A RESISTANCE BASED
STRUCTURAL HEALTH MONITORING SYSTEM
FOR
COMPOSITE STRUCTURE APPLICATIONS

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo, CA

In Partial Fulfillment
of the Requirements for the Degree of
Master of Science in Aerospace Engineering

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August 2012

COMMITTEE MEMBERSHIP

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Structural Health Monitoring System
for
Composite Structure Applications**

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SUBMITTED: June 30, 2012

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ABSTRACT

A Resistance Based Structural Health Monitoring System for Composite Structure Applications

by

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This research effort explored the possibility of using interwoven conductive and nonconductive fibers in a composite laminate for structural health monitoring (SHM). Traditional SHM systems utilize fiber optics, piezoelectrics, or detect defects by nondestructive test methods by use of sonar graphs or x-rays. However, these approaches are often expensive, time consuming and complicated.

The primary objective of this research was to apply a resistance based method of structural health monitoring to a composite structure to determine structural integrity and presence of defects.

The conductive properties of fiber such as carbon, copper, or constantan - a copper-nickel alloy - can be utilized as sensors within the structure. This allows the structure to provide feedback via electrical signals to a user which are essential for evaluating the health of the structure. In this research, the conductive fiber was made from constantan wire which was embedded within a composite laminate; whereas prepreg fiberglass, a nonconductive material, serves as the main structural element of the laminate. A composite laminate was constructed from four layers of TenCate 7781 "E" fiberglass and BT250E-1 resin prepreg. Integrating the constantan within the composite laminate provides a sensory element which supplies measurements of structural behavior. Thus, with fiberglass, epoxy, and a constantan conductive element, a three-part composite laminate is developed.

Test specimens used in this research were fabricated using a composite air press with the recommended manufacturer cure cycle. A TenCate BT250E-1 Resin System and 7781 "E" impregnated glass-fiber/epoxy weave was used. A constantan wire of 0.01" gauge diameter was

integrated into the composite structure. The composite laminate specimen with the integrated SHM system was tested under tensile and flexural loads employing test standards specified by ASTM D3039 and D7264, respectively. These test methods were modified to determine the behavior of the laminate in the elastic range only. A tension and flexural delamination test case was also developed to investigate the sensitivity of the SHM system to inherent defects. Moreover, material characteristic tests were completed to validate manufacturer provided material characteristics. The specimens were tested while varying the constantan configurations, such as the sensor length and orientation. A variety of techniques to integrate the sensor were also investigated. Two different measurement methods were used to determine strain. Strain measurements were made with Instron Bluehill 2 software and correlated to strain obtained by the structural health monitoring system with the use of a data acquisition code written to interact with a micro-ohm-meter.

The experimental results showed good agreement between measurements made by the two different methods of measurement. Observations discovered that varying the length of the sensor element improved sensitivity, but resulted in different prediction models when compared to cases with less sensor length. The predictions are based on the gauge factor, which was determined for the each test case. This value provides the essential relationship between resistance and strain. Experiments proved that the measured gauge factor depended greatly on the sensor length and orientation. The correlation was of sufficient accuracy to predict strain values in a composite laminate without the use of any added tools or equipment besides the ohm-meter.

Analytical solutions to the loading cases were developed to validate results obtained during experiments. The solutions were in good agreement with the experimental results.

ACKNOWLEDGEMENTS

Firstly, thank you to Dr. Faysal Kolkailah. His wisdom has been extremely helpful in aspects related to this project as well as non-technical issues. His advice and inspiration have helped guide me in many aspects related to engineering and life. I am sincerely grateful for the faculty understanding, support and dedicated assistance to my project efforts, education and non-scholastic development.

Secondly, I would like to thank Dr. Eltahry Elghandour who has been essential to the success of this research effort. I am very grateful to have been provided with the opportunity to work with him on this project and many more. His guidance in the lab provided insightful solutions to the many questions posed during the project effort. Additionally his experience proved immensely valuable during experimental validation by providing direction in efforts which may otherwise have been time consuming to explore.

Thank you, Gabe Sanchez and Kodi Rider for being great research associates. The help I received in the lab is not without gratitude. And thank you to all other students and SAMPE Club members who have accompanied me on this journey. Jay Lopez, Cameron Chan, Albert Liu, Abe Shabbar, and Vanessa Wood who made lab time much more enjoyable.

Also many thanks to Kendall Oblak of TenCate for donating necessary materials for this project. Also to Dr. Moelter for making test equipment available and offering guidance on test software. Thank you to Dr. Opava for taking the time to review the work.

I am also grateful for my family and friends. This opportunity would not be possible without them. Thanks to my mother and father for always believing in and supporting me even with opposed opinions. Thank you to my aunts, uncles and grandparents for ensuring I am well fed and never without entertainment. Thank you to my roommates and peers this job would have been difficult without the merriment and distractions.

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CHAPTER 1. INTRODUCTION

In this chapter, an introduction to composite materials, measurement devices, and traditional structural health monitoring systems is presented, as well as composite materials, manufacturing procedures, advantages and disadvantages. Additionally, the devices and methods normally used to analyze composite laminates will be presented. The goal of this research was to develop an inexpensive and simple system for structural health monitoring; thus familiarity with traditional health monitoring systems will assist in understanding the goals of this research effort. Within each section, the relevance to this research is discussed. Lastly, the purpose and importance of this study will be discussed at the end of the chapter.

1.1 COMPOSITE MATERIALS

Materials come in a variety of different forms. Most of these forms are well known as macroscopically isotropic homogenous materials, such as metals. These materials are made solely of one material and the molecular structure is organized to be the same in all directions. Composites differ in that they are often made out of two or more very different materials which are combined on a macroscopic scale to form a more useful material. A typical fibrous composite is shown in Figure 1.^[1] These attributes often allow the material properties to vary depending on direction. Thus, composite materials can be optimized

Figure 1. A fibrous composite laminate consists of two macroscopically different materials, fibers and resin.

depending on how they will be used and which direction the material will experience applied loads. Additionally, by using two unlike materials and uniting them, a composite material that

exhibits the advantages of each component material can be created while simultaneously reducing the disadvantages of the child materials.^{[1][2]}

Composite material is a term that has been commonly used to describe modern structures such as carbon fiber or fiberglass. However, composite materials have a long history of usage in a wide variety of ways. The methods of creating composite materials date back to at least 1500 BC when early Egyptians, Israelites, and Mesopotamian settlers reinforced mud bricks with straw. Other examples include the Mongol composite bow made from wood, bone, and animal glue around 1200 AD, as well as concrete, which is made of aggregate, cement, and sand which continue to be used today.^[1]

1.1.1 Different forms of composites

There are three main forms of composite materials: fibrous composites which consist of fibers in a matrix, laminated composites which consist of layers of different materials, and lastly particulate composites which are composed of particles in a matrix. There are of course many other variations of composite materials, as seen in Figure 2.^[2]

Fibrous composites consist of long fibers bound together by a matrix. Materials often exhibit more strength in fiber form than material form. This stems from the crystal orientation along the fiber; moreover there are many more defects in a bulk material. Fibers are normally characterized by strength and density. Additionally, fibers that are longer normally demonstrate the highest strength values. However, many applications utilize shorter or chopped fibers which are still very effective in composite structures. The fibers must be bound together with a matrix. This can be any material that creates a structural element from the fibers; however, it is normally a two-part epoxy. Metal matrices are often used depending on the application.

Figure 2. Different types of composites: (a) particles in a polymer, (b) disk-loaded composite, (c) spheres in a polymer, (d) diced composite, (e) rods in a polymer, (f) sandwich composite, (g) glass-ceramic composite, (h) transverse reinforced composite, (i) vertical honeycomb composite, (j) horizontal honeycomb composite, (k) single-side-perforated composite, (l) two-side-perforated composite, (m) replamine composite, (n) burps composite, (o) crisscross sandwich composite, and (p) ladder-structured composite.

The matrix serves as support, protection and stress transfer; thus, its properties add many attributes to the composite structure. ^{[1][2]}

Laminate composite is another type of composite material which consists of layers of two or more different type of materials. Examples include bimetals, clad metals or laminated plastics and glass. Bimetal materials are often used to utilize the thermal expansion properties of each such as in a thermostat, where the temperature causes the two materials to expand at different rates effectively creating a lever arm. Some high strength metals do not have good corrosion

resistance; thus, clad materials are often used to provide protection from the elements or insulation. However, the most common modern example of laminate composites is actually laminated fibrous composites. This utilizes the structure of fibrous composites but develops it in different layers. They are commonly referred to as laminated fiber reinforced plastics or composites.^{[1][2]}

Particulate composites consist of one or more materials suspended in a matrix of another material. A common example of this type of composite is concrete, a mixture of cement and aggregate. Rocket propellant is also a particulate composite, where particles can be mixed into the fuel to optimize burn characteristics. Additionally, other metals or ceramics can be mixed into other metals to improve ductility, machinability or temperature resistivity.^{[1][2]}

Many combinations of the composite types described above also exist, such as where particulate matrices may be formed with fibers, such as rebar reinforced concrete. The main focus of this research effort is fibrous composite laminates integrated with a conductive property.

This research employs a fibrous composite in the form of fiberglass, epoxy resin, and constantan wire.^{[1][2]}

1.1.2 Composite material advantages and disadvantages

Composite materials exhibit many advantages over metallic substitutes. As described earlier, composite materials are highly customizable thus allowing them to be tailored for each application. This normally results in a higher strength and stiffness on a unit weight basis when compared to other materials. Additionally, composites usually show higher resistance to corrosion due to the epoxy resin that most composites are made of. They are also fatigue resistant and can be made to allow for radio frequency transparency. Products developed using

composite layup techniques also have far fewer parts. There are no fasteners or labor associated with joining parts. This can sometimes reduce cost depending on the application.^{[1][2]}

However, composite material cost is normally more than aluminum or steel substitutes. Additionally, the capital necessary to buy and make molds for composite layups can be more expensive than machining metal parts. Thus, cost can be an advantage or disadvantage depending on the application. Another significant disadvantage includes difficulty of repair. Because fibrous composites lose strength if the fiber in the matrix is compromised, it is often very difficult to repair and sometimes results in complete replacement of the part. Additionally, damage is often non-visible and may occur within the layers of the laminates. Thus expensive sonograph or x-ray tools are necessary to achieve any type of damage analysis. Lastly, recyclability of composites is more complex than materials such as aluminum alloys which can be melted and remade into new parts. Currently, there is still no effective and widely used way to recycle modern composite parts.

With the evident difficulty of determining damage to composite structures, this research effort attempts to simplify techniques by developing a nervous system for the structure during the manufacturing process. Such a method can greatly improve the disadvantages of composite materials associated with non-visible damage and structural health.

1.1.3 Fibrous Composite Weave Varieties

Weaving is a method of combining multiple fibers into a fabric or cloth by use of a loom. This process dates back to ancient times using materials such as flax, wool or linen. Most modern high tech woven fibers like carbon or glass are purchased in a plain or twill weave, shown in Figure 3. The weaving pattern of a composite can play a very important role in the strength and look of a structure. Additionally, the weave may serve as an essential method for

incorporating electrotiles or sensors into a fabric for use of structural health monitoring. Interweaving conductive elements as part of the fabric may serve as the sensory network of the material. ^[3]

In this research constantan is used on a plain woven fiberglass; however, carbon is also experimented with. Carbon is an already popular fiber due to strength but has significant untapped conductive properties.

Figure 3. Weave varieties

1.1.4 Manufacturing processes

Composite materials are fabricated in a variety of ways. One way to manufacture a composite structure is by hand. The process, commonly known as hand lay-up, starts by creating a mold to the like of the desired structure. A gel may be applied and rolled into the mold, commonly made of tooling material like foam, to ensure good contact; the gel will provide a good surface for the composite material to be applied to. Often times aluminum is used as a mold. It provides excellent thermal transmission to assist in resin cure cycles. Additionally, because the surface is already smooth after machining, a gel coat is usually not necessary but normally a wave or release is applied. Hand lay-up materials require the use of dry fiber materials, in the form of fiberglass, carbon fiber, or natural fiber. The resin is applied separately by use of a roller or applicator similar to a spatula. The resins normally come in two parts and

Figure 4. A typical wet layup setup

must be mixed in exact quantities to provide good curing. The dry fiber to resin content ratio is also very important for developing a high strength and lightweight part. Parts made this way normally require considerable consumable materials in the form of peel-plies, vacuum bags, and breather cloths as well. A typical wet layup setup for vacuum bag pressure is shown in Figure 4.

[1][2]

Another technique of composite manufacturing is spray lay-up. A chopper head may be used for quick fabrication. The chopper head sprays short fibers and resin simultaneously. This results in a weaker product, but it is a much easier and faster fabrication process. Spray lay-up requires the proper tools and the health hazards are even more evident due to the vaporous component of the process.

Pultrusion is a process where the fiber reinforcements are drawn through a resin bath where the material is coated and impregnated with resin. The reinforcements are then pulled through a heated die to shape the fibers into the final shape of the part. This method is common

for creating composite rods or bars. A machine which accomplishes this is shown in Figure 5. This process has a cost disadvantage, as the equipment used to manufacture by pultrusion is normally relatively expensive. However, the process results in low cost for high quantity of parts once the machine is purchased. ^{[1][2]}

Resin transfer molding or RTM is a method where dry fiber reinforcement is clamped between two mold surfaces. Resin is then injected under pressure into the fiber reinforcement. This method is capable of using continuous, chopped, or woven fibers. RTM

Figure 5. Pultrusion composite part manufacturing

processing can quickly make parts, however, the molds require some investment. Thus high production quantities are necessary to recover costs. Additionally, a mold may only make a single part, so any alterations are extremely limited. ^{[1][2]}

There are numerous different techniques to developing composite structures; those described above are just some common methods. This project utilized pre-preg fiberglass in a heated press to create laminate plates and coupons. The pre-preg fabrication method utilizes fibers already impregnated with the optimized amount of resin. Pre-preg sheets have a good ratio of fibers to resin because they are created by reputable manufacturing companies that specialize in optimizing the resin to fiber ratio. These types of sheets are often chilled in a refrigerator to prevent the resin from curing at room temperatures.

Poor fabrication in either method may lead to voids. The voids will result in a weaker structure. Some sources of voids are air bubbles, out-gassing and poor application of resin on fibers. The operator should take extra time working out sources of voids to ensure a quality product.

The structural health monitoring system in this research can be applied to nearly any composite manufacturing process. Because it can be integrated, or woven directly into the structural fiber weave it can be used either during a hand layup or prepreg applications. Curing parts under severe temperature may result in melted or damaged sensors, depending on the material.

1.2 STRUCTURAL HEALTH MONITORING SYSTEMS

The principal types of damage and failure that occur in composite structures are process induced defects from porosity or delaminations. A second form is damage occurring during assembly due to improper drilling of holes, forced fits and other inadequate processing. Thirdly, damage can occur during the service of the structure. To reduce these types of risks, generally parts go through extensive nondestructive testing methods prior to going in to service or repair.

However, these methods are often time consuming and result in downtime of composite vehicles. Thus, a structural health monitoring system is an ideal method of addressing these issues. Various traditional and popular structural health monitoring

Figure 6. Fiber Bragg grating system

systems will be discussed.^{[4][5][6][7][8][9]}

1.2.1 Fiber Bragg

Fiber Bragg grating (FBG) is a type of reflector used in waveguides such as optical fibers. These types of reflectors are called Bragg reflectors. They utilize alternating materials with a varying refractive index to induce partial reflection of an optical wave. Fiber Bragg wavelengths are sensitive to strain and temperature, which makes them perfect for sensing elements in optical fibers. As strain or temperature changes it causes a shift in Bragg wavelength, allowing it to serve as a structural health monitoring device.^{[10][11][12][13][14][15]}

Shown in Figure 6 is how a typical Fiber Bragg grating system would be used to measure strain. As the fiber becomes strained the measured wavelength shifts due to changes in reflections within the fiber; thus it is correlated with strain/stress.

1.2.2 Piezoelectric

Piezoelectricity is used in a variety of methods for structural health monitoring. It works by analyzing the charge that is stored in certain materials. Piezoelectric sensors use the piezoelectric effect, or the resulting charge or voltage from mechanical stress, in order to measure pressure, strain, force or acceleration.

Piezoelectric sensors can be coupled with lamb waves to measure amplitude and phase changes in solids. Lamb waves are popular in ultrasonic testing to find flaws in objects. The flaws are detected by reflections or scattering that occurs from the

Figure 7. Piezoelectric patch transducers

imperfections, these scattered waves propagate back to the unit which measures the intensity. Thus, a reading on the flaws can be determined.^{[16][17]}

For example, vibrations in a piezoelectric transducer can be induced by a controller. When connected to an array of other transducers, a signal pattern for damaged and undamaged materials can be measured. A controller can then measure the system and collect information regarding the condition of the material. Often times this type of system can be active, providing electrical signals to dampen the vibrations.

1.2.3 Resistance & Strain Based

Many structural health monitoring methods involve the use of sensors. For example, strain gauges use resistance measurements to correlate to strain. Similarly, embedded sensors can be used to measure strain and temperature without applying a strain gauge. Additionally, if the structure is not completely insulative, the entire part can be used to measure resistance. Of all the structural health monitoring systems, resistance and strain based systems receive the least attention.^[18]

A goal of this research is to demonstrate the feasibility and usefulness of an interwoven embedded system to provide structural health to a user at any given time, thus, further developing the field of resistance based monitoring.

1.3 ELECTROTEXTILES

Embedded sensors are commonly made from metallic materials. However, there are also many conductive textile products that could be used as sensors which may integrate better into a fibrous composite than their metallic counterparts. Textile based composites have been heavily used in recent years for their high strength, light weight, and electromagnetic properties. Synthetic fibers like carbon fiber or fiberglass are commonly used, but there are many examples

of natural fiber composites as well. When additional electromagnetic protection or radio frequency properties are desired an electrotexile may be used to alter the resistivity in the composite. Commonly used naturally conductive materials are copper, aluminum, or ferrous alloys; they are normally used as wires which is very similar to the size of a fiber tow. Carbon fibers are also naturally conductive which presents the potential of using them as a conductive element of the woven fabric. Even though they are used for the excellent strength to weight, they may also be used for electrical properties; thus, allowing this research to be applied to many already existing materials and applications.

To develop a conductive fiber, a nonconductive substance may be augmented with small parts of conductive fiber as well. This can be done during a spooling process when the fiber is made, or the nonconductive fiber can be dipped into a conductive coating. For example, shown in Figure 9 is a conductive yarn produced from 60% polyester and 40% Inox steel fiber, a conductive element.^[19]

In this research, constantan is used as an electrical element to simulate an

Figure 9. Electrotexile yarn made from polyester and Inox steel fiber

Figure 8. Spool of constantan wire, non-insulated.

electrotextile. Constantan is a copper nickel alloy consisting of 55% copper and 45% nickel. It normally comes in a spool of wire, shown in Figure 8, very similar to how any fibrous textile tow would be packaged. The similar shape allows the constantan wire to be easily incorporated into the nonconductive structural elements of the composite. In this research, fiberglass serves as the structural fiber element of the composite because of its insulating properties. However, utilizing electrotextiles could be of great importance in future work. Thus, even though a more traditional material was chosen for this study, the potential of other materials and their advantages should be noted.

1.4 NONDESTRUCTIVE TEST METHODS

The only practical alternative to structural health monitoring is nondestructive testing (NDT). This allows a user to investigate the structural integrity of a part without damaging it. If the part is good it can return to service, otherwise it can be repaired or scrapped before any catastrophic failures occur. Destructive testing is still one of the best ways to determine the structural integrity of a part; however, when the testing is complete the part is destroyed so it is not realistic to test parts this way. Nondestructive testing has both benefits and drawbacks when compared to structural health monitoring. Normally the testing equipment is completely separate from the part, so the part does not acquire any additional weight or complexity during fabrication. However, it can be extremely time consuming to investigate a large part by a nondestructive testing method. Structural health monitoring could provide a way to quickly test a large part for structural integrity. Because nondestructive testing and structural health monitoring are fairly closely

Figure 10. Cracks are revealed by liquid penetration testing

related, an introduction to the many types of NDT is presented.^{[20][21][22]}

1.4.1 Liquid Penetrant

Liquid penetrant is a very old technique normally used in aircraft maintenance. A physical and chemical procedure is used to detect surface discontinuities in nonporous materials. The process works by creating a contrast between a flaw and its background. Developer reveals the evidence of cracks, porosity, or other discontinuities. It is fairly cheap, portable, and can be automated. However, it only makes sense to test small parts and only works on the surface. Thus interior delaminations would never be detected. An example of how liquid penetrant is used to reveal a crack is shown in Figure 10.^{[20][21][22]}

1.4.2 Magnetic Particle

Magnetic particle testing is another method for detecting surface flaws and sub-surface flaws in ferro-magnetic materials. This is done by magnetizing the part, creating a magnetic flux. Discontinuities result in a distortion of magnetic flux which indicates a flaw. Fluorescent or black oxide particles can be used in conjunction with magnets to uncover flaws. The method works well for metals that can be magnetized. It is also simple and can be applied to shafts, engines or hard to reach areas. However, in a composite application it does not work well because

Figure 11. Magnetic flux is distorted by flaws

Figure 12. Flaws reflect ultrasonic waves during Ultrasound NDT

composites are not ferro-materials.^{[20][21][22]}

1.4.3 Ultrasonic

Sound above the limit of audibility is referred to as ultrasound, in the frequency range of 0.2 MHz to 800 MHz. Ultrasonic inspection provides a sensitive method of nondestructive testing in nearly any material. It is capable of estimating the location and size of the defect via only one accessible surface. The method operates on the principle of transmitted and reflected sound waves. Sound has a constant velocity in a given substance, thus changes in the acoustic impedance of the material results in a velocity change in the sound wave. The distance of the flaw can be determined by the time taken for the sound wave to return. There are a variety of different kinds of ultrasonic inspection such as pulse echo and transmission techniques. Ultrasonic is a dependable method for obtaining accurate results of flaws. However, it requires calibration standards and trained operators. A typical ultrasonic NDT test setup is shown in Figure 12.^{[14][15][20][21][22]}

1.4.4 Radiography

A radiograph is a photographic record produced by the passage of electromagnetic radiation such as x-rays or gamma rays through an object onto a film, the same way x-rays are taken in the medical field. These methods require equipment to produce x-rays or gamma rays. X-rays require a source of electrons and means of propelling them at high speeds through the object. Gamma rays on the other hand are generated by the disintegration of radioactive substances such as Iridium-192 or Cobalt-60. Gamma ray equipment is normally simpler than x-ray equipment. Radiography provides good penetration on a large variety of material types. However, it also requires trained personnel. Additionally, radiation is a hazard and personnel should not be in the area when it is being used.^{[20][21][22]}

1.4.5 Thermography

Thermography is based on the principle that heat flow in a material is altered by the presence of anomalies. The changes in heat flow cause localized temperature changes. Imaging the thermal patterns reveals flaws in the material. This is normally done with infrared waves. The

Figure 13. Thermographic image of delaminations in a fiber reinforced composite

frequency and wavelength of the radiation can be correlated closely with the heat of a radiator. This process requires significant equipment, a thermal imager, detector scanning system, and more. It can be used to detect many different types of voids and is flexible enough to be used on fluids as well. However it also requires trained personnel and significant capital for equipment.^{[20][21][22]}

1.4.6 Nondestructive Test Methods Summary

There are many more methods that have not been presented. However, it is evident that some NDT methods work better for fiber reinforced composite materials than others. Defects in fiber materials are often difficult to detect and may arise from the raw product, during the fabrication process or while in service. A table from Nanyang Technological University in Singapore has been recreated in Table 1 and summarizes the capabilities of each of the major NDT techniques.^[21]

Table 1. Composite defects which can be detected by various NDT techniques

Defect Type	Ultrasonics	Radiography	Eddy Current	Acoustic Emission	Thermography	Optical Holography	Mechanical Impedance
Voids, porosity	Yes	Yes			Some	Some	Some
Debonds	Yes	Some		Some	Yes	Yes	Yes
Delaminations	Yes	Some		Some	Yes	Yes	Yes
Impact damage	Yes	Yes	Yes		Some	Some	Some
Resin variations	Yes	Some					
Broken fibers	Yes	Some	Yes	Yes			
Fiber misalignment	Yes	Yes	Yes				
Resin cracks	Yes	Some			Yes	Yes	Yes
Cure variations	Yes						
Inclusions	Yes	Yes					
Moisture	Yes						

1.5 LITERATURE REVIEW

A variety of structural health monitoring studies were reviewed. The most popular and available studies utilized Fiber Bragg grating, piezoelectric and Lamb waves. Very few were resistance or strain based. However, a few relevant studies were completed and are described in this section.

Structural Health Monitoring by Electrical Resistance Measurement by D.D.L Chung of State University of New York in Buffalo^[23], was one of the few studies available specifically studying resistance based SHM. The author utilizes a theory of volume electrical resistivity to detect structural changes in bulk materials. Resistance can be measured across the entire component as long as the material is not completely insulative. This can be done real-time with no sensors. In a graphite/epoxy laminate the fibers are conductive. Within a single lamina there is a finite number of adjacent fiber contacts, this creates a specific path of resistance. Between lamina within the laminate there are also a finite number of contacts in the through-thickness direction. The summation of the resistance these contacts develop is the volume resistance. The

author uses the four-lead Kelvin resistance measurement technique to measure resistance changes between fiber contacts within a lamina and between lamina within a laminate under different types of mechanical degradation. Chung showed the effectiveness of using graphite fibers as a conductive sensor element within a laminate. This is very similar to the goals of this study; however, the author used a different approach.

Strain-based Structural Health Monitoring of Complex Composite Structures by Ajay Kessavan, Sabu John, and Isreal Herszberg of RMIT University in Melbourne, Australia^[18] was another paper that was reviewed. The authors developed a system in order to address the evident composite material disadvantages of matrix cracking and delamination. Using traditional strain sensors, they developed a neural network within a fiberglass T-joint structure. The sensors were adhered over the component, *not* embedded. The system is based on the principle of load paths. Change in load paths occur during delaminations or fractures, which results in a change of strain measurements. The software the authors developed measures degraded strain values and compares them to a healthy reading. With a significant number of sensors the system is capable of predicting the sizes and locations of delaminations within the T-joint part. The authors showed that using a large number of sensors, a neural network can be developed to determine size and location of damages. This is a future goal of this study, albeit a different mode of sensing.

Structural Integrity of Composite Laminates with Embedded Micro-sensors authored by Yi Huang and Sia Nemat-Nasser from UC San Diego^[24], was also reviewed. The authors researched the mechanical consequences of embedding micro-sensors within a composite structure. They developed a finite element model to analyze a case of an embedded sensor. For sensors of significant thickness, 1/7 scale of the length, load is distributed around the sensor. Their model predicted premature failure due to stress concentrations created by the corners of a rectangular

sensor. However, they concluded that sensors that do not alter the through-thickness significantly have negligible effects on the material integrity. The authors showed that embedding large micro-sensors may compromise structural integrity. However, in this study, *A Resistance Based Structural Health Monitoring System for Composite Structure Applications*, the through-thickness is not affected and the sensors are round. Thus it can be concluded they do not have an effect on the structural properties of the test specimens developed in this study.

1.6 SCOPE OF WORK

This research encompasses the use of a conductive fiber element integrated into a nonconductive fiberglass composite structure for use in structural health monitoring. The main objective of this study is to develop a simple method for measuring deviations from baseline health and identifying potential catastrophic events of a composite laminate by utilizing an integrated resistance based measuring system.

Chapter 1 provides background information and introduction to composites, structural health monitoring and this research effort.

Chapter 2 describes the theory of the structural health monitoring system. It presents the idea and design process that led to the development of the strain based structural health monitoring system. Additionally, it describes the test equipment and software used to obtain data for health monitoring.

Chapter 3 describes the manufacturing processes for the test specimens used in this research. This research is to test the theory of utilizing an integrated conductive fiber element in the form of a constantan wire into a composite laminate for structural health monitoring. The integration of the sensor element involved specific manufacturing and process; thus, methods to

best integrate the sensor are developed. In addition, the length and orientation of constantan wire was varied to determine a relationship to the sensitivity of the measurements.

Chapter 4 describes the results for each test case. Plots present the correlation between strain and resistance. Discussion of the results is also provided.

Chapter 5 presents correlation with an analytical approach using equations and theory from Chapter 2. These solutions are compared to experimental results presented in Chapter 4.

Chapter 6 provides a conclusion, importance of work, and suggestions for further improvement of the system.

CHAPTER 2. THEORY OF SYSTEM

The structural health monitoring system developed in this research is presented in this chapter. The methodology of the system is discussed from elementary strain gauge theory and extended to the composite manufacturing process. The issues and processes for developing such a system are also presented.

2.1 SYSTEM ARCHITECTURE

The structural health monitoring method described in this study utilizes a conductive fiber interwoven with a nonconductive fiber and embedded in a matrix to develop a composite laminate. The conductive fiber, a single continuous constantan wire, serves as a sensor in the structure by measuring resistance changes in the wire under various loading cases. The nonconductive fiber serves as a structural fiber element. This approach can be accomplished by using other conductive fiber elements, such as carbon or copper; however, most of these materials exhibit variations in temperature and resistance. Thus, to develop a straightforward and viable study, the fiberglass was used in conjunction with the constantan wire. This idea can be expanded to use solely carbon fiber as the conductive and nonconductive element in the future.

To simplify the objective of testing this method as a viable option for structural health monitoring, the constantan wire was embedded within the fiberglass plies rather than interwoven with them. Weaving them into the fabric would require starting from a tow and utilizing a loom to combine both elements. Currently, no weaves are readily available that consist of conductive and nonconductive fibers interwoven.

A variety of manufacturing processes were developed. Each resulted in advantages and disadvantages for using the strain sensor. Three main processes were used, full length wires

protruding from each end, a parabolic shaped sensor with leads protruding from one end, and a threaded through specimen which resulted in leads out the side. Each of these is discussed in more detail in Chapter 3. The lead wires are connected to an Agilent micro-ohm-meter and data acquisition measurement device that measures the resistance values of the constantan wire. The change in resistance values is small due to the length and cross sectional area of the wire. Thus a measurement device with sufficient accuracy is required. The resistance values can be transformed into strain and stress values by use of strain gauge theory explained in the following section.

2.2 STRAIN GAUGE THEORY

The structural health monitoring method described in this study borrows many ideas from the strain gauge, a widely used measurement device. Normal strain is defined as the amount of deformation per unit length when a load is applied to an object. Thus, normal strain is calculated by dividing the total deformation by the original length as shown in Equation 1.

$$\text{Strain} \equiv \epsilon = \Delta L / L$$

Equation 1: Strain

Strain is normally very small and expressed in micro-strain. It is also unit-less, but is often expressed as inch/inch. The strain may be negative or positive which denotes a compressive or tensile load, as shown in Figure 14. Strain gauges work by converting mechanical motion into electrical signals. When a wire in a strain gauge is under tension the wire slightly lengthens and the diameter cross section is reduced. Shown in Equation 2 is the commonly used equation for resistivity of uniform cross section materials, such as wires.

$$R = \rho \frac{l}{A}$$

Equation 2: Resistance

Where ρ is the resistivity of a material, l is the length of the material, and A is the cross sectional area of the material. Thus, it is very apparent how changes in length or area result in changes of resistance. Also note that if the length of a wire is doubled, the resistance is also doubled. Similarly, if the cross sectional area is doubled, the resistance is reduced by a factor of one-half.

The change in resistance can be correlated to strain of the material. The relative change in electrical resistance to mechanical strain is called the gauge factor. Shown in Equation 3, is the correlation between strain and relative resistance.

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\text{Strain}} = \frac{\Delta R/R}{\epsilon}$$

Equation 3: Gauge factor

Note that the relationship is linear and correlated by the gauge factor. The results section will present information in terms of resistance plotted versus strain. The gauge factor represents the slope of the linear relationship. Thus Equation 3 may be rewritten in a $y=mx$ form, as shown in Equation 4.

$$\Delta R/R = GF * \epsilon$$

Equation 4: Linear gauge factor relationship

Figure 14. Strain gauge. (a) Strain sensor (b) Tension of strain gauge (c) Compression of strain gauge

The gauge factor can also be calculated from resistivity and Poisson's ratio, ν , given in Equation 6.

$$GF = \frac{\Delta\rho/\rho}{\epsilon} + 1 + 2\nu$$

Equation 5: Gauge factor from resistivity

Normally for most applications the resistivity can be assumed to be constant. In the case of piezoresistive materials, the resistivity, ρ , of the material is not constant. Thus, $\Delta\rho/\rho$ represents the piezoresistive term. However, a more exact solution for the gauge factor takes into account temperature, such as presented in Equation 6.

$$GF = \left(\frac{\Delta R}{R} - \alpha\theta\right) \frac{1}{\epsilon}$$

Equation 6: Gauge factor variation due to temperature

Where R is resistance, α is the temperature coefficient, ϵ is strain, and θ is temperature change. Expanding or contracting of the material can lead to changes in resistance, which can be the result of temperature change. However, that is not the only result of temperature change. Activity of atoms within the material changes; thus, the material property of resistivity may also change. In general, conductors tend to increase resistivity due to an increase in temperature. These changes can result in inaccuracies of measurements for resistance, and consequently, strain. By using constantan as the conductive fiber element to act as a strain sensor the temperature issue is addressed. Constantan gets its name from maintaining a constant resistance with varied temperatures. It is a material already commonly used in most strain gauges.^[25]

Often strain sensors are attached directly to the surface of a structure using an adhesive, which may be done poorly and result in inadequate readings. By embedding the strain sensor within the composite laminate during manufacturing, the issue of bonding is easily addressed.

This process results in improved bonding over the alternative of adhesion over a surface affixed strain device.

Commonly used strain gauges are made of metallic foils that are extremely small and measure strain over a very small area. This is ideal for measuring strain accurately and precisely at desired locations. However, for measuring average strain of a part over larger areas it is less effective. An additional benefit of using a sensor that is interwoven with the composite laminate is that it covers more area. Thus, even though it is not necessarily more accurate it can generalize strain over a larger area.

2.3 EXPERIMENTAL TESTING METHODS

Testing standards are developed for international coherence and consensus of technical information. The standards develop a medium which allows work to be compared with significance. In the field of composites many standards are used. Many are developed by companies such as Boeing or NASA. However, one of the most widely used is a public testing standard, ASTM International

The American Society for Testing and Materials (ASTM) is a global leader in the development of testing standards. The compilation of ASTM standards includes testing methods for a wide variety of subjects, from chemistry related projects to imaging, construction or water testing. Their database includes over 100 areas of interest and 12,000+ standards covering metals, petroleum, construction and more. Under lamina and laminate test methods, ASTM provides twenty relevant testing methods for tension, compression or flexural strength of a sample.

For this experiment, D3039 *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials* will be used^[26]. Any testing method could be used to test the effectiveness

of the embedded structural health monitoring scheme described in this study. However, tensile testing serves as a valuable way to start simply and provide a good understanding of the effects that occur under stress as well as the process of incorporating the sensor into the laminate.

D7264 *Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials*^[27] was used as a guideline for flexural tests. In order to evaluate the effectiveness of the structural health monitoring system while experiencing out of plane loads, a flexural test was conducted. Following the standard as a guideline, the sensors were tested in compression and tension as well as with delaminations introduced to the specimens.

In compliance with the testing standards, a force must be applied to the sample. Often, simple weights can be used. However, for improved accuracy of this study, and taking advantage of the availability of effective test equipment, the Instron 8801 servo-hydraulic system fitted with clamping jaws was used. This is a common, yet expensive test device for applying strain to a sample.

2.4 MEASUREMENT DEVICES

Recall that measurements were made via two different systems. First, the Bluehill

Figure 15. Bluehill 2 home screen interface

Figure 16. Micro-ohm-meter with multiplexer (MUX)

2 software made by Instron for material testing applications was used to measure strain. This study investigated the tensile and flexural effects on an embedded structural health monitoring device utilizing a constantan wire element. The software provides an easy to use interface and presents test data clearly. Secondly, An Agilent 34420a micro-ohm-meter was used to measure resistance values and correlate them with strain. Thus, two independent systems were used. In the field, measurements would be made via the ohm-meter only. The Agilent meter uses a four wire Kelvin resistance measurement by use of four banana-alligator connectors. The alligator connectors attach directly to the leads of the embedded wire. Software for the ohm meter was written in Visual Basic through Excel.^[28]

Other devices and software can be used for this experiment such as LabView or C. In a real application, a multiplexer, a device that selects one of several available input signals, would likely be wired directly to multiple leads in the structure to transmit a multitude of signals to the monitor. This method would provide data over a greater area and for the overall structure; thus, providing continuous data to a monitor where a user can review structural health.

Details of the measurement devices and test setup for experiments are discussed further in Section 4.2.

2.5 SYSTEM DESIGN

The structural health monitoring system discussed in this research provides the foundation for future work. Because this study was analyzing the fundamental aspects of the sensor and not the

Figure 17. Woven fabric showing warp and weft fibers

entire system, there are many applications to investigate. Additionally there are numerous different ways to employ the system developed during this research study. Some of these different ways are discussed.

During this study, the sensor was embedded between two nonconductive woven layers. However, in a truly interwoven specimen the conductive fibers will exist in the same layer. This can easily be done on most looms which are already in widespread use to develop the weave patterns purchased by manufacturers. By weaving plain fibers with a warp and main weft with use of a loom and inserting the wire as a supplementary weft or warp at regular intervals a completely interwoven layer can be developed. Thus, when developing a composite laminate, the interwoven sensory layer can be used and separated by an insulation layer from other conductive layers or elements. On the other side of an insulation layer a similar SHM layer can be placed at a ninety degree orientation. This develops a grid that can measure resistance values in a 2-D plane. The grid points would be spaced by as many leads as necessary for accuracy in the structure. The leads can then be connected to a multiplexor. By using a DAQ measurement device, strain can be continuously measured along the x-axis and y-axis simultaneously from each lead. The leads that exhibit the highest strain on the x-axis can be associated with the highest strain on the y-axis. This allows a user to develop a plane to pinpoint where stress is occurring on the structure. Having a system that can approximate the location where damage is on a structure can be extremely helpful, especially if the structure is very large.

Additionally, the system is capable of determining the type of stress. A negative value may denote compression, whereas, high positive values could denote pressure forces from the opposing side. Additionally, if the system is continually monitored, it can determine events such as an impact or collision. If an open circuit is detected it may indicate a puncture in the structure

which has destroyed the continuity of the conductive elements. Thus, users can have real-time structural health measurements that allow them to infer what issues may be occurring.

The system can also be used to measure deviations from baseline structural health values. By measuring values using the integrated system prior to use, a user can determine if any deviation of structural health occurs in the structure throughout its lifetime. When resistance or strain values approach a limit that may indicate fracture, maintenance can replace the part before any catastrophic damage occurs. This is very important for composite parts which are difficult to analyze while in use. Many times perfectly good parts are removed prior to their end of life and replaced, however, a system that can provide continuous health monitoring is capable of determining when exactly the components should be replaced; thus, saving time and costs associated with maintenance in many applications.

These ideas present some of the ways this research can be utilized to provide a better understanding of composite materials while in the field. It serves as a way to maintain safety and improve quality of composite parts while also reducing costs associated with maintenance. Many other applications are likely to exist which can be based upon this type of embedded sensor.

CHAPTER 3. MANUFACTURING PROCESS

The specimen manufacturing process will be discussed in this chapter. A detailed step by step on the fiber preparation, curing cycle, and test preparation is presented. The conductive fiber sensor and embedding process is also presented.

3.1 COMPOSITE LAMINATE PLATE PREPARATIONS

To simulate a composite structure, laminates are prepared. Fiberglass/epoxy prepreg is used as the main structural element of the composite laminate. Sensors are then embedded within the laminates for structural health monitoring.

3.1.1 Material Characteristics

The material used for the structural component of the composite laminate should be simple, easy to manufacture and be insulating as not to interfere with the conductive properties of the strain sensor. For this application, a pre-preg fiberglass was the ideal choice for the structural component of the specimen. Thus, the BT250E-1 Resin System in conjunction with 7781 "E" Fiberglass Reinforcement by TenCate was used for this purpose.

The BT250E-1 resin system displays good toughness and strength in a standard epoxy matrix. It resulted in a shiny surface finish with a heated press cure and is a good choice for applications in a low to medium service temperature. It has a shelf life of 30 days at 25°C and 12 months at 0°C. This product is normally used in secondary aircraft structures, racing vehicles, radomes, reflectors, sporting goods, medical items, and general purpose composites. The BT250E-1 Cirrus Optimized Epoxy that was donated by TenCate is actually the same material used for Cirrus aircraft construction. It is a unique type of the 7781 "E" fiberglass because the woven fabric is impregnated with resin on only one side. Thus, one side of the pre-preg remains dry until the cure cycle begins. This helps during the layup process because the layers are easy to

position when dry. It also helps orient the fibers during the embedding process, otherwise they would continually stick to the prepreg sheets as they were integrated. The resin and mechanical properties of the fiberglass were supplied by TenCate as part of a technical data sheet and are presented in Table 2.^[29]

Table 2. Resin and Mechanical Fiber Properties

Resin Properties		7781 "E" Fiberglass Reinforcement	
Density.....	1.17 gm/cc	Tensile Strength.....	63.0 ksi
Tg.....	125°C	Modulus.....	3.8 Msi
Dielectric Constant.....	3.0 @10Ghz	Compressive Strength.....	70.6 ksi
Loss Tangent.....	0.019 @10Ghz	Modulus.....	3.2 Msi
Moisture Absorption.....	2.0% after 24hr boil	Flexural Strength.....	84.8 ksi
Tensile Strength.....	10.9 ksi	Modulus.....	3.2 Msi
Tensile Modulus.....	0.44 Msi	Short Beam Shear Strength...	7.9 ksi
Tensile Strain.....	2.5%		
Compression Strength...	16.7 ksi		
Compression Modulus...	0.40 Msi		
Flexural Strength.....	22.6 ksi		
Flexural Modulus.....	0.50 Msi		
Flexural Strain.....	5.5%		

The Tetrahedron heat press, shown in Figure 18 was used for manufacturing of the laminates. The resin used on the selected material utilized a Tencate specified Cirrus Optimized Epoxy 90600 Rev C cure cycle provided by the manufacturers, shown in Figure 19. The press was set to a heat-up rate of 4°F/min, 180°F soak for 45 minutes, 260°F dwell for 100 minutes and naturally cooled at ambient temperature. A pressure of 1000

Figure 18. Tetrahedron Press

pounds across the 12"x12" plate was applied during the cure cycle, resulting in approximately 7 psi. The Tetrahedron heat press is a pneumatic press engineered for precision lab research and prototype testing. It is capable of pressuring up to 1000 lbf with an accuracy of $\pm 1\%$, and applying temperatures of up to 850°F with a temperature uniformity of $\pm 4^\circ\text{F}$.

Figure 19. BT250E-1 Cirrus Optimized Epoxy cure cycle

3.1.2 Laminate Preparation Process

The pre-preg fiberglass was purchased as a 56" wide roll. Shown in Figure 21, is the roll being prepared to be cut into lamina, or individual sheets. The Tetrahedron press only has space for a maximum size of 12"x12" area layups. Thus, the lamina was cut into 12.5"x12.5" sheets. This was slightly larger than the area of the press, however, the 0.5" extra length allows for some tolerance during the fabrication process.

Figure 21. BT250E-1 Resin with 7781 "E" Fiberglass Reinforcement pre-preg

Even so, not even the full 12"x12" press area produces parts of useable quality. Thus, this method allows for, at best, ten 1" wide test specimens after all preparations are completed.

Layers are cut using a handheld roller cutter along a straight edge. Working from the roll shown in Figure 21, a horizontal 12.5" cut was made,

Figure 20. Prepared fiberglass lamina

developing a 12.5"x56" long strip. The 56" allows sufficient material to cut four layers. Thus, also using a straight edge and cutter, four 12.5"x12.5" layers are fabricated, shown in Figure 20.

In addition, non-stick Teflon sheets are used between the fiberglass sheets and mold surface of the press. This prevents the sheets from sticking to the mold and allows them to be removed after the cure process. The Teflon sheets must be cut slightly larger than the lamina sheets to prevent the excess resin from dripping onto the machine. In some cases these sheets were actually very useful during the manufacturing process, described further in Section 3.2.

Next, the fiberglass laminates are paired up and combined. Utmost care must be made to align the fibers and even though the intention was to have a completely symmetric, 0° by 90° layup, in reality it is impossible. The two pairs will consist of the top and bottom of the laminate, where the structural health monitoring device will be inserted into the middle surface. Placing it here will result in a more symmetric layup. Additionally, it will see the least amount of out of plane stresses if they somehow occur.

3.1.3 Delaminated Specimen Preparation Process

One objective of this study was to determine the sensor effectiveness of detecting delaminations. Thus a delamination was introduced to the composite laminate during the layup process. This was in the form of a 1" wide strip created by inserting a non-stick, non-porous

Figure 22. (left) Threaded Through Linear Sensor (right) With Delamination

Teflon sheet into the middle surface. The sensor was laid up directly on top, also in the middle surface. This prevents bonding between the lamina in this area and results in a delamination.

Delamination samples were made for two cases: the threaded through linear tensile and flexural cases.

3.2 CONDUCTIVE SENSOR PREPARATION

Following preparation of the structural lamina elements, the conductive sensor can be integrated in the laminate. A variety of different methods can be used to integrate the sensor into the specimens and test them. Collectively, ten different cases were analyzed. Some embedding methods were found to be more effective than others and are described in detail. Additionally, predictions of test results are made for some cases.

3.2.1 Material Characteristics

As mentioned, the sensor in this study was made of constantan wire. Constantan is a copper-nickel alloy which normally consists of 55% copper and 45% nickel. It is commonly used because of its unique resistivity characteristics. Constantan gets its name because its resistivity remains constant over a wide range of temperature. The resistivity for constantan is relatively high when compared to other metals. Thus, this metal is ideal for measuring changes in resistance due to strain rather

than temperature; making it a great choice for studying stress-strain effects on a composite laminate.^[30] Constantan is the most widely used material for

Table 3. Constantan material properties

Material Property	
Resistivity (70°C)	0.0000489 ohm-cm
Temperature coefficient (20°C)	8 parts-per-million Kelvin
Density	8900 kg/m ³
Melting point	1221 to 1300 °C
Specific heat capacity	19.5 W/(mK)
Thermal conductivity	14.9 x 10 ⁻⁶ per Kelvin
Tensile strength	455 to 860 MPa
Elongation at fracture	<45%
Elastic modulus	162 GPa

strain gauges and thermocouples. In addition to having very high insensitivity to temperature, it has a fairly high strain sensitivity or gauge factor. This allows for more accurate readings during strain measurements. It also has very good elongation characteristics which will allow it to deflect significantly within the composite without fracturing. The physical properties for constantan are presented in Table 3.

The diameter of the sensors was 0.010". During integration of the constantan wire sensor in the composite laminates a length of 18 inches was used for all linear sensors and 36 inches for all parabolic sensors. This was to investigate the sensitivity and effectiveness of the sensor as it related to length of the wire.

3.2.2 Full Length Linear Sensor

The first and most forward approach to integrating the sensor into the laminate was to create a straight length of wire and protrude it from each side. These are placed in the center of 1" wide sections measured on the laminate plates, leaving space for about 9 or 10 sensor samples. Some space was left between each 1" section to allow space during the machining process and for the kerf of the blade, or the width of material removed during cutting.

During pilot studies of this method it was noted that the wires would become curved when in the heated press. This was a result of significant pressure and the flow of resins out to the side of the plate. This flow would cause the wires to bend outwards and result in specimens with non-aligned sensors. This approach was resolved by putting tension on the wires while it was curing. This was done by taping the sensors to the Teflon sheets at distances that were slightly shorter than the actual wire, causing the Teflon sheets to bow. However, when the Teflon sheets were flattened, it would put pressure on the wire sensors. Thus, once the plate was inserted into the heated press, methods were employed to flatten the Teflon sheet to apply a

tensile force. This was done by using a water bottle as weight on the Teflon sheet. The weight could be varied by how much water was inside the bottle, but a completely full 16oz bottle worked effectively.

Once the samples were completely cured, they were machined into 12" by 1" samples. The entire plate before the machining process was shown in Figure 23. However, one end of the plate could not be machined because the leads protruded out the end. Thus this end was left un-refined. It must be noted that

Figure 23. Full length linear sensor

during the cure process the resin was squeezed out of the prepreg laminate. This resin would have a tendency to build up around the wire protrusions developing an area of significant resin. Because this normally occurred at the edge of the heat press, the samples were not always flat, but slightly curved around the mold. Additionally, this area was nearly impossible to clean up because of the possibility of damaging the sensitive wire.

During testing of these samples the pneumatic clamping jaws of the Instron would crush this area with significant force. Normally this would cause a portion of the wire to shear off from the rest of the wire still embedded within the laminate. Therefore, it became a useless test specimen. As a result, it is not recommended to recreate this experiment with this fabrication process unless these issues can be addressed. Moreover, a parabolic sample that had wire leads protruding from the end was not created. It would likely result in the same difficulties as the linear sensor.

3.2.3 Threaded Through Linear Sensor

Another approach was taken to integrate the sensor into the laminate. This approach was driven by three main purposes: first, to determine if the clamping jaws of the Instron had any effect on the resistance measurements of samples; second, to improve machinability and develop clean cut edges on the samples; third, to be more representative of an application.

These samples were developed by using a needle. Similarly to all the other specimens they were laid up in the middle surface of the laminate. However, constantan was threaded through the eye of the needle, then through a marked surface on the lamina sheet, shown in Figure 24. This marked surface indicates the center of the 1" wide strip. The wire was also threaded through a porous non-stick sheet and a non-porous Teflon sheet. These sheets ensure the wire will not become infused with the outer surface of the laminate during the cure

Figure 24. Preparation of the threaded linear sensor

processes. Thus, a linear length of wire was created on one side of the laminate and the wires protrude from the other side. The side with the linear length was placed against the other half of the laminate into the middle surface. The lead side was laid flat against the non-stick sheet surface. On top of this, a sheet of thick cotton was added to allow the wires to be absorbed into the cotton and prevent the wires from creating crevices in the samples. During the cure process, tension can be applied much the same way as previously. Using a weight, tension was applied during the cure cycle to ensure that the wires are straight.

During removal of the sample, resin was actually squeezed through the small holes in the nonporous sheet and became infused with the cotton. However, it was extremely easy to remove, did not damage the wire leads, and did not create any surface abnormalities on the surface.

As discussed previously, the effectiveness of a straight through sample resulted in difficulties during the testing. The leads would be completely sheared off, thus no measurements could be made with these samples. Even though one of the goals of creating a threaded-through sensor was to investigate the effects of the jaws, this could not be addressed.

The machinability of the samples was far easier for the threaded through sample. It was very easy to square up edges and machine without worry about cutting the leads. Thus this method resulted in a far more effective product for specimen refining. The samples before they were cut down

Figure 25. Cured threaded through linear sensor

to size are shown in Figure 25. A drawing of the specimen was shown previously in Figure 22.

If this method were ever to be used effectively on a plate or laminate of a structure, it would be very difficult to work with wires that protruded from the edge. Instead, they would likely be routed into an interior section of the structure where they can be connected to a harness and measurement device. Thus, developing a sample that has leads protruding from the edge of the specimen would be a more effective way of demonstrating the capabilities of the sensor for application use.

3.2.4 Threaded Through Delaminated Linear Sensor

In addition to monitoring overall structural health of a sample, one of the goals of this study was to investigate the effectiveness of the sensor's ability to detect structural flaws such as a delamination. Thus, a sample for the threaded through linear sensor case was developed with a 1" delamination introduced at the center of the specimen. Shown in Figure 26 is the refined specimen with the delamination located at the center. The manufacturing processes are identical except for the addition of the nonporous strip.

Figure 26. Delaminated specimen with threaded through linear sensor

3.2.5 Threaded Through Parabolic Sensor

A parabolic sensor was created to investigate the effects of additional length in the wire. Theoretically, this would result in twice the resistance and a greater change in resistance during strain events. Thus, it can provide higher accuracy of measurements. Wires for this process were twice as long as the wires in the previous, straight-through cases, for a total length of 36 inches.

Although this method would be

Figure 27. Threaded through parabolic sensor and schematic

easily employed by letting the curved end of the wire protrude from the sample, preliminary tests showed that the excessive resin build up on the lead caused the wires to shear off during testing. Therefore these wires were looped within the laminate by threading them between two of the warps in the weave. This allowed the wire to bend around one of the wefts as it returned to the opposite end of the sample. Here the wires were threaded upwards through the lamina and out of the two non-stick sheets; the very same method used for the threaded-through linear sensors. This was to prevent any leads from sticking out the ends which would result in machining and testing issues. A completed specimen ready for testing is shown in Figure 27.

3.2.6 Threaded Angled Linear Sensor

One concern when using linear sensors was the quality of alignment within the sample and along the fibers. Because these sensors are applied directly and not interwoven with the fabric, they can never be directly parallel to the fibers. Additionally, due to marcelling, or fiber waviness caused by flow of the resin, it is very difficult to develop sensors that are completely straight. Therefore the issue of alignment as it relates to the accuracy of sensor measurements becomes very apparent.

To address this issue, a variety of samples were created to investigate the accuracy of the sensors as they relate to alignment in the sample. To do this, sensors were embedded within the lamina at a purposely angled orientation. As shown in Figure 28, the maximum angle available within a 9.5"x1" sample was 84.3 degrees. The 9.5" allows some clearance from the grips of an actual sample size of 10".

Figure 29.
Completed angled
sensor

Therefore, the idea can be fabricated with an approximate angle of 84 degrees, or 6 degrees off perfectly parallel. However, due to tolerances these samples were made with an approximate angle of 4 degrees off perfectly parallel, measured by a conventional protractor. A completed specimen is shown in Figure 30. The sensor was difficult to see, so it has been darkened using a photo editor.

During tensile testing this would cause portions of the cross section to change due to forces and not due to lengthening of the wire. Additionally, the wire was not perfectly parallel thus the magnitude of change in length would be less. Therefore, Equation 2 predicts less change in the measured resistance values. Consequently, the resistance values from the ohm meter would predict smaller values of $\Delta R/R$ and $\Delta L/L$. The strain would actually be more than the predicted values. However, investigation of this issue is further discussed in the experiment sections.

3.2.7 Linear Perpendicular Sensor

To further address concerns of disorientation of the sensor, an absolute worst case scenario was investigated. A sensor was embedded in a specimen perpendicular to the direction of applied force.

This orientation may also glean information on how to detect strain in the direction perpendicular to any sensor. In this case, the length was expected to shorten slightly and the cross section should slightly increase. This was predicted to result in a reduction in resistance values, or a negative trend in the change of resistance.

Figure 30. Linear perpendicular sensor oriented within a specimen

To simplify fabrication of these samples, they were cleaned up during the layup process to reduce any need for machining after the cure process. Therefore, each sample was made individually. A total of five samples for this case were developed.

3.2.8 Full Length Carbon Tow Sensor

Another question to be answered by using this type of structural health sensing device concerns the use of constantan. Even though constantan is a widely used testing material that results in high accuracy of measurements, it is also fairly expensive and delicate. Even when compared to carbon, an already fairly expensive material, constantan is still more precious. Therefore, it may not be viable for use on a large scale due to affordability. An alternative is to use other conductive elements such as Texalium, Celion or Panex, all conductive yarns.

Figure 31. T300 6k carbon tow

These substitutes are cheaper than carbon and still have conductive properties. Normally they are made of

Table 4. T300 6k carbon tow material properties

Material Property	
Tensile Strength	545 ksi
Tensile Modulus	33.5 msi
Elongation (%)	1.60
Density	1.78 g/cm ³
Resistivity of graphite	~7.837 $\mu\Omega$ -m

fiberglass that has been coated or spun with small bits of aluminum or other conductive metal.

To investigate the use of other materials and how they can be employed in this structural health monitoring system, Thornel (owned by Cytec) T300 6k carbon tow was embedded within the fiberglass layers. The material properties of the tow are presented in Table 4. A completed specimen is shown in Figure 32. It was observed that the elongation for the carbon tow was extremely less than the constantan. When embedded in the fiberglass it may result in very small changes in resistance because the elongation was minimal. Additionally, an average resistivity of carbon (graphite) is presented. This value is far larger than the resistivity value presented for constantan. Recalling Equation 2, the changes in length and cross sectional area are multiplied by the resistivity. Because the resistivity of carbon is larger, it is expected to experience larger changes in resistance values. However, coupled with the stiffness and poor elongation of carbon, this may not be the case. This case was analyzed more in the experimental results section.

Figure 32. Full - length carbon sensor

3.2.9 Threaded Through Linear Sensor for Fracture

The last tensile case investigated in support of this study was a fracture case using the same samples created for studying the effects of the threaded-through linear sensor presented in Section 3.2.3.

During fracture of the specimen a variety of things can occur. The sensor could fracture within the fiberglass specimen. The fiberglass could fracture and leave the sensor still intact. Or they could both fracture simultaneously. The first case was very difficult to measure, because the

Instron machine would not detect any change in structural integrity and would not stop the test. Thus the only way of measuring the event would be by developing a unique test system or by eye. More likely one of the two latter cases would occur.

If the sensor fractures the ohm-meter will begin measuring an open circuit and the resistance will approach infinity. The ohm-meter actually reports a number around 10×10^{34} when this happens. Thus, a fracture can be detected by the structural health monitoring device.

If the sensor does not fracture but the fiberglass does, the ohm-meter will not return open circuit values, but it may exhibit a significant discontinuity in measurements. Thus, specimen fracture may or may not be detected by the monitoring device.

3.2.10 Threaded Linear Sensor for Flexural

Another objective of this study was to determine the sensitivity and feasibility for the sensor to detect damage within the composite layers. One main type of interlaminar damage is a delamination. A delamination is very difficult to test in a plane stress case where load is applied

Figure 33. Schematic of flexural specimen

in only one dimension. The delamination would have no effect on the sample strength during a tension test because there are no interlaminar forces being exhibited

To effectively investigate a delamination case, a flexural test was used. When a sample is in bending it undergoes tension, compression, and vertical shear force simultaneously. Thus, a delamination has a large effect on these out of plane forces.

The samples developed to support this test are in accordance with ASTM Standard D7264 *Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials*. As such, the standard recommends a thickness of 0.16" and a 32:1 span-to-thickness ratio. The fiberglass layers used in this study are approximately 0.00875" thick. Therefore with 18 layers a thickness of 0.1575" was achieved and a span of 5.04" was calculated. This specimen width was 0.5", as recommended by the standard. The recommended dimensions are represented in a sketch, as shown in Figure 33. A completed specimen is shown in Figure 34.

The sample width was significantly thin; therefore a linear sensor was employed. A parabolic sensor could be used to double the effective sensor length within the specimen, however, it was very difficult to manufacture within the width of the specimens. Unlike the tensile specimens, there was no consequence from resin build up on the leads because there are no clamping jaws in a bending test. Therefore there was no risk that the jaws would destroy the leads, as in the case of the full length linear

Figure 34. (left) Flexural specimen (right) Delaminated flexural specimen

sensors discussed in Section 3.2.2. Therefore these samples can be machined or cleaned up during the specimen refining process.

These sensors are embedded between layer 1 and 2 of the 18 layer laminate. This extreme outer edge will experience the greatest effects of bending due to a greater distance from the neutral axis. Additionally, this case was tested with the sensors oriented on the upper most surface of the specimen resulting in compression forces during a 3-point bend test. This was repeated with the sensors oriented on the bottom most surface, resulting in tension forces. This method can simultaneously determine the quality of the sensor in a bend test and its ability to detect compression or tension forces during flexural loads.

3.2.11 Delaminated Threaded Linear Sensor for Flexural

A delaminated case of the threaded linear sensor for flexural testing was developed for comparison against the previously mentioned non-delaminated case. A 1” delamination was introduced across the width of the samples. Because the samples are only 5.04” long, this was a significant delamination. The samples for this case are created in exactly the same way as those in section 3.2.9. The delamination was introduced between layer 1 and 2 of the laminate; the same layer that the sensor was embedded within.

Theoretical prediction would estimate that the change in resistance for the delaminated case would be less than that for the bonded case. Because the sensor was not attached to the specimen in the delaminated region, it will not experience significant change in length. Therefore most of the strain in the wire will occur in the remaining 4” of wire length embedded within the specimen. The 1” difference in strain length can result in variations in resistance measurements, thus providing a method for detecting delaminations in layers adjacent to the sensor.

3.3 SPECIMEN PREPARATION

3.3.1 Cure Process

Once the fiberglass and sensors are integrated into the middle surface, the plates are ready to go into the Tetrahedron press for curing. Recall Figure 19 in section 3.1.1, the cure cycle for the given prepreg material. The cure process takes approximately 90 minutes for the cure processes and another 30-60 minutes for the plate to cool to room temperature.

3.3.2 Specimen Refinement

Once the plates have been cured in the Tetrahedron press they must be cut down to standard sizes. ASTM standard D3039 *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials* recommends sample sizes of 10"x1" and 0.1" thick. However, it must be noted that the actual requirements are more lenient. The standard calls out no required width or thickness of the specimen. The minimum length must be the gripping length + 2x the width + gauge length. The specimens made in this study were created from four layers of fiberglass resulting in a total thickness of 0.035", thus not the recommended value but still meeting the requirements. The length used was 9.5" and the width was 1".

Each case must be refined differently. Because some of the cases result in wire leads out of the top or bottom of the sample, they could not be cleaned up without completely cutting through the lead. Thus, the specimens were cut length-wise only and left as unrefined along the top and bottom. As mentioned previously, excessive resin buildup in these areas resulted in difficulties during testing. This often resulted in the

Figure 35. RIDGID tile saw

clamping jaws destroying the wire leads when put into the Instron machine.

Thus, many of the samples were fabricated in a manner to allow for specimen refinement and cutting of clean edges. These samples normally had leads that extruded out of the surface of the specimens, thus allowing the specimen to be cut and squared up.

Using a RIDGID brand tile saw shown in Figure 35, the samples were cut into the sizes specified by the D3039 standard. The specimens are cut to $\pm 1\%$ of the specimen width in compliance with the D3039 standard. This means that the specimens are within 0.01" of the 1" specimen width, or between 0.990" to 1.010".

CHAPTER 4. EXPERIMENTAL ANALYSIS

The specimen testing process will be discussed in this chapter, including the determination of various material characteristics and pretest values. Results for each of the specimen cases explained in Chapter 3 will be summarized and discussed.

4.1 DETERMINATION OF MATERIAL PROPERTIES

4.1.1 Poisson's Ratio

As mentioned in section 3.1.1, a Tencate BT250E-1 Resin System in conjunction with 7781 "E" Fiberglass Reinforcement was used in this experiment. To validate the given material characteristics a monotonic tensile test was conducted. In order to determine E_1 , E_2 , and ν_{12} strain gauges were used with the built in Bluehill 2 versa channel test software.

To accomplish this test, Vishay general purpose strain gauges were used. These strain gauges use a gauge factor of 2.110, as shown in Figure 36. Vishay Measurements Group *Student Manual for Strain Gage Technology* procedures were used for installation of strain gauges.

Figure 36. Five Vishay general purposes strain gauges used to determine Poisson's ratio

Five specimens were tested in support of determining material characteristics. The specimen surface was prepared by surface abrading, degreasing, applying layout lines, and neutralizing. First, the specimen was cleaned using acetone. Next the surface was lightly abraded using 150 grit emery cloth sand paper. Next, layout lines perpendicular to the longitudinal length of the specimen were drawn using pencil. These lines will be used to align the strain gauge in later steps. Next, using M-Prep Neutralizer, shown in Figure 37, the surface was neutralized to provide optimum alkalinity for adhesives.

Once surface preparation has been completed, the strain gauges can be bonded to the specimen. The strain gauges are extremely small and delicate, thus should not be handled by hand. The strain gauges were removed by the acetate envelope packaging using tweezers and placed on a clean surface.

Also used are solder terminals, shown in Figure 38, which are used with the strain gauge. These are placed next to the strain gauge at a 1/6" distance.

Figure 37. A neutralizing agent is applied to the specimen surface prior to strain gauges

Figure 38. Bondable terminals are used to bridge leads to the strain gauges

Using cellophane tape, also called Scotch tape, the strain gauge and terminals were taped to the clean surface with the soldering surface side upwards, against the tape. Next, the tape was removed with the strain gauge and terminals attached to the tape. It was then placed on the specimen in the transverse direction. Using the small alignment triangles on the strain gauges, the gauge was aligned with the pencil layout lines drawn earlier. Next, the tape was partially removed allowing the underside to be exposed and looped backwards so that the bottom side of the strain gauge was exposed. M-Bond 200 catalyst was lightly brushed onto the surface of the strain gauge, still attached to the tape. M-Bond 200 adhesive was applied to the composite specimen along the pencil layout line. Next, the tape was repositioned in the original orientation, along the pencil layout line. Using a piece of thin cotton, the tape was firmly rolled into position, allowing excess adhesive to move off the side of the specimen. Lastly, firm thumb pressure was applied for 60 seconds. The tape was removed and the strain gauge was secured firmly in place, along the layout line, which was along the transverse axis of the specimen. The five specimens with installed strain gauges are shown in Figure 39. Further details can be found in Vishay Measurements Group *Student Manual for Strain Gage Technology*^[31], presented in the Appendix.

The Vishay manual also provides soldering techniques, however, these were not strictly followed. No M-Coat A was used as called for in the manual. Solders

Figure 39. Test specimens with installed strain gauges

were made using a generic soldering iron, shown in Figure 40. The best method found to solder small terminals such as those on the strain gauge was to heat the surface using the soldering iron and bring the solder into the region. This quickly melts the solder and allows it to pool on

Figure 40. Soldering iron used for strain gauge application

the terminal. Once the soldering has melted sufficiently, the iron can be removed. However, it was important to be careful as some solder will stick to the iron. Additionally, it was important to not overheat the surface and cause the strain gauge to burn out.

Twenty-gauge non-insulated solid copper wires were bridged between the strain gauge terminals and the copper solder terminals, as shown in Figure 41.

The copper solder terminals are used to better connect braided copper lead wire to the strain gauge. In a similar method as used for soldering previously, the lead wires were soldered to the remaining half of the terminals. A completed test specimen is shown in Figure 42.

Figure 41. Strain gauge and terminal bridges applied to test specimen

Figure 42. Completed test specimen for Poisson's determination test

To determine Poisson's Ratio, the ASTM standard was used. E132-04 *Standard Test Method for Poisson's Ratio at Room Temperature*^[32] outlines the procedure for evaluating data to determine Poisson's ratio.

The Instron measures extension and true strain directly. Thus to obtain values for longitudinal strain, no strain gauges were necessary. The longitudinal strain values provided by the Instron Bluehill 2 software are presented in Figure 43.

Figure 43. Longitudinal strain obtained from Instron using Bluehill software

Values for transverse strain must be obtained by a strain gauge that was aligned with the lateral direction of the specimen. These values are measured with the versa channel through a National Instruments BNC-2111 data acquisition box, shown in Figure 44. Values obtained from

the strain gauges are presented in Figure 45. Note that the transverse strain is shown as positive strain. The strain measured is actually negative strain, however, the absolute value has been taken to represent the data similar to the ASTM standard.

Figure 45. Transverse strain data obtained by Vishay strain gauges

Pursuant to the ASTM standard, the average longitudinal strain and average transverse strain should be plotted against applied force. It was important to determine Poisson's ratio prior to averaging values. Each calculation was dependent on the sample. If averaging was done at the strain level, the Poisson's calculation will be distorted due to deviations between samples. Thus, it was important to determine either Poisson's or

Figure 44. NI BNC-2111

strain/load slopes for each case separately and then average them. The slopes of the lines represent $d\epsilon_l/dP$ and $d\epsilon_t/dP$. The ASTM standard defines Poisson's ratio as follows:

$$v = \frac{(d\epsilon_t/dP)}{(d\epsilon_l/dP)}$$

Equation 7: Poisson's ratio

Each case is plotted in a manner shown by Figure 46 from ASTM E132-04. Additionally, the $d\epsilon_l/dp$ and $d\epsilon_t/dp$ slopes for each test specimen are presented in Table 5. With these values and information, Poisson's value can be determined for each case. With data for strain in the longitudinal and lateral directions, in addition to the applied load a plot can be developed per section 9 of E132-04, presented as Figure 47 on the next page.

Figure 46. Plot of Average strains versus Applied Force for Determination of Poisson's Ratio. (Figure 2 from ASTM E132-04)

Table 5. Strain slopes for each specimen case

Sample	1	2	3	4	5	average	std dev.
$d\epsilon_l/dp$	0.000900	0.000866	0.000923	0.000859	0.000930	0.000896	0.000032
$d\epsilon_t/dp$	0.000092	0.000093	0.000091	0.000099	0.000096	0.000094	0.000003
ν	0.102610	0.108364	0.099474	0.116379	0.103998	0.106165	0.006453

Figure 47. Plot of average longitudinal and transverse strains versus applied load

The slope of each line was determined by linear regression using Excel trend-line function. The slope of the longitudinal strain and transverse strain was determined for each case. Thus, Poisson's for each specimen was determined. The average for these five specimens is presented in Table 5. Therefore the average Poisson's ratio as determined by Equation 6 was determined to be:

$$\nu = 0.1061 \pm 0.008$$

This value was compared to TenCate test data. TenCate tested a total of five specimens and determined an average Poisson's ratio of 0.12. Thus a 12.29% difference was determined.

Note percent difference was used and not percent error. This method is best when neither test value can be assumed to be absolutely correct.

4.1.2 Weight Fraction

One of the most important factors determining the properties of composites is the proportions of matrix to reinforcing materials. This is normally presented as a volume fraction, but, can be also indirectly presented as a weight fraction. The volume and weight fractions are used exclusively in theoretical analysis of composite materials. Thus it was important to determine the fraction of the material used for this experiment.

Because volume fraction cannot be determined directly, the weight fraction and density was measured instead. With these values the volume fraction can be calculated if needed. The weight fraction is defined as follows:

$$w_c = w_f + w_m$$
$$W_f = \frac{w_f}{w_c} \qquad W_m = \frac{w_m}{w_c}$$

Equation 8: Weight fraction

Where c represents composite, f represents fiber, and m represents matrix. A relationship between volume fraction and weight fraction can be determined by the density of the composite material. Replacing Equation 8 above using density, it can be rewritten as follows:

$$W_f = \frac{w_f}{w_c} = \frac{\rho_f V_f}{\rho_c V_c} = \frac{\rho_f}{\rho_c} V_f$$
$$W_m = \frac{\rho_f}{\rho_c} V_m$$

Equation 9: Weight fraction in terms of density

Where V_f and V_m are fiber and matrix volume fractions, respectively.

The volume of the fiber and matrix can be calculated by solving Equation 10. Thus the relations of volume to weight fraction for a composite of two constituents is presented below.^{[1][2]}

$$V_f = \frac{\rho_c}{\rho_f} W_f$$

$$V_m = \frac{\rho_c}{\rho_m} W_m$$

Equation 10: Volume fraction

The density of the resin was given by TenCate and presented previously in Section 3.1.1 as 1.17 g/cm³ or 19.17 g/in³. The fiber density was not provided by TenCate. However, the composite density can be determined by measuring the dimensions and weight of a sample. Five samples were measured in support of determining this value. After volume and weight of composite specimens were measured a burn test was conducted. This was done at approximately 1000°F and 25 minutes per sample until the resin in each specimen was completely burned out. A summary of results for this test are shown in Table 6. A photo of the burned test specimen compared to a non-burned test specimen is shown in Figure 48.

Table 6. Summary of weight fraction data

Specimen	Pre-Burn			Post-Burn			
	w_c (g)	V_c (in ³)	Density, ρ_c (g/in ³)	w_f (g)	w_m (g)	W_f	W_m
1	2.4	0.076	31.6	1.4	1.0	0.58	0.42
2	2.4	0.077	31.2	1.5	0.9	0.62	0.38
3	2.2	0.075	30.1	1.3	0.9	0.59	0.41
4	2.3	0.073	29.3	1.3	1.0	0.57	0.43
5	2.7	0.087	31.0	1.7	1.0	0.63	0.37
avg	2.4	0.078	30.9	1.44	0.96	0.60	0.40
std dev	0.19	0.01	0.93	0.17	0.05	0.03	0.03

The average weight fraction of the fiber was calculated to be 0.60. The average weight fraction of the matrix was calculated to be 0.40. These were compared to the supplied manufacturer data of 60 to 70% and 30 to 40%, fiber and matrix respectively. It can be seen that the weight fractions are within the range of specified manufacturer data.

Figure 48. (left) Burned test sample compared to (right) unburned sample

Volume fraction of the fiber can be calculated using the given density of the matrix from TenCate, measured volume and weight of the composite, and indirect measurement of the fiber density. Using the average of the five specimens, the volume fraction calculation is shown below with use of Equation 11.

$$V_f = \frac{W_f / \rho_f}{\left(W_f / \rho_f \right) + \left(W_m / \rho_m \right)} = \frac{0.0325}{0.0325 + 0.0286} = 0.61$$

$$V_m = 1 - V_f = 0.39$$

Equation 11: Weight to volume fraction relation

The density of the fiber was not provided directly from TenCate. However, assuming that the volume does not change between pre- and post-burn, the fiber density can be calculated. This was a fair assumption, as the composite was not deformed during the burning process. The matrix was simply being removed, but the fibers retain the same shape.

The volume fraction for the entire composite should be equal to one. Thus the matrix volume fraction was calculated as shown above. Most pre-pregs are optimized to have a

maximum volume of fiber and minimum volume of resin. Theoretically, fiber volume fractions of 90% are predicted; however, actual fiber volume fractions are normally between 70 to 80%. Comparatively, the experimentally determined volume fractions were 61 and 39%, fiber and matrix respectively. The values in TenCate's data sheet are for a fiber volume fraction of 0.60. Thus, these values are within range by about 1%. The volume fraction plays an important role for analytical solutions of the composite lamina which is presented in Chapter 5.

4.1.3 Elastic Modulus

In support of determining analytical solutions to validate experimental results, Young's modulus was needed. The manufacturer supplied a modulus and ultimate strength, but these were assumed to be inaccurate. The material used for this project was donated and likely exceeded the expiration date. Thus, the material properties given by the manufacturer may have changed.

Using ASTM D3039 *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, the stress-strain curves were obtained. Specimens were created using the recommended standards; however, no sensor was inserted into the specimen. Shown in Figure 50 is the stress-strain curve obtained from testing five specimens. Note that specimen number four fractured significantly before the other specimens. This is acceptable, as only the linear portion of the curve is needed for determining Young's modulus. Additionally, the ultimate strength for the material greatly differs from the manufacturer which was given as 63.0 ksi ultimate tensile strength.

The first 10% of the data and the last 30% were removed in order to narrow down the data to the elastic range only, as shown in Figure 49. The first 10% of the data, although in the elastic range, is not always linear. To determine the slope it is important to obtain a linear relationship. Additionally the last 30% approaches the plastic range of the material; thus, it is

Figure 50. Stress-strain curve of fiberglass material

Figure 49. Elastic range of stress-strain curve of the fiberglass

ignored to maintain the linear elastic relationship. The slope of the elastic range was determined for each case using Excel's trend-line function. They were then averaged to obtain the average tensile modulus for the TenCate 7781 "E" fiberglass BT250E-1 Resin System material.

Shown in Table 7 are the modulus values for each specimen. The average Young's modulus was determined to be 30.119 ksi.

Table 7. Summary of tensile modulus

#	E (ksi)
Specimen 1	29.6
Specimen 2	29.191
Specimen 3	30.936
Specimen 4	30.688
Specimen 5	30.182
Average	30.119
std dev	0.729

Whereas the manufacturer-supplied modulus was 38.0 ksi. For analytical purposes, the modulus determined experimentally will be used.

4.1.4 Gauge Factor

The gauge factor of a strain gauge is the ratio of change in electrical resistance to mechanical strain, as defined in section 2.2. It is an important value that is dependent on the mechanical properties of the material.

The widely accepted gauge factor for Constantan alloy thin-film strain gauges is nominally 2. This is a very common value, as most gauge factors for strain gauges range from about 2 to 2.1. However, the sensor in this study was not specifically a strain gauge; nor was it a thin film. It will have a significantly different gauge factor. Thus, to investigate the gauge factor for the material used in this study an experiment was conducted. This value will be determined independently of values during specimen testing and may assist in predicting strains as they relate to resistance during the case studies.

Recall Equation 3, the equation for gauge factor of a strain gauge, defined as:

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon}$$

Therefore, to determine the gauge factor for the wire sensors an experiment was conducted to measure resistance, change in resistance, and strain. Eight specimens were fabricated, shown in Figure 51, consisting of solely an 18" length of wire which was 0.010" in diameter. 1"x1" aluminum tabs are adhered to each of the wires using 2-part adhesive at a distance of 9.5" centered about the middle of the constantan wire. The majority of the laminate samples developed previously consisted of approximately 9.5" of sensor length within the specimen and a total length of 18". Therefore these lengths are used to mimic values in the case tests.

Figure 51. Wire only tensile specimen

Figure 52. Determination of gauge factor using aluminum tabs

of constantan to be 455 to 860 MPa (65.992 to 124.723 ksi), as presented in Table 3, some expectations of testing can be developed. With a wire of cross section 0.010", the cross sectional area was calculated to be $7.85 \times 10^{-5} \text{ in}^2$. Therefore, a tensile force of 5.18 to 9.79 pounds was expected to result in fracture of the wire. However, the wire exhibits significant elongation. Therefore the wire will never experience a force over 5 pounds. Instead, it will stretch to nearly double its length before it fractures.

Knowing this, a test method for tensile testing was developed. The test was set to stop at an extension of 0.3 inches. This was approximately four times greater than the strain that was experienced in the specimen case studies. Initial resistance of the wire was measured at points within the 9.5" length of the wire. Also note that the tabs are aluminum and therefore conductive. However, they are assumed to experience no strain after the clamping jaws are applied and thus contribute nothing to the resistance readings during the test. Four samples were tested. During the test, strain and resistance was measured. Because this test duration was significantly long it results in over 6000 measurement values. Consequently, a moving average of 50 measurement samples was used to reduce noise in measurements. From these data, a plot was developed between the strain and $\Delta R/R$ at each point in the test segment. The slope of this line represents the gauge factor. A trend-line of the data from each test specimen case was developed using Excel. The slope of the trend-line was recorded as the gauge factor. Various observations can be made from the plot:

Firstly, Specimen 2 and Specimen 3 are plotted directly on top of each other; next, it is evident that even though all cases show linear relationships, they do not have the same slope. In determining the gauge factor, this slope is the most important factor. There are several explanations for this result. Wires may have small kinks in the length that result in varying

values of strain. The Instron machine is purely metallic, if any wires or leads touch it, it can interfere with measurements. Also the tabs used to grip the wires may not be ideal; they are conductive and used adhesive which may not result in sufficient bonding.

Thus, it is apparent that some improvements to this test were necessary. Issues with the conductive aluminum tabs are the most obvious error. Therefore, the test was recreated using fiberglass tabs. The fiberglass used was identical to the fiberglass used in the other test cases, four layers of BT250E-1 TenCate fiberglass.

Figure 53. Determination of gauge factor using fiberglass tabs

The test using the fiberglass tabs was repeated using the methods described. The results for four specimens are shown in Figure 53. Shown are results that are far more consistent. A fair amount of noise is evident due to the sampling time of the Agilent micro-ohm-meter; however, this is expected and does not have a large effect on the gauge factor after a linear trend line is

developed. To develop a single value, the average of the four test specimens was used. The trend-line slope of the averages is the gauge factor.

Shown in Figure 54 is the average with the linear trend-line. Also shown is the slope of the line, 0.0296. This value is the gauge factor of the constantan wire.

Figure 54. Average of the gauge factor found when using fiberglass tabs

The gauge factor can provide very good information about the interaction between resistance and mechanical strain on the wire. However, it is important to note that this value changes when integrated with other materials. Just like traditional fibrous composites, the fiber and matrix exhibit individual properties of their own. However, when combined, these properties change significantly. Thus new mechanical characteristics are needed. This is why many values for composites are listed in terms of fiber, matrix, and total composite. Similarly for the constantan wire, its properties change when it was integrated into the fiberglass laminate. It is important to

note this change, as it affects the methods used to predict the strain on the system based on resistance values.

4.2 TEST DEVICES

Recall Section 2.3 which introduces measurement devices. As mentioned, an Instron 8801 servo-hydraulic system and an Agilent 34420a micro-ohm-meter are used in this study. Details of how these devices work and how they are used are discussed in this section.

4.2.1 Strain -Stress Test and Measurement Device

The Instron 8801 is an easy to use, precise and versatile servo-hydraulic testing system. The machine is shown in Figure 55 with installed 100kN hydraulic wedge grips. This is the standard setup for most of the cases in this study.

The software used in conjunction with this instrument is called Bluehill 2. The data it presents includes elapsed time, extension (of the lower jaw), applied load, and strain. The extension is directly applied to the machine; whereas the applied load is measured by load cells.

Similarly much of the other information presented by the interface was calculated indirectly.

Figure 55. Instron 8801

The software requires the user to input the dimensions of each sample. This was mainly used to calculate the stress and strain of the sample. It calculates stress by dividing the applied load at each time step by the cross sectional area entered by the user. Thus the dimensional measurement

accuracy of the sample is very important. In addition, the software calculates strain measurements by dividing the change in extension between two moments in time by the length entered by the user. Therefore, even though the software provides much data, the data are actually dependent on one or two variables.

4.2.2 Resistance Measurement Device

The device used to measure resistance values during this experiment was an Agilent 34420A 7½ digit, high-performance nanovolt, micro-ohm meter. The model has a GPIB (IEEE-488) interface for data acquisition at 250 samples per second. This device is shown in Figure 57 along with the 4-wire red and black terminal leads.

Figure 57. Agilent 34420A micro-ohm-meter

The micro-ohm meter utilizes the 4-wire resistance measurement method to provide accurate measurements of small resistances. Test lead resistance and contact resistances are automatically eliminated by

Figure 56. Four-wire measurement method

using this method, thus, the values measured are for the wire sensor alone. Shown in Figure 56 is the typical configuration of a 4-wire measurement system. The device uses a known current source and measures the voltage produced by the resistor, thus the resistance can be calculated indirectly. The micro-ohm meter also comes standard with a GBIP connector which can be used to record measurements on a computer. This connects directly to a CPU using a USB interface.

To interface with the measurement remotely, a variety of software can be used. The Agilent hardware supports C++, LabView, and more. In this study, code was developed using Visual Basic (VBA) through a macro written in Excel. This was the most straight-forward approach. Often times LabView makes an excellent interface for complicated testing methods; however, this test was fairly straight-forward and simply measures resistance continually. Thus the code need only be capable of obtaining resistance values at a sufficient sampling rate.

Setting the sampling rate depends on multiple variables. The ohm-meter has multiple functions built in and the defaults only allow for a sampling rate of about three measurements per second. In this test, it was desired to have a sampling rate of approximately ten measurements per second, as that was the rate the Instron measures. In order to accomplish this, a variety of variables are changed and the default was not used.

First, the measurement device was set into remote configuration. Next, all commands are cleared and the meter was reset. The display was then turned off. Using the display uses memory and reduces the speed of sampling. Additionally, the display does not need to be used because it does not provide anything valuable when all the measurements are being recorded into an Excel data sheet. Next, a command was sent to the meter to put it into four-wire resistance measurement mode. When the meter measures it integrates multiple measurements over a time period. Increasing this value results in less noise between consecutive measurements and a

higher accuracy; however, it also increases the sampling period. Thus, to increase the sampling rate the integration time must be reduced. Agilent refers to this integration time as Number of Power Line Cycles (NPLC). This was set to 0.2, resulting in a maximum of digits shown of 6.5 (micro-ohms) and approximately 16 samples per second. Next, statistics are turned off. This was more data that the meter was capable of completing, but all the data analysis was completed separately. Leaving this on just reduces available memory. Lastly, the trigger was set to immediate with a delay between triggers of zero. This tells the machine to take another measurement immediately and not use any delay between consecutive measurements. This completes the remote initialization of the micro-ohm meter; all of the commands can be entered remotely from a computer. This process only needs to be completed once before each time the machine was used. The complete VBA code used for this experiment is included in the Appendix.^[27]

Figure 58. Test setup schematic

A schematic of the test setup is presented in Figure 58. A photo of the complete test setup showing the Instron machine, Agilent micro-ohm-meter, both computers used for data acquisition and a tensile sample are shown in Figure 59.

Figure 59. Picture of Test Setup

Also shown are the four wire leads connected to a tensile specimen current being held in place by the Instron clamping jaws.

4.3 TEST SETUP

4.3.1 Tensile Testing Standards

Recall, the tensile test carried out in this experiment was done per ASTM D3039 *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*.^[25] D3039 calls out a few items of note which are important when conducting the experiment.

Material and specimen preparation remains an art rather than a science. The recommendation provided by the standard states test coupons should be 10" long, 1.0" wide and 0.100" thick. However, the actual requirement states that the length only need be twice the width + grip length. Additionally, at least five samples per condition should be tested for statistically significant data. In this experiment 9.5" was used for the length, 1.0" for width, and 0.035" for thickness.

Use of tabs was not required. However, one of the standard recommendations is the use of friction tabs. Friction tabs are essentially non-bonded tabs held in place by the pressure of the grip often made of emery cloth (80 to 150 grit) or other light abrasive. The tabs used are cut to 1"x2" strips and wrapped completely around the edge of the specimen. They are held onto the sample by masking tape and further secured by the pressure of the clamping jaws during testing.

Machining methods that are recommended are via the use of diamond tooling that was water lubricated.

Grip/Tab failures may occur. Failure should not occur within one specimen width of the tab or grip. Essentially, the failure should occur near the center of the sample and not near the grips. Prior studies have shown high grip pressure may cause failures near the grips. Thus reducing the grip pressure will result in acceptable fractures. In this study, only one case of fracture was investigated.

The majority of the test samples are not tensioned until fracture. In these cases the test method was set to stop at a 1000 lb. applied load.

4.3.2 Flexural Testing Standards

The flexural testing standards are completed to ASTM D7264 *Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials*.^[26] Specifically, this standard points out recommended dimensions for a test specimen. It is presented in terms of ratios. The standard span-to-thickness ratio is 32:1, the standard specimen thickness is 0.16 inches, and the standard specimen width is 0.5 inches, where the length is 20% longer than the support span. Either three-point or four-point bend can be utilized. For this experiment three-point bend was used because the specimen was fairly small. It would be difficult to apply two loading points as in four-point bend.

To accommodate these suggested dimensions, a specimen was made from 18 layers. This results in a thickness of approximately 0.15 inches. The length of the specimen was 5.04 inches and the width was 0.5 inches. The sensor was placed between the 1st and 2nd layer of the composite specimen.

The support span for testing was set to 3 inches. As the standard recommends a support span-to-thickness ratio of 20:1, 0.15 inch thickness times twenty was 3 inches.

The load rate was set to 0.05 in/min, as specified by the speed of the testing standard. Normally this standard is used to test the specimens until fracture. However, the end of test criteria was a 0.15 inch extension. Thus the test ends before the specimens break. This was sufficient deflection to obtain valuable data, and the specimen can be reused.

Using this method, the specimens were tested with the sensor in compression, located on the top of the beam. Then they were retested with the sensor in tension, located on the bottom of the beam.

4.4 EXPERIMENTAL RESULTS

Results from the cases discussed in Section 3.2 are presented. Note: the full length linear sensor is not presented due to the manufacturing difficulties discussed in Section 3.2.2. Only summaries of the cases are presented.

4.4.1 Threaded Through Linear Sensor

One of the most basic approaches to integrate the sensor within the fiberglass laminate was by making the sensor linear. The difficulty was in threading the wire through the laminate in the through-thickness direction. A total of eight specimens were tested in pure tension and compared to a predicted case using the gauge factor value determined in Section 4.1.2.

A view of a test specimen within the jaws is shown in Figure 60. The leads from the four wire micro-ohm-meter measurement device are connected. Additionally, a close-up view is shown in Figure 61.

Figure 60. Linear sensor test setup

Figure 61. Close-up of linear sensor test setup

True strain expressed as a percent was measured using the Bluehill 2 software in conjunction with the Instron machine. Strain was measured as a function of elapsed time, as shown in Figure 62. Observe that all the resulting curves are plotted directly on top of each other. All specimens were made from the same material. Thus, it was expected that they all display the same strain properties.

Figure 62. Threaded through linear sensor, strain as a function of elapsed time

Similarly, the change in resistance was measured as a function of elapsed time. This was done independently of the Instron. This would be more representative of a structural health monitoring system in the field, where it may not rely on interaction with other test equipment. Shown in Figure 63 on the next page, is the change in resistance per initial resistance values.

Figure 63. Threaded through linear sensor, change of resistance vs. initial resistance

The values presented have been evaluated by a moving average of ten samples. Note that there is notable noise within the curve. This was due to setting the Agilent micro-ohm-meter configuration to sample very quickly. This reduces the integration time and does not allow the machine to average values as it measures. However, this setting was necessary to have sufficient sampling rates.

An average of the specimens for strain and change in resistance is developed. These values are plotted against each other in Figure 64. Note that the wavy blue curve represents the experimental values. The slope of this line represents the gauge factor of the constantan while embedded within the composite. Recall that the gauge factor for the sensor within the composite was expected to differ from the gauge factor of the wire on its own. Shown in Figure 64, a gauge

factor for the composite system can be developed from the slope. For this case, the gauge factor was determined to be 0.008445 using Excel's trend-line fit. Recall that the gauge factor for the constantan by itself was 0.0294, meaning, the change in resistance for the wire alone was significantly more than when it was embedded in the composite. This was because the composite reinforces the sensor and it does not elongate as much.

Figure 64. Threaded through linear sensor, change in resistance vs. strain

This value will be used to compare to future experimental cases. As different loading cases are applied, the strain may become more difficult to predict accurately, as will be discussed in later sections.

Most importantly, this plot exemplifies strain gauge theory. As strain was applied to the system the resistance changed. In the case of uni-axial tension, the change was very apparent. Recall Section 2.2 which introduces the theory of this system. One of the goals of this work was to develop a system that translates physical strain into electrical measurements and embed the

system into a composite laminate. The results of this case prove this relationship to exist within the developed laminate system. Next, the effectiveness of this relationship will be further investigated.

4.4.2 Threaded Through Delaminated Sensor

Another goal of this study was to investigate the effectiveness of the structural health monitoring device to detect delaminations within a composite laminate. One method of doing this was to test the sensitivity of the sensor to a delamination purposely embedded in the laminate during an in-plane tension test. Using the specimens fabricated in Section 3.1.2 and 3.2.4, the same test was carried out as described in Section 4.4.1. The data for the change in resistance as a function of strain is shown in Figure 65. The equation obtained was $0.008504x + 0.000125$, as shown on the plot for the delaminated case. A prediction model, obtained from the gauge factor of the previous test is also plotted. This gauge factor is the gauge factor for the sensor while in the composite.

Figure 65. Threaded through delaminated case, change in resistance vs. strain

Figure 66. Percent difference between delam and no-delam tensile cases

The results from the delam and no-delam cases were compared using percent difference. Meaning the difference between predicted and measured is divided by the average of the two. This method is best when neither solution can be assumed to be ideal. Shown in Figure 66, is the percent difference plotted as a function of strain on the specimen. Note that the percent difference is relatively high at very low strain values. This was due to the fact that the change in resistance measurements is on the order of 10^{-7} . Thus, even an extremely small change in resistance can have a fairly large effect. This effect could be improved by forcing the change in resistance to be larger or having a measurement device with more accuracy. One way to make the change in resistance larger is to use different materials or a material of different size. As there is more material, there will be more length and thus greater change in overall resistance. The total average percent difference was 7.06%.

Additionally, from Figure 65, it is apparent that no significant percent difference or change in trend was observed between the delam and no-delam cases. This was as expected. Delams are not revealed as structural weaknesses during an in-plane test. Therefore, even though the sensor could provide overall measurements of the resistance and strain, it could not detect the delam during tensile loading.

4.4.3 Threaded Through Parabolic Sensor

As mentioned, one method to improve measurement accuracy is to increase the length of the sensor within the composite laminate. This will create higher fidelity in the ΔL measurement shown in Equation 3 of Section 2.2. For a laminate that has fully interwoven sensors, there would be a significant amount of area. The idea is that as more conductive fibers are added, the better the measurements will be. To test this theory, a parabolic sensor was developed. This utilizes twice the length of the linear sensors, thus the ΔL measurement would be twice as much.

A total of eight specimens were tested. The results presented are for a moving average of 10 measurement samples, shown in Figure 67.

Figure 67. Parabolic sensor case, change in resistance vs. strain

First observations of this plot show there is slightly more variation between specimens when compared to the linear sensor test case. This was most likely caused by the accuracy of sensor placement. The parabolic sensors are slightly more difficult to manufacture, and sensor placement has an effect on resistance measurements. This is discussed in later sections for the angled and perpendicular sensor test cases. An average of these eight specimens was taken to provide an average change in resistance per strain plot, shown in Figure 68. Note that the relationship is very linear and exhibits less noise than the linear sensor case. Having more length of wire allows for less variation in measurements from the micro-ohm-meter.

Figure 68. Parabolic sensor case average change in resistance vs. strain

Next, the parabolic case was plotted against the linear sensor case to compare how having additional wire length affects the relationship between stress and resistance. Shown in Figure 69, are the two cases plotted together. It is visually apparent that there is significantly less noise in the parabolic case. Also one of the most obvious observations is that the slopes of the

relationship are not the same. In fact, the slope of the parabolic sensor is more similar to the gauge factor of the wire only test case, completed in Section 4.1.2.

Figure 69. Parabolic vs. linear sensor change in resistance vs. strain

The slope, or gauge factor value, obtained in the parabolic test case was determined to be 0.0153. This differs from the linear sensor value of 0.008445, but relates more closely to the gauge factor test of 0.0294. Thus, as more sensor length was added the gauge factor of the composite begins to appear more similar to the gauge factor of the wire.

In a case that has excessively more sensor length, the curve is expected to contain even less noise. Additionally, the slope would be more consistent between test cases, as there would be a larger change in resistance being measured. This would also allow for less accurate measurement devices and thus less expensive equipment.

4.4.4 Threaded Angled Linear Sensor

To test the variation in measurements as it relates to the alignment of the sensor within the composite laminate, an angled test case was developed. The angled sensor was tested following the same testing procedures as those for the linear sensor. The only difference was that the angled sensor has an approximately 6-degree angle within the width of the specimen.

As the sensors that are integrated in this manner cannot always be assumed to be perfectly straight and along the fiber direction, this test case was done to examine what the consequences of misalignment are. The test case was compared to the linear sensor case, which was assumed to be aligned along the fiber direction and in complete tension.

In the angled case, the entire length of the wire was not being taken advantage of. Although there was slightly more wire within the composite laminate because it was at an angle, the load was not stretching the wire in the longitudinal direction. Thus some lateral expansion will occur in the wire while simultaneously the change in length causes the lateral dimension to compress, thereby having a canceling effect.

To investigate these outcomes, a plot was developed as shown in Figure 70. It represents the change in resistance per strain for the eight specimens tested. The consistency between test cases was less than that for the linear cases, which is evident in the plot. This was mostly attributed to the fact that the angled sensors are more difficult to angle consistently. When the resin flows it can alter the angle of the sensor somewhat. In case of the linear sensor, tension can be applied so that the resin flow does not affect the alignment of the sensor. Additionally, the resistance measurements exhibit far more noise. This was because the stretching that occurs in the longitudinal direction of the wire, which was not the same as that of the composite, which was consistently linear. It undergoes longitudinal and lateral tension at the same time.

Figure 70. Angled sensor, change in resistance vs. strain

Next, the average of these eight test specimens was developed and plotted in Figure 71.

Figure 71. Angled sensor, average of change in resistance vs. strain

Note that the graph exhibits the same linear properties as the other cases. However, it actually differs quite a bit. To show this difference, it was compared to the linear case and plotted on Figure 72 .

Figure 72. Comparison between angled and linear sensor cases

Note the difference in slope between the two cases. Again, this slope represents a gauge factor, which is dependent on the change in length of the wire and change in resistance. However, resistance depends on the resistivity of the material, length, and cross sectional area of the wire. This relationship is given by Equation 2 in Section 2.2. Thus if the cross sectional area is increasing, the resistance value is actually decreasing. And because this plot represents $\Delta R/R$, where R is decreasing in this angled case, the slope is actually higher than the case where cross sectional area is decreasing or staying the same. Thus, it is observed that the angled case actually

results in a steeper slope. The slope was determined via a trend-line to be 0.0196, nearly 2.3 times greater than the slope of the completely linear case.

The observation shows that if the angle of the sensor is off, it will underestimate the strain on the system for any measured resistance value. This underestimation and error increases as the strain on the system increases. However, if the angle is known, the gauge factor could be adjusted to compensate for the underestimation.

Recalling, however, that the intention of this system was to detect changes from baseline resistance or significant discontinuities in measurements, if a case exists where the sensor was indeed angled poorly it would not affect a deviation measurement based on baseline measurements. Because a measurement is always being compared to the initial measurements, the system will still note a change in strain. However, what will become a problem is the accuracy of the strain measured. Thus the system may detect an issue, but will not properly assess the severity.

4.4.5 Linear Perpendicular Sensor

Consider the extreme case of the angled sensor being completely perpendicular to the direction of loading. This would be an absolute worst case for sensor positioning. However, it was important to discover how this type of loading may affect sensor measurements. In the case of this system being used in a real application, there will likely be many times when loading will not be as ideal as can be created in the lab. Five samples were created to test this scenario, shown in Figure 73 is the change in resistance response for each case.

Note the extreme noise in the plot. This noise was exaggerated because of the very small values of $\Delta R/R$. In reality it was not much more than any of the other cases shown previously. However, note that the trends are not linear. The measurements fluctuate around zero. Specimens

4 and 5 have a slight negative trend which may be due to a perfectly perpendicular sensor or abnormalities in the deformation due to how the composite was laid up.

Figure 73. Perpendicular sensor, change in resistance vs. strain

To glean a little more understanding of these effects, the average of all these cases was plotted in Figure 74. Additionally, the total average of the cases was plotted as a red horizontal line on the graph. This represents the value about which most of the readings are fluctuating. It is 0.00166 away from a change in resistance of zero. What is most evident about these results is that no apparent trend is observed. Thus, sensors oriented perpendicular to the load direction of the specimen provides no useful feedback. These readings are similar to what would occur if no load was applied, as even static loads exhibit significant fluctuation. From this test it can be deduced that sensors oriented in different directions will measure strain independently of each

other. Thus, if multiple sensors are to be used in an application it can be easily determined in which direction the part is being loaded.

This test case shows that when the specimen was loaded perpendicular to the sensor orientation, there was little effect on the resistance measured by the micro-ohm-meter. Additionally, it shows that very little information can be determined from measurements of this type. If this were a measurement in an application study, it would be difficult to understand the effects of loading directly from the resistance plots.

Figure 74. Average of perpendicular sensor case

4.4.6 Full Length Carbon Tow Sensor

Although very good at providing accurate and consistent results, constantan wire was fairly difficult to work with and was quite expensive. It is actually more expensive than carbon fiber tow. However, constantan retains the benefits of low resistance, minor temperature dependence,

and high elongation, and thus it is very sensitive to measurements. However, many other materials can be used that may improve ease of embedding the sensor in the laminate. The system should be easy to use with little effort needed to perfect the sensors. Therefore, other avenues were explored.

Carbon fiber is already widely used for its high stiffness properties. However, an under-utilized property of carbon fiber is its conductive properties. Although very strong, it is very capable of carrying a current. Additionally, when compared to constantan it is more readily available, comes in many different forms and is less expensive. The disadvantages are that it will likely not be very sensitive to measurements because of its high stiffness and low elongation properties. To combat this, there are many other materials that could be used such as Texalium. Texalium is one form of a fiberglass that has aluminum fibers intertwined with each fiber of the glass, thus creating a fiberglass that is actually conductive. There are many more examples of this which utilize other materials.

To study how carbon fiber might be used as a sensor, it was embedded within the fiberglass laminate in a similar fashion as the constantan wire. However, unlike the other cases, it was not threaded through the laminate in the through-thickness direction. Instead, it was fabricated by allowing the end to protrude out of the end of the laminate. When constantan was constructed this way it caused problems because the leads would break off. However, carbon is much stiffer than the constantan and less prone to breaking.

Using these samples, the same test procedure for the linear sensor was carried out. The results are shown in Figure 75.

Note that the linear trends that are representative of tension were similar for the previous cases. However, also note the inaccuracy of measurements. This was because carbon was so stiff

that it does not begin to strain until higher loads are applied. Thus the fiberglass has already begun to deform and the carbon had not been able to detect these strains. It was also not as consistent under loading conditions because the sensor was now fibrous and not solid. However, for an application case, these strains may be sufficient. Even though the carbon sensors result in inaccurate results, they may still be used to determine structural integrity; however, their use should definitely be improved upon for reliability.

Figure 75. Carbon sensor, change in resistance vs. strain

The average of the samples was taken and plotted in Figure 76. The plot is very similar to that of previous averaged cases.

Figure 76. Carbon sensor, average change in resistance vs. strain

Figure 77. Comparison between carbon, angled, linear and parabolic sensor

Additionally, the values were compared to the parabolic and linear sensor cases, shown in Figure 77. A difference in slope was expected, as this was a sensor that was completely different than the constantan. However, noting that the same trend was followed is important. Again, because the system can be used to measure deviations from initial measurements, the carbon sensor can be used in much the same way constantan can. However, because of its properties it may have a different reaction to continued fatigue or thermal properties. In any case this test shows that common carbon tows could be utilized as a sensor. Therefore many existing and newly fabricated parts could integrate a sensor without changing the material being used to fabricate it.

4.4.7 Threaded Through Linear Sensor for Fracture

Consider the scenario where the specimen is not simply experiencing strain then elastically returned to its original shape, but where fracture actually occurs and the specimen breaks. In this case there are a couple of possible outcomes for how the micro-ohm-meter might determine the current health of the structure.

During a fracture the fiberglass specimen will break, however, the sensor within the composite may or may not break. If it does completely fracture with the fiberglass the circuit will become open and the resistance readings will approach infinity. In this case the ohm-meter returns an extremely large resistance reading. Another possible outcome is that the fiberglass snaps in an area that exposes the wire, but it remains intact. During the fracture the stress will be relieved. Thus the strain will be as well, and the resistance measurements will return to a nominal value around where the readings started. However, due to plasticity the values may not return to exactly the same value. The last case was when the fracture was localized in an area that does not cause the sensor to become exposed or damaged in any way. In the case where the wire was

threaded in the through-thickness direction, the fracture might occur outside the area of the integrated sensor. In this case the resistance measurements will increase as the specimen is loaded under tension. However, when fracture occurs, that change in length will return back to the nominal value. Thus the resistance readings will quickly return back to their original value as well.

This last case was observed during an experiment to test the tension samples to failure. During the experiment the specimens were loaded under tension until they failed. All the failures occurred at areas at least an inch away from the end of the sensor. Even though these failures occurred outside the area of the sensor, it was still capable of sensing the fracture that occurred by measuring a significant discontinuity in resistance. The results for nine test specimens are shown in Figure 78.

Figure 78. Linear sensor to fracture, change in resistance vs. # of samples

Note this plot shows resistance in terms of sampling measurements, and not in terms of strain. Because the systems are independent it can be difficult to correlate the strain values from the Instron to the measurements from the micro-ohm-meter. The machines sample at different rates even though the test takes the same length of time. Thus the points of fracture would be difficult to observe if they were plotted against strain. However, this system was intended to be independent. Thus measurements during an application would look similar to what is presented in Figure 78.

More importantly, this graph shows the discontinuities that represent a fracture or immediate relief in strain. As the specimens fracture, the machine continues measuring. In many cases the resistance returns to the nominal value. However, in some cases the resistance actually returns to a value slightly less than nominal. This test exemplifies the system ability to rapid changes in strain, which are often characterized by fractures.

4.4.8 Linear Threaded Through Sensor for Flexural

One of the most important uses for a structural health monitoring device in a composite is to detect delaminations. These are defects that are normally non-visual and difficult to detect. In the tensile tests, the delamination had little or no effect on the strength of the material. Additionally, it was nearly impossible to detect using the constantan wire. However, this was expected for an in-plane test.

In order to investigate the sensitivity of the sensor to delaminations, a uniaxial test cannot be used; thus a flexural test was completed. The flexural test specimens exhibited more susceptibility to the delamination in strength. Additionally, because strain is not in one-dimensional, the hope was that the sensor would detect delaminations.

First a case with no delamination was completed. This will be used to compare to the delaminated case in the next Section. Four cases were tested with the sensor along the top surface, putting it into compression. The test was then repeated with the sensor along the bottom, in tension.

The test specimen under load is shown in Figure 79. The ohm-meter leads are connected to the sensor protruding from the ends of the beam.

The results from the compression case for all four specimens are presented in Figure 80. Specimen 1 exhibited more noise in measurements than the other specimens. This was likely due to electrical interference. All the test equipment was metallic and it was very difficult to insulate the test. This noise was discovered in other trials where contacts with test equipment were made.

Figure 79. Flexural test setup

Figure 80. Compression flexural test case, change in resistance vs. strain

As expected, the trend shown is negative for all cases. A negative change in resistance correlates to a compression force on the upper surface of the bending specimen. The variation in results was likely due to a difference in specimen dimensions. The heated press was not very good at making consistent thicknesses when working with material 18-layers thick. This was simply a limitation of the lab equipment. If the specimens were created under better tolerances, the plot would likely have less variation. However, this would require better lab equipment.

The average of these measurements was taken at each strain value and shown in Figure 81.

Figure 81. Average of flexural bending test under compression

Next, consider the case where the sensor was located along the bottom of the beam. Here the sensor will experience tension.

Figure 82. Tensile flexural test case, change in resistance vs. strain

Note the positive trend. This was evidence of the tensile forces that the bending specimens are experiencing. Specimen 1 shows a slightly different trend, but still following a positive trend. The samples are a little more consistent than in the compression test.

The average of these test cases is plotted in Figure 83. It shows a similar trend to that of the compression case, but in the opposite direction.

Figure 83. Average of flexural bending test under tension

The test cases show that the sensor was capable of detecting strain on the specimen under flexural loads. More importantly it was easy to determine the difference between tensile and compression loads. The accuracy of the measurements was more difficult to determine. The system provides a fair amount of noise between measurements at its current settings. However, more important is the system's ability to measure deviations from baseline measurements and to determine deviations from ideal structural health. One deviation from ideal structural health would be a delamination within the composite laminate. This case is discussed in the next Section.

4.4.9 Delaminated Linear Threaded Through Sensor for Flexural

Detecting delaminations in the composite laminates is essential for determining the structural health of the specimen. Normally, delaminations are nearly impossible to detect. With the aid of non-destructive test equipment such as ultrasound or x-ray, they can sometimes be detected. However, this requires considerable equipment, time and trained personnel.

A structural health monitoring system's greatest advantage is that it can provide real time structural health data to a user at any time with minimum equipment and personnel. Thus to further validate the use of embedded sensors for the use of structural health monitoring in composite laminates a flexural test was conducted. Unlike the delaminated case under tension, the flexural test was greatly affected by the existence of a delamination.

Figure 84. Delaminated flexural test case under compression

The test setup is shown in Figure 84. Note that the delamination was clearly observable. During compression, the area becomes significantly debonded from the rest of the beam.

The results for four test specimens are plotted in Figure 85

Figure 85. Delaminated compression flexural test case, change in resistance vs. strain

Recall Figure 80 for the nondelaminated case. The plots look similar with a overall negative trend. A comparison will be done later to better understand the similarities and differences.

The average of these data is plotted in Figure 86.

Figure 86. Average of delaminated flexural bending test under compression

Next, consider the case where the sensor was located along the bottom of the beam and experiences tension. Shown in Figure 87 are the results for each test case.

Figure 87. Delaminated tension flexural test case, change in resistance vs. strain

The average of these four specimens was taken and plotted in Figure 88, shown below. Note that it follows a similar trend as the non-delaminated case.

Figure 88. Average of delaminated flexural bending test under tension

Again, as expected, a positive trend was observed. One note on the bending cases was that the trends were not completely linear. This differed from the tensile cases.

Next, a comparison between the delaminated and nondelaminated cases was done. Both the compression and tension cases were compared. This comparison showed the sensor's sensitivity to the delamination and, thus, its ability to detect a delamination while under load. Of course, if no load was applied, this sensing method would most likely not detect the delamination. The compression test cases for the delaminated and nondelaminated averages are shown in Figure 89.

Figure 89. Comparison between delaminated and nondelaminated flexural cases under compression

Observe that the delaminated case has overall a greater value of change of resistance. This was because the sensor was not bonded within the composite laminate and not constrained to compress with the composite. Instead, this area does not undergo compression. Therefore, less of a compression effect was measured. There was a notable difference between the delaminated and nondelaminated cases. Thus the sensor was capable of differentiating between a delaminated and nondelaminated test case under certain conditions: the specimen needs to be under load and needs to be within the layer of delamination.

Next, the tensile case was compared. Shown in Figure 90 are the delaminated and nondelaminated test case averages.

Figure 90. Comparison between delaminated and nondelaminated flexural cases under tension

Under tension, the sensor in the delaminated case was not being loaded as much as in the nondelaminated case. Thus, the change of resistance readings is less for all values of strain.

The compression and tension cases both exhibited differences between delaminated and nondelaminated specimens. This shows that the sensor was capable of detecting structural health defects in the composite laminate.

4.5 SUMMARY OF EXPERIMENTS

Each test conducted in support of this research has been in support of the development of a resistance-based sensor to monitor the structural health of a composite laminate. Each test provided a significant conclusion. These tests and conclusions are summarized in Table 8.

Table 8. Summary of tests and significant findings

Test	Significant Findings
Threaded Through Linear	Strain can be determined by an embedded constantan sensor
Delaminated Threaded Through Linear	Delaminations cannot be detected in a uniaxial test
Parabolic	Additional sensor length reduces measurement noise and changes value of gauge factor
Angled	Angled sensors result in inaccurate predictions of strain, but can still measure deviations from baseline measurements
Perpendicular	No significant measurements are obtained from applying load perpendicular to the sensor.
Carbon Tow	Strain can be determined by using a carbon tow in place of a constantan sensor
Linear to Fracture	Fracturing specimens results in a sharp discontinuity which the measurement device can detect
Compression Flexural	Compression during flexural testing leads to a negative linear trend, which the sensor can detect
Tension Flexural	Tension during flexural testing leads to a positive linear trend, which the sensor can detect
Delaminated Compression Flexural	Delaminated flexural specimens result in significantly different measurements. Thus the system can accurately predict the presence of a delamination.
Delaminated Tension Flexural	Delaminated flexural specimens result in significantly different measurements. Thus the system can accurately predict the presence of a delamination.

All the test cases completed show that integrated sensors are capable of detecting strain and, indirectly, stress effects on a composite laminate structure. The tensile cases show that the sensor performs very well at detecting the magnitude of strain occurring within the specimens. Additionally, the angled and perpendicular test cases show that alignment is important for accuracy of results. However, if only deviation is being detected then the initial accuracy is less important. The carbon tow test shows that many other conductive materials can be utilized, not

just constant. In fact, carbon would make a great sensor because it is already widely used for a large variety of parts. The discontinuities discovered under testing the fracture cases show that the sensor is capable of detecting rapid changes in strain. Additionally, the bending cases show that the sensor is capable of not only detecting flexural strain, but also differentiating between delaminations for compressive and tensile loads. These tests provide a foundation for a better integrated sensor. They prove that this method works, but inherent challenges are also present. By developing a more careful integration process, having a greater length of sensor, or better alignment and layup techniques this method can easily be implemented in the many new structural parts with little cost. This would allow composite parts to be monitored at any given time for their structural health; thus providing essential information to engineers and maintenance to resolve issues before catastrophic damage is done.

CHAPTER 5. THEORETICAL ANALYSIS

Analytical solutions of select test cases are developed for comparison to experimental values. The solutions are used to validate the experimental measurements and show the results are as expected. Strain was predicted for comparison to the experimental values measured by the Instron machine. Resistance was predicted for comparison to the experimental values measured by the Agilent micro-ohm-meter.

5.1 STRAIN PREDICTION

For a composite laminate under load in a single direction, the stress-strain relationship in the same direction is simplified to Hooke's Law, shown in Equation 12.

$$\sigma = E * \epsilon$$

Equation 12: Hooke's Law

Young's modulus was determined to be to be 30.119 ksi from Section 4.1.3. Also, the relationship $\sigma=F/A$ can be used. The normal force ranges from 0 to 1000 pounds, and the area of each specimen was calculated from the width times thickness. Using the full length linear sensor case as an example, an analytical solution can be developed. Strain was calculated for each specimen for a range of forces. The average was then taken and plotted, as shown in Figure 91. Also plotted is a comparison to the average of the experimental measurements for the full length linear sensor. Good agreement is observed between the two cases. The experimental values show deviation from the linear relationship; whereas the theoretical solution remains linear for all loads.

The percent difference between the two cases was calculated and plotted as shown in Figure 92. The difference is larger at low values of applied force because the values being compared are extremely small. However, error converges to about 11% and higher loads.

Figure 91. Comparison between experimental and theoretical strain solutions for full length linear sensor test case

Figure 92. Percent difference between experimental and theoretical strain solutions for full length linear test case

The analytical solution shows that experimentally obtained values are in agreement with expected values. Thus, the strains of the fiberglass specimens obtained by the Instron machine are within approximately 11% of an ideal test case.

5.2 RESISTANCE PREDICTION

Another important validation was the resistance measurements made by the Agilent micro-ohm-meter. These values can be obtained by directly correlating the strain to resistance by the gauge factor. However, results show the gauge factor to differ significantly due to length and orientation. Thus, resistance was validated using the material constant of resistivity. For constantan the resistivity is 1.925×10^{-5} ohm-inch. Recall Equation 2 for determining resistance of a wire based on resistivity.

$$R = \rho \frac{l}{A}$$

Resistivity, ρ , is a known material property. Additionally the cross section area, A , is known, as the diameter of the wire used was 0.010 inches. The initial length, l , is known. This value changes as load is applied to the specimen. However, this change is dependent on the extension of the Instron machine. Thus resistance can be measured at every point during testing based on the change in length of the specimen.

Using these methods, a theoretical model can be developed. Shown in Figure 93, is the theoretical model plotted against the measured experimental values. Similar to the prediction for strain which over predicted strain values; the theoretical resistance model obtained larger values of resistance. Also, the experimental values again stray from an ideal linear case.

The percent error between the theoretical and experimental cases is plotted in Figure 94. Note, percent error is used for this analysis as the theoretical solution is assumed to be ideal.

Figure 93. Comparison between experimental and theoretical resistance solutions for full length linear sensor test case

Figure 94. Percent error between experimental and theoretical resistance solutions for full length linear test case

However, the average percent error was approximately 14%, which relates more closely to the error obtained during the theoretical and experimental strain comparison. The trend also assumes that resistivity of the wire was the published value. Variations in alloy elements can cause this value to change slightly, a better estimate can be obtained by measuring resistivity of the material directly. Moreover, the analytical solution again shows fairly good agreement with the experimentally obtained values. Additionally, the error was very similar to the error obtained in the strain case. The trends are both very similar. Meaning the resistance follows a similar trend to strain, which was expected.

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

The goal of this research was to develop a simple method for measuring deviations from baseline health and identifying potential catastrophic structural failures in a composite laminate by utilizing an integrated resistance-based monitoring system.

The strain in a fiberglass laminate was determined by using an embedded constantan wire as a conductive element. With no other tools besides an ohm-meter, the system could predict the strain and stress on the structure. A variety of orientations were tested to investigate the fidelity in the measurement sensitivity and necessary placement of the sensor. The orientation had a significant effect on accuracy of measurement values, but not on deviations from baseline measurements. Additionally, using a sensor of greater length resulted in higher fidelity and less noise of measurements.

In investigating other materials, the tests showed that carbon could also be used as a conductive element. Therefore, further development could lead to a system that uses an already widely used material as a structural health monitoring device.

During the bending test the sensor accurately predicted the existence of a delamination within the flexural test specimen, thus, being able to predict structural defects in the same layer as the sensor.

Using strain-based measurements to determine the structural integrity of a part is an effective way of determining the health of the structure. However, using embedded sensors is a difficult and time-consuming manufacturing process. In a real application, it would likely not be justified by the benefits. Thus, to further build upon these findings, more work is needed as described in the Future Work Section.

6.1 FUTURE WORK AND IMPROVEMENTS

The tests completed in support of this structural health monitoring approach show that it was feasible, yet requires improvements to be made practical. First, embedding the sensors was a time-consuming and difficult manufacturing process. No real application would utilize the sensors due to this extensive effort. Instead, work should be done on obtaining the same valuable data without having to embed the sensors. This means the woven fiber should be capable of serving as the sensor already. There are many different types of conductive fibers that could be utilized.

Additionally, to optimize the sensory capabilities of the fibers, weaving methods should be analyzed. There are many different methods of weaving which could place the sensors in ideal locations or orientations within the weave.

For example, weaving fibers at zero, ninety, or forty-five degrees can develop a strain rosette. If the woven fabric is laid-up in this orientation it can provide significant information to a user. This can also provide a means for determining the location of damage, as it essentially creates a grid on the composite laminate. A multiplexor can then be used between the sensors and an ohm-meter to measure differences between each sensor.

With the introduction of new materials to be used as sensors, an investigation of differences in length, gauge diameter or elasticity of the material will be very useful. By increasing the size of a sensor the change in resistance would be more noticeable. Thus, a less expensive measuring device could be used to accomplish the same task.

Also, utilizing carbon would be an ideal material for this application as it is already widely used for a large quantity of composite products. Users would not have to purchase new material or change their processes to utilize structural health monitoring.

The leads between the actual integrated sensors and the measurement device should be investigated. This area can often fracture, or not provide sufficient contact surface for good readings. Having leads between each layer in the through-thickness direction can also help in determining the effects of delaminations.

This research only investigated tension and flexural three-point bending. Other test methods should be used, specifically, dynamic testing such as impact or vibration. This will show that the system is capable of accurate continuous monitoring with respect to time.

Only a delamination case was investigated. Many other defects that pose significant issues for composite laminates can be investigated, such as cracks or voids. Additionally, only composite materials were used. Many bridges do not use composite laminates, but could benefit from the same technology. Some isotropic or concrete type materials could be investigated.

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A.1 Agilent vBA code used for resistance data acquisition

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Global nextTime As Variant

Dim DMM As VisaComLib.FormattedIO488

```
TimeInMS = Strings.Format(Now, "dd-MMM-yyyy HH:nn:ss") & "." &  
Strings.Right(Strings.Format(Timer, "#0.00"), 2)
```

Sub SetIO(ByRef ioAddress As String)

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On Error GoTo ioError

ioAddress = InputBox("Enter the IO address of the DMM", "Set IO address", ioAddress)

If Len(ioAddress) > 5 Then

Set mgr = New AgilentRMLib.SRMClS

Set DMM = New VisaComLib.FormattedIO488

Set DMM.IO = mgr.Open(ioAddress)

End If

With DMM

.WriteString "*RST"

delay 500

.WriteString "*CLS"

delay 500

.WriteString "DISPlay OFF"

delay 500

'.WriteString "*FUNctIon """

delay 500

.WriteString "CONFigure:FRESistance"

delay 500

.WriteString "SENse:FRESistance:NPLCycles 0.2"

delay 500

'.WriteString "ZERO:AUTO OFF"

delay 500

'.WriteString ":RANGe:10"

delay 500

.WriteString "CALCulate:STATe OFF"

delay 500

.WriteString "TRIGger:SOURce IMMEDIATE"

delay 500

.WriteString "TRIGger:DELay 0"

delay 500

End With

Exit Sub

ioError:

MsgBox "Set IO error:" & vbCrLf & Err.Description

```

End Sub
Sub Update()
    ' Calling the recorded macro to get the measurement
    ' and place in cell 'A1'

    If continueMonitor Then ' continue the monitor function
        ' set the time for the next reading, do before the reading
        ' for better accuracy between readings
        nextTime = TimeInMS()

        Measure
        DoEvents

        ' Now set the timer for the next reading
        Application.OnTime nextTime, "Update"
    End If
End Sub

```

```

Sub Measure()

    ' Sends a command to the 34401A to measure dc volts
    Dim reply As Double
    With DMM
        ' Send the RS232 remote command, only for RS232
        .WriteString "Syst:Rem"
        .WriteString "READ?"
        ' query the meter for a dc reading
        ' This delay may be required for RS232 on some PC's

        reply = .ReadNumber
    End With
    Dim LastRow As Object
    Set LastRow = Sheet1.Range("a65536").End(xlUp)
    LastRow.Offset(1, 0).Value = nextTime
    LastRow.Offset(1, 2).Value = reply

End Sub

```