically activated smart material composed of Terbium (Tb), Dysprosium (Dy), and Iron (Fe). Typical ferromagnetic magnetostrictive materials have a saturation magnetostriction strain of only $\lambda_s \approx 10^{-6}$, however, at room temperature Terfenol-D has the highest observed Joule magnetostriction with saturation magnetostriction strain of $\lambda_s \approx 10^{-3}$ [18]. Along with Terfenol-D’s high magnetostrictive
properties, it also has magneto-mechanical coupling properties, meaning as the material is exposed to a magnetic field, the material becomes stiffer [1, 18, 21]. In a demagnetized state, Terfenol-D particles have a C15 cubic laves crystal structure. Terfenol-D is a polymorphic structure which means that it can change into different crystalline structures and still possess the same chemical composition [1]. This characteristic allows Terfenol-D to strain 3 orders of magnitude greater than any other ferromagnetic or paramagnetic material.

Magnetostriction is the change in shape and size of a body when its state of magnetization is changed [8, 18]. The variation of material’s magnetization is due to a change in the induced magnetic field that simultaneously changes the magnetostrictive strain until reaching its saturation value. This phenomenon is governed by magnetocrystalline anisotropy, such as it takes more energy to magnetize a crystalline material in one direction than another [19, 25]. Terfenol-D’s high magnetostrictive properties allow it to be used as a sensor to detect damage in CFRPs. By embedding Terfenol-D particles into CFRPs, one can track real-time the magnetostriction responses. Implementing the Villari effect to the magnetostriction responses, which defines the induced stress by a change in magnetostriction, will allow one to back out critical information about the structural health of the material [11, 18, 20].

A permanent ±0.5 Tesla (T) magnet was used to produce a constant uniform magnetic field while a magnetometer was used to determine the change in magnetic flux density through the Terfenol-D embedded CFRP. Characterizing this system dynamically will pose a great challenge initially. To model and understand the characteristics of
Terfenol-D, the system was initially treated as a statically indeterminate system (i.e. acceleration =0). As stated before, the magnetostrictive material has the capability to be used as a sensor with respect to the Villari effect; which will be parameterized as a magnetostrictive coupling effect. To accurately represent this effect, there are two primary governing equations that define this coupling between magnetic flux density and strain (i.e. damage) of the Terfenol-D material. Defining the magnetic flux density yields equation (1) [18].

$$\delta B_i = d_{ij} \delta \sigma_j + \mu^0_j \delta H_j$$  \hspace{1cm} (1)

\(B_i\) = *magnetic flux density*;

\(d_{ij}\) = *magnetostrictive coefficient*;

\(\mu^0_j\) = *permeability at constant stress*;

\(\sigma_j\) = *material stress*;

\(H_j\) = *magnetic field*

\(\delta\) = *Small perturbation symbol*

Defining the strain yields equation (2) [18]

$$\delta \epsilon_i = S^H_{ij} \delta \sigma_j + d^T_{ij} \delta H_j$$  \hspace{1cm} (2)
\( \varepsilon_i \equiv \text{strain} \)

\( d_{ij} \equiv \text{magnetostrictive coefficient (Transposed)}; \)

\( S^H \equiv \text{compliance at constant magnetic field}; \)

\( \sigma_i \equiv \text{material stress}; \)

\( H_i \equiv \text{magnetic field} \)

\( \delta \equiv \text{Small perturbation symbol} \)

As seen in the equations above, there is a magnetostrictive coupling between the magnetic flux density equation and the strain equation. The symbol \( \delta \) means that, in ferromagnets, the above equations are valid only for small perturbations of the variables around their equilibrium static values [18]. This coupling will allow critical information about the overall condition of composite materials with embedded magnetostrictive particles to be monitored. The objective of this research is to use stress-induced change in the magnetic signature of resin-embedded magnetostrictive particles to track in-plane, over time and with use, the structural health of resin matrix composite structures. This new capability could transition the Army to condition based maintenance (CBM) rather than interval based maintenance for composite structures.
2. EXPERIMENTAL PROCEDURE

<table>
<thead>
<tr>
<th>Test Specimens Specifications (Table 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Perg Panels</td>
</tr>
<tr>
<td>Fabrication Process</td>
</tr>
<tr>
<td>Fiber Orientation</td>
</tr>
<tr>
<td>Number of Plies</td>
</tr>
<tr>
<td>Dimension of Panel</td>
</tr>
<tr>
<td>Grips</td>
</tr>
<tr>
<td>Width to Cut</td>
</tr>
<tr>
<td>Gage Area to Sprinkle Terfenol-D</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Tabbing Material</td>
</tr>
<tr>
<td>Tabbing Adhesive</td>
</tr>
</tbody>
</table>

2.1 Baseline Samples

10 baseline samples with no embedded Terfenol-D particles were fabricated. Although these samples were fabricated with the exact specification as the Terfenol-D CFRP sample, they were untabbed. Baseline sample testing only allowed for the validation of non-ferromagnetic material interaction.

2.2 Terfenol-D embedded CFRP Fabrication

Before fabrication of the carbon fiber panel using the VARTM process, the predetermined 15 weight percent of Terfenol-D powder was embedded evenly between each ply. This embedding process was done on a magnetic chuck to pre-align the dipole
moment of the Terfenol-D. This was done because magnetostrictive researchers such as Hamann and Dahlberg believe that pre-aligning the dipole moment of magnetostrictive material will yield greater response to induced magnetization [12]. The pre-fabrication process of embedding the particles was performed inside of an Argon glove box due to Terfenol-D’s pyrophoric nature. After the glove box preprocess lay-up, the Terfenol-D embedded CFRP panel was transferred to an autoclave machine for processing and curing. Each test sample was equipped with four G-10 tabs that were bonded to the specimen using HYSOL 9309; a high strength adhesive. These tabs allowed for the specimen’s to be gripped by the mechanical testing system (MTS) without creating stress concentration and preventing delamination at the ends of the carbon fiber specimen.

### 3.3 Mechanical Testing Equipment

a. Helmholtz Coil/ Permanent Magnet

<table>
<thead>
<tr>
<th>Helmholtz Coils Specification (Table 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coil Diameter</strong></td>
</tr>
<tr>
<td><strong>Average Coil Diameter</strong></td>
</tr>
<tr>
<td><strong>Number of Turns</strong></td>
</tr>
<tr>
<td><strong>Maximum Current</strong></td>
</tr>
</tbody>
</table>
| **Coil Resistance** | Cold: approx. 20.5 ohms  
Hot: approx. 25 ohms |
| **Max Flux** | $4.9 \times 10^{-3}$ T |
| **Power Source** | Direct Current (Current Controlled) |
Helmholtz Coils are air wound coils of large diameter that can be connected to a power supply and be aligned on a common axis for the measurement and study of magnetic fields. Figure 1 illustrates the testing fixture using the Helmholtz Coils connected in series. Once the Helmholtz Coils are set at a radius distance apart and connect in series, a uniform magnetic field is generated at the center of coils at the mid-plane. However, there was an observed in-plane field gradient of -0.0067 mT/cm from the mid-point outward in radial direction. The amount of flux that is produced at the center of the coil is governed by equation (3); which is derived from Biot-Savart law.

$$B = \frac{32\pi NI}{5\sqrt{5R}} \times 10^{-7} \ T$$  \hspace{1cm} (3)
\[ B \equiv \text{magnetic flux density}; \]

\[ N \equiv \text{Number of Turns} \]

\[ I \equiv \text{Current}; \]

\[ R \equiv \text{Radius}; \]

As seen in the Helmholtz Coils Specification (Table 1), the performance of the coils depends on their operating temperature; as higher coil temperature yielded higher resistivity. To achieve consistent magnetic flux, the coils were allowed 20 minutes of warm-up time before any data was recorded. In this research Helmholtz Coils were used to supply a constant magnetic field around the Terfenol-D embedded CFRP to detect and study changes in magnetic energy as high loads and damage were induced on the specimens.

Although Helmholtz Coils produce a constant magnetic field, due to the relatively large radius of the coils, the produced magnetic field was not significant enough to interact with the Terfenol-D embedded CFRP since the saturation magnetization of Terfenol-D is around 1 T. The large radius of the Helmholtz Coils also caused them to be a source of error. The surrounding testing equipment, mainly the MTS grips, interacted with generated field making the produced magnetic flux a function of the actuator distance from the coils; as the actuator moves during testing, this produced a source of error.
Dr. Derje Seifu of Morgan State University has done torque magnetometry work with 15 wt. % embedded Terfenol-D in CFRPs. It was shown that at relatively small magnetic fields (around 0.5-1 kOe), the observed torque is negligible (± 100 Dyne-cm for θ 0-360); compare to magnetic fields of 20 kOe or higher where the observed torque was ± 1200 Dyne-cm for θ 0-360 [25]. The strongest field generated by the Helmholtz Coils was around 0.05 kOe. This suspected weak interaction was validated preforming a pendulum test. A 15 wt% Terfenol-D sample was suspended between the Helmholtz coils. Current was sent through the coils to study the rotation and body force generate on the specimen. There was no appreciable change in θ before and after the current was applied.

<table>
<thead>
<tr>
<th>Permanent/Neodymium Magnet Specification (Table 3)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet Diameter (approx.)</td>
<td>5.6 mm</td>
</tr>
<tr>
<td>Magnet Height</td>
<td>12.7 mm</td>
</tr>
<tr>
<td>Max Flux (@ 0.001 mm)</td>
<td>±0.5 T (North/South Poles)</td>
</tr>
</tbody>
</table>
The permanent magnet was chosen to replace the Helmholtz coils due to the simplicity, strength, and consistency. The permanent magnet produced a large enough magnetic flux to physically interact with the Terfenol-D specimen on a nano, micro and macro levels, generating a body force that physically moved the specimen in the pendulum test. The produced field was even strong enough to cause specimen to physically stick to the magnet.

Figure 2. Permanent Magnet Testing Diagram
b. Tesla Meter

<table>
<thead>
<tr>
<th>Gauss/Tesla Meter Specifications (Table 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Gauss Tesla</td>
</tr>
<tr>
<td>3 G</td>
</tr>
<tr>
<td>30 G</td>
</tr>
<tr>
<td>300 G</td>
</tr>
<tr>
<td>3 kG</td>
</tr>
<tr>
<td>30 kG</td>
</tr>
<tr>
<td>300 kG</td>
</tr>
</tbody>
</table>

Figure 3. Gauss/Tesla Meter

Magnetic measurement equipment was used to detect the magnetic flux change across the Terfenol-D embedded CFRP. The magnetometer uses an attached probe with a Hall Generator connected to the end. Hall Generators measure changes in magnetization parameters by calculating changes in current and voltage between four leads that are attached at the midpoint of each edge of a semiconductor material. The Hall voltage is also a function of the direction in which the flux lines pass through the material. The Hall Generator is positioned so the probe can be parallel to the magnetic flux but the Hall Generator is still perpendicular to the flux.
The use of a Tesla meter allowed for real-time non-contact detection of changes in magnetic energy around the specimen with an active area from 0.2 mm (0.008”) to 19 mm (0.75”) in diameter. The target uniform driving magnetic flux value was 155 mT ±5 mT.

c. Digital Image Correlation (DIC) by Correlated Solutions

<table>
<thead>
<tr>
<th>DIC Specifications (Table 5)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition Interval</td>
<td>200 ms (5 Hz)</td>
</tr>
<tr>
<td>Acquisition Dimensions</td>
<td>2D</td>
</tr>
<tr>
<td>Camera Lens</td>
<td>8.5 mm - 1:1.5</td>
</tr>
<tr>
<td>Subset Size</td>
<td>65</td>
</tr>
<tr>
<td>Step</td>
<td>13</td>
</tr>
<tr>
<td>Virtual Stain Gauge (VSG) Standards</td>
<td><a href="http://idics.org/guide/">http://idics.org/guide/</a></td>
</tr>
</tbody>
</table>
Due to limited space and overall repeatability of the testing methodology, 2D DIC was chosen over an extensometer for axial displacement and strain data tracking. The 2D DIC assumptions that were made included the camera was mounted and remained perpendicular with the specimen’s surface throughout testing, the camera’s optical axis remained on the geometric center of the specimen, and the specimen’s surfaces were planar with the out of plane movement considered to be negligible.

The specimens were speckled using the sharpie technique [24]. Before black sharpie speckles were placed on the sample, they were first coated with a TOUGH GUY 4WGD2 multi-purpose paint flat white matte white finish to provide sufficient contrast for the DIC. Figure 6 illustrates a DIC post-process example of global $e_{yy}$ strain.

Figure 6. DIC post-processing example
d. Mechanical Testing System (MTS)

<table>
<thead>
<tr>
<th>MTS Specifications (Table 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grip Pressure</td>
</tr>
<tr>
<td>Loading Rate</td>
</tr>
</tbody>
</table>

MTS tensile testing machines were used to simulate loading and induce damage in the Terfenol-D CFRP specimens. To define what the non-ferromagnetic material interaction should be, all 10 baseline and 4 15 wt. % samples were taken to failure as seen in figure 7.

Figure 7. Fractured Sample
3. RESULTS

3.1 Baseline Testing Results

Figure 8 illustrates normalized stress vs. localized magnetic flux density vs. strain graphs of each individual baseline specimen. The positive linear stress/strain curves are associated with the left y-axis (Normalized Stress), and the horizontal lines are associated with the right y-axis (Localized Magnetic Flux).
Figure 8. Baseline Stress vs Magnetic Flux vs Strain
The stress axis was normalized with average UTS of 1.4 GPa to make a direct correlation between failure stress and magnetic flux values; this allowed for relationships to be studied regardless of the composite stacking sequence. The magnetic flux data in figure 8, horizontal lines colored to match there appropriate loading profile, illustrates a uniform driving flux that was produced by the permanent magnet. There was no observed divergence in flux from the produced driving flux with respect to the applied stress; the assumption of non-ferromagnetic material interaction was confirmed.

An overall modulus of elasticity of the untabbed baseline samples was exacted by converting the baseline data into a mass stress vs. strain matrix and performing linear regression over the entire matrix. This is show in figure 9.
The average modulus of elasticity of the untabbed baseline samples fabricate to the specifications listed in Table 1 was 90 GPa; compared to 168 GPa for unidirectional IM7 8552 (HexPly data sheet).

3.2 15 Weight Percent Terfenol-D Results

Figure 10 illustrates stress vs. strain graphs of each individual 15 wt.% Terfenol-D embedded CFRP. Contrary to the baseline results, the Terfenol-D embedded specimens were tabbed. This allowed the Terfenol-D embedded CFRP to achieve a higher UTS
(approx. 1.6 GPa) and a higher modulus of elasticity (approx. 100 GPa), as seen in figure 11. For this reason, strain/stress data between baseline and 15 wt.% samples could not be compare to observe structural integrity verification. In order to have a bench mark parameter to compare the Terfenol-D embedded sample to, classical lamination first ply maximum strain failure criteria was use to validate structural integrity degradation. The numerical solution for UTS using classical lamination maximum strain failure criteria was approx. 1.7 GPa with a modulus of elasticity of 85 GPa.

Due to the fiber/matrix/particle interphase bonding and Terfenol-D’s magneto-mechanical coupling properties, it was hypothesized that embedding Terfenol-D particles in CFRP’s could increase interphase shear strength and shear modulus [6, 11]. Comparing stress/strain data of the 15 wt.% Terfenol-D embedded CFRP to the maximum strain failure criteria has shown desirable results, however, more mechanical testing must be performed to conform this notion.
Figure 10. 15 wt.% Stress vs Strain
To study localized early damage precursor magnetic respond of 15 wt.% Terfenol-D embedded CFRP, a load controlled test was performed on specimen 5714-1. For the early damage precursor test the load increments were 5 % UTS up until 40 % UTS was achieved. Once 40 % UTS was achieved the load was stepped back down to 0 % UTS. All of the AE, loads, and magnetization testing parametrics were sent to a data acquisition computer (DAC) at a sampling rate of 1000 Hz for uniform test step acquisition. Since all
of the testing preformed was quasi-static, the time steps were converted to indices for simplicity. Figure 12 illustrates the relationship between localized magnetic flux density (32 mm² FOV) and applied external load with respect to time (Index).

As seen in figure 12, there exists an inverse relationship between applied loads and localized flux. This relationship can be explained by thinking, as the load is increased more of the available magnetic energy is used to mechanical work on maintaining/changing particle shape. More analytical and numerical studies must be done to prove this hypothesis. With damage precursors in mind, there was an observed jump in the localized magnetic flux at the 30 % UTS load increment (red circle in figure 12). It is thought that this is a sign of a damage precursor. The hypothesis is that the sudden increase in load caused micro cracking in the matrix material. Since the Terfenol-D is embedded in the matrix of the material, the micro cracking causes a release in stress/strain surrounding the particles. This release in stress would explain the sudden jump in localized magnetic flux because more of the available magnetic energy is not used to do work on the particles (to maintain its shape). More experimental, analytical, and numerical studies must be performed to prove this hypothesis. After the 30 % UTS loading increment, the inversely related magnetic flux density vs. load relationship follows its trend.
Figure 12. 5714-1 Magnetic Flux vs Normalized Stress vs Index; precursor marked (0-40 % UTS)
Figure 13 shows the 100% reversible flux achieved with a maximum load of only 40% UTS. Hamann and Dahlberg suggest that irreversible changes in flux and strains are an indication that permanent damage exists [12]. Since the maximum load was only 40% of the UTS (elastic regime), it was expected to achieve reversible flux.
Figure 13. 5714-1 Magnetic Flux vs Normalized Stress vs Index; reversible flux marked (0-40 % UTS)
To study localized failure damage magnetic response of 15 wt.% Terfenol-D embedded CFRP, a load controlled test was performed on specimen 5714-1. For the failure damage response test the load increments were 5 % UTS up until 70 % UTS was achieved. Once 70 % UTS was achieved the load was stepped back down to 0 % UTS. As seen in figure 14, the inverse relationship between applied loads and localized flux still exist, however, 100 % reversible flux was not achieved. With failure damage in mind, there was an observed drop off in the return rate of reversible flux after 70 % UTS was achieved. It is thought that this is a sign permanent damage in the matrix material (plasticity). The hypothesis is that the high load intensity caused permanent deformation in the matrix and/or Terfenol-D material. At this stress level relatively large plasticity regions and macro cracking have arisen in the matrix material. Since the Terfenol-D is embedded in the matrix of the material, it can be assumed that the degradation reversible flux is associated with severe damage in the matrix material. This conclusion is validated with AE data.
Figure 14. 5714-1 Magnetic Flux vs Normalized Stress vs Index; reversible flux marked (0-70 % UTS)
3.3 Acoustic Emission (AE) Data Correlation

Acoustic Emission is a well-known, well-respected method for analyzing damage propagation in composite materials. It uses highly sensitive piezoelectric transducers that passively detect acoustic (elastic stress or pressure) waves by dynamic surface motion on sub-nanometer scale and convert it into an electric signal [3, 5]. AE sensors were attached 1 in (25.4 mm) away from the localized scanning region of the Terfenol-D specimens during quasi-static testing. This was done to correlate the internal damage with the magnetization response. As seen in figures 15 and 16, the green points represent sensor 1 and the red points represent sensor 2.

When coupled with the magnetostriction sensor, there is a noticeable correlation between the amount/intensity of hits recorded by the AE sensors and the localized magnetic flux density recorded by the magnetometer device. Figure 15 illustrate the inverse relationship between the localized magnetic flux density and the normalized stress in a linear fashion. For a loading interval 0-40 % UTS, as the stress increase the localized magnetic flux decrease. In reference to equation (1), the gradient of these localized flux vs normalized stress plot experimentally gives you a solution for the magnetostriction coefficient $d_{33}$; which is $-11 \text{ nm/A}$. This magnetostriction coefficient can be used in numerical solutions to yield a more accurate result.

In regard to the damage precursor assumption made in section 3.2 and in figure 12, the AE data in figure 15 shows that at the 30 % UTS load increment there was an observed peak amplitude of 85 dB. At this dB level, mode II shear/ply delamination failure has initiated [3]. Although this type of defect is not what the Army would consider
a precursor, it is still significant that Terfenol-D embedded CFRP respond to this type of damage initiation.
Figure 15. 5714-1 Localized Magnetic Flux vs AE Peak Amplitude vs Normalized Stress (0-40% UTS)
Figure 16 illustrate the inverse relationship between the localized magnetic flux density and the normalized stress. For a loading interval 0-70 % UTS, as the stress increase the localized magnetic flux decrease. However, the rate of return of the localized magnetic flux with respect to the stress was significantly dimensioned. For the max load of 70 % UTS, the peak amplitude observed was more than 100 dB. At this dB level, mode I and mode II inter fiber/fiber matrix debonding/fiber cracking and shear/ply delamination failure has initiated and propagated [3, 5]. The irreversible flux is attributed to the high level of onset damage in the specimen. Although this is type of defect is not what the Army would consider a precursor, it is still significant that Terfenol-D embedded CFRP respond to this type of damage propagation.
Figure 16. 5714-1 Localized Magnetic Flux vs AE Peak Amplitude vs Normalized Stress (0-70 % UTS)
Acknowledging that AE is a well-known and well-accepted NDE technique helps in solidifying the idea that Terfenol-D embedded CFRP could be a valuable solution in NDE for the Army’s vertical lift vehicles.

### 3.4 X-Ray Computed Tomography (CT) Image Correlation

X-Ray CT is a 3-D imagining methodology that reconstructs series of 2-D X-Ray images into a 3-D image. X-Ray CT was used as a post-processing technique in an effort to capture images of actual damage and compare them to recorded magnetostriction data. Due to extremely intense beam hardening artifacts, very little information about the damage around the embedded Terfenol-D particles was captured, however, areas away from the conglomeration of particles did validate the was severe onset of damage after 70 % UTS load (fiber breakage, surface ply delamination/cracking) as seen in figure 17.
Figure 18 illustrate a X-Ray CT post-processing technique called nominal actual comparison. Nominal actual comparison takes images of a specimen, before and after testing, and measures the deformation. As seen in figure 18, the observed deformation in the Terfenol-D conglomerates did not exceed 26 μm. These measurements can be used in numerical and analytical solutions in strain energy deformation.
Micro X-Ray CT scans were also taken of a 15 wt.% Terfenol-D specimen to help better understand the homogeneity of the dispersion of embedded Terfenol-D particles inside the CFRP. As seen in figure 19, there is not a uniform distribution of Terfenol-D particles embedded inside the CFRP. This presents an opportunity for improvement in the manufacturing process of embedding the Terfenol-D particles. More analysis must be done to observe damage propagation from X-Ray CT images.
Figure 19. Micro X-Ray CT scan of distribution embedded particles
For the initial model of this problem, there was a single ply Terfenol-D magnetostrictive particles embedded between two identical AS4 CFRP plies. Making the initial assumptions for a pristine (undamaged) section that deformation
\[ \delta = 0 \]
and the strain
\[ \varepsilon = 0 \]
To simplify the derivations of the Terfenol-D embedded CFRP system, it must be noted that all iterations are under statically indeterminate conditions (i.e. \( a=0 \)). To begin these series of iterations, the initial objective was to determine the residual stress due to fabrication since it is a compressive process. Results from testing have shown that with the progression of internal degradation there will be a decrease in internal stress (i.e. decrease in residual stress of the magnetostrictive particles). Internal damage due to degradation also causes a decrease in permeability and magnetic flux density. Calculating the initial residual stress parameter is paramount to the following iteration. Without an
accurate initial with residual stress calculation, it will be more challenging to distinguish internal damage values.

The fabrication residual stress that exists was considered. Do to this residual stress, there will also exist a residual magnetic field. This residual magnetic field is governed by equation (1):

\[ B_{msp} = d_c \cdot \sigma + \mu^\sigma \cdot H \]

Where \( B_{msp} \) is the magnetic flux density due to the ferromagnetic Terfenol-D particles, \( \sigma \) is the applied stress, \( \mu^\sigma \) denotes the permeability at constant mechanical stress, \( H \) is the applied magnetic field, and \( d_c \) is the magnetostrictive coefficient; contrary to what was previously assumed to be the magneto-mechanical coupling coefficient in [11].

Ferromagnetic (i.e. magnetostrictive) material have a variety of magnetostriction effects. The magneto-mechanical couple coefficient, \( k_{nn} \), is a unitless parameter that can be used to determine the magnetostrictive coefficient but is predominantly used in the \( \Delta E \)-Effect. The \( \Delta E \)-Effect is the change of the Young's Modulus because of a magnetic field [11]. The \( \Delta E \)-Effect is governed by [11, 18]:

\[ E^B = \frac{E^H}{(1-k_{33})} \]  \hfill (3)

where \( E^B \) is Young's modulus at a constant value of magnetic flux density, \( E^H \) is Young’s modulus at a constant magnetic field, and \( k_{33} \) is the magneto-mechanical coupling coefficient in the outward direction. There are numerous methodologies to
equate the magneto-mechanical coefficient, for consistency, the following equation can calculate the magneto-mechanical coupling coefficient [11, 18]:

\[ k_{33}^2 = \frac{d_{33}^2}{\mu_{33}} \cdot E^H \quad (4) \]

where \( d_{33}^2 \) is the magnetostrictive coefficient. In this equation the magnetostrictive coefficient is the slope of the strain versus magnetic field; thus governed by [11, 18]:

\[ d_{33} = \frac{(d\lambda)}{(dH)} \quad (5) \]

Neither the magneto-mechanical coupling factor \( k_{33} \) nor the magnetostrictive coefficient \( d_{33} \) will remain constant throughout the operating conditions in real magnetostrictive applications [11, 18]. The magnetostrictive coefficient \( d_{33} \) can be graphically depicted by the following; figure 21 [11, 18]:

Along with applied magnetic field, applied pressure has a significant impact on both the magnetostrictive and magneto-mechanical coefficients. With applied pre-stress there will
exist variability in the coefficients, this effect can be captured in the following, figure 22 [11]:

In this current iteration, the applied residual stress which can be thought of as negligible. For Terfenol-D the magnetostrictive coefficient is in the range of 5-70 nm/A [18]. The equation (2):

$$\epsilon = S^H \sigma + d_{\mu} H$$

where $\epsilon$ is the mechanical strain, $\sigma$ is the applied stress, $d_\epsilon$ is the magnetostrictive constant at constant stress, and $H$ is the applied magnetic field. In this iteration of a pristine sample the assume was that the initial strain is 0, thus the equation to calculate residual magnetic field due to the residual stress due to fabrication simplifies to:
\[ H_{\text{res}} = -\frac{S^H \sigma_{\text{res}}}{d_c} \]  

(6)

Where \( H_{\text{res}} \) is the residual magnetic field, \( S^H \) is the compliance of the material, and \( d_c \) is the magnetostrictive coefficient. Since this magnetostrictive coefficient is field and stress-dependent, the fabrication processes was just enough stress to yield a 5 nm/A magnetostrictive coefficient. This will allow us to calculate a theoretical \( H_{\text{res}} \). The material was treated as transversely isotropic to maintain consistent material properties in the loading direction.
5. FEA OF TERFENOL-D EMBEDDED CFRP

5.1 FEA Method

This analysis was carried out in COMSOL; which is an FEA package that specializes in Multiphysics platforms. Because Terfenol-D is a magneto-elastic material, COMSOL will allow the magnetic and solid mechanic coupling to be studied in parallel. Since the Terfenol-D particles are circular in shape, it is expected that stress concentration and crack propagations will develop along the particles at the continuum level. However, the embedded Terfenol-D particles can not be treated as void because they will retain compliance and stiffness (i.e. mechanical properties). Modeling a laminate with multi-ferroic constituents along with externally applied loads and magnetic fields will help in better understanding stress concentrations and crack propagations in CFRP’s.

The geometry of this model was constructed on the microscale level with homogenous and isotropic conditions. An indeterminate condition was assumed initially so there are no initial displacement, velocity, or rotational fields. The accepted radii for each Terfenol-D and CFRP’s ply thickness was 120 microns. All micro-particles created with uniformed shapes.

After the geometry had been established in the model, the solid mechanic state of the composite was initialized. This initialization included parameterizing mechanical properties as well as setting boundary conditions. This step is necessary to compute the solid mechanics and the magnetic response portion of the model. Each constituent’s
internal property and external boundaries were initialized. If is worth noting that the boundary condition and the fixed constraints will change with respect to the loading conditions that will be presented in the results and conclusion.

As stated before, COMSOL specializes in Multiphysics platforms. In order to study the effects that magnetostriction has on the solid mechanic portion and vice versa, a magnetostrictive relation was added to the circular model Terfenol-D particles as seen in the figure below. In case of linear magnetostriction model, the material data can be entered in the strain-magnetization form using the elasticity matrix and the coupling matrix, or in stress-magnetization form using the compliance matrix and the coupling matrix (COMSOL). To enforce indeterminate static condition, the displacement, velocity, and rotational fields were all initialized to zero. The initial values node adds initial values for the displacement field and structural velocity field that can serve as an initial condition for a transient simulation or as an initial guess for a nonlinear analysis (COMSOL Documentation).

Before applying external loads to the model composite, internal compressive loads were applied to the top and bottom of the Terfenol-D region to simulate residual stress fabrication. In order to solve the solid mechanics portion of the model it is mandatory that the modeled domain have a surface to a fixed constraint. Fixed constraint node adds a condition that makes the geometric entity fixed (fully constrained); that is, the displacements are zero in all directions. If there are rotational degrees of freedom (DOF), they will also be zero.
To study the magnetostrictive effect of the now semi-ferroic composite material, an external magnetic field must be applied to the domain of the modeled geometry. This will allow for high magnetic flux regions to be located and measured. This also allows for the physics interface to solve Maxwell’s equations, which are formulated using the magnetic vector potential. The main node is Ampere’s Law, which adds the equation for the magnetic vector potential and provides an interface for defining the constitutive relations and its associated properties, such as the relative permeability (COMSOL Documentation).

Since the circular modeled Terfenol-D particles are the only ferromagnetic material in the composite, it is the material that is give the magnetostriction relationship as seen in the figure below. The magnetostriction Multiphysics coupling node passes the appropriate magnetization contribution from the magnetostrictive material node in the solid mechanics interface to the Ampere’s Law, magnetostrictive node in the magnetic fields interface. It also passes the mechanics stress contribution due to applied magnetic field back to the magnetostrictive material node (COMSOL Documentation).

Proper meshing of the domain is key to accurate FEA model. COMSOL is equipped with an adaptive mesh capability that allow the refining of the mesh to be physics driven. The adaptive meshing allows CFRP-Terfenol-D interphase to be a much finer mesh than the far field domain. Stationary studies were performed on the modeled composite to reduce complexity of the solution as well as save computation time and power. Stationary studies are used when field variables do not change over time, such as in stationary problems.
5.2 Fabrication Solution

The first model was computed with only the fabrication stress applied. This solution will help better understand where the stress concentration and initial cracking is located from the fabrication process. In the figure 23 there is the Multiphysics representation of composite. It depicts magnetic flux density (color bar), displacements/deformation (deformed body), principle stress (red, green, and blue vectors), and magnetic fields (white lines).

Figure 23. 2-D Multiphysics FEA model of Pristine Terfenol-D embedded CFRP

To better understand where the potential crack propagation may be initializing from after fabrication, a second sub-model was computed that excluded magnetostrictive
information as seen in figure 24. With this it is easier to conclude where the stress concentration is.

Figure 24. Von Mises Stress FEA model of Pristine Terfenol-D embedded CFRP

This plot shows that most of the initial cracks and stress concentration occur at the CFRP-Terfenol-D interface and at the 0- and 45-degree position along the particles.
6. CONCLUSION

The baseline results (CFRP specimen without embedded Terfenol-D) the average percent change from the magnetostriction sensor was only 0.02%. For quasi-static testing procedure of specimen 5417-1 (15 wt.% Terfenol-D embedded CFRP) on a 0-40% loading interval of the material’s UTS, there was an observed localized (32 mm² field of view) magnetic flux gradient of more than 5 mT (4%) with a reversible flux of 100%. The observed AE data showed to micro damage initiation had occurred and the onset of mode II failure may be associated with flux increase at 30 % UTS.

For 15wt% quasi-static testing procedures of specimen 5417-1 (15 wt.% Terfenol-D embedded CFRP) on a loading interval 0-70 % UTS, there was an observed decrease reading from the magnetostriction sensor by more than 3 mT (2%). The observed AE data showed to high levels of damage propagation had occurred and the onset of mode I and II failures were associated with irreversible flux (only 25 % reversible flux) in the Terfenol-D embedded CFRP. For the max load of 70 % UTS, the peak amplitude observed was more than 100 dB. At this dB level, mode I and mode II inter fiber/fiber matrix debonding/fiber cracking and shear/ply delamination failure has initiated and propagated [3, 5].

Figure 18 illustrate a X-Ray CT post-processing technique called nominal actual comparison. Nominal actual comparision takes to images of a specimen, before and after testing, and measures the deformation. As seen in figure 18, the observed deformation in the Terfenol-D conglomerates did not exceed 26 µm. These measurement can be used in
numerical and analytical solution in strain energy deformation. Micro X-Ray CT scans were also taken of a 15 wt.% Terfenol-D specimen to help better understand the homogeneity of the dispersion of embedded Terfenol-D particles inside the CFRP. As seen in figure 19, there is not a uniform distribution of Terfenol-D particles embedded inside the CFRP. This presents an opportunity for improvement in the manufacturing process of embedding the Terfenol-D particles. More analysis must be done to observe damage propagation from X-Ray CT images.

The current mathematical model for this magnetostrictive system are preliminary and need to be more rigorous to truly support this research. In the future, there will be a FEA approach to this to study the physical properties of Terfenol-D as an isolated system to better understand how to work with it. In the figure 23 there is the Multiphysics representation of composite. It depicts magnetic flux density (color bar), displacements/deformation (deformed body), principle stress (red, green, and blue vectors), and magnetic fields (white lines). Figure 24 shows that most of the initial cracks and stress concentration occur at the CFRP-Terfenol-D interface and at the 0- and 45-degree position along the particles.

Though the end goal may be to detect early damage propagation real-time using embedded magnetostriction techniques, one take away from this current research is that the observed magnetostrictive reading can be used to determine the instantaneous level of stress/strain at which the material has experienced. For example, in figures 12-16 there is a direct correlation between load localized magnetic flux. This information could be
further used to define the instantaneous state of stress in material and the fatigue life of CFRP’s more accurately.

Terfenol-D embedded CFRP’ have shown promising results for structure health monitoring (SHM). In time with manufacturing and testing improvements, there is evidence that Terfenol-D embedded CFRP’s could play a vital role in real-time tracking of damage progression of structural composite parts for the U.S. Army’s future vertical lift vehicles. Future plans for fabrication include implementing new techniques for embedding Terfenol-D into the CFRP’s to ensure more uniform distribution of particles. This will allow for more consistent testing, thus, yielding more accurate results.

There are also plans to increase the weight percent of Terfenol-D in the CFRP’s to seek stronger magnetostriction response without compromising structural integrity of the composite. With this increase weight percent by 5-10 % of Terfenol-D particles in the CFRP’s, there comes a risk of compromising the structural integrity of the carbon fiber part. To ensure that the parts are not prone to catastrophic failure there will also be advanced strength test designed, because there is currently not an efficient methodology to perform fatigue testing on the test specimen.

Along with more quasi-static testing, fatigue testing must be developed Fatigue testing analysis will play a vital role in the completion of this research. There exists an inverse relationship between applied loads and localized flux. This will allow the coupling of the damage propagation analysis to seek a more definitive relation between magnetostriction damage sensing, AE damage sensing, permeability damage sensing, CT
scans, and SEM scans. This research has shown that Terfenol-D embedded CFRP can be a solution for non-contact strain/stress sensing.
7. References


Aeronautical Design Standards (ADS)


