SYNTHESIS AND CHARACTERIZATION OF A CARBON NANOTUBE BASED
COMPOSITE STRAIN SENSOR

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SYNTHESIS AND CHARACTERIZATION OF A CARBON NANOTUBE BASED COMPOSITE STRAIN SENSOR

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In order to more effectively monitor the health of composite structures, a fuzzy fiber strain sensor was created. The fuzzy fiber is a bundle of glass fibers with carbon nanotubes or nanofibers grown on the surface using a novel chemical vapor deposition process. The nanotube coating makes the fiber bundle conductive while the small conductive path increases sensitivity. The fuzzy fiber sensor can replace conventional metal foil strain gauges in composite applications. The sensor was first characterized by use of a micro-tension test to generate load vs. resistance plots to demonstrate the feasibility of the sensor. The fibers were then cast into epoxy dogbone specimens to enable testing with an extensometer to quantify its strain sensitivity. Sensors were then embedded in carbon fiber prepreg panels. Specimens were prepared to demonstrate their performance in a composite laminate typical of aerospace structures. A multi-axial specimen was constructed to test sensor response to longitudinal, transverse and off-axis loading cases. Cyclic tests were performed to check for hysteresis or non-reversible
changes to the sensor. A finite element model was created to compare the experimental results to the expected behavior based on the Poisson effect.
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<tr>
<td>CNT</td>
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<td>CNF</td>
<td>Carbon Nano Fiber</td>
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<tr>
<td>CVD</td>
<td>Chemical Vapor Deposition</td>
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<td>MWCNT</td>
<td>Multi Wall Carbon Nano Tube</td>
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<td>SEM</td>
<td>Scanning Electron Microscope</td>
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<td>SWCNT</td>
<td>Single Wall Carbon Nano Tube</td>
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<tr>
<td>GFRP</td>
<td>Glass Fiber Reinforced Plastic</td>
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<td>SHM</td>
<td>Structural Health Monitoring</td>
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<tr>
<td>UDRI</td>
<td>University of Dayton Research Institute</td>
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<td>NAHF-X</td>
<td>Nano Adaptive Hybrid Fiber</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
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<tr>
<td>FEM</td>
<td>Finite Element Method (Modeling)</td>
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<tr>
<td>AFEM</td>
<td>Atomic [scale] Finite Element Method</td>
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<tr>
<td>FE</td>
<td>Finite Element</td>
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<tr>
<td>ATL</td>
<td>Automated Tape Laying</td>
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<td>AFP</td>
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1.0 INTRODUCTION

The current push toward composite structures of increasing complexity has led to an increased need for structural health monitoring. Proper SHM methods provide an indication of the condition of the structure so that inspection costs and downtime can be reduced and service life can be increased. These systems must be easily integrated into the composite structure in order to be of the most use. Current SHM approaches often use strain gages, optical fibers, accelerometers and, more recently, piezoelectric sensors. These sensors generally provide data only at specific points and therefore must be placed in the correct locations to detect the desired event. Algorithms have been developed to triangulate the location of damage based on the response of nearby sensors [1, 2]; however, this method is not ideal. Additionally, these sensor technologies are difficult to imbed in a composite structure and may not be compatible with composite chemistry or the local geometry requirements. Many of these issues may be remedied with the use of CNT based sensors which can be integrated directly into the composite laminate without any foreign materials, can provide sensitivity over a large area and can conform to virtually any geometry or without special consideration.

This thesis serves as a feasibility study into the incorporation of carbon nanomaterials into structural composites as sensors. CNT covered fiber sensors were created and tested under a plurality of conditions in order to better characterize their performance. Strain sensing properties were compared to commercially available strain gages and a numerical
model was constructed to predict the strain response of a composite with embedded fiber sensors in order to compare results with the experimental data.
2.0 BACKGROUND AND LITERATURE REVIEW

2.1 Carbon Nanotubes and Nanofibers

CNTs are made of graphene sheets of hexagonal structure rolled up into a nanoscale-tube. For SWCNTs, only one graphene sheet is used to form the tube, while additional graphene tubes around the core of an SWCNT lead to MWCNTs. These CNTs have diameters in the range between one to tens of nanometers, with both their ends normally capped by fullerene-like structures. CNFs are larger and more disordered than MWCNTs and have diameters in the range of tens to hundreds of nanometers. The unique structure of CNTs and CNFs bring the materials some outstanding properties, which make them suitable for applications in various areas of materials, including the development of a new generation of sensors.

Many applications in composites find benefit for a hierarchical structure, one that incorporates components on the nano, micro and macro scales [1]. Such structures enable an engineered approach to materials development wherein each constituent part can be ideally chosen to suit the application. Figure 1 shows an SEM image of CNTs attached to a carbon fiber. Such a structure benefits from the nanoscale CNTs which are bonded to a microscale carbon fiber, which can then be incorporated into a macro scale composite part. Due to their appearance, such CNT-coated fibers are often referred to as “fuzzy fibers.
2.2 Synthesis of Carbon Nanotubes

Carbon nanotubes are most commonly made using some form of chemical vapor deposition, although other processes (arc, laser, plasma) are used for certain applications. The standard CVD process requires some form of catalyst, a controlled atmosphere containing a carbon source and an energy source. Typical catalysts include nanoparticles of a transition metal such as iron, cobalt or nickel. Catalyst particles can be deposited on a substrate or can be suspended in a fluidized-bed reactor. In either case, the catalyst particles are held in a controlled environment consisting of some percentage of a carbon source such as a hydrocarbon gas (methane, acetylene, ethylene, etc.), a liquid vapor (hexane or benzene) or another carbon source such as an alcohol. At an elevated temperature (500-900°C), the carbon source is split by the catalyst particle and the carbon deposits around the catalyst particle, thus forming a carbon nanotube [2-4].
There are dozens of parameters which can be tailored to impact the morphology and properties of the resulting CNTs and CNFs. Catalyst material, particle size, particle density, component compounds of the atmosphere, carbon source material, substrate material, reactor geometry, temperature, flow rates, pressures are a few of the most important ones [5-11]. Additional process modifications can be made to improve the adhesion of the CNTs to the substrate material. Use of an alumina substrate provides a strong bond anchoring the CNTs to the substrate [12-13]. Special processes have been designed [14] to deposit alumina particles on a variety of substrate materials, thus providing the strong anchoring of the alumina substrate without limiting choices for substrate materials. This process can have the added benefit of isolating the catalyst from the substrate, thereby preventing any catalytic activity on the substrate, which could be detrimental to the substrate material, the CVD process, or the intended application.

2.3 CVD Reactor Equipment and General Layout

A typical research scale CVD reactor consists of some type of gas flow control system, catalyst delivery or application system and a tube furnace with quartz tube to contain the controlled atmosphere. Figure 2 shows a typical system with quartz tube installed in the furnace and gas flow plumbing connected to the end. In the background the gas cylinders are visible and the flow control system is out of sight, behind the furnace. This type of system only permits small experiments on substrates which can easily fit within the quartz tube. The small size also provides a relatively inexpensive environment for testing and experimentation. The furnace requires minimal power to heat and the small tube requires very little gas flow to maintain proper proportions for CVD growth.
Once process parameters have been optimized, the process can be transferred to a larger system. A larger system allows much larger substrate materials inside the reaction chamber and may be capable of running a continuous substrate material through the furnace to greatly increase production of nanomaterials over a batch type process. A larger system requires a larger furnace with better controls to enhance temperature uniformity, gas control system capable of larger flows and a system to uniformly deliver the gases to the substrate material. The University of Dayton Research Institute has a larger CVD reactor system shown in Figure 3, which is capable of growing carbon nanotubes on a variety of sheet substrates up to 30cm wide. In addition to the above mentioned features, it also has an Inconel (nickel alloy) muffle, unroll and motorized reroll and guiding systems, supplemental process heaters and full data acquisition capabilities. The Inconel muffle is much more durable than a quartz tube and has a rectangular cross section to reduce dead space and excess gas consumption. The unroll
and reroll system allows continuous processing of an entire roll of substrate material. Success has been proven on rolls exceeding 30m in length. The supplemental process heaters ensure uniform temperature control at critical locations and the data acquisition capabilities allow logging of process conditions to track parameter values for each run.

Figure 4. UDRI NAHF-X CVD Reactor Facility

UDRI has recently scaled up their process to production scale with a 1.5m wide furnace and ancillary equipment capable of continuous pretreatment, catalyst application,
nanotube growth and post processing. Figure 4 shows a portion of the $3M facility, ready to produce their line of Nano Adaptive Hybrid Fiber (NAHF-X) materials. Target markets include mechanical properties of composites, lightning strike protection, energy storage and sensing.

2.4 Carbon Nanotubes as Sensors

2.4.1 Electrochemical sensors

Electrochemical sensors and biosensors are possibly among the most intensively studied applications for CNTs. Carbon nanotubes are promising materials for detecting the presence of chemicals and biochemicals due to several intriguing properties. These include their outstanding ability to mediate fast electron-transfer kinetics for a wide range of electroactive species, and large length-to-diameter aspect ratios that provide high surface area. This large surface area offers an opportunity for depositing external materials or performing surface functionalization that may bring or enhance the activity of electrodes. Factors that make CNTs impressive for electroanalytical applications include the ability of this nanomaterial to promote electron transfer in electrochemical reactions, high electrocatalytic activities towards chemicals and biomolecular species, and anti-fouling capability of the electrode surfaces [15-18].

CNTs have large surface area, which gives significant gas molecular adsorption capacity. The adsorption of electron withdrawing or donating gas molecules on CNTs can cause charge transfer between the nanotubes and the molecules [19]. The charge transfer can lead to changes in the electrical conductance of the nanotubes. The direct change in their
electrical properties in response to the interaction with probed molecules forms the basis for gas molecular sensors.

Coatings or modification of the nanotubes with certain metals (e.g., Pd nanoparticles [20], etc.), metal oxides (e.g., SnO2 nanoparticles [21], etc.), polymers (e.g., polyethyleneimine [22] and poly-(m-aminobenzene sulfonic acid [23], etc.) have been demonstrated to impart selectivity to the sensors for certain gases and vapors, as well as to allow for detection of molecular species at low concentrations. Functionalization of CNTs may also give biomolecular recognition that may lead to biosensors, in addition to gas and vapor molecular sensors based on change of electrical conduction [24]. In addition to coating or surface modification, doping CNTs with certain elements (e.g., nitrogen doping during CNT synthesis) can enhance sensitivity and selectivity to certain gas molecules. After coating CNTs with metal, a corrosion sensor can be fabricated with a sensitivity based on the type and thickness of metal coating applied [25].

2.4.2 Electromechanical sensors

Strain and bending of CNTs may cause reproducible changes in their conductance, making it possible to construct electromechanical sensors [26, 27]. The piezoresistive nature of various composites has been studied in some detail in various forms. The conductive nature of carbon fibers allows their use as a sensing element [28, 29]. Based on this fact, a carbon fiber composite can perform a self-sensing function as the bulk conductivity of the composite changes as it acquires damage [30, 31]. Several studies have focused on piezoresistive polymers made by dispersing CNTs into a polymer to form a conductive matrix [32–41]. This conductive polymer can then be molded into a
thin film [36], a bulk composite shape, a ribbon or any other shape desired. One unique approach utilizes CNTs, spun into a thread, as a conductive element to embed into a composite for sensing functionality [42]. A similar element was fabricated by growing CNTs directly onto glass fiber, creating a sensitive CNT network with a non-conductive glass scaffold [43-44].

There are a number of other CNT sensors under study that may have working principles completely or partially different from the above sensors. For example, based on the change of mechanical resonant frequency of CNTs due to variation of temperature, pressure, mass and strain, the corresponding thermal sensors, pressure sensors, mass sensors and strain sensors were suggested [26]. They also have large length-to-diameter aspect ratios that can provide high surface area for depositing external materials or performing functionalization for electrodes used for a variety of applications.

2.5 Sensors for Structural Health Monitoring

The onset of local damage in composite structures, such as delamination, cracking and fastener loosening can often be difficult to detect and has long term implications on the performance of the structure. Applications in aerospace, energy and infrastructure, among other areas, are becoming increasingly dependent on structural composites [45-47]. These structures are often exposed to a variety of conditions including impact, shock loading and extreme changes in temperature. Non-destructive techniques, such as X-ray, ultrasonic or eddy current inspection can shed some light on local damage, but frequently structures may require disassembly for inspection. These techniques are not capable of real-time monitoring of damage evolution. Acoustic emission is often utilized during
testing to detect the occurrence of damage, but interpretation of the results is often qualitative or the analysis is complex. As a result, it is crucial to develop innovative techniques to monitor the state of damage in composite structures. SHM seeks to provide ongoing monitoring of a structure’s integrity, minimizing the need for programmed inspections and allowing maintenance to be need-driven, rather than usage-driven. Currently emerging SHM approaches include the use of strain gages, accelerometers, piezoelectric or piezoresistive sensors and fiber optic sensors to measure strain, vibration, harmonic frequencies, or other parameters which can be used to assess the health of the structure by comparing these values to a known healthy dataset [48–59]. Many of these methods provide sensing only near the sensor itself; therefore, they must be placed at or near critical regions of interest in order to detect damage. Should damage occur at other unanticipated regions, it may go undetected. Methods have been devised to use the sensor network to ‘‘triangulate’’ readings or locations of interest based on Lamb wave propagation using piezoelectric sensors, which provide an actuation, as well as a sensing function [60] or similar techniques based on a discrete number of finite measurements [61-63]. The cost, weight or physical size of a plurality of sensors restricts the total number of sensors a structure can accommodate, not to mention the, often complex, data processing required to get useful information from the sensor network.

CNT based SHM sensors show promise due to their low cost, low weight, simplicity and ease of integration within a composite. They require only a simple resistance measurement to read and are not particularly sensitive to fabrication methods or alignment [64-67]. These characteristics would allow an extremely high number of sensing elements to be embedded within a composite structure with minimal cost, weight
or performance penalty. A grid or matrix of sensing elements is envisioned whereby a row and column measurement technique could use the resistance of each sensor node or cross-point to more accurately locate the damage.

2.6 Mechanical Testing of Composites

In order to test the response of the sensing elements to mechanical loads, the sensing elements must be placed inside a specimen and loaded in a mechanical test frame. Figure 5 shows a typical electromechanical test frame and associated computer and data acquisition software. Various fixtures can be placed inside the machine to perform a wide variety of tests. The simplest form of mechanical test is a tensile test. For composites, tensile testing is generally conducted in accordance with ASTM Standard D3039 [68], which provides a standard methodology so that all tests can be compared without bias due to the test method. This type of test is carried out by gripping each end of a rectangular specimen in a jaw and then slowly applying tensile load until it breaks.

![Figure 5. Electromechanical Universal Test Frame](image)

The results of the test include tensile modulus and tensile strength data calculated from measurements of strain, load, displacement and time. The data acquisition system may
also allow collection of additional information, such as extensometer strain, strain gages, etc. A similar method of ASTM Standard 5766 [69] is used to measure the sensitivity of the material to a stress concentration, which is achieved by cutting a hole in the center of the specimen. The test is otherwise conducted similarly to the standard tensile test.

### 2.7 Modeling of CNT Based Mechanical Sensors

The strain sensing abilities of carbon nanotubes (CNT) in various formulations have been studied exhaustively. The most often studied formulation being some type of nanocomposite film or ink composed of dispersed carbon nanomaterials in a polymer matrix [32-41]. The strain sensing behavior of such nanocomposites has been studied in depth. Their piezoresistive behavior and tunneling effect are very well understood. Prior studies of the strain sensing abilities of fuzzy fiber CNT sensors have shown a linear and reversible electrical response to applied strain. Studies have been performed both on single fibers [43] and on bundles of fibers [70], however little has been done to model the behavior of these sensors. Some efforts have been made to model the strain response of CNTs dispersed within a polymer matrix [71], however the dominant response mode in that case is the tunneling effect, which is thought to have a minor role in the response of a CNT-on-fiber type sensor such as those presently studied. Current work to model the response of these sensors shows promise for future research and development [72].

Modeling of mechanical interactions is typically done through use of finite element methods. A problem is broken down into small portions (elements) so that it can be solved numerically. After each element has been solved, the result from all of the elements can be combined to show the results on the entire model. The quality of the
results are greatly influenced by the care taken in assigning elements to the model, called meshing, and choosing appropriate boundary conditions to accurately represent true conditions. The resolution of the mesh can be adjusted so that many more, smaller elements are placed in areas of interest and fewer, larger elements can be placed elsewhere to reduce the total number of elements and therefore reduce the computing power and solving time required. Composites problems are typically more difficult to attack with finite element methods because of their microscale interactions and highly anisotropic properties. Nonetheless, methods have been devised and refined over the last several decades, as composites have become more common in highly engineered structures [73-76].

In addition to the complexities of modeling composites, nanomaterials increase those difficulties exponentially. Meaningful modeling of nanomaterials requires finite elements that are also nanoscale. This is not an issue for very small models but is impractical for any macroscale structure containing nanomaterials. An accurate model would require billions of elements and could take days or weeks to solve even with access to modern supercomputers. Some efforts have been made toward an atomic scale FEM [77] however difficulties still remain in gaining continuity between an accurate atomic model and a typical macroscale FE model. Figure 6 shows effort by Liu et al. [77] to combine AFEM with FEM in order to obtain an atomic scale model where nanoscale interactions are important and to use typical FE to represent the bulk of the model. A realistic problem, such as nanotubes grown on a fiber, is still beyond the practical capabilities of modeling. In order to remain manageable, models must make assumptions about the
nanoscale behavior of materials and assign uniform properties to nanoscale components to avoid unnecessary complexity.

Figure 6. Combined AFEM/FEM Multiscale Computation of 64 Million Atoms in a Plane Subject to Nanoindentation. Liu et al. [77]
3.0 EXPERIMENTAL

3.1 Synthesis of Carbon Nanotube Sensor Structures

Glass fiber was chosen as the substrate for the CNTs as it is non-conductive, strong and compatible with composite manufacturing processes. The non-conductive glass fiber serves as a scaffold to secure the CNTs to a specific orientation and location. It is believed that the complexity of the conductive network helps increase the response of the sensor to damage. The high surface area of the CNTs on the fiber and the mechanical strength of the fiber both help to insure that the sensor is intimately joined with the bulk composite. This sensor differs from prior efforts [32-41] by providing a fiberglass scaffold for the nanotubes. This scaffold provides a preferential orientation of the nanotubes which may be important to tailor the sensitivity of the fiber. Additionally, and possibly more importantly, the scaffold allows the material to be handled in a dry state. This allows the use of the fuzzy fiber in any desired polymer (or ceramic, carbon, metal) matrix system without worry of contamination or incompatibilities between different materials. Dispersed nanotube polymer mixtures would require a special batch for every polymer, lot number and customer. A dry material could simply be laid into the layup and be wet out by the polymer already present in the prepreg composite preform. This material also lends itself to ATL and AFP processes used in industrial scale composite production, allowing accurate and complicated sensor arrangements to be fabricated without additional equipment.
Electrodes were fabricated using glass fiber with CNTs uniformly attached by low-cost thermal CVD using the process patented by Lafdi et. al. [14]. The reactor used was that shown in Figure 3, which had already been configured and optimized for this process.

Figure 7. Fiber Substrate Prior to CVD Nanotube Growth

Figure 7 and Figure 8 show the fiber before and after the CVD process. The carbon nanotubes are seen adhered to the fibers in Figure 8. Similarly, Figure 9 shows a macroscale view of the same material showing a roll of fiberglass fabric before (right) and after (left) CVD nanotube growth.
Alumina was used as a seed material and the catalyst was Ferrocene. Growth was carried out in a continuous process at a temperature of 700°C and in an atmosphere of nitrogen, argon, hydrogen, acetylene and ethylene. The parameters of the CVD can be altered to change the density and length of the CNTs. Figure 10 shows an SEM micrograph of a
CNT fuzzy fiber with low density, relatively short CNTs, compared to Figure 11, which shows a CNT fuzzy fiber with a longer, high density CNT coating. Only the growth time (transit time through the reactor) was varied to achieve these two configurations. The low density condition used a reactor time of two minutes while the high density condition used ten minutes. The two configurations were tested separately to determine which one would provide the best response to mechanical stimulus.

Figure 10. SEM Micrograph of Fuzzy Fiber with Low Density, Short Length CNTs
3.2 Single Fiber Tension Specimens

3.2.1 Preparation of single fiber tension specimens

Single fiber specimens were prepared by carefully removing single fibers from the bundles shown in Figure 8. This was a tedious task as the fibers are very small (<10µm) and the nanotube coating is relatively brittle. Eventually, a process was developed to select single fibers by use of a wooden toothpick with adhesive on the tip. Each fiber was removed and placed into the test machine with the help of a stereo microscope. The fiber was carefully examined before testing; to be sure the nanotube coating had not cracked or flaked off, which would result in a failed test.
3.2.2 Testing of single fiber tension specimens

A specially designed tension stage was built which provided the ability to perform tension tests on a single fuzzy fiber. The tension stage was constructed to hold the specimen horizontally so that the entire tension stage could be placed on an optical microscope, and the entire test could then be observed with the aid of magnification. The stage provides 0.75 μm displacement resolution and a maximum load of 50 g.

Figure 12 shows a detailed diagram of the tension stage with major parts labeled while Figure 13 provides a detailed view of the specimen platens with test specimen in place. The two halves of the specimen platen, where the fuzzy fiber is attached, are coated with epoxy to electrically insulate them from each other. A small drop of silver-filled epoxy was placed on top of the epoxy on each half of the sample plate. Before the silver-filled epoxy had cured, the fuzzy fiber was pushed into it, so that the fiber bridged the gap.

Figure 12. Single Fiber Tension Stage
between the two halves of the specimen platen. A copper lead wire was also pushed into each drop of silver-filled epoxy, which provided the ability to measure the resistance of the fuzzy fiber before and during the test.

The tension stage was placed in an optical microscope, which provided the ability to record a video of each test using the digital camera on the microscope. The microscope images were used to observe the test and validate it by ensuring that the fiber was not slipping in the epoxy and that the electrical resistance jumped to infinity at the instant the fiber failed, showing that the recorded strain and resistance values were correct and the fiber had not been shorted through a stray electrical path. Figure 14 shows a time series of stills taken from a video of one test. The pictures show the initial position, a position during the test and the final position where the fiber failed. At this point, the load dropped to zero and the resistance went to infinity. The stage was controlled using a custom Labview application, which provided the displacement drive signals and recorded the load data. The resistance data was recorded separately using a Keithley 2700 multimeter.
Timestamps were used to synchronize the two data sets after each test was performed to synchronize the load, displacement and resistance data.

Figure 14. Time Series of Typical Fuzzy Fiber Sensor Tension Test

3.3 Preparation of Fiber Bundle Sensor Elements

Sensor elements were made by removing a bundle of coated fibers from across the width of the fabric produced in the CVD reactor. Each bundle was bonded to a varnished copper wire with silver filled epoxy to enable electrical connection to the sensor. The active length of the sensor was determined by the distance between the two epoxy connections. Figure 15 provides an illustration of a completed sensor with lead wires attached. Nominal sensor element resistances were 50kΩ for the low density CVD and 3kΩ for the high density growth.
When placed inside a carbon fiber composite, the electrical conductivity of the composite itself may be orders of magnitude higher than the sensing element, making it necessary to electrically isolate the sensor from the composite. This isolation was provided by sandwiching the sensor between two thin layers of plain weave E2 glass having a [0°/90°] fiber orientation. The width of the glass strip was less than 10mm and the length varied with the length of the fuzzy fiber sensor element. The isolation layer was pre-cured in an autoclave for these tests but could be co-cured with the prepreg panel if desired. Figure 16 shows one of these insulated sensors, which also has heat-shrink tubing around the wire to provide an extra measure of insulation between the lead wires and the composite panel. This material was used only as a safeguard and could likely be omitted in a more controlled production environment.

Figure 15. Carbon Nanotube Coated Fiber Bundle Sensor Element
3.4 Instrumentation of Fiber Bundle Sensor Elements

The sensors were monitored with a wheatstone bridge, much the same as a commercial strain gage. A variable resistance box was used as the balance resistor in the wheatstone bridge so that the bridge output was 0V when the specimen was under no load. A Vishay 2310 signal conditioner with a gain of 100 was used to amplify the sensor response, and bridge excitation was set to 10 V, with no concerns with self-heating due to the large (>1 kΩ) resistance of the sensors. This arrangement was used for all of the testing utilizing a bundle style sensor element.
3.5 Monocomposite Tension Specimens

3.5.1 Preparation of monocomposite tension specimens

Monocomposite specimens were prepared by placing a sensor element inside a silicone mold and then pouring epoxy into the mold. The specimen was shaped like a typical tensile dog bone to provide a large section to grip and a reduced gage length to promote failure within the gage section. The mold was placed in a vacuum oven to remove air bubbles and cure. After curing, the specimen was removed from the mold and prepared for testing. Figure 17 shows the process of pouring epoxy into the silicone mold.

![Figure 17. Pouring Epoxy into Silicone Monocomposite Mold](image-url)
3.5.2 Testing of monocomposite tension specimens

To get an idea of the piezoresistive behavior of the fuzzy fiber sensor element, initial testing was performed on the monocomposite prepared as described in Section 3.5.1 above. Specimens were tested in a hydraulic test system as shown in Figure 18, using an MTS 458 analog controller and 100 kN servo actuator. Tests were run in load control, at a ramp rate of 10 N/s. Load, strain, actuator stroke, and sensor output were recorded. Sensor output was conditioned as described in Section 3.4 above.

![Testing of Monocomposite in a Hydraulic Test System with an Extensometer to Measure Strain](image)

Figure 18. Testing of Monocomposite in a Hydraulic Test System with an Extensometer to Measure Strain

3.6 Carbon Fiber Composite Tension Specimens

3.6.1 Preparation of carbon fiber composite tension specimens

Carbon fiber composite specimens were designed to produce specific geometry-induced responses. These included straight-sided and Poisson’s-effect specimens. All composite specimens were fabricated with both unidirectional [0°]₈ and orthotropic [±45°]₄s fiber orientations. All composite specimens were fabricated through a similar process. Six 30 cm square composite panels were fabricated with IM7/977-2 prepreg unidirectional
carbon fiber tape. Three panels each were prepared with unidirectional $[0^\circ]^8$ or orthotropic $[\pm 45^\circ]^{4s}$ layups. Sensors were embedded at specified positions in the layup of the panels before curing. Panels were then processed in an autoclave. Following cure, specimens were machined from the panels using a diamond abrasive saw. Fig. 19 shows several panels placed on a steel caul plate, which is then sealed with vacuum bagging film and sealant tape. A vacuum hose is fitted to the bagging material to remove air from the specimens and provide pressure to compact the laminate prior to autoclave processing.

![Figure 19. Carbon Fiber Panels Bagged and Ready for Autoclave Curing](image)

Autoclave curing provides increased compaction during cure, which helps improve fiber volume fraction and improves mechanical properties. The increased compaction comes from the increased pressure inside the autoclave. For these specimens, the autoclave was pressurized to 700kPa and then a tightly controlled temperature profile was run, with a peak temperature of 175°C. Figure 20 shows the autoclave used for curing the carbon fiber panels.
A typical cured panel with embedded sensor elements is shown in Figure 21 prior to cutting into individual specimens. The sensor locations inside the composite are apparent and the wires for each sensor extend out the top and bottom of the panel. GFRP tab material is then bonded to the top and bottom portions of the panel, where the specimens will eventually be gripped in the test machine. After tabbing, the individual specimens can be cut from the panel.
3.6.1.1 Uniaxial and orthotropic tension specimens

Two composite panels, one for each layup ([0°]₈ or [±45°]₄s), were fabricated with 15 cm long fiber strain sensors embedded at the midpoint of the laminate plies. Specimens were cut from each panel as shown in Figures 22 and 23, using dimensions taken from ASTM Standard D3039 [68]. Cutting was done on a diamond wet saw and final dimensions were dressed on a precision grinder. Eight straight-sided specimens were machined from each panel. The specimens had nominal width and thickness of 25mm and 2mm respectively.
3.6.1.2 Open hole tension specimens

Open hole tension specimens were made to test the sensor response to localized strain fields, as are encountered near a stress concentration such as a hole. Two sensors were placed into each specimen to evaluate near-field and far-field behavior.
Specimens were cut from uniaxial and orthotropic panels as was done for the straight sided specimen in Section 3.6.1.1 above, except that the sensor placement in the panels was modified as shown in Figure 24. Specimen dimensions were taken from ASTM Standard D5766 [69]. Cutting was done on a diamond wet saw and final dimensions were dressed on a precision grinder. Holes were cut with a water cooled diamond core drill. The larger specimen width allowed only four specimens from each panel. The specimens had nominal width and thickness of 75mm and 2mm respectively.

3.6.1.3 Poissons effect tension specimens
Specimens were also designed and fabricated to evaluate sensor response in both longitudinal and transverse orientations relative to the loading axis. The specimens were fabricated in both uniaxial and orthotropic layups, as explained in Section 3.6.1.1 above. Two 8 cm long fuzzy fiber sensors were embedded in each layup, one in the longitudinal direction (parallel to the 0° unidirectional fibers) and the second in the transverse direction (perpendicular to the first). Removal of the specimens from the panel by machining a cut parallel to the longitudinal axis necessitated that all sensor instrumentation wires exit the specimen along its ends rather than sides. Panels were cut using a method similar to that described in Section 3.6.1.1 above; however, special care was taken to create a specimen shape that would optimize the transverse sensors response to the Poisson effect. Figure 25 shows the specimen in final form and a schematic with sensor locations. These specimens had a main body width of 63mm and a nominal thickness of 2 mm.
3.6.2 Testing of carbon fiber composite tension specimens

Composite tests were performed using the same sensor instrumentation and test frame hardware as described in Section 3.5.2 above. Straight sided tension tests were run in stress control at ramp rates of 0.2, 2.0, and 20 MPa/s, using a vertical MTS servo hydraulic system with a 100 kN actuator. Load, strain, stroke, and sensor output were recorded. Tests were stopped at stress levels of 40 MPa for the weaker [±45°]_{1s} specimens, and 400 MPa for the stronger [0°]_{8} specimens. These limits were imposed to prevent failure of the specimens so that their response could be further characterized or
the tests repeated at a later time. An illustration of a typical test is shown in Figure 26. After inserting the specimen in the load frame and stabilizing the load near zero, the specimens were surrounded by a fiberglass blanket to isolate them from ambient air and allowed to thermally stabilize before testing. Tests at slower rates were repeated if substantial offsets in sensor signal were noted after a test, indicating thermal drift.

Figure 26. Composite Straight Sided Specimen Tensile Test with Red and Black Test Leads Connected to Sensor Lead Wires

Open hole tension tests were performed in the same manner as the straight sided specimen, however an additional strain channel was required to record the output of both sensors. Testing of the Poissons specimens were conducted as shown in Figure 27. The tests were meant to simultaneously evaluate sensor response in both longitudinal and
transverse orientations relative to the loading axis. Test setup was essentially the same as for the earlier tension tests, with the requirement of a second (transverse) channel of sensor amplifier and data collection. The extensometer was moved from the center of the specimen to a section of uniform area. In a second set of tests, the specimens were modified to lengthen the kerf connecting the “body” to the “arms” of the specimen in order to minimize the effect of the “arms”, which were necessary to accommodate the transverse sensor.

Figure 27. Transverse Sensor Specimen Test Setup
3.7 Quasi-Isotropic Off Axis Tension Specimen

To further investigate sensor response to longitudinal, transverse, and off-axis loading conditions, a unique specimen was fabricated from randomly-oriented chopped strand fiberglass mat and Epon 862 epoxy. The randomly-oriented fiber provided a quasi-isotropic planar specimen which minimized any possible influences of fiber directionality on sensor response.

3.7.1 Preparation of quasi-isotropic off axis tension specimen

The 11-ply specimen contained 4 independent sensors of 25 mm gage length, each at different layers and orientations in the laminate. The sensors were located in the center of the laminate, each being separated by one layer of fiberglass to provide electrical isolation. Figure 28 shows an illustration of the panel layup, with the top three and bottom three layers hidden for clarity.

![Figure 28. Illustration of Sensor Placement Within Composite Panel](image)

The specimen was fabricated as a square panel using the resin film infusion process. As each layer was placed, the assembled sensors were placed inside the layup. The panel was autoclave cured after layup was completed. A diamond wet saw was used to cut the final
specimen shape from the square panel. The fillet radius between each arm was accomplished with a diamond coated hole saw with 13 mm diameter. Each leg of the specimen had nominal width and thickness of 25 mm and 5 mm, respectively. Figure 29 shows the final specimen, with sensors clearly visible in the center. The arms of the specimen were labeled A,B,C,D to identify each of the principal loading directions.

![Figure 29. Off-axis Specimen Machined and Ready for Testing](image)

3.7.2 Testing of quasi-isotropic off axis tension specimen

The off-axis specimen was tested in a different MTS servo hydraulic test system with smaller hydraulic wedge grips open on the sides and a digital controller. The open sided grips (shown in Figure 30) were required to allow clearance of the 45° arms, which would have contacted the grip body on the standard tensile grips. No reference extensometer was used in this test as there were only three available strain channels and the specimen ideally required four channels for each of the four sensors. A workaround for this issue
was to do each test twice, moving one sensor channel each time so that all four sensor responses could be recorded for each of the four principal loading directions. Tests were run dynamically, with a triangle wave of 0–4.45 kN applied at 0.3 and 0.03 Hz. This load was applied to opposite arms of the specimen, while sensor response was monitored in three of the four possible directions. The wheatstone bridge for each sensor was zeroed to provide zero output when the load was at half scale (2.225 kN) in order to maximize dynamic range within the -10 to +10V range of the signal conditioner. In order to cancel any effects from sensor location or fabrication, the test sequence was structured so that three channels were connected and, then, the response was recorded to load applied across each of the four sets of arms. One amplifier was moved to the previously unmonitored channel and the test sequence was repeated.

Figure 30. Off-axis Specimen Loaded into Test Machine
4.0 MODELING

4.1 Quasi-Isotropic Off Axis Specimen Modeling

A finite element model was constructed to corroborate the experimental data from the quasi-isotropic off-axis specimen test. Abaqus/CAE software was used to construct the model, which is shown in Figure 31. To reduce calculation time, only half of the thickness of the specimen was modeled. The boundary conditions and material properties were set to mimic the loads applied during the experimental test.

Figure 31. Initial FE Model of Quasi-isotropic Off-axis Specimen
As is evident from the image in Figure 31, the six legs of the specimen which are not loaded are under very little stress outside the center region of the specimen. In order to simplify the model and allow refinement of the mesh near the sensors, the model was trimmed to focus on the part of the model where the stresses were highest. Figure 32 shows this modified model with inactive arms removed and a fine mesh around the sensor areas.

Figure 32. Refined FE Model with Inactive Portions Removed

The overall goal of the modeling effort was to attempt to backup and explain the experimental data. The result sought is to calculate the change of resistance of the sensors from the model and use those values to calculate the expected wheatstone bridge output, so that the model can be compared with the experimental data. The physical phenomenon of the change of resistance is not yet fully known and is not yet practical to model accurately. The piezoresistance mechanism involves the flexure and changing contact between millions of CNTs, in a complex, entangled network on the surface of the fiber. Previous tests showed that the resistance of the fuzzy fiber sensor varies linearly with
strain when loaded in pure tension (Li and Chou [71]). Therefore, it was assumed in the model that the sensor's resistance change should be calculated based on the strain along the longitudinal axis of the sensor, independent of the loading direction. A linear correspondence law was used. For the model, the specimen was assumed to have isotropic properties in the plane. To simplify the model, the same properties were assumed in the z direction. We know this is not true in practice but it is a safe assumption in this case because there is very little Z axis stress. This assumption allowed treating the specimen as an isotropic and homogeneous linear elastic material. The Young’s modulus was set to 8 GPa to follow published mechanical properties of similar random orientation GFRP. In this specimen, the sensors are stiffer than the surrounding material due to the random orientation in the specimen and the uniaxial orientation within the sensor. The Young’s modulus was set to 70 GPa (the tensile modulus of glass fiber) in the model to reflect this. The four sensors are each made out of a fuzzy fiber tow composed of approximately 3000 filaments with a diameter of 7 μm. As it is not realistically possible to represent each filament in a FE model, the tow was assumed as one equivalent isotropic linear elastic fiber, with the same cross section as the 3000 filaments together. Figure 33 shows a typical cross section view of a fiber bundle inside a composite with bundle outline highlighted.
To accurately represent the physical specimen, an elliptical cross-section was used in the model, as shown in Figure 34. Each sensor was separated from the next by 1 ply, each about 0.5 mm thick. The length of the sensor was set equal to the length between the two silver points connectors (25 mm) in the specimen. This is the active length of the sensor.
The interfacial bond between the sensors and the composites was modeled with a complete six degree of freedom constraint between the shared nodes of the interface surface. In order to achieve this bond, the sensor geometry is modeled as cells with different material properties inside the composite solid. This method allows the meshes to correspond across the interface. Quadratic tetrahedron elements were selected to accommodate the curved shapes, especially near the interfaces of the sensors. When meshing, Abaqus first creates linear tetrahedrons, and then transforms them into quadratic elements. Sizing control is set in order to get mesh elements of 4mm maximum approximate global size for the GFRP, and 1.7 mm maximum for the sensors. The mesh surrounding the sensors will be further refined by dividing the sensors in 25 cells, resulting in elements of 50µm approximate size. The sensor being in the main load direction will be meshed with a 0.5 mm sizing control, resulting in an even more refined mesh, but a quick mesh sensitivity study proved that this does not have any significant impact on the result. The elements appeared to be of the appropriate size as there was no more than 10% of the Von Mises fringe stress and strain discrepancy between two adjacent elements. The boundaries conditions are defined as a fixed constraint on the tip of one arm of the loaded direction, and a surface traction of -4.445 kN on the tip of the opposite arm. Simulation shows that the stress is well distributed inside the arms of the loaded direction, and that they are not creating any improper discontinuity. The strain data is acquired after computation of the job by creating four paths, one for each sensor. The paths are geometric segments 25 mm long that run through the center of the sensor’s cross-section. It has been verified that the stress is homogeneous along the section of the sensor, so reading the strain in the middle of it is a fair assumption in order to get its
surface strain. Two reference systems are used in order to extract the strain data along the path, in regards to the direction of the fiber.
5.0 RESULTS AND DISCUSSION

5.1 Single Fiber Tension Tests

The single fiber tension tests provided load and displacement data, as well as the resistance data measured from the fuzzy fiber. Figure 35 shows the response of a low density fuzzy fiber sensor. The fuzzy fibers with a low density CNT coating exhibited a high resistance (>100kΩ) and were therefore more susceptible to noise than the higher density sensors. The low density fibers are more sensitive but may not be useful for practical applications as they are easily damaged and their high resistance makes them more difficult to instrument.

Figure 35. Load, Displacement and Sensor Response Data for a Low Density Fuzzy Fiber Tension Test
The higher density fuzzy fibers were easier to handle and more reliable in testing. Figure 36 shows the data from a typical tension test of a high density fuzzy fiber sensor. The response of the higher density sensor exhibits a similar response to the low density sensor; however, the data has less noise and the resistance change is not as pronounced.

![Figure 36. Load, Displacement and Sensor Response Data for a High Density Fuzzy Fiber Tension Test](image)

The gage factor of the fuzzy fiber sensors is similar to that of commercially available metal foil strain gages. However, the large resistance and therefore large change in resistance of the sensors means that smaller strains can be detected due to the larger electrical response. This improves the signal to noise ratio and makes data acquisition more reliable. A common metal foil strain gage may exhibit a change in resistance of only several tens of ohms. The fuzzy fiber sensors, with similar gage factor, may exhibit a change of hundreds or even thousands of ohms. Both sensor configurations demonstrate
that the sensor has a significant response to strain. The response curves are not perfectly straight but it is believed that some slippage of the fiber occurred which may have led to this. Figure 37 shows a test with known fiber slippage. The fiber initially picks up load quickly, and then the load plateaus as the fiber begins to pull out of the conductive epoxy mounting. The finite steps in displacement can be seen in the data where the sensor will pick up load, only to relax again. In this case, the sensor follows the true strain of the fuzzy fiber, rather than the apparent strain indicated by the displacement.

![Figure 37. Load, Displacement and Sensor Response Data for a High Density Fuzzy Fiber Tension Test Which Exhibited Slippage in the Fiber End Connection](image)

**5.2 Monocomposite Tension Tests**

The monocomposite sensors were shown to produce consistent response, low noise, high strain capability, and were repeatable for elastic strain in same specimen (no hysteresis or offset). Several generations of monocomposite were tested before confidence was gained
that the tests were representative of the sensor behavior. Fig. 38 shows the results from testing two specimens to failure, with extensometer strain used as a reference. These

Figure 38. Monocomposite Tensile Test

specimens displayed low noise, a consistent response in the elastic region, and reasonable linearity and sensitivity. In addition, they showed the potential for measurement of high strains, well above 1%. This was very encouraging and provided enough confidence to move onto the next phase, incorporating the sensors into actual composite panels.

5.3 Carbon Composite Tension Tests

Once the test protocol was developed, tension tests showed that sensor response was insensitive to loading rate, but dependent on composite layup. Typical data is shown below in Figures 39 and 40. In both cases, the sensitivity (slope) is almost identical at all loading rates, with only slight separation at higher strains.
Figure 39. Uniaxial Specimen Sensor Response

Figure 40. Orthotropic Specimen Sensor Response
After testing all of the uniaxial and orthotropic specimen, the mean response was used to calculate the sensor gage factor for 22 tests performed on seven uniaxial specimens. Likewise, the mean response was used to calculate the sensor gage factor for 20 tests performed on six orthotropic specimens. The gage factor calculated from sensor response of these tests is shown in Figure 41.

![Figure 41. Uniaxial and Orthotropic Sensor Gage Factor](image)

If not for the initial outlier, which is unexplained, the orthotropic test would have had very low standard deviation. Possibly, the additional scatter in the uniaxial data is caused by its higher stiffness or a complex state of stress around the sensor tow; thermal effects (described below) may also play a significant role and might explain the difference in scatter between the two layups. These responses give a mean gage factor for the uniaxial sensor of 2.3 and a mean gage factor of 1.6 for the orthotropic layup, similar to metal foil gages.

The Poisson’s effect tests involved sensors subjected to transverse loading, with an additional longitudinal sensor as a control. Two specimens of each layup were tested. The response of the sensors aligned with the loading direction was, again, consistent with the initial tensile tests, with a uniaxial sensitivity of 0.67 mV/µε and an orthotropic sensitivity of 0.38 mV/µε. For the orthotropic layup, the transverse sensor showed a
response of 0.13 mV/µε, an expected value for a Poisson’s ratio of 0.3. However, the uniaxial specimens were not consistent with predictions, as shown in Figure 42.

Figure 42. Sensor Response in Uniaxial Composite Loaded Along its Axis

These should have had a much higher Poisson’s ratio and, therefore, stronger lateral contraction. In addition, the transverse sensors showed a positive response, 0.12 mV/ µε, when a negative response was expected. In order to confirm the observed behavior, the specimens were modified to reduce a possible non-uniform stress field at the ends of the transverse sensor, but no substantial change in sensor response was observed upon retesting. An additional test along the third axis consisted of placing the flat specimen between compression platens and applying a compressive stress; the sensor had zero response to this loading. It is thought that there is a complex interaction between interlaminar stresses and the CNT conduction mechanism. For instance, the compressive
load likely had no response because the autoclave cure densified their arrangement, such that additional compression did not cause an increase in conductivity. A related effect may have occurred in the transverse sensors. Further work will be required to study the response mechanism of the fuzzy fiber and determine why the sensor does not respond purely due to Poisson effects. This result suggests that a complex interaction in the CNT coating is at least partially responsible for the response of the sensor.

Open hole tensile tests did not show any sensitivity to the stress riser formed by the hole and reacted identically to the straight-sided tensile specimen. It is believed that the long sensor length relative to the hole created a strain averaging effect across the sensor which responded to the bulk strain rather than the strain in the immediate vicinity of the hole.

5.4 Quasi-Isotropic Off Axis Tension Tests

In order to further investigate sensor response to Poisson effects, the additional off-axis specimen, described in Section 3.7 above, was used to look at the longitudinal, transverse, and off-axis response for four sensors simultaneously. In general, these performed similarly to the orthotropic sensors in the carbon composites described in Section 5.3 above. Figure 43 shows the data from one test, where the specimen was loaded along axis ‘‘A’’. The sensor aligned with the loading had the highest response; the sensor at 45° to the loading had a lower positive response, and the sensor at 90° to the loading showed a negative response due to Poisson effects. Due to the lack of a reference strain measurement, the magnitude of these sensitivities cannot be compared directly with results from previous sensors. Fig. 44 is a compilation of the sensitivity results from all tests on this specimen, with each data point representing the average of 6, 12, or 24 tests,
depending on the sensor and the sensing mode. Data from all sensors was recorded with loading along all axes. In every case, the strongest response was in the longitudinal mode, followed by the oblique mode, and, finally, by the transverse mode, which was negative (or zero for sensor D). Some geometry effect is apparent, as sensors A and B were in the longer arms of the star and C and D were in the shorter arms. The gage length for all four sensors was the same.

Figure 43. Typical Off-axis Sensor Response
These tests confirmed the behavior of the fuzzy fiber sensors in an orthotropic composite, but did not provide insight into the anomalous transverse behavior in the uniaxial layup. At the beginning of tensile testing, substantial thermal response was observed, causing unacceptable drift in the strain signal. Faster loading rates or insulating the specimen from the air and allowing it to thermally stabilize before testing overcame the thermal issues. However, a separate investigation was performed to determine the magnitude of error in strain measurement that could be expected due to thermal errors. The test was performed with one specimen incorporating a first batch (50 kΩ) sensor and one with a second batch (3 kΩ) sensor. Figure 45 shows the thermal response of the sensors. This is a substantial change in resistance, as it corresponds to a potential error on the order of 2000 με/°C. Temperature compensation of deployed sensors is indicated if static strain or changes over time are required to be measured. While not explored in this study, this...
thermal sensitivity indicates the potential for the use of unstrained fuzzy fiber as a temperature sensor.

![Figure 45. Fuzzy Fiber Sensor Thermal Response](image)

5.5 Modeling

Around 300 strain data points were extracted for each path. These points were averaged over each 1mm of the path to correspond with the 25 cells composing the sensor in Abaqus. This averaged strain was used to calculate a resistance using a linear relationship. This relationship was constructed from the experimental electrical resistivity of the sensors and includes the wheatstone bridge transformation from resistance to volt output, so that bridge output voltages can be compared to experimental results.

Engineering strain is defined as

\[ \varepsilon = \frac{\Delta L}{L} \]  

(1)

where \( \varepsilon \) is engineering strain, \( \Delta L \) is the change in length and \( L \) is the initial length. Therefore

\[ \Delta L = \varepsilon \cdot L \]  

(2)
Poisson effects can now be calculated by introducing the concept of an equivalent sensor diameter $d$, which will change from its initial value by some amount $\Delta D$ which can be calculated as follows

$$\Delta D = -D \cdot \nu \cdot \varepsilon$$  \hspace{1cm} (3)

where $\nu$ is the Poisson’s ratio of the sensor material. The sum of $\Delta L$ and $L$ is the length of the sensor, $\ell$, under strain $\varepsilon$, stated as

$$\ell = \Delta L + L$$  \hspace{1cm} (4)

And similarly for the equivalent diameter, $d$

$$d = \Delta D + D$$  \hspace{1cm} (5)

The formula for electrical resistivity is stated as

$$R = \rho \frac{l}{A}$$  \hspace{1cm} (6)

where $R$ is resistance, $\rho$ is the electrical resistivity, $l$ is the length and $A$ is the cross-sectional area. From Eq. (6), initial resistance (substituting in $L$ and $D$) and current resistance (substituting $\ell$ and $d$) can be calculated

$$R_l = \rho \frac{4L}{\pi D^2}$$  \hspace{1cm} (7)

$$R = \rho \frac{4\ell}{\pi d^2}$$  \hspace{1cm} (8)

where $R_l$ is the initial resistance of the sensor and $R$ is the resistance of the sensor with applied strain, $\varepsilon$. A wheatstone bridge voltage output can be calculated as follows

$$V_{OUT} = \left( \frac{R_2}{R_1+R_2} - \frac{R}{R+R_3} \right) \cdot V_s$$  \hspace{1cm} (9)

which reduces to
\[ V_{OUT} = (0.5 - \frac{R}{R + R_b}) \cdot V_S \]  

when a single active resistor is used, where \( V_{OUT} \) is the output voltage, \( R_b \) is a bridge balancing resistor and \( V_S \) is the applied voltage to the wheatstone bridge. Eq. (10) can be used to construct a plot of model response (calculated from strain values extracted from the model) to compare to experimental wheatstone bridge output values recorded previously. Figure 46 shows the comparison between the experimental results and the model for one loading case. Other loading cases provided similar responses to that of Figure 46. The experimental data is extracted from a cyclic loading case wherein the tensile load is varied from 0 to 4.45 kN. The half cycle shown is from half load to maximum load and then back to half load.

![Figure 46. FE Model and Experimental Results](image)

The longitudinal (0°) response of the model was scaled based on the experimental results, resulting in a near perfect match. The off-axis (+/-45°) response predicted by the model
was slightly higher than the experimental result and the transverse (90°) response was much higher (~600%) in the model than what was found in the experimental testing. As discussed in Section 5.3 above, it is suspected that the fuzzy fiber sensor exhibits a unique response to compressive loading which is not accounted for in the model with assumed linear response. Since the nanotubes are normal to the surface of the fiber and in close proximity and tightly packed, the change in the conductive path of the sensor is large when the nanotubes are spread apart under tensile loading. The response to compressive loading is much smaller due to the dense nature of the conductive nanotube network.
6.0 CONCLUSIONS

The efforts presented here highlight the feasibility of incorporating carbon nanomaterials into structural composites as sensors. The CNT covered glass fiber has been shown to be a viable alternative to conventional metal foil strain gages. The fuzzy fiber sensors exhibit similar sensitivity to conventional strain gages, having a gage factor of 1.6–2.3. The small size and compatible materials of the fuzzy fiber sensors makes it easy to embed them within composite structures. Fuzzy fiber sensors comprised of a bundle of fuzzy fibers can be fabricated continuously at any practical length. These long lengths could provide wide area strain sensing in locations not accessible to conventional strain gauging techniques, as well as detection of cracks, delamination or other structural failure. A spool of the fuzzy fiber sensor material could be laid into any composite part during automated manufacturing or hand layup and could be cured into the composite. A small conductive patch at each end of the fuzzy fiber would provide the electrical connections to an onboard monitoring system.

Measurement of the sensor response in longitudinal, transverse and off-axis orientations shows that the sensor does indeed respond to these stimuli. Further study is needed to better understand the exact mechanism responsible for the observed behavior, specifically the unexpected positive response in some transverse tests and the smaller than expected transverse response in the off-axis specimen. This phenomenon may be due to the compressive stress causing a combined effect wherein the resistance of the sensing
element decreases due to Poisson effects while the resistance simultaneously increases
due to stress on the conductive CNT network. The net response of the sensor will depend
on the relative magnitudes of these two effects. By better understanding these effects, it
may be possible to tailor the fabrication of the sensor so that its performance is
predictable under both tensile and compressive stresses. The fuzzy fiber may be tailored
so that the same sensor can be used for a multitude of sensing applications. The
sensitivity of the fuzzy fiber to a certain stimulus can be amplified by its application so
that the sensor will sense the desired parameter, without significant cross talk from other
stimuli the sensor may be inherently susceptible to.

The longitudinal sensor output from the model matches nearly perfectly with the
mechanical test results. The peak values are the same because the model was normalized
to match the experimental data. Both the model and the experiment show linear responses
to stresses in each loading case. The transverse and off-axis tests follow the correct
trends; however the magnitude of the output does not match well with the experimental
data. The model does not account for shear sensitivity, which may be one cause for the
discrepancy, and could help correct the error in the off-axis fiber response. The
experimental transverse response is much smaller than the model predicts. The model has
assumed a purely piezoresistive effect with similar sensitivities to tensile and
compressive strain, which obviously does not adequately fit the actual sensor behavior.
The complex microstructure of the sensor may explain the difference in sensitivities. The
closely packed conductive nanotube network may be easily stretched apart, but cannot be
easily compressed and so has a lower sensitivity to compressive strain. This phenomenon
can be visualized with a Slinky or Jacob’s ladder toy. Each can be easily pulled apart, but
cannot be compressed further once in their relaxed state. Further work should be performed to investigate shear sensitivity and orthotropic sensitivity of the fuzzy fiber sensor to various loading conditions.

The fuzzy fiber strain sensor will find application in the aerospace, performance marine and wind energy markets, where the heavy use of composite materials dictates the need for SHM. Fuzzy fiber sensors will allow engineers to assess the integrity of the structure in real time and repair or replace critical components which are showing signs of structural damage. Embedded sensors will reduce costs by increasing the service life of components and allowing maintenance procedures to be performed before catastrophic failure occurs.
REFERENCES


