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Damage Detection in Carbon Fiber Composites Using Electrical Resistance Measurements

Ryan Gory
THE FLORIDA STATE UNIVERSITY

COLLEGE OF ENGINEERING

DAMAGE DETECTION IN CARBON FIBER COMPOSITES USING ELECTRICAL RESISTANCE MEASUREMENTS

By

RYAN GORY

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The members of the supervisory committee were:

Arda Vanli
Professor Directing Thesis

Okenwa Okoli
Committee Member

Richard Liang
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.
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ABSTRACT

This thesis proposes a methodology for structural health monitoring that incorporates the inherent multi-functionality of carbon fibers. The hypothesis of the thesis is that by monitoring the electrical resistance of composite panels it is possible to detect impacts and statistically model their effects on the remaining useful service life of structures. The proposed research investigates the application of statistics-based analysis to the measured electrical resistance signals during loading. The research also investigates the use of electrical resistance as a stress sensor by monitoring the resistance of test samples under tensile loading.
CHAPTER 1: INTRODUCTION

Carbon fiber composites are a lightweight and high-strength alternative to metals in aircraft structures. However, they exhibit complex behavior as a result of their multiple-phase composition. This results in various types of damage and propagation characteristics. The most commonly encountered type of damage in composites is caused by impact [1]. Low Velocity impact damages often result in significant degradation of mechanical properties and can leave little to no trace of the surface [2, 0].

In order for composite structures to be used more extensively in load carrying aircraft structures, they must be maintained in a safe and economical manner. Critical flaws and damages may be induced in the structure in between regular scheduled maintenances are often not visible on the composite surface and can go unnoticed under visual inspection. Therefore, it is crucial to develop a built-in sensing system that enables us to continuously monitor the integrity of structures. In literature, such sensing systems are collectively referred to as Structural Health Monitoring (SHM) systems [1].

1.1 PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Impact damage in composites is difficult to detect in real time with traditional inspection methods. The research studies an electrical resistance method or damage detection utilizing the electrical resistance of carbon fibers to develop a self-sensing structure and real-time health monitoring without requiring to install external sensors. Monitoring the electrical resistance of composite panels it is possible to detect impacts and statistically model their effects on the remaining useful service life of structures. The objectives of this research are (1) Characterize behavior of electrical resistance of CFRP, (2) Determine important features of electrical resistance data for predicting impact
energy, (3) Quantify impact damage size and (4) Construct a statistical model between electrical resistance and strain.

1.2 APPROACH

To develop this methodology several tasks must be accomplished. The first step is to develop a method for fabricating electrodes onto the carbon fiber panels. These electrodes are used to attach the current leads to the carbon fibers in the composite panel. Next, impact experiments are conducted on the samples while measuring the resistance. These experiments are conducted at various heights in order to capture the effect of impact energy on the electrical resistance. Impact events generate spike in the resistance followed by a characteristic decay. Features of the measured resistance profile, like the height of a peak or the settling rate, are recorded for each impact and used as inputs for statistical testing. The damage created in impacted parts is imaged with C-scan. The measured area of such damage can be used to predict the damage area of future impact events. This research will conclude with the construction of a statistical model will be constructed that estimates the impact energy and resulting damage area, based on the features of the measured resistance profile.

1.3 MOTIVATION

Sensing systems for continuous structural health monitoring (SHM) has important practical implications such as reducing maintenance costs and increasing operational safety. The electrical resistance based impact damage and reliability assessment methods proposed by this thesis therefore will enable developing cost-effective monitoring systems for composite material systems. Real-time flaw detection will allow flaws to be repaired as they develop during the service time of the components hence will eliminate the need for costly inspections. Information acquired from real-time structural monitoring will also benefit the understanding of failure mechanisms of composites.
The thesis is organized as follows. The next chapter gives a review of the relevant work from literature in the areas of structural health monitoring, and electrical resistance based damage detection. Chapter 3 summarizes the results of impact experiments to characterize failure modes from electrical potential measurements. Chapter 4 studies methods to extract features of electrical resistance profiles sensitive to damage and impacts. Chapter 5 presents results for quantifying the size of impact damage and discusses how they correlate to the electrical resistance based assessment. Chapter 6 provides conclusions and future directions of research.
CHAPTER 2:
LITERATURE REVIEW

2.1 GENERAL STRUCTURAL HEALTH MONITORING REVIEW

2.1.1 BACKGROUND INFORMATION

Composites are a lightweight and high-strength alternative to metals in aircraft structures. However, they exhibit complex behavior as a result of their multiple-phase composition. This results in various types of damage and with different propagation characteristics. The most commonly encountered type of damage is caused by impact [1]. Impacts damages often result in significant degradation of mechanical properties and can leave little to no trace of the surface [2, 0].

In order for composite structures to be used more extensively in load carrying aircraft structures, they must be maintained in a safe and economical manner. Critical flaws and damages may be induced in the structure in between regular scheduled maintenances are often not visible on the composite surface and can go unnoticed under visual inspection. Therefore, it is crucial to develop a built-in sensing system that enables us to continuously monitor the integrity of structures. In literature, such sensing systems are collectively referred to as Structural Health Monitoring (SHM) systems [1].

Continuous Monitoring will significantly increase operational safety while simultaneously reducing maintenance costs. Real-time flaw detection will allow flaws to be addressed as they arise thus eliminating the need for costly inspections. Information acquired from real-time structural monitoring will also benefit the understanding on fracture mechanics of composites.
2.1.2 NON-DESTRUCTIVE INSPECTION TECHNOLOGIES FOR COMPOSITE MATERIALS

In composites damage caused by impact is encountered most often. In particular, low velocity impacts pose a serious threat, as they can result in considerable reduction of residual strength and stiffness, even for barely visible impact damage (BVID) that are very difficult to detect by surface inspection. Types of damage associated with impacts include matrix cracking, delamination, and broken fibers.

Current non-destructive inspection (NDI) techniques include visual inspection, optical methods, eddy-current (electro-magnetic testing), ultrasonic inspection, laser ultrasonics, acoustic emission, vibration analysis, radiography, thermography and Lamb waves [1, 0, 0]. Diamanti and Soutis [1] reviewed various NDI methods for composites and presented the benefits of lamb waves for damage detection and Djordjevic [0] provided a useful classification of the various commonly applied NDI techniques, which is cited in Table 1. The rest of this section will briefly describe some of these practices.

Table 1: Summary of NDI practices for composites

<table>
<thead>
<tr>
<th>Ultrasonic</th>
<th>Advanced Techniques:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Emission</td>
<td>X-ray Tomography</td>
</tr>
<tr>
<td>Tap Test</td>
<td>Laser Ultrasonic</td>
</tr>
<tr>
<td>Resonance</td>
<td>Holography</td>
</tr>
<tr>
<td>X-ray</td>
<td>Laser-optical</td>
</tr>
<tr>
<td>Visual</td>
<td>Vibro-thermography</td>
</tr>
<tr>
<td>Optical</td>
<td>Acousto-ultrasonic</td>
</tr>
<tr>
<td>Thermal...</td>
<td>D-sight</td>
</tr>
<tr>
<td>Emerging Technologies:</td>
<td>Neutron radiography</td>
</tr>
<tr>
<td>In-process monitoring</td>
<td>Microwaves...</td>
</tr>
<tr>
<td>In-Situ Sensors</td>
<td>Thermal (Time resolved...)</td>
</tr>
<tr>
<td>Remote Sensors</td>
<td>TECHNOLOGIES:</td>
</tr>
<tr>
<td>Embedded Sensors</td>
<td>Health monitoring</td>
</tr>
<tr>
<td></td>
<td>Prognostics</td>
</tr>
</tbody>
</table>

5
Visual inspection is used to look for damage on the surface of a composite structure [1]. Proper lighting is required. Since BVID is common, special impact sensitive coatings have been developed to improve flaw visibility. Visual inspection is limited to surface location and cannot determine the depth/degree of damage. The coin-tap is a common vibration-based inspection method. Damage is indicated by the change in sound between defected and defect-free areas.

Shearography is a commonly used optical method that has been developed to interpret variations in transmission intensity [1, 0, 0]. This technique is capable of producing images known as speckle patterns. These images can be compared over time to reveal changes in strain and concentrations of strain indicate the presence of a flaw. Optical fiber sensors, including Fiber Bragg grating (FBG) sensors, are used for temperature and stain readings in SHM [1]. However, practical issues still exist with these systems including difficulty in embedding them within a composite structure and their high cost.

The eddy-current technique is used to identify flaws in electrically conductive materials [1, 0, 0]. An electrical current is applied to the surface of a conductive structure and the resulting impedance measurements are then correlated to find the damage size based on the reduction when compared with a pristine structure.

Ultrasonic C-scan inspection is capable of producing high quality images of internal damage by bouncing high-energy acoustic waves through a structure and analyzing the reflections [1, 0, 0]. Acoustic emission (AE) techniques are based on measurements of acoustic response, generated by movement in the material during fiber breakage, fiber pullout, matrix cracking and delamination [1, 0]. Noisy inspection environments are a challenge.

C-scan, AE and thermography are extensively utilized in the industry due to their high accuracy in detecting internal flaws in materials. However, most of these techniques involve removal of test piece from the structure, which may become costly and time consuming and they are limited to point scanning which may become impractical for scanning large surfaces. Lamb waves, sometimes called plate waves, are developed in an attempt to address some of the shortcomings of conventional NDI techniques [1, 0]. Lamb waves are elastic waves that can be exited and transmitted across large areas giving
them the advantage to scan and inspect large areas in a short amount of time. This technology provides the possibility of continuous monitoring by periodically rescanning the structure and comparing to an original baseline to reveal damage indications. However, this technology requires an embedded sensor network within the structure. Inserting sensors into composite panels in this way reduced the mechanical properties of the structure.

2.2 LOW VELOCITY IMPACT INDUCED DAMAGES

Low velocity impacts can cause significant damage in fiber reinforced composite laminates in the form of matrix cracks and delaminations which are not visible to surface inspection but can result in significant reduction in strength of structural materials. This section reviews methods for characterization and quantification of impact induced damages in composites.

2.2.1 CHARACTERISTIC PARAMETERS

Sources of damage inducing impacts on structures include weather phenomena such as hail, and storm winds containing airborne debris, runway debris kicked up during landing, and even birds. Impacts can also occur during maintenance due to dropped inspection tools. The main factors characterizing impact damage are impact energy, the shape of the impacting object and the stiffness of material impacted [50]. Impact energy is determined by the mass and velocity of the object that impacts the composite structure. The impact energy is composed of the energy absorbed by the composite, the energy used up by any bouncing-up of the impacting object, and the energy lost to the environment in the form of sound and heat. Many factors affect the stiffness of a composite structure including constituent materials, stacking sequence, geometry, span and possible ageing [0].
2.2.2 MATERIAL RESPONSE TO IMPACTS

Various authors have investigated modeling the effects of impacts on materials. Guillaumat et al. [6] modeled impact damage due to tool dropping by fitting regression model from the impact factors to response measurements. The impact factors included span of the plate, the velocity and mass of the projectile. Related response measurements are duration of contact, maximum force of contact, the dissipated energy. Their results indicate the importance of the span of the impacted sample. With larger spans the system will be more elastic. When the span increases, the dissipated energy decreases.

Zhang and Richardson characterized impact events with force/time and force/deflection traces. They help give a better understanding of the materials response to impacts. They employed electronic speckle pattern interferometry (ESPI) to visualize and quantify damage and related impact energy to damage area. They showed that impacts could result in as much as 30% reduction in residual properties [0]. Zhang et al. [0] evaluated the potential of ESPI and compared with C-Scan. Showed that there was consistent correlation between impact event parameters and extent of revealed damages.

Huang [0] developed quantitative relationships for predicting the residual strength of laminated composites subject to impact loading. Richardson and Wisheart [0] reviewed low velocity impact properties of composites and established a definition for low velocity impact events. The authors describe failure modes of matrix cracking, delamination and fiber failure found in impacted composites as well as the influence of various constituents on the resulting properties of the composite under impact loading and present an evaluation of the post impact residual strength.

Jih and Sun [0] proposed a method for predicting impact-induced delamination in composite laminates. Static fracture toughness was used to predict delamination crack growth. In addition they reviewed impact damage modes. Their experiment investigated growth of delimitation cracks under stating loading for various layups. Static tests were performed on pre-cracked specimens to obtain crack growth data. Fracture mechanics was used to predict delimitation crack growth and total strain energy release rate.

Experimental results indicated that inter laminar fracture toughness is independent of crack length, layup, and geometry, and is equal to 300j/m^2. Low velocity impact-
induced delimitation can be predicted by using the static inter laminar fracture toughness in conjunction with the static linear beam model.

Choi [0] used a line-nosed impactor to investigate damage mechanisms in composites due to low-velocity impact. This produced a uniformly distributed, transient dynamic load across the specimen’s width. This simplified the damage mode.

Matrix cracking was found to be associated with initial impact damage and delamination is always accompanied by a critical matrix crack. In addition, considerable micro-crack could be generated along with delamination growth. Preexisting micro-cracks induced by thermal stresses can substantially reduce impact resistance of composites. Stacking sequence also significantly affects impact resistance of composites. There exist an impact energy threshold above which impact damage occurs.

Todoroki and Yoshida [0] investigated the electrical resistance change in CFRP as a result of an applied load. They pay careful attention to the effect of poor electric contact at the electrodes and showed this to be responsible for reported negative piezoresistivity in the literature. It was reported that measured resistance change rises linearly with increasing strain with gage factor of 2 and 4 in the longitudinal and transverse directions respectively. In addition, shear loading was found to have no effect on electrical resistance.

2.3 ELECTRICAL RESISTANCE BASED DAMAGE DETECTION IN CFRP

Carbon fibers are electrically conductive and some authors have exploited this characteristic in the recent years to develop sensing methods for detecting damages in CFRP composites from changes in electrical resistance without requiring any additional built-in sensors.

Wang and Chung [0] studied CFRP composite as a sensor of its own strain. Strain sensing is more complex than damage sensing in that not all strains lead to damage. In this sense strain can be reversible and irreversible strain induces damage.
2.3.1 ELECTRICAL PROPERTIES OF CFRP

Abry et al. [0, 0] investigated an in-situ damage detection method for CFRP laminates by electrical resistance measurements. They found that conduction occurred both along the fiber and in the transverse direction since the fibers are in contact. Some electrode configurations they have considered are shown in Figure 1.

Abry et al. [0] further noted that the resistivity, \( \rho \) of carbon fibers is on the order of \( 1500 \times 10^{-8} \Omega \text{m} \) and the resistivity of the insulating matrix is on the order of \( \rho \approx 10^{20} \Omega \text{m} \) and shown that the effect of fiber resistivity, \( \rho_f \), contact resistance, \( R_c \), on the resistivity can be modeled using Equation 1.

\[
R = \frac{\rho_f}{b h V_f} L + R_c
\]

Equation 1

They have presented several quantitative models relating the electrical resistance to the geometry of the sample, the volume fraction, and the resistivity of the fibers as well as investigated changes in resistance under static tensile loading. Figure 2 shows the longitudinal and transverse resistance as a function of the length.
Seo and Lee [0] used electrical resistance change as a damage parameter for assessing the degradation of strength and stiffness under fatigue loading. Like stiffness, they showed that electrical conduction is a degrading signal under fatigue loading. This can allow for residual life predictions with the aid of a failure threshold.

2.3.2 DAMAGE DETECTION VIA ELECTRICAL RESISTANCE CHANGE

Abry et al. [0] recommended a four-wire measurement approach to measure the resistance since resistance values are far less than $100\Omega$ and it becomes difficult to measure it with traditional two-wire methods. Their experiments examined the response of electrical resistance to monotonic and cyclic loading for various carbon fiber volume fractions. These experiments showed that damages, like fiber breaks, affect the conducting pathways resulting in significant changes in resistance [0]. These changes can be used to make inferences on the location and extent of damage in CFRP. Figure 3 shows a schematic of the different processes occurring during a monotonic loading/unloading cycles below the strain to failure.
Seo and Lee [0] also investigated the electrical resistance change as a damage detection parameter of fatigue damage such as the degradation of residual strength and stiffness. Electrical resistance gradually increased as the stiffness reduced, and showed a very abrupt change when final fatigue failure was imminent. Figure 4 shows a schematic of the specimen used for this experiment.

Figure 3: Schematic of different processes occurring during a monotonic loading/unloading below the strain to failure.

Figure 4: Schematic of specimen
Wang et al. [0] used electrical resistance to study impact damage in CFRP. They have found that this method is more sensitive to small damages than the ultrasonic method. Various conducting pathways were examined. It was found that the oblique resistance at an angle between the longitudinal and through-thickness directions was more effective than surface longitudinal resistance in indicating damage.

2.4 MACHINE LEARNING AND STATISTICAL METHODS FOR IMPACT DETECTION AND QUANTIFICATION

In damage detection literature, both model-driven and data-driven methods have been studied. Model-driven methods employ a physical model of the structure, (e.g., finite element analysis), to infer if the model indicates departures from normal (undamaged) condition. Data-driven methods, or more generally machine learning methods, use a statistical representation of the system and signal departures from normality if measured data falls in low probability regions. In this thesis we will explore machine-learning methods for damage detection.

Worden and Manson [0] argue that machine learning theory offers a natural framework for addressing several problems in SHM. They break SHM down into four levels: detection, localization, assessment and prediction and discusses how machine learning can be utilized to address the first three levels of SHM by presenting application of machine learning algorithms to detection, localization and assessment.

Abry et al., [0, 0] and Seo and Lee [0] applied machine-learning algorithms for detecting impact damages by electric resistance measurements of CFRP. Impact events impart stress and therefore change the electrical resistance of the structure. The measured changes in resistance are used along side the impacts location and damage extent to train a machine-learning algorithm. Future impacts, when detected, are analyzed by this algorithm to determine the location and extent of the.

A crucial problem in machine learning is to identify good features from observed data that can later be used as classifiers or predictors. It is usually necessary to convert measured data into features, i.e. quantities that make the rule to be learned explicit [0].
Seo and Lee [0] used neural networks to learn the relationship between electrical resistance and both stiffness reduction and fatigue life. Worden addressed the problem of impact detection in composite panels by training neural networks to locate and quantify impact events.

Worden and Manson [0-0] present an experimental validation for an SHM methodology. Part I deals machine-learning methods for with novelty detection on a laboratory structure. Damage is made in duplicated inspection panels and machine-learning methods are applied to detect the damage. Parts II and III move to an aircraft wing. The removal of inspection panels from an aircraft wing was used to simulate damage. Machine-learning methods were used to detect and locate removal of inspection panels.

2.5 DEGRADATION MODELING AND RELIABILITY PREDICTION SUBJECT TO IMPACT INDUCED DAMAGES

Meeker and Escobar [0, 0] presented an overview of reliability. Reliability is defined as the probability that a component will perform its function for a given time under given conditions. Traditional reliability methods focus on analyzing a distribution of failure time from a given population. However, for high reliability systems, such data is difficult to obtain, especially under the constants of decreasing product development times [0].

One approach to this problem is to accelerate the failure of components in question, by conducting tests under high temperature or high stress environments. Although this approach is helpful, the long life of composite structures as well as the high variability present in their manufacturing processes, still make collecting life data difficult [0].

Since accelerated life testing does not suffice, it is important to find some other measure to indicate failure. In physical structures damage can accumulate over time. If this degradation can be measured, then a specific level of degradation can define the failure of components. This would allow for the estimation of the time-to-failure
distribution. Lu and Meeker [0] have developed general statistical methods for using degradation measures to estimate a time-to-failure distribution.

Lack of adequate reliability prediction tools for composites makes it difficult to assess the remaining service life of impacted structures. Meeker and Escobar [0] reviewed statistical methods for analysis of degradation data. Degradation testing and modeling methods allow statistically modeling degradation behavior of materials and making inference of future performance including the failure time and useful service life based on experiments. Some issues of statistical modeling discussed in the literature are accelerated testing and experimental design. Soutis [2] reviewed the application of carbon fiber reinforced plastics in aircraft construction. Impact damage results in a significant reduction of residual stiffness and strength. These properties have strong ties to residual fatigue life and component reliability. Fatigue process in composite is very complex, involving several mechanisms of damage.
CHAPTER 3:
EXPERIMENTS FOR CHARACTERIZATION OF IMPACT DAMAGE AND FAILURE MODES

3.1. INTRODUCTION

The objective of this chapter is to conduct experiments in order to characterize the behavior of the proposed electrical resistance based impact damage quantification method. In particular, we present drop weight impact tests, static tensile and cyclic tensile test results.

3.2. DROP WEIGHT IMPACT EXPERIMENTS

We first illustrate the impact tests and how we fabricate samples with electrodes soldered on the ends. The proposed fabrication approach is similar to the one used by Seo and Lee [0] and as shown in Figure 5(a). We attach copper strips to the ends of the sample using industrial adhesive. Then silver paste is applied to achieve electrical contact between the copper and the fibers. The current input wire and voltage measurement electrodes are soldered to the copper plate. Preliminary experiments have been carried out using this approach. An alternative approach, presented in the literature is electroplating [0] in which a thin layer of copper is deposited directly onto the sample surface. This method creates a firm electrical connection to the carbon fibers and has a low contact resistance.

Samples are multi-layer carbon fiber/epoxy laminates cut into rectangular strip coupons, with electrodes on each end. We have inserted thin strips into the samples as shown in Figure 5(b), to accelerate the development of delamination. In the literature on resistance testing samples are often made of unidirectional fibers [0, 0, 0]. In addition to
the woven fabric composites, the proposed research will include an investigation on unidirectional fibers as well. Preliminary experiments were carried out on woven carbon fiber composites with nominal dimensions of $158\text{mm} \times 55\text{mm} \times 2.6\text{mm}$. Samples have 6 layers. Stacking sequence was $[0]_6$.

**Figure 5:** (a) Resistance measurement specimen (b) Insert strip via C-scan

The proposed drop weight experiment will investigate the relationship between impact energy, measured resistance change and the resulting damage in both unidirectional and woven carbon fiber composites. In addition, two different tip geometries were considered– a rounded circular tip and a line-nosed tip. Literature suggests that the line-nosed tip will simplify damage mechanisms to a 2-D effect. Electrical current will be applied to the samples using a Keithley DC and AC Current source. The resulting change in resistance will be measured using a National Instruments data acquisition card and Labview Signal Express 3.0 software using a sampling rate of $100\text{kHz}$.

A small impactor and a large impactor were used for the experiments. **Figure 6** shows the impact tips used in the experiments. The weights of these tips are: small-tip = 50g, circular-tip = 2194g, and line-nose tip = 2800g. The circular and line-nose tips are attached to a sled which weighs about 1900g.
3.3 DESIGN OF EXPERIMENTS TO OPTIMIZE THE ELECTRICAL RESISTANCE METHOD

Preliminary impact experiments showed large variations in the electrical resistance measurements. In order to reduce the amount of variation in the electrical resistance measurements we conducted a designed experiment to test the effects several sample and electrode preparation variables. The factors considered in the experiment are given in Table 2. These factors were tip geometry, span, sample width, number of electrodes, and the location of the electrodes.

Table 2: Factors and levels used in the experiment

<table>
<thead>
<tr>
<th>Factor</th>
<th>Low Level</th>
<th>High Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Tip Geometry</td>
<td>Circular</td>
<td>Line-nosed</td>
</tr>
<tr>
<td>B: Span</td>
<td>25mm</td>
<td>75mm</td>
</tr>
<tr>
<td>C: Specimen Width</td>
<td>50mm</td>
<td>100mm</td>
</tr>
<tr>
<td>D: No. of Electrode Pairs</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>E: Position of Electrode Pairs</td>
<td>Ends</td>
<td>Surface</td>
</tr>
</tbody>
</table>
The circular-tip is rotationally symmetric and was expected to produce a uniform damage pattern along both the width and length of the impacted sample. The line-nosed tip was designed to produce a uniformly distributed load across the sample width. This was expected to introduce a more uniform damage propagation throughout the sample width. The span is defined as the distance over which the sample is suspended across. Samples spanning a larger gap are expected to bend more under impact loading. Abry [15] showed that the electrical resistance is a function of the sample geometry and fiber resistivity. As such, it is expected that increasing the sample width would decrease the resistance. The use of multiple electrodes was included to compare the signals recorded from two simultaneous sources.

Electrode mounting positions shown in Figure 7 was also considered as a factor. End mounted electrodes, Figure 7(a), were connected to the ends of the fibers with silver paste. This type of electrode was expected to be more sensitive to fiber breakage. Surface mounted electrodes, Figure 7(b), were connected with silver pasted to exposed fibers on opposite surfaces of the sample. This created a conduction path diagonally through the thickness and along the length of the sample. This type of electrode was expected to be more sensitive to delamination damage.

With the five factors explained above a $2^{5-2}$ fractional factorial design giving 8 unique factor-level combinations was used as the experiment. The defining relation of the design was $I = ABD = ACE$ therefore the design was resolution III (length of shortest letter word in the defining relation). This means that main effects estimated from this experiment will be aliased with two factor interactions.
The drop impact experiment was conducted under each combination of the factor levels. The experiment was repeated at two different heights and the difference in peak resistance from these two impacts was recorded as the response variable. The two heights used were 152mm and 304mm. In doing so the goal of this experiment is to find the factor-level combination that provides the largest difference in the peak resistances thereby allowing to differentiate impact energies most effectively. The collected data, summarized in Table 3, was analyzed using the Design Expert statistical software [0]. An analysis of variance was performed and the results are summarized in Table 4. A power transformation with $\lambda = 0.3$ was used in the linear model in order to stabilize the residual error variance.

Table 3: Factor levels and the measured responses in the factorial experiment

<table>
<thead>
<tr>
<th>Run</th>
<th>Peak Resistance (Ohms) 152mm height</th>
<th>Peak Resistance (Ohms) 304mm height</th>
<th>Difference in Peak Resistances (Ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>15.4098</td>
<td>14.2196</td>
<td>1.1902</td>
</tr>
<tr>
<td>bc</td>
<td>0.0052</td>
<td>0.0248</td>
<td>0.0196</td>
</tr>
<tr>
<td>be</td>
<td>25.5800</td>
<td>2.9730</td>
<td>22.6070</td>
</tr>
<tr>
<td>cd</td>
<td>0.0059</td>
<td>0.0047</td>
<td>0.0012</td>
</tr>
<tr>
<td>de</td>
<td>6.5946</td>
<td>0.1437</td>
<td>6.4509</td>
</tr>
<tr>
<td>abd</td>
<td>3.4453</td>
<td>2.7962</td>
<td>0.6491</td>
</tr>
<tr>
<td>ace</td>
<td>6.9314</td>
<td>0.4125</td>
<td>6.5189</td>
</tr>
<tr>
<td>abcd e</td>
<td>5.1486</td>
<td>1.3775</td>
<td>3.7711</td>
</tr>
</tbody>
</table>

Table 4: ANOVA result for designed experiment

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>DF</th>
<th>Mean Square</th>
<th>F-Value</th>
<th>Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>3.342</td>
<td>1</td>
<td>3.342</td>
<td>16.424</td>
<td>0.0067</td>
</tr>
<tr>
<td>Residual</td>
<td>1.221</td>
<td>6</td>
<td>0.203</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cor Total</td>
<td>4.563</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Matlab software [0] was used to find the maximum value of each recorded resistance signal. Two plots of electrical resistance versus time are given in Figure 8 as examples. The signal was first normalized to zero with respect to the initial resistance values. The Matlab function ‘max’ was used to find the peak and it’s time index. When 2 electrodes were used, Figure 8 (right), the 2 peaks were averaged together. The absolute difference between the peak for 152mm and 304mm drops was recorded as the response.

**Figure 8:** Resistance versus time from the impact experiments different experiments (a) be combination (b) abd combination from Table 3.

ANOVA table shows that only factor E is significant. Factor E is the position of the electrodes on the sample. The Model F-Value 16.42 implies the model is highly significant and there is only a 0.67% chance that a “Model F-Value” this large could occur due to noise. Similarly, the R-Squared value of the model 0.732 indicates a decent fit. Figure 9 gives the normal probability plot of residuals, which also shows acceptable fit. The fitted model is given in Equation 2.

\[ R^{0.3} = 1.24 + 0.65 \times E \]  
Equation 2

The surface mounted electrodes seem to reduce noise in the electrical resistance signal and produce a larger difference in peak resistance change during impact. Table 5 gives
the coefficient estimates, standard errors and confidence intervals. This experiment was limited by its resolution. Since it is only resolution III only the main effects can be estimated. It is likely that some two-factor interactions are significant. To determine if that is the case additional runs would be required.

![Normal plot of residuals](image)

**Figure 9:** Normal Plot of Residual for DOE model

**Table 5:** Coefficient estimates, standard error and confidence intervals

<table>
<thead>
<tr>
<th>Factor</th>
<th>Coefficient Estimate</th>
<th>DF</th>
<th>Standard Error</th>
<th>95% CI Low</th>
<th>95% CI High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.239</td>
<td>1</td>
<td>0.159</td>
<td>0.849</td>
<td>1.629</td>
</tr>
<tr>
<td>E-E</td>
<td>0.646</td>
<td>1</td>
<td>0.159</td>
<td>0.256</td>
<td>1.036</td>
</tr>
</tbody>
</table>

### 3.4 STATIC TENSION TESTS
Tensile tests were conducted in order to characterize sensing properties of the proposed electrical resistance based damage detection approach. In particular the objective was to identify the failure modes of the CFRP samples and how do they relate to the measured electrical resistance profiles. Samples were prepared according to the ASTM standards. End tabs were used to ensure proper grip during tensile testing. Electrodes were sandwiched between the tabs. Silver paste was used to create an electrical connection between the electrodes and either the end or surface of the samples.

The elastic properties of the carbon fiber composite samples measured from the test are summarized in Table 6. The plots of stress versus time for two samples of each type of electrodes (end mount and surface mount) are given in Figure 10. The plots of resistance versus time, obtained from two samples of each type, are given in Figure 11. These plots show a gradual increase in resistance until failure at which point the conductive pathways are destroyed and the resistance increases abruptly.

<table>
<thead>
<tr>
<th>Elastic Modulus</th>
<th>Yield Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>20400 MPa</td>
<td>500 MPa</td>
</tr>
</tbody>
</table>

Table 6: Elastic modulus and yield strength properties of laminates tested

Figure 10: Stress versus strain plot for static tensile test
Figure 10 shows a reduction in strength for the surface mounted electrodes. Surface mounting electrodes to the sample requires two steps. The first step is sanding to expose the fibers and the second step is silver paste to create the electrical connection. Embedding this electrode within the tabs of a tension sample is not without difficulties. Excessive sanding can weaken the outer layers of the composite, which in turn may result in premature failure. In addition, a sacrifice in bond strength is made when using silver paste to make an electrical connection between the sample surface and electrode. This reduced the surface area available for glue when attaching. Figure 11 shows that during failure the electrical resistance changes with the stress. Large drops in stress in Figure 10 correspond to delamination of the outer layers and failure at the tabs as described above. These changes are also visible in the resistance graphs as spikes in the resistance at the corresponding time.

From both the stress-time (Figure 10) and the resistance –time (Figure 11) plots it is clear that there are distinct failure modes that causes step changes in the stress and the resistance plots. The failure modes usually progress in the order of matrix cracking, delamination and fiber breaking [10,15]. For example in Figure 11 the end-mounted electrode there are two noticeable step changes in the resistance at times 80 and 115 seconds (blue line). These correspond to the downward changes in the stress in Figure 10 (blue line) at approximately 80 and 110 seconds. In order to avoid the reduction in strength due to surface mounting the electrodes were moved from the tabs into the gage section of the samples.
3.5 CYCLIC TESTS

Cyclic tests were applied to characterize the dynamic response of the resistance measurement system. In addition the strain sensitivity or the gauge factor of the CFRP samples is calculated from the results of the tests using Equation 3.

\[
\frac{\Delta R}{R_0} = k \varepsilon
\]

where \(\Delta R = R - R_0\) is the resistance change, \(R_0\) is the initial resistance, \(\varepsilon\) is strain and \(k\) is the gauge factor.

Load controlled tensile tests were conducted in which a cyclic tension to stress amplitude equal to 30 % of the yield stress was applied (The mean tensile load for the cyclic tests were set as 0.30*500 = 155 MPa. The rectangular cross section of the sample was 22.5 mm²). Figure 12 shows the electrical resistance and longitudinal strain measurements collected during the test.
Figure 12: longitudinal electrical resistance and strain versus time under cyclic tension

Table 7 summarizes the calculated gage factor from 4 sets of cycles at various stress levels. The average applied force was increased from 1kN to 3kN and the applied force amplitude was increased from 0.5kN to 2kN. We see that for cycle-sets 2, 3, and 6 the gage factor is between 6 and 7. At a lower stress level of 1kN ± 0.5kN we see a larger gage factor of 13.4. The gauge factor values obtained from the experiments appear to be in agreement to the values reported in the literature (see e.g., [0])
Table 7: Average applied force, amplitude and calculated gage factor

<table>
<thead>
<tr>
<th>Cycle Set</th>
<th>Average Force (kN)</th>
<th>Force Amplitude (kN)</th>
<th>Gage Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>1.5</td>
<td>7.0240</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1.5</td>
<td>6.1872</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>2</td>
<td>7.4045</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0.5</td>
<td>13.4229</td>
</tr>
</tbody>
</table>

Figure 13 summarizes the results in graphical form and gives the fitted model for each cycle set. The applied load for sets 2 (red) and 3 (blue) was 2kN ± 1.5kN. This resulted in a strain between 0% and 0.4%. The applied load for set 3 (green) was 2kN ± 2kN. This resulted in a strain between 0% and 0.5%. The applied load for set 3 (green) was 1kN ± 0.5kN. This resulted in a strain between 0% and 0.1%. The sample cross sectional area was 22.5mm², and so the stress (MPa) can be found by dividing the force (N) by the cross sectional area (mm²). For example 3kN corresponds to a stress of 133.3MPa.
Figure 13: Gage factor estimation for cycle sets 2, 3, 6 and 8
CHAPTER 4:
FEATURE SELECTION OF ELECTRICAL RESISTANCE DATA

This chapter focuses on extracting impact sensitive features from resistance profiles collected from impact experiments. Figure 14 shows a resistance profile over time for a composite laminate given in Figure 5(a) during a drop impact test with the circular tip from a height of 6 in. The magnitude of a spike in resistance caused by an impact may contain information about the impact energy. It is expected that impacts with larger energies would cause larger changes in resistance. The features used, in the preliminary experiments are peak height, time to settle, settling rate, and difference between initial and final resistance. The objective is to analyze the resistance time series data and extract important features that can be used to predict the impact magnitude. Sometimes the falling weight can bounce of the sample and fall again creating a second peak. In this case the time between peaks and the ratio of their magnitudes are also candidate features.

Sohn and Farrar [28] applied Principle Component Analysis (PCA) to measurements from a reinforced concrete column that is subjected to static/dynamic testing in a laboratory environment. They project time series onto the first principal component and use the projected time series for subsequent feature extraction and statistical process control. The proposed research will investigate these features as well as any other features that may arise.
From preliminary experiments, the peak resistance change seems to be good indicator of the impact magnitude. Impact test were conducted with the small weight (50g weight) under three drop heights to investigate effect of impact energy on resistance: drop heights 381mm, 762mm and 1143mm (these correspond to 0.187J, 0.374J and 0.561 J impact energies, respectively). Each test was replicated 10 times to account for experimental variability. All experimental runs were conducted on the same sample since such low energy impacts produce no damage. After the experiment the sample was imaged with C-scan to confirm that no permanent damage has been induced.
Figure 15: (a) Resistance data from 10 tests in 381mm (15”) impact height (b) Resistance data from 10 tests in 1443mm (45”) impact height (c) Average of the resistance data from 381mm (15”) and 1443mm heights (45”).

Figure 15(a) and Figure 15(b) shows the resistance-time measurements during the 10 impact tests at 381mm and 1443mm heights. As the impact energy is increased it is clear that several features of the resistance-time profile changes. To see these features more clearly we take the average of the resistance data for the two heights as shown in Figure 15(c). The important features that appear to have different values for different impact heights as summarized on Figure 15(c) are (i) height of first peak $Y_p$ (a measure of impact energy) (ii) time between the first and second peaks, $T_s$ (a measure of energy absorbed by material during impact) (iii) difference between final and initial heights, $Y_f$ (a measure of permanent damage after impact).
Figure 16: ANOVA for peak resistance, time between peaks, and final resistance responses as a function of drop heights 381mm, 762mm and 1143mm

Figure 16 shows the box plots of $Y_p$, $T_s$ and $Y_f$ measurements from individual tests as a function of drop heights. A one-way Analysis of Variance (ANOVA) for the test for equality of the features for different the drop heights is rejected at 0.05 significance ($p < 0.01$) for $Y_p$, $T_s$ and $Y_f$, therefore we conclude that each feature have significant effect on the drop height and can be used as predictors of the impact magnitude.

Further experiments have been conducted using the large impactor and with circular and line-nosed tips. This larger impactor allows for higher energy impacts sufficient to produce damage in the specimens and so each impact was conducted on a separate specimen cut from the same composite plate. Line-nose tip was designed to ensure that the delamination damage covers the entire width of the specimen and generates break point in the path between the two electrodes. This is the type of setup recommended in literature for impact tests [0]. In these experiments weights were dropped from 152mm and 304mm with sufficient energy to cause damage.
Circular-tip impact tests were conducted on 10 composite laminates. Figure 17(a) and Figure 17(b) show the resistance-time measurements during the 5 impact tests at 152mm and 304mm heights using the circular/rounded tip. As the impact energy is increased it is clear that several features of the resistance-time profile changes. To see these features more clearly we take the average of the resistance data for the two heights as shown in Figure 17(c).

The settling rate feature used here is defined as the rate at which the measured resistance moves from the peak value to the average final value. This rate is estimated using an exponential decay function given in Equation 4.

\[ Y = Pe^{-\phi t} \]  
Equation 4

where \( P \) is the peak value and \( \phi \) is the settling rate. Figure 18(a) shows an exponential decay curve fitted to the resistance profile in Figure 14. We expect that the settling rate and impact height are strongly correlated however further investigation will be conducted.
to more clearly explain their relation. In Figure 18(b) exponential decay curves for two different, $\phi$, settling rate parameters are shown; as it can be seen as the settling rate increase the time it takes to settle decreases.

**Figure 18:** Exponential Settling rate parameters
Figure 19: Analysis of Variance for peak resistance, time to settle, and final resistance responses as a function of drop heights 152mm and 304mm.

Figure 19 shows the box plots of peak, settling rate, and net resistance change measurements from the circular-tip impact tests as a function of drop heights (5 tests conducted at 152mm and 304mm heights). A one-way Analysis of Variance (ANOVA) for the test for equality of the peaks for different the drop heights is rejected at 0.05 significance ($p = 0.0117$), therefore it can be concluded that the peak contains significant information on the drop height and can be used as predictor of the impact magnitude. A test for equality of settling rates for different drop heights cannot be rejected at 0.05 significance ($p = 0.4188$). Settling rate still shows promise as a feature but further standardization of the estimation method is needed to make it more reliable. The last feature, net resistance change, was not found to be significantly different for different drop heights ($p = 0.3274$).
The impact tests were repeated with the line-nosed tip on 14 composite laminates. Figure 20(a) and Figure 20(b) show the resistance-time measurements from the 7 laminates under 152mm and 304mm impact heights. To see the features more clearly and remove effect of experiment variability we take the average of the resistance data for the two heights, which are shown in Figure 20(c).
Figure 21: Analysis of Variance for peak resistance, time to settle, and final resistance responses as a function of drop height s 152mm and 304mm.

Figure 21 shows the box plots of peak, settling rate, and net resistance change measurements from the line-nose tip impact tests as a function of drop heights (7 tests were conducted at 152mm and 304mm heights). A one-way ANOVA for the test for equality of the features for different the drop heights cannot be rejected at 0.05 significance (p-value of the test are 0.8259, 0.535, 0.636 for peak, settling rate, and net resistance change), therefore we conclude that the features do not show significant information about the drop height.

From the tests of significance it can be seen that impact damages from a circular-tip could be detected with higher confidence than those from a line-nose tip using the features of the resistance-time data. This could be due to the fact that the electrodes attached on the ends may not be sensitive to delamination damages, which occur parallel and in the plane of the sample along the conduction path. In order to detect resistance
changes due to delaminations, a through the thickness component should be considered for the conduction path. One additional factor is that the line-nosed tip distributes the force over a wider area (a line) than the circular tip (a point).

The problem of damage locating is among the most difficult and costly. So far, in this thesis we focus on the first and third levels, of SHM as presented by Worden and Manson, namely the detection and assessment levels. The next experiment attempts to incorporate the second level, localization. Although this problem will not be considered in this thesis, we include here a brief discussion of how electrodes soldered at multiple ends of a sample can be used to apply this method to the location problem. The current electrode pair approach was expanded to include the monitoring of multiple electrode pairs simultaneously. 4 pairs of electrodes were mounted on a 2-layer carbon fiber composite panel as shown in Figure 22(a). The edges of the panel were sanded to expose the fiber ends. Silver paste was used to make contact between the fibers and the copper electrode. The panel was then divided into 9 regions as shown in Figure 22(b), and each electrode pair was label.

A preliminary impact experiment was conducted. The sample was subjected to impacts of the small drop weight from 20” at the centers of the 9 regions. One impact was
performed on each region in a random order and the whole experiment was replicated 3 times. The resistance was measured and recorded during impacts using the 4-wire method for 8 seconds with a sample rate of 25kHz per channel. Figure 23 shows the measured resistance from the 4 electrode pairs. Having 4 channels allows for more complex features such as the time differences between channels when detecting impacts. It is possible that features like this contain information on the impacts location. The current features may also be sensitive to location. For example, if an impact is further away from the electrodes it may generate a smaller spike in resistance or take longer to settle. Further experimentation is required in this area.

Figure 23: Resistance Measurements form 4 electrode pairs at two different sections
CHAPTER 5:
QUANTIFICATION OF IMPACT DAMAGE SIZE

The objective of this chapter is to study methods to quantify the extent or size of impact induced damage using ultrasonic c-scan. A gauge capability analysis was conducted to assess capability of this method for quantifying varying sizes of impact damages.

The area of the damage is measured from C-scan images. The resulting damaged area will be measured using imaging software. A freehand selection tool was used to outline the circular damage. The software then uses the dimensional data from the c-scans to convert the measured area from pixels to mm$^2$. A rectangular selection tool was used to measure the damage area produced by the line tip. Since damages span the entire width of the samples, this allows only one dimension to be variable during selection. A gage repeatability study has been conducted on the measurement software to determine the number of samples needed in order to ensure sufficient signal-to-noise ratio and discrimination ratio are accomplished in the tests [0]. Samples impacted at various drop heights are scanned to investigate effect of impact energy on damage patterns.

An Image obtained from c-scan of a sample before impacting is shown in Figure 24, and images obtained after impact testing for two samples are shown in Figure 25 and Figure 26.

Figure 24: Before impact damage, Teflon strip insert
In Figure 25 a circular damage was generated with the circular tip and the area was estimated as 2126.4 mm\(^2\). In Figure 26 a rectangular damage was generated with the line-nose tip. The damage area was estimated as 2724.2 mm\(^2\).

After conducting drop weight experiments using two impact tips (line-nosed and circular) the resulting damage areas were measured using C-scan. Figure 27(a) gives the boxplot of the damage areas from the 12 samples with the circular tip impact tests and Figure 27(b) shows the damage areas of the 20 samples with the line-nosed tip impact tests. In both cases we can see that impacts with larger energies produce larger damage areas.
The process of specifying the outline of the damage was in the C-scan imaging system by an operator involves a level of measurement error. In order to assess the capability of the C-scan measurement system to distinguish different damage levels, a gage repeatability and reliability study was conducted. The circular tip was found to produce circular shaped damages. These were measured 3 times using a freehand selection tool. The damage areas in mm² of each sample were measured in a random order and are summarized in Table 8.

**Table 8:** Circular tip impact damage area measurements (mm²)

<table>
<thead>
<tr>
<th>Height</th>
<th>Rep</th>
<th>Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A1</td>
</tr>
<tr>
<td>152mm</td>
<td>1</td>
<td>1241</td>
</tr>
<tr>
<td>152mm</td>
<td>2</td>
<td>1327</td>
</tr>
<tr>
<td>152mm</td>
<td>3</td>
<td>1252</td>
</tr>
<tr>
<td>304mm</td>
<td>1</td>
<td>1235</td>
</tr>
<tr>
<td>304mm</td>
<td>2</td>
<td>1236</td>
</tr>
<tr>
<td>304mm</td>
<td>3</td>
<td>1241</td>
</tr>
</tbody>
</table>

**Figure 27:** (a) Box plots of C-scan impact damage area measurements from drop weight tests (a) Tests with circular tip for 152mm and 304mm drop heights, (b) Tests with line-nosed tip for 152mm and 304mm drop heights
From this data, the signal-to-noise ratios (SNR) and discrimination ratios (DR) were calculated using the equations in Burdick and Borror [0]. They recommend that the lower bounds on these quantities should be above 5 and 4 respectively. Table 9 shows that the lower bounds on the signal-to-noise and discrimination ratios are lower than recommended. This indicates that more parts are needed to properly estimate the part-to-part and measurement errors. The proportion of variation due to the measurement was found to be 0.4423% and 1.0235% respectively for the 152mm and 304mm drop heights.

<table>
<thead>
<tr>
<th>Height</th>
<th>SNR</th>
<th>95% CI</th>
<th>DR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>152mm</td>
<td>21.2163</td>
<td>(3.3844, 61.6137)</td>
<td>451.1</td>
<td>(12.5, 3797.3)</td>
</tr>
<tr>
<td>304mm</td>
<td>13.9068</td>
<td>(2.2184, 40.3864)</td>
<td>194.4</td>
<td>(5.9, 1632.1)</td>
</tr>
</tbody>
</table>

The line-nosed tip was found to produce rectangular shaped damages. These were measured 3 times using a rectangular selection tool. The damage areas (in mm$^2$) of each sample were measured in a random order and are summarized in Table 10.

<table>
<thead>
<tr>
<th>Height</th>
<th>Rep</th>
<th>Area (mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A1  A2  A3  A4  A5  A6  A7  A8  A9  A10</td>
</tr>
<tr>
<td>152mm</td>
<td>1</td>
<td>1766 1944 1649 1664 1939 2111 1989 1990 2351 1893</td>
</tr>
<tr>
<td>152mm</td>
<td>2</td>
<td>1735 2024 1687 1672 1957 2148 2017 1980 2322 1853</td>
</tr>
<tr>
<td>152mm</td>
<td>3</td>
<td>1784 1892 1655 1687 1968 2088 1989 2001 2340 1878</td>
</tr>
<tr>
<td>304mm</td>
<td>1</td>
<td>2192 1893 2008 2005 1830 1883 2050 1961 2279 2545</td>
</tr>
<tr>
<td>304mm</td>
<td>2</td>
<td>2209 1960 2074 1926 1804 1860 2086 1955 2297 2586</td>
</tr>
<tr>
<td>304mm</td>
<td>3</td>
<td>2165 1980 2106 1970 1829 1875 2079 1934 2288 2566</td>
</tr>
</tbody>
</table>
From this data, the signal-to-noise ratio and discrimination ratios were calculated. **Table 11** shows that the signal-to-noise and discrimination ratios above the values recommended by Burdick and Borror [0]. The proportion of variation due to the measurement was found to be 0.0889% and 0.1147% respectively for the 152mm and 304mm dropt heights.

**Table 11: Signal-to-Noise and Discrimination Ratio for impacts with line-nosed tip**

<table>
<thead>
<tr>
<th>Height</th>
<th>SNR</th>
<th>95% CI</th>
<th>DR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>152mm</td>
<td>47.4113</td>
<td>(7.5545,113.338)</td>
<td>2249</td>
<td>(58,12847)</td>
</tr>
<tr>
<td>304mm</td>
<td>41.7404</td>
<td>(6.6509,99.7823)</td>
<td>1743</td>
<td>(45.2,9957.5)</td>
</tr>
</tbody>
</table>
CHAPTER 6: 
STATISTICAL MODELING TO PREDICT DAMAGE SIZE AND VALIDATION

The objective of this chapter is to develop statistical relationship between the electrical resistance measurements of the composites and the stress level under cyclic loading. If statistically valid relationships can be established, such models can then be utilized to predict the remaining strength of a structure from the in-situ measurements of electrical resistance.

In Figure 28, the stress during the loading segments of cyclic tests is plotted against the electrical resistance of the samples at the corresponding time. For each sample a regression model was fitted using the electrical resistance as the predictor and stress as the response. A linear model provides a good approximation to the trend for samples 1 and 2. A second order model was used for sample 3. This analysis indicates that a plausible trend exist between the applied static stress and the resulting electrical resistance. The $R^2$ values of 84-89% indicate that the models have relatively good fit to the data. Table 12 gives the analysis of variance results for the first sample of the three using the loading segments. Based the F statistic and P-value we can conclude that the regression model is significant and captures a plausible trend in the data.

In Figure 29, the stress during the unloading segments of cyclic tests is plotted against the electrical resistance of the samples at the corresponding time. For each sample a regression model was fitted using the electrical resistance as the predictor and stress as the response. A linear model provides a good approximation to the trend. This analysis indicates that a plausible trend exist between the applied static stress and the resulting electrical resistance. The $R^2$ values of 84-94.5% indicate that the models have relatively good fit to the data. These unloading portions were more linear than the loading segments and so the linear model provided a better fit this is reflected in the $R^2$ values.
Figure 28: Models fitted to the loading portions of cyclic tests for three samples.

Table 12: ANOVA results from model fitted to loading segments.

<table>
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<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
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<td>571923</td>
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<td>1207</td>
<td>680965</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

In Figure 29, the stress during the unloading segments of cyclic tests is plotted against the electrical resistance of the samples at the corresponding time. For each sample a regression model was fitted using the electrical resistance as the predictor and stress as the response. A linear model provides a good approximation to the trend. This analysis indicates that a plausible trend exist between the applied static stress and the resulting
electrical resistance. The $R^2$ values of 84-94.5% indicate that the models have relatively good fit to the data. These unloading portions were more linear than the loading segments and so the linear model provided a better fit this is reflected in the $R^2$ values. Table 13 gives the analysis of variance results for the first sample of the three using the unloading segments. Based the F statistic and P-value we can conclude that the regression model is significant and captures a plausible trend in the data.

Figure 29: Models fitted to the unloading portions of cyclic tests for three samples.
Table 13: ANOVA results from model fitted to unloading segments

<table>
<thead>
<tr>
<th>Source</th>
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CHAPTER 7:  
RESEARCH CONTRIBUTIONS AND FUTURE WORK

7.1 Research Contributions

In Chapter 3, a designed experiment indicated that electrode position had a significant effect on the measured resistance during impacts. Further experiments under tensile loading showed that during failure, sudden drops in the stress associated, with fiber breakage, produced corresponding increases in the electrical resistance. Cyclic Tests were also performed, and the gage factor was calculated from data obtained at different stress levels. The data shows that the gage factor is higher for lower stress levels.

Chapter 4 investigated feature selection and identified peak resistance, settling rate, and the difference between initial and final resistance as good features with statistically significant relationship to the impact energy.

Chapter 5 focused on showing the relationship between impact energy and damage size. We showed that for larger damage areas were produced by impacts of higher energy.

In Chapter 6, A statistical model was constructed to predict the magnitude of a step decrease in stress for a given magnitude step increase in resistance.

7.2 FUTURE WORK

Future work is to include an analysis of the reversibility of the electrical resistance using a hysteresis test. This test will subject samples to static loading and unloading to increasing stress levels in order to examine the behavior or electrical resistance during the transition from elastic to plastic deformation.
REFERENCES


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9. Huang, J. Y. Prediction of the residual strength of laminated composites subjected to impact loading 1995


Ryan Gory is currently a master’s student in Industrial Engineering at FAMU-FSU College of Engineering and expecting graduation in May 2012. He was born in November of 1987 and received his Bachelor’s of Engineering in Industrial Engineering in May 2012 from Florida State University. His research work investigates a data-driven methodology for structural health monitoring that incorporates the inherent multi-functionality of carbon fibers and proposes the use of electrical resistance of CFRP as a possible stress and impact sensor. For more information, please feel free to contact him at ryangory@gmail.com.