A THREE-DIMENSIONAL NUMERICAL ANALYSIS OF THE EFFECT OF EMBEDDING CYLINDRICAL MICROWIRE SENSORS ON THE COMpressive STRENGTH OF CARBON-FIBER REINFORCED COMPOSITE LAMINATES

A Thesis by
Raghav Maini
Bachelor of Engineering, University of Petroleum and Energy Studies, 2014

Submitted to the Department of Aerospace Engineering and the faculty of the Graduate School of Wichita State University in partial fulfillment of the requirements for the degree of Master of Science

December 2017
A THREE-DIMENSIONAL NUMERICAL ANALYSIS OF THE EFFECT OF EMBEDDING CYLINDRICAL MICROWIRE SENSORS ON THE COMPRESSIVE STRENGTH OF CARBON-FIBER REINFORCED COMPOSITE LAMINATES

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Aerospace Engineering.

_______________________________
Suresh Keshavanarayana, Committee Chair

______________________________________
Nicholas Smith, Committee Member

______________________________________
Ramazan Asmatulu, Committee Member
DEDICATION

To my parents, Veena and Vijay
ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Suresh Keshavanarayana for providing me with his valuable insights, exposing me to challenging research areas and guiding me throughout the course of my graduate studies. I am grateful to Dr. Nicholas Smith and Mr. Duane Davis for giving me valuable feedback for my research, Dr. Ramazan Asmatulu for being part of my thesis committee, and Mr. Luis Gomez for providing me with the computational resources at the Virtual Engineering Laboratory in National Institute for Aviation Research (NIAR). I would also like to thank Mr. Akhil Bhasin for encouraging me to supplement his research into embedded sensors in laminated composites.

I will forever be indebted to my parents for giving me the opportunity to pursue my interests and believing in me. Lastly, I would like to thank all my colleagues and supervisors at the Virtual Engineering lab/NIAR for all their support and words of encouragement throughout the course of my research.
ABSTRACT

The objective of this 3D finite element analysis study is to evaluate the effect on compressive strength of a laminated composite specimen, when cylindrical microwire tubes are embedded inside the structure. These microwire tubes cause geometric disturbances in the fiber architecture of laminated composite specimens and act as defects, resulting in the potential weakening of the structure. Hexahedral finite elements are used to study the three-dimensional state of stress in the vicinity of the free-edge and the interface of the embedded sensor and neighboring plies. Finite element models of two laminated composite stacking sequences, [0]_{22} and [(90/0/90)_{3} /90/0]_{s}, with octant symmetry are developed. Induced thermal stresses in composite specimens post-curing are also included in the finite element model. The impact of out-of-plane, interlaminar stresses is studied on the onset of failure in compression. Stress concentrations developed due to the presence of the sensor and resin pocket at different locations are recorded to compare their respective criticality. Lastly, numerical progressive failure analysis is performed using different failure criteria to compare the computational results to historically available experimental data.
1. INTRODUCTION .................................................................................................................. 1

1.2 Thesis Structure ............................................................................................................. 3

2. LITERATURE REVIEW ..................................................................................................... 4

2.1 Introduction to Structural Health Monitoring ................................................................. 4
  2.1.1 Applications of SHM ............................................................................................. 4
  2.1.2 Component Level Testing and Analysis .................................................................. 5

2.2 Microwire Sensor Assembly .......................................................................................... 6

2.3 Mechanical Degradation Studies with Embedded Sensors in Composites .................. 7

2.4 Delamination due to Interlaminar Stresses ................................................................. 11

2.5 Objectives and Methodology ....................................................................................... 13

3. EXPERIMENTATION AND MICROSCOPY .................................................................. 15

3.1 Material System ............................................................................................................ 15

3.2 Sensor .......................................................................................................................... 16

3.3 Cure Cycle .................................................................................................................... 16

3.4 Microscopy ................................................................................................................... 17

3.5 Combined Loading Compression (CLC) Test ............................................................... 18

3.6 Test Results ................................................................................................................. 19

4. FINITE ELEMENT ANALYSIS ....................................................................................... 22

4.1 Finite Element Analysis Procedure ............................................................................. 23
  4.1.1 Element Type ......................................................................................................... 23
  4.1.2 Discretization ........................................................................................................ 25
  4.1.3 Material Properties .............................................................................................. 29
  4.1.4 Contact Definition ............................................................................................... 30

4.2 Boundary Conditions ................................................................................................... 32
  4.2.1 Thermal Boundary Conditions ............................................................................. 32
  4.2.2 Mechanical Boundary Conditions .......................................................................... 33

4.3 Composite Failure Criterion ....................................................................................... 34
  4.3.1 Maximum Stress Failure Criterion ....................................................................... 35
  4.3.2 Hashin Tape Failure Criterion ............................................................................... 35
# TABLE OF CONTENTS (continued)

- **Chapter 5.** RESULTS AND ANALYSIS ......................................................................................... 38
  - 5.1 Stacking Sequence [0]_{22} ................................................................................................. 40
  - 5.1.1 Thermal Loading ............................................................................................................. 40
  - 5.1.2 Compressive Loading ..................................................................................................... 45
  - 5.1.3 Progressive Failure Analysis ......................................................................................... 48
  - 5.2 Stacking Sequence [(90/0/90)_{3} 90/0]_{s} ...................................................................... 54
  - 5.2.1 Compressive Loading .................................................................................................... 55
  - 5.2.2 Progressive Failure Analysis ......................................................................................... 57

- **Chapter 6.** CONCLUSIONS AND FUTURE WORK .............................................................. 61
  - 6.1 Conclusions ...................................................................................................................... 61
  - 6.2 Future Study ...................................................................................................................... 62

REFERENCES .................................................................................................................................. 64

APPENDIX .................................................................................................................................. 69
<table>
<thead>
<tr>
<th>Figure</th>
<th>LIST OF FIGURES</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Building Block Approach for Structural Health Monitoring</td>
<td>4</td>
</tr>
<tr>
<td>4.</td>
<td>Sensor Embedment perpendicular to loading and fiber direction [21]</td>
<td>8</td>
</tr>
<tr>
<td>8.</td>
<td>Stress distribution and stress singularity at the free-edge [19]</td>
<td>12</td>
</tr>
<tr>
<td>12.</td>
<td>5320-UD fiber waviness when sensor is placed perpendicular to fiber direction [11]</td>
<td>18</td>
</tr>
<tr>
<td>16.</td>
<td>Initiation of Failure near the sensor</td>
<td>20</td>
</tr>
<tr>
<td>17.</td>
<td>(a) Before Loading; (b) Failure Initiation in the specimen; (c) Ultimate Failure in the specimen [11]</td>
<td>21</td>
</tr>
<tr>
<td>18.</td>
<td>Process chart for Finite Element Analysis</td>
<td>23</td>
</tr>
<tr>
<td>19.</td>
<td>Assumed Strain for Element Type 7 [32]</td>
<td>24</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>20</td>
<td>Description of Integration Points in Hexahedral element type 7 [32]</td>
<td>24</td>
</tr>
<tr>
<td>21</td>
<td>Side View of the mesh discretization</td>
<td>26</td>
</tr>
<tr>
<td>22</td>
<td>Octant Symmetric FE Model</td>
<td>26</td>
</tr>
<tr>
<td>23</td>
<td>Mesh discretization for specimen without symmetry</td>
<td>27</td>
</tr>
<tr>
<td>24</td>
<td>Chart of Computational runtimes vs. Number of elements</td>
<td>28</td>
</tr>
<tr>
<td>25</td>
<td>High density mesh in the vicinity of the free edge</td>
<td>28</td>
</tr>
<tr>
<td>26</td>
<td>Contact definition between model components</td>
<td>30</td>
</tr>
<tr>
<td>27</td>
<td>Breaking glue parameters for Contact definition</td>
<td>32</td>
</tr>
<tr>
<td>28</td>
<td>X-, and Y-Direction Fixed Boundary Conditions and Nodal Compressive displacement condition</td>
<td>33</td>
</tr>
<tr>
<td>29</td>
<td>Load Application Boundary Conditions in the width and thickness direction</td>
<td>33</td>
</tr>
<tr>
<td>30</td>
<td>Description of Free Edge on the Specimen</td>
<td>38</td>
</tr>
<tr>
<td>31</td>
<td>(a) FE Model Y-Z Plane; (b) FE Model X-Y Plane</td>
<td>39</td>
</tr>
<tr>
<td>32</td>
<td>Contour Band representation of Residual Thermal Stresses in the transverse direction ( (\sigma_{yy}) ) for [0]_{22}</td>
<td>41</td>
</tr>
<tr>
<td>33</td>
<td>Residual Thermal Normal Stresses ( (\sigma_{yy}) ) in the transverse direction due to curing</td>
<td>42</td>
</tr>
<tr>
<td>34</td>
<td>Residual Thermal out-of-plane Shear Stresses ( (\tau_{yz}) ) due to curing.</td>
<td>43</td>
</tr>
<tr>
<td>35</td>
<td>Effect of Sensor Material on Transverse Normal Stress due to curing.</td>
<td>44</td>
</tr>
<tr>
<td>36</td>
<td>Effect of Sensor Material on out-of-plane Shear Stress ( (\tau_{yz}) ) due to curing.</td>
<td>44</td>
</tr>
<tr>
<td>37</td>
<td>Contour Band representation of Thermal + Mechanical Stress in the transverse direction ( (\sigma_{yy}) ) for [0]_{22}</td>
<td>45</td>
</tr>
<tr>
<td>38</td>
<td>Transverse Interlaminar Normal Stresses at the Free Edge – Through Thickness [0]_{22}</td>
<td>47</td>
</tr>
</tbody>
</table>
39. Transverse Interlaminar Shear Stress $\tau_{yz}$ and $\tau_{xz}$ at the Free Edge – From the top edge of the laminate to the midplane for $[0]_{22}$ ................................................................. 47

40. Residual Stresses in the Composite due to curing ................................................................. 49

41. Start of Compression load-case for $[0]_{22}$ UD Laminate .................................................. 50

42. Crack initiation due to compression for $[0]_{22}$ UD Laminate ........................................... 50

43. Direction of crack propagation for $[0]_{22}$ UD Laminate .................................................. 51

44. Ultimate Failure for $[0]_{22}$ stacking sequence specimen .................................................... 52

45. Stress-Strain curve for $[0]_{22}$ UD Laminate and comparison with Bhasin [11]............... 53

46. FE Model Material Properties for $[(90/0/90)_3/90/0]$s stacking sequence laminate..... 55

47. Generation of Interlaminar shear stresses in a crossply laminate [8] ................................. 56

48. Transverse Normal Stress, $\sigma_{yy}$ at the free edge, from the top edge to the midplane... 56

49. Interlaminar shear stress, $\tau_{xy}$ at the free edge, from the top edge of the laminate to the sensor-composite interface .......................................................... 57

50. Progressive Failure Analysis for $[(90/0/90)_3/90/0]$s laminate ...................................... 58

<table>
<thead>
<tr>
<th>Table</th>
<th>LIST OF TABLES</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.</td>
<td>Comparison between Computational Runtimes and Model Size</td>
<td>27</td>
</tr>
<tr>
<td>5.</td>
<td>Mechanical and Thermal properties of Microwire sensor material</td>
<td>30</td>
</tr>
<tr>
<td>8.</td>
<td>Stress concentrations in [0]22 stacking sequence</td>
<td>46</td>
</tr>
<tr>
<td>10.</td>
<td>Stress concentrations in [(90/0/90)3/90/0]s stacking sequence</td>
<td>55</td>
</tr>
<tr>
<td>11.</td>
<td>Comparison between Compressive strengths of Finite element models and test data for [(90/0/90)3/90/0]s</td>
<td>60</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------</td>
<td></td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
<td></td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Polymer</td>
<td></td>
</tr>
<tr>
<td>CLC</td>
<td>Combined Loading and Compression</td>
<td></td>
</tr>
<tr>
<td>CLT</td>
<td>Classical Laminate Theory</td>
<td></td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
<td></td>
</tr>
<tr>
<td>CVM</td>
<td>Comparative Vacuum Monitoring</td>
<td></td>
</tr>
<tr>
<td>EO</td>
<td>Extended Overtime</td>
<td></td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
<td></td>
</tr>
<tr>
<td>FOS</td>
<td>Fiber Optic Sensor</td>
<td></td>
</tr>
<tr>
<td>MEMS</td>
<td>Microelectromechanical systems</td>
<td></td>
</tr>
<tr>
<td>MWS</td>
<td>Micro-Wire Sensor</td>
<td></td>
</tr>
<tr>
<td>NDI</td>
<td>Non-Destructive Inspection</td>
<td></td>
</tr>
<tr>
<td>SHM</td>
<td>Structural Health Monitoring</td>
<td></td>
</tr>
<tr>
<td>UD</td>
<td>Unidirectional</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>$E_{11}$</td>
<td>Young’s Modulus along the $x$-direction</td>
<td></td>
</tr>
<tr>
<td>$E_{22}$</td>
<td>Young’s Modulus along the $y$-direction</td>
<td></td>
</tr>
<tr>
<td>$E_{33}$</td>
<td>Young’s Modulus along the $z$-direction</td>
<td></td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>Poisson’s Ratio associated with loading in $x$-direction and strain in $y$-direction</td>
<td></td>
</tr>
<tr>
<td>$\nu_{23}$</td>
<td>Poisson’s Ratio associated with loading in $y$-direction and strain in $z$-direction</td>
<td></td>
</tr>
<tr>
<td>$\nu_{31}$</td>
<td>Poisson’s Ratio associated with loading in $z$-direction and strain in $x$-direction</td>
<td></td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>Shear Modulus along $xy$-Plane</td>
<td></td>
</tr>
<tr>
<td>$G_{23}$</td>
<td>Shear Modulus along $yz$-Plane</td>
<td></td>
</tr>
<tr>
<td>$G_{31}$</td>
<td>Shear Modulus along $zx$-Plane</td>
<td></td>
</tr>
<tr>
<td>$F_{1t}$</td>
<td>Tensile Strength along $x$-direction</td>
<td></td>
</tr>
<tr>
<td>$F_{2t}$</td>
<td>Tensile Strength along $y$-direction</td>
<td></td>
</tr>
<tr>
<td>$F_{3t}$</td>
<td>Tensile Strength along $z$-direction</td>
<td></td>
</tr>
<tr>
<td>$F_{1c}$</td>
<td>Compressive Strength along $x$-direction</td>
<td></td>
</tr>
<tr>
<td>$F_{2c}$</td>
<td>Compressive Strength along $y$-direction</td>
<td></td>
</tr>
<tr>
<td>$F_{3c}$</td>
<td>Compressive Strength along $z$-direction</td>
<td></td>
</tr>
<tr>
<td>$F_{4}$</td>
<td>Shear Strength along $xy$-Plane</td>
<td></td>
</tr>
</tbody>
</table>
\( F_5 \)  Shear Strength along \( yz \)-Plane

\( F_6 \)  Shear Strength along \( zx \)-Plane

\( F_{DH} \)  Fiber disturbance height

\( L_{RP} \)  Length of lenticular resin-rich pocket

\( \sigma_x \)  Normal Stress in \( x \)-direction

\( \sigma_y \)  Normal Stress in \( y \)-direction

\( \sigma_z \)  Normal Stress in \( z \)-direction

\( \alpha_1 \)  Coefficient of Thermal Expansion along the 1-direction

\( \alpha_2 \)  Coefficient of Thermal Expansion along the 2-direction

\( \alpha_3 \)  Coefficient of Thermal Expansion along the 3-direction

\( \sigma_{\text{yield}} \)  Material Yield Strength

\( \sigma_{\text{remote}} \)  Remote Stress

\( \sigma_N \)  Normal component of stress

\( \sigma_S \)  Shear component of stress

\( \tau_{xy} \)  Shear Stress acting in the \( xy \)-plane

\( \tau_{yz} \)  Shear Stress acting in the \( yz \)-plane

\( \tau_{zx} \)  Shear Stress acting in the \( zx \)-plane
Chapter 1

INTRODUCTION

The appeal of composite materials comes from their ability to be tailored to meet specific structural requirements, usually for high performance applications [1]. Several components on aircraft, which have conventionally been made out of metal, are increasingly being made out of composites because of better strength to weight ratios and ability to optimize the stacking sequence of the laminate in order to strengthen the component in a particular direction [2].

More than 50% of the structural components in Airbus A350 XWB and Boeing 787 are made of composite materials [3]. Improving fuel efficiency by reducing weight wherever possible, without compromising on strength, has been a common practice for aircraft manufacturers since the 1970s [4].

One downside to composite material use is that even minor damage has been shown to cause overall performance of parent structures to be degraded [5]. Failure and damage in composites is not as straightforward as in metals. Correctly predicting failure modes, damage initiation, and failure progression has proven to be a challenge for researchers, and continues to be an active area of research [6].

Of particular interest to this study is the nascent field of Structural Health Monitoring (SHM) [4, 7]. The aim of SHM is to detect various types of damage during the operational life of the structure by means of sensory equipment. Microwire sensors, shape memory alloys, embedded MEMS, comparative vacuum monitoring (CVM) sensors, and piezoelectric wafers are examples of some of the popular sensing equipment used for SHM [4, 8, 9, 10]. Monitoring is accomplished either by employing sensors on the surface of the parent material or by embedding the sensors within the structure.
For thermal applications such as curing a composite, a thermocouple placed on the surface does not measure the temperature in the interior of the laminate, which may cause incorrect level of curing and leave the composite unfit for its intended use [11, 12]. Microwire sensors embedded between plies of a composite laminate counter this problem by correctly monitoring temperature inside the laminate while curing. [13]

One of the disadvantages of embedding sensors in a laminate is that it acts as a defect and distorts the neighboring plies [14]. Due to varying material properties of the orthotropic laminate and the isotropic microwire sensor, a complex state of stress develops in the vicinity of the sensor and there is loss of tensile and compressive strength of the material [13, 14].

For structures with embedded sensors to be certified and universally accepted in the aerospace industry, it must be shown that the embedment of microwire sensors does not significantly reduce the strength of the host material [13]. Several studies have been conducted to investigate the effect of embedding sensors in composites on individual material properties of composites [15, 16, 17, 13, 18].

In the present study, the role of interlaminar stresses near the free edges of laminated composites embedded with sensors has been investigated with the help of finite element analysis techniques. Classic Lamination Theory (CLT) assumes that the laminate and all its plies are in a state of plane stress. All out-of-plane stress components are not considered and/or assumed to be zero [1]. Although CLT holds true for composites, a three-dimensional state of stress is observed in the vicinity of material discontinuities and/or abrupt changes in geometry, such as cutouts, notches and free-edges [19]. If the magnitude is comparable to transverse strength, interlaminar stresses cause the laminate to split from the sensor and initiate failure.
1.2 Thesis Structure

The main aim of this thesis is to perform three-dimensional numerical analysis for a composite embedded with a sensor, and evaluate the reduction in compressive strength by comparing the finite element analysis results with test and computational analysis data performed by Bhasin [11].

Chapter 2 gives an overview of past research in the area of sensor-embedded composites and structural health monitoring. It also delves deeper into the development of interlaminar stresses near the free-edges and attempts to explain why it is important to study interlaminar stresses for composites embedded with sensors.

Chapter 3 summarizes details about the material system used for this analysis and also presents test results from Bhasin [11] for a $[(90/0\/90)_{3}/90/0]_s$ coupon which will be used for validation of the numerical analysis performed in this study.

Chapter 4 discusses the intricacies of finite element modeling with MSC Marc. Contact definition, boundary conditions and composite Failure criterion are also discussed.

Chapter 5 details the finite element analysis results for two different stacking sequences. Stresses induced due to thermal loading, stresses at the end of the compressive loading and progressive failure analysis of the two stacking sequences studied.

Chapter 6 presents the conclusions of this study and discusses future avenues in this active area of research.
Embedding sensors in a composite for purposes of monitoring temperature or strains has been employed by researchers since the early 1990s. Many studies resulting from this, characterize the effect sensor embedment has on material properties and failure mechanisms of composite structures.

2.1 Introduction to Structural Health Monitoring

Structural health monitoring has a wide array of applications and it is necessary to understand the whole process involved with SHM testing and analysis. A building block approach is followed to map out the various stages involved with the development of SHM.

Assembly and SHM Validation
Coupon Level Testing and Analysis
Potential Applications

Figure 1. Building Block Approach for Structural Health Monitoring

Assembly and large scale implementation of SHM is beyond the scope of this research study. The main focus of this study is on coupon level analysis and testing intended to characterize material behavior and effects from different types of loading. For the sake of completeness, some applications of SHM are discussed in the next subsection.

2.1.1 Applications of SHM

Use of an SHM system can be utilized for composites in two main applications:
1. Temperature sensing during cure – As Vodicka [12] aptly states, cure procedures for composite parts consist of a recipe prescribing correct temperature, vacuum, pressure, and associated cycle timing. Improper cure could damage the composite or deem it unsuitable for use in its intended application. Manufacturing of composites is a costly process, and curing is irreversible; therefore, it is pivotal to monitor the state of cure. Process temperatures are examined using thermocouples mounted on the surface, which may not be an accurate representation of the temperature at the specimen midplane [11]. Because of this, embedded sensors in composites can help with constant monitoring of temperature while curing.

2. Thermal or mechanical strain measurement – In the event of visible or hidden damage due to cyclic loading, strains can be measured in the vicinity of the damage, and optical signals can help quantify the damage. This method is a useful alternative for NDI methods and helps save time and resources allocated to routine inspections.

2.1.2 Component Level Testing and Analysis

To understand if sensor embedment is feasible or not, a small laminated composite coupon is embedded with a sensor, and its behavior in different loading conditions is recorded. The effect of a sensor’s introduction into the host material is then studied. Usually, the introduction of a foreign material does weaken a structure and due to the complex, orthotropic nature of composites, it is worthwhile to study the extent of weakening of the host material. This step is vitally important, as the whole approach fails if there is significant weakening of a structure as a result of sensor embedment. Therefore, an effort must be made to test and validate by analysis, the state of stress around the sensor, and whether the structure is significantly weakened by the presence of a foreign material.
For any product or technology to be implemented in a high-risk applications in industries such as aviation, defense or space, it must meet stringent certification standards. To make use of embedded sensors in a composite material for high-risk operations, its strength and stiffness must not be significantly affected as a result of sensor embedment.

2.2 Microwire Sensor Assembly

A microwire assembly that has the ability to withstand temperatures during cure is used for embedment in the host material. The temperature is monitored throughout the curing process and can be controlled externally. The sensor [20] has the following features:

- Three inner microwires, one each for temperature sensing, calibration, and reference, respectively. These microwires are made of iron or cobalt alloys and must be coated appropriately with glass. Microwires are suitable for observation at both lower and higher temperatures.
- The outer metal core, which is made using an alloy of titanium and nickel (NiTi). The alloy is chosen to be of this material as it doesn’t magnetically bias the microwires housed within the core.
- A magnetic field generating coil for sending the signal, a detection coil for detecting the signals from the coil, and a signal processor to decode the output signal are also part of this assembly. Since the scope of this study does not include physical temperature sensing, the detailed process of measuring the temperature is not discussed at length and can be found in literature. [20]
2.3 Mechanical Degradation Studies with Embedded Sensors in Composites

Early attempts to design and embed sensors into laminated composites led to the observation that a lenticular resin rich pocket was formed around the sensor [21]. The sensor was placed at the mid-plane of the laminate, and the upper half plies were then placed on top of each other. The diameter of the sensor (100-400 μm) is significantly larger than the diameter of typical reinforcing fibers (5-10 μm). Therefore, a geometric disturbance of the neighboring plies takes place in the form of fiber waviness as can be seen in the figure below. [15, 22, 23].

Jensen et al [14] studied the effect of sensor orientation relative to the fiber direction on the tensile and compressive strength of the composite laminate. It was found that the largest
degradation in mechanical properties occurred when the fibers were embedded perpendicular to the fiber direction.

Shivakumar and Bhargava [21] were among the first to discuss failure of composites with embedded fiber optic sensors in tension and compression. They embedded sensors mutually perpendicular to the loading direction and the direction of fibers in a unidirectional AS4/3501-6 laminate.

They performed finite element analysis to compare those results with experimental results and characterized initial and final failure with the help of maximum stress criteria.

![Figure 4. Sensor Embedment perpendicular to loading and fiber direction [21]](image)

For a uniaxial tensile load, it was found that a transverse tensile stress developed at point A and a transverse compressive stress developed at point B, as shown in Figure 5. Due to low transverse strength in tension, a fiber-matrix split occurred at point A, followed by ultimate failure due to fiber breakage.
For a uniaxial compressive load, it was found that a transverse tensile stress developed at point B and a transverse compressive stress at point A. This led to interfacial cracking between the sensor and the plies in contact with the sensor. The interfacial crack is then found to propagate towards the root of the resin rich pocket. Upon continued loading, the ultimate failure is caused by microbuckling/kinking.

Huang et al. [15] analyzed the effect of embedded vasculatures on composite laminates. In this case, instead of the region where the sensor is usually embedded, there was a hollow vasculature. It was found that the size of vasculures was directly proportional to the size of resin rich
pocket and fiber disturbances (waviness). Under compressive loading, the results of this analysis corroborated the findings of Shivakumar and Bhargava [21], but noted that when the laminate Mode I fracture toughness is greater than the Mode I fracture toughness of the resin pocket, the failure will initiate at point C in the form of a crack as shown in Figure 7. Both alternatives (interfacial crack propagating to the root of resin pocket and resin pocket cracking) were possible and depended on the choice of material used.

![Image of failure modes in Compression for vasculatures in composite laminates](image)

**Figure 7.** Failure modes in Compression for vasculatures in composite laminates [15]

There has also been significant research in this field to study the effect of embedded cylindrical sensors on the in-plane tensile properties [24], in-plane compressive properties [11], fatigue life of laminated composites [25], and Mode-II fracture behavior of adhesively bonded laminated composites [26].

The topic of this study is to understand the influence of interlaminar stresses on composite laminates embedded with sensors. At this stage, it is important to review some important studies related to development of interlaminar stresses near free edges.
2.4 Delamination due to Interlaminar Stresses

Delamination is one of the most frequent types of damage in composite laminates [27]. The in-plane fibers do not offer strength in the thickness direction. Consequently, most of the load bearing responsibility in the transverse direction falls to the matrix, which in turn is susceptible to brittle failure. The strength of a composite material in the thickness direction is usually a fraction of the strength in the longitudinal direction, and that causes a potential for delamination in the laminate at the interface between plies [6]. Delamination is a very complex failure mechanism, and it is very difficult to detect such a failure as it can result due to impact, longitudinal shear stress between the layers, or transverse tensile stress across the layers.

Interlaminar stresses have been studied extensively in the past 4 decades. It is also important to study these stresses because they help in formulating the strength of composite laminates. Pipes and Pagano are pioneers of computational interlaminar stress analysis in composites. Their study revealed a rise in certain interlaminar shear stresses near the free-edge region (a distance equal to the laminate thickness from the free edge) as illustrated in Figure 8. They were among the first to discuss the presence of a possible stress singularity at the free edge [19].

Although this study by Pipes and Pagano presented some valuable findings, there were a few shortcomings. The mesh discretization for the finite element analysis was coarse. It is obvious that this shortcoming stemmed from computational limitations at the time. Computational power has progressed leaps and bounds since 1970’s, reducing computational time and cost by many factors.

Wang and Crossman [27] in 1977 published results attempting to improve on the observations of Pipes and Pagano. An improved finite element model and a better time-conserving
technique was used to model interlaminar stresses at the free-edges. Wang and Crossman argued the presence of a singularity and whether it is significant or not. They proposed that even if these singularities existed at the free edge, they would dissipate within the laminate and be redistributed among neighboring plies, and as a result, weakening them.

![Stress distribution and stress singularity at the free-edge](image)

Figure 8. Stress distribution and stress singularity at the free-edge [19]

Kim and Soni [28] brought forward the idea of average stresses in the vicinity of the free edges of a notched specimen. They predicted failure at locations where the average longitudinal stresses were exceeded beyond a critical value. The same authors also concluded that an interaction of interlaminar normal and shear stresses was responsible for the onset of delamination.

Wisnom [29] distinguished between three cases in which interlaminar stresses are developed in a composite: interlaminar stresses due to out-of-plane loading; interlaminar stresses due to geometry effects; and localized interlaminar stresses at specific regions. The present study discusses both the second and third cases, as the composite with a sensor embedded in it presents
locations of material discontinuity, and also causes a waviness of layers in the vicinity of the embedded microwire which causes a geometric discontinuity near the top and bottom of the sensor.

Sharp discontinuities in the geometry and material properties can result in stress singularities at the free edges of the specimen and trigger the initiation of delamination. This is precisely the reason why it is so important to discuss interlaminar stresses in the current application of a sensor embedded in a laminate. The failure strength in transverse and longitudinal directions for the composite, although computed with in-plane loads, does not account for geometric and material nonlinearities.

2.5 Objectives and Methodology

From research discussed in the above sections, it is clear that embedment of sensors in a laminated composite, for structural health monitoring purposes, leads to the reduction of failure strengths in tension and compression. Finite element numerical analysis has been performed to predict the reduction in compressive strength of a Cytec CYCOM 5320-1 toughened epoxy resin system [30], when a microwire titanium-based sensor is embedded at the mid-plane of the laminated composite.

The main focus of this study is to understand the generation of interlaminar stresses near the free-edge of the composite specimen embedded with a sensor, through finite element analysis. Previous research in this field [13, 15, 24, 14, 21] has been limited to the use of two-dimensional numerical analysis. But out-of-plane interlaminar stresses are generated through Poisson ratio mismatches between plies, and due to material and geometric discontinuities. These discontinuities cause high stress concentrations at the free-edges and introduce the risk of delamination failure. Therefore, an attempt has been made with this study to perform a three-dimensional linear elastic and failure analysis for two different stacking sequences: [0]_{22} and [(90/0/90)_3 90/0]_s.
Residual stresses are induced in a composite laminate upon cooling in the curing process. These residual stresses are also simulated in this numerical analysis, to ensure that the FE model is as close to the test specimen as possible.

A three-dimensional state of stress is observed near the free-edges, and one of the most effective ways to represent this phenomenon computationally is to use three-dimensional solid elements, albeit with a computational cost penalty. Finite element models for laminated composites embedded with sensors are created to better understand failure modes and the onset of failure through progressive failure analysis.

Finite element numerical analysis results are then compared and correlated with previously conducted experimental tests and FE analysis from Bhasin [11] as a means of validation, and reduction in compressive strength due to sensor embedment is tabulated.

An attempt has been made with this study to explore possibilities for finite element analysis of composite sections with embedded sensors. The final objective is to add to current literature and show how finite element analysis would help in designing composite structures complying with foreign material embedment such as the microwire sensors used for this study.
Chapter 3

EXPERIMENTATION AND MICROSCOPY

A brief discussion of the compression procedure of the composite system with an embedded sensor used for this study is presented in this chapter. The composite material system used was manufactured by Cytec Engineered Materials, Inc. [30]

3.1 Material System

The composite material system used for this study has been summarized in Table 1. The material properties for matrix and fiber alone have also been summarized in Table 2.

Table 1. Material System used in the Present Study [30]

<table>
<thead>
<tr>
<th>Material</th>
<th>5320-1 EO Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>Thornel® T-650/35 3K UD Tape</td>
</tr>
<tr>
<td>Fiber Areal Weight</td>
<td>145 gsm</td>
</tr>
<tr>
<td>Resin Content</td>
<td>33%</td>
</tr>
</tbody>
</table>

Table 2. Material Properties for Fiber and Matrix Material [30]

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (GPa)</th>
<th>Density (g/cm³)</th>
<th>Poisson’s Ratio</th>
<th>Coefficient of Thermal Expansion (μm/m-°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-650/35 3K Carbon Fiber</td>
<td>241</td>
<td>1.77</td>
<td>N/A</td>
<td>-0.5</td>
</tr>
<tr>
<td>5320-1 EO Resin</td>
<td>3.76</td>
<td>1.31</td>
<td>0.3</td>
<td>44.89</td>
</tr>
</tbody>
</table>

This material system is attractive because of low void content, low temperature cure capability, and offers mechanical properties equivalent to those of autoclave cured toughened epoxy systems. This system is also suitable for producing complex aerospace parts, which is why it is a choice for this application [30].
3.2 Sensor

The sensor tubes (obtained from AvPro Inc. [20]) to be embedded in the composite system were made from a titanium alloy, but the exact composition was not available, leading to material properties for the core of the sensor to be approximated. The microwires used for sensing, housed in the interior of the shell were not modeled as they held no real structural significance. The sensor tubes were 0.0102” in diameter. The tubes, available in sizes from 40-60” were cut and sealed as per embedment requirements.

3.3 Cure Cycle

CYCOM 5320-1 toughened epoxy resin system is designed for both vacuum bag only or out of autoclave manufacturing of primary structural parts. The system has the capability for low temperature curing, which is advantageous for vacuum-bag-only curing. Cytec [30] datasheets recommend cure cycles for the composite system and they were followed to prepare the composite panels. The scheme as shown in Figure 9 was followed to cure the composite panel.

![Diagram of Vacuum Bag arrangement for cure](image-url)
The process of curing for this particular composite panel is discussed in detail by Bhasin [11]. For the unidirectional 5320-1 panel, the cure cycle is as shown in Figure 10.

![Figure 10. Cure Cycle log for 5320-1 UD laminate [11]](image)

### 3.4 Microscopy

As discussed in the literature review, the embedment of sensors causes the resin from the neighboring plies to seep out and settle in a pocket around the sensor, as shown in Figure 11.

![Figure 11. Cross Sectional View of UD laminate with sensor embedded at 90° to the fiber direction [11]](image)

Bhasin [11] extracted the locus of points from the above image was retrieved with the help of a microscope and used the coordinates to accurately depict the waviness in the mesh.
discretization process. This was done to compare how the extent of waviness in the fiber path contributed to stress concentrations at critical points on the resin pocket-first ply interface.

Figure 12. 5320-UD fiber waviness when sensor is placed perpendicular to fiber direction [11]

These coordinates from the microscopy performed by Bhasin [11] were later used in the process of discretization of the specimen for finite element analysis.

3.5 Combined Loading Compression (CLC) Test

The CLC test, as described in ASTM D6641 [31] is performed to determine the compressive strength and stiffness properties of composite materials. This test is only applicable to general composites that are balanced and symmetric. A combined end and shear loading introduces a compressive force in the laminate. The dimensions of the specimen as used are presented in Figure 4.

The compression testing was performed by Bhasin [11] for [(90/0/90)₃/90/0]s stacking sequence. Specimens were attached with a biaxial strain gage at the gage section with the help of an adhesive. The thickness of the specimen had to be greater than a threshold value to prevent
Euler buckling from occurring [31]. The thickness of the laminate was chosen to be greater than the minimum thickness for Euler buckling, deeming ASTM D6641 test method applicable.

Figure 13. Dimensions of coupon for ASTM D6641 [31]

The testing was carried out for five specimens, each with sensor oriented at 0° to the fiber direction of the neighboring plies, with the sensor oriented at 90° to the fiber direction of the neighboring plies, and without sensor. [11]

3.6 Test Results

The results for [(90/0/90)_3/90/0]_s stacking sequence can be compared to a [0],n laminate, as the sensor was embedded in the mid-plane, between two zero degree plies. In this way, fiber waviness was observed in the specimen, as depicted in Figure 14.

Figure 14. Fiber Waviness for [(90/0/90)_3/90/0]_s stacking sequence laminate [11]
The comparison of the specimens was done to experimentally obtain the effect on compressive strength and compressive modulus due to sensor embedment and inherent fiber waviness.

Figure 15. Test results comparing the compressive strengths and modulus for Cytec 5320-UD [11]

Bhasin [11] found, that for [(90/0/90)₃ 90/0]s, there was a 5.3% reduction in compressive strength, and the failure initiation was due to transverse tension in the vicinity of the sensor. The crack rapidly progressed towards the root of the resin pocket before ultimate failure occurred due to microbuckling. The failure mechanism was also discussed in the literature review and the test results were compared to the findings of Shivakumar et al [21].

Figure 16. Initiation of Failure near the sensor
The stepwise procedure of load application and failure is shown in Figure 17. The resin pocket and the sensor are highlighted before the failure.

Figure 17. (a) Before Loading; (b) Failure Initiation in the specimen; (c) Ultimate Failure in the specimen [11]
Chapter 4

FINITE ELEMENT ANALYSIS

FE simulations were conducted for the dual purpose of validating test results and to better understand different failure mechanisms for the specimen. Analysis has been done for two different configurations – \([0]_{22}\) and \([(90/0/90)_3\ 90/0]\). Stresses induced during the cure process, and the geometrical effects of fiber waviness were also considered in the simulations, to ensure that the FE model was accurate and as close to the test specimen as possible. Stress concentration factors were calculated at the critical points for a better understanding of the stress field around the sensor region. Finally, experimental data and results for 2D analysis performed by Bhasin [11] were compared with the numerical models from this study using progressive failure analysis. (Maximum Stress, Hashin Tape). As discussed in the previous chapter, the mesh discretization for the FE model was modeled by referring to the fiber waviness coordinates from the specimen micrograph observations.

For 2D analysis, assumptions are made to simplify a problem by assuming plane stress or plane strain analysis. A significant advantage of 3D analysis is that the solution will look like the actual problem and there would be no need of setting assumptions. Some of the difficulties of using 3D analysis is the complexity that comes with discretizing elements in 3 dimensions, more computation time, hardware resources required, and more post-processing effort to analyze the results in three dimensions, and those limitations are addressed in later sections. All the numerical analysis effort is carried out primarily with the help of MSC Marc [32], which is a powerful non-linear finite element analysis solver. For all purposes in this study, the X-Direction is the length dimension, Y-Direction is the thickness dimension, and Z-Direction is the width dimension.
4.1 Finite Element Analysis Procedure

An organized method must be followed in order to validate tests, so that the numerical simulations can accurately represent the findings of the testing data. The procedure for FE model setup in no particular order is as follows:

![Figure 18. Process chart for Finite Element Analysis](image)

4.1.1 Element Type

To correctly predict the stresses and displacements in the vicinity of a sensor embedded in a composite part, where all three dimensions are comparable, it is important to perform 3D stress and strain analysis. More importantly for this study, a state of three-dimensional stress develops near the free edges [19] due to shearing between different components or plies bonded together. Therefore, a 2D shell element is unable to capture the out-of-plane stresses which a 3D element in that location is able to do.

Another option was to use tetrahedral elements, but it is known from literature that for an identical problem, they act stiffer in bending than hexahedral solid elements. Additionally, to capture the fiber disturbance and the geometric non-linearity of the problem at hand, it was
important to use 3D hexahedral/pentahedral elements, and also properly varying the fiber waviness as per micrographs observed after layup/cure.

In MSC Marc, Element type 7 is an 8-node, isoparametric hexahedral element. This element type uses trilinear interpolation functions [32]. This element type is known to show poor representation of shear behavior, but it can be countered by choosing an assumed strain flag. It increases the computational costs per element, but results in improved accuracy.

Figure 19. Assumed Strain for Element Type 7 [32]

Hexahedral elements fare well for contact analysis, which is an important consideration in this study. The element stiffness is formed by 8-point Gaussian integration as shown in Figure 20.

Figure 20. Description of Integration Points in Hexahedral element type 7 [32]
4.1.2 Discretization

An implicit finite element scheme is carried out for this analysis, which enforces equilibrium at every increment through Newton-Raphson iterations. Unlike explicit FE methods, here the computational cost does not depend on element size, density, or Young’s modulus. Equilibrium with external forces is met at every increment, which makes this type of analysis more accurate and allows for larger steps.

Before the process of mesh discretization, it is important to review the application of the simulation. For a computation intensive explicit simulation, minimum element size, density and Young’s Modulus dictate the time step intervals at which the stiffness matrix is evaluated. Since this analysis is quasi-static and involves implicit analysis, no such considerations have to be made for element length.

Numerical simulations are usually a compromise between accuracy and computational cost. Lessons were learned from previous research [11, 21, 15] and different iterations were made before finalizing mesh density for this study. These iterations are presented in Appendix A. Since using three-dimensional elements is vital for this study, a computational penalty was expected for the same specimen. In case of a two dimensional shell mesh, a thickness property is given to a 2D shell mesh, but for a 3D mesh, there is a multiplication of elements along the width and the thickness which results in a larger number of elements.

To compare the computational penalty, the dimensions of the specimen and load cases applied must be the same. It was observed that only the region near the sensor and resin pocket was of interest, so only the area in their vicinity was modeled to reduce computational times. Bad element quality regions were addressed and elements with low Jacobians and high warpage angles were reduced.
The mesh modeling and the coordinate system is as labeled in Figure 21. In this model, the length is modeled in the X-direction (5mm), thickness in the Y-direction (1.37mm), and width in the Z-direction (6.35mm for half the width or 12.7mm for full width). All these dimensions are in accordance with ASTM D6641 [31]. The waviness in the mesh is modeled by comparison with the micrographs shown in Figure 12.

![Figure 21. Side View of the mesh discretization](image)

As in previous research [13, 11], a quarter FE model with symmetry boundary conditions in X and Y-directions was designed. To reduce computational runtimes even further, Z-direction symmetry was also added, as the geometry and loading still remains symmetric. The octant symmetry model and the full model is as shown in Figure 22 and Figure 23.

![Figure 22. Octant Symmetric FE Model](image)
A comparative study between different FE models with varying number of elements and their respective CPU runtimes was done to arrive at the appropriate mesh density for this model. Table 3 shows different simulations and their respective runtimes.

Table 3. Comparison between Computational Runtimes and Model Size

<table>
<thead>
<tr>
<th>Description</th>
<th>Type of Symmetry</th>
<th>Number of Elements</th>
<th>Runtime in seconds</th>
<th>Runtime in minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D Coarse</td>
<td>Quarter</td>
<td>634</td>
<td>47</td>
<td>0.78</td>
</tr>
<tr>
<td>2D Big Diameter Sensor</td>
<td>Quarter</td>
<td>2514</td>
<td>223</td>
<td>3.72</td>
</tr>
<tr>
<td>3D Intermediate Mesh</td>
<td>Octant</td>
<td>10144</td>
<td>2388</td>
<td>39.80</td>
</tr>
<tr>
<td>2D Fine Mesh</td>
<td>Quarter</td>
<td>14327</td>
<td>2122</td>
<td>35.37</td>
</tr>
<tr>
<td>3D Coarse Mesh</td>
<td>Quarter</td>
<td>19020</td>
<td>5439</td>
<td>90.65</td>
</tr>
</tbody>
</table>

As can be seen from Table 3 and Figure 24, the computational runtimes show direct proportionality to the number of elements (assuming same computation and load cases). Hence, it is important to pick a mesh density which gives a precise solution without excessive computational runtimes. For example, introducing symmetry in Z-direction reduces the runtime by more than half, without any significant change in results.
Another consideration for the mesh in Z-direction was to better capture the 3-dimensional stress field near the sensor. This could be done by increasing the mesh density near the free edge as demonstrated in Figure 25.

A mesh sensitivity study was performed as shown in Appendix A. The study was done to arrive at an appropriate mesh density for this study.
4.1.3 Material Properties

The materials used in the numerical simulations are for the bulk composite, 5320 resin and titanium microwire. The composite material was modeled as an elastic-plastic orthotropic material, whereas the sensor and resin rich region were modeled as isotropic. The composite elements were oriented at 0 degrees using the ‘3D Local’ Geometric Properties option in MSC Marc. The x-axis was defined as the 1-direction, y-axis as the 2-direction, and z-axis as the 3-direction.

Cytec data sheets [30] were used to refer to material and thermal properties for the resin and composite. These properties are summarized in Table 4.

Table 4. Material Properties for 5320-UD 0 degree plies [30]

<table>
<thead>
<tr>
<th>Properties</th>
<th>5320-UD 0 deg plies</th>
<th>Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$ (MPa)</td>
<td>138586</td>
<td></td>
</tr>
<tr>
<td>$E_2$ (MPa)</td>
<td>10893</td>
<td>3760.71</td>
</tr>
<tr>
<td>$E_3$ (MPa)</td>
<td>10893</td>
<td></td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>$\nu_{23}$</td>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>$\nu_{31}$</td>
<td>0.0235</td>
<td></td>
</tr>
<tr>
<td>$G_{12}$ (MPa)</td>
<td>5502</td>
<td></td>
</tr>
<tr>
<td>$G_{23}$ (MPa)</td>
<td>2700</td>
<td></td>
</tr>
<tr>
<td>$G_{31}$ (MPa)</td>
<td>5502</td>
<td></td>
</tr>
<tr>
<td>$\alpha_1$ (*10E-06 °C)</td>
<td>2.62</td>
<td></td>
</tr>
<tr>
<td>$\alpha_2$ (*10E-06 °C)</td>
<td>58.5</td>
<td>44.9</td>
</tr>
<tr>
<td>$\alpha_3$ (*10E-06 °C)</td>
<td>58.5</td>
<td></td>
</tr>
</tbody>
</table>
To understand the effect of material properties of sensor on the composite, different materials for the microwire sensor were tried. The sensor in the test conducted was made of titanium alloy, but more materials were also input to see how stress concentrations varied with load carrying capabilities of the sensor tubes. The mechanical and thermal properties for different sensor materials is summarized in Table 5.

Table 5. Mechanical and Thermal properties of Microwire sensor material

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Titanium</th>
<th>Tungsten</th>
<th>Teflon</th>
<th>Optical Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (MPa)</td>
<td>108000</td>
<td>411000</td>
<td>620</td>
<td>72900</td>
</tr>
<tr>
<td>ν_12</td>
<td>0.3</td>
<td>0.28</td>
<td>0.46</td>
<td>0.17</td>
</tr>
<tr>
<td>α (*10E-06 °C)</td>
<td>9.2</td>
<td>4.6</td>
<td>126</td>
<td>0.75</td>
</tr>
</tbody>
</table>

4.1.4 Contact Definition

Due to varying mechanical properties of constituent materials, they are expected to behave differently under loading. Dissimilar components are modeled as deformable bodies; segment-to-segment contact is defined between the three components. When there are multiple contact bodies, it is advantageous to reduce the contact body pairs. A contact table, as shown in Figure 26, helps implement the same.

Figure 26. Contact definition between model components
Parameters used for each contact pair can be defined, such as breaking stress, where the contact between two or more bodies is designed to break. For failure analysis, a glued contact is defined with a breaking stress. The following equation, when satisfied, results in the release of the contact specified.

\[
\left(\frac{\sigma_n}{S_n}\right)^m + \left(\frac{\sigma_t}{S_t}\right)^n > 1
\]  

[1]

In the equation above, \(\sigma_n\) is the contact normal stress

\(\sigma_t\), the contact tangential stress

\(S_n\) and \(S_t\), the user defined allowable normal and tangential stress

Cytec [30] datasheets have been used to extract the mechanical strength of the composite system and the resin, and they are summarized in

Table 6. Failure Strengths of composite lamina used for progressive failure analysis [30]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Material</th>
<th>5320- Unidirectional 0° Ply</th>
<th>5320 Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_{1t}) (MPa)</td>
<td>2469.7</td>
<td>84.757</td>
<td></td>
</tr>
<tr>
<td>(F_{2t}) (MPa)</td>
<td>75.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{3t}) (MPa)</td>
<td>75.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{1c}) (MPa)</td>
<td>1648.5</td>
<td>103.4</td>
<td></td>
</tr>
<tr>
<td>(F_{2c}) (MPa)</td>
<td>268.895</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{3c}) (MPa)</td>
<td>268.895</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{4}) (MPa)</td>
<td>162.716</td>
<td>42.378</td>
<td></td>
</tr>
<tr>
<td>(F_{5}) (MPa)</td>
<td>81.358</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{6}) (MPa)</td>
<td>162.716</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The allowable stress values in Equation [1] are derived from the least strength values from the composite and resin. The glued contact is designed to release as soon Equation [1] is satisfied,
and a touching contact between the components that allows sliding takes its place. After the glued contact is released, the nodes of resin, sensor, and composite components are free to slide.

<table>
<thead>
<tr>
<th>Glue Type</th>
<th>Breaking Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>Normal &amp; Tangential</td>
</tr>
<tr>
<td>Breaking Normal Stress</td>
<td>75.84</td>
</tr>
<tr>
<td>Breaking Normal Exponent</td>
<td>2</td>
</tr>
<tr>
<td>Breaking Tangential Stress</td>
<td>42.3785</td>
</tr>
<tr>
<td>Breaking Tangential Exponent</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 27. Breaking glue parameters for Contact definition

4.2 Boundary Conditions

For the finite element analysis, two load cases were modeled. A thermal load case to simulate the cooling down of the specimen to room temperature, and a compression loading to estimate the compressive strength and observe stress fields in the vicinity of the sensor. Taking into account, the octant symmetry of the model, the mesh had to be constrained in x-, y-, and z-direction for both load cases.

4.2.1 Thermal Boundary Conditions

Laminates in this study were originally cured to a post-cure temperature of 143°C. Residual stresses develop in a composite laminate when it cools down post-cure. Similarly for this specimen, it was expected that residual stresses would be introduced when it cooled down to room temperature (25°C). Garstka et al [33] observed that the first half of cooling doesn’t really have an impact on residual stresses since the material’s viscoelastic relaxation is still at a high level. Therefore, a reduction of 71°C was applied to the model, to observe the formation of residual stresses in the specimen. For this analysis, the thermal expansion coefficients and elastic properties of the cured laminate are not considered temperature dependent. The residual stresses depend on temperature change and not the initial and final readings of temperature. [24]
4.2.2 Mechanical Boundary Conditions

Fixed displacement boundary conditions were applied in the x-, y-, and z-direction to accurately represent the octant symmetry of the FE model as can be seen in Figure 28.

![Figure 28. X-, and Y-Direction Fixed Boundary Conditions and Nodal Compressive displacement condition](image)

Nodal links were used to tie all the nodes to a single node for providing a remote load, and help with calculation of remote stress. A fixed displacement of -0.05mm was applied to the anchor node.

Considering the middle of the sensor as the origin, a summary of all boundary conditions applied is as follows:
X=0 for all nodes at Y=0

Y=0 for all nodes at X=0

Z=0 for all nodes at Z= -6.35 mm

4.3 Composite Failure Criterion

There is gradual selective degradation [32] of element stiffness after initial failure occurs. Six reduction factors dictate the reduction of strength in the component. These reduction factors are stored and updated every increment. They are used at every increment to scale the material modulus and Poisson’s ratio values in each direction. The incremental contribution to the total reduction factor is calculated as:

$$\Delta r_i = -(1 - e^{1-F})$$

Where F is the Failure Index; 0 < F < 1

The new, degraded material moduli are calculated according to:

$$E_{11}^{new} = r_1 E_{11}^{original}$$
$$E_{22}^{new} = r_2 E_{22}^{original}$$
$$E_{33}^{new} = r_3 E_{33}^{original}$$

$$G_{12}^{new} = r_4 G_{12}^{original}$$
$$G_{23}^{new} = r_5 G_{23}^{original}$$
$$G_{31}^{new} = r_6 G_{31}^{original}$$

Another topic of interest in the discussion of progressive failure analysis is element erosion. One of the many advantages of a 3D analysis is to properly observe the kinematics of the loading process and failure propagation. FE Analysis with element erosion is conducted using maximum stress and Hashin-tape failure criteria and the results are then compared to the findings of Bhasin [11].
4.3.1 Maximum Stress Failure Criterion

This failure criterion is non-interactive, and does not take into account the interaction between different components of stress. Individual lamina stresses are compared with corresponding failure strengths [32]. Failure occurs when at least one of the components of stress exceeds the corresponding strength. Maximum Stress criterion is used because of its simplicity and due to the nature of loading being uniaxial. MSC Marc evaluates 6 failure indices and strength ratios at each integration point of every element [32]. Six reduction factors are calculated from each different failure index. For example, \( r_1 \) is calculated from the first failure index, \( r_2 \) from the second failure index and so on. There is no coupling of the different failure modes.

The failure criterion is expressed in Equations [4] to [9].

\[
\begin{align*}
\sigma_1 &= \begin{cases} F_{1t}, & \text{for } \sigma_1 > 0 \\ -F_{1c}, & \text{for } \sigma_1 < 0 \end{cases} & [4] \\
\sigma_2 &= \begin{cases} F_{2t}, & \text{for } \sigma_2 > 0 \\ -F_{2c}, & \text{for } \sigma_2 < 0 \end{cases} & [5] \\
\sigma_3 &= \begin{cases} F_{3t}, & \text{for } \sigma_3 > 0 \\ -F_{3c}, & \text{for } \sigma_3 < 0 \end{cases} & [6] \\
|\tau_{12}| &= F_4 & [7] \\
|\tau_{23}| &= F_5 & [8] \\
|\tau_{31}| &= F_6 & [9]
\end{align*}
\]

Note that the residual stiffness factor, \( a_1 \), which determines the lower bound on stiffness reductions was assumed to be 0.1 for all stiffness properties.

4.3.2 Hashin Tape Failure Criterion

Hashin Tape criterion is a variant of Hashin criterion tailored especially for tape type materials. This criterion is partially interactive, as the failure modes are coupled in a complex
manner. The failure criteria for the fiber and matrix are defined separately, both in tension and compression.

Hashin Tape criterion uses the transverse components of stress similar to the Maximum Stress criterion, and hence is suitable for three-dimensional failure analysis. Note that a quadratic function is used for matrix failure in compression and tension, as a linear function underestimates material strength. [34]

MSC Marc calculates failure indices and strength ratios at every integration point based on equations [10]-[13].

For tensile fiber 1 mode, $\sigma_1 > 0$

$$
\left[ \left( \frac{\sigma_1}{X_f} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 \right]^{1/2}
$$  \[10\]

For compressive fiber 1 mode, $\sigma_1 < 0$

$$
\left[ \left( \frac{\sigma_1}{X_c} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 \right]^{1/2}
$$  \[11\]

For tensile matrix mode, $\sigma_2 + \sigma_3 > 0$

$$
\left[ \left( \frac{\sigma_2+\sigma_3}{Y_f} \right)^2 - \left( \frac{\sigma_{22}\sigma_{33}}{S_{23}^2} \right)^2 + \left( \frac{\sigma_{23}}{S_{23}} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 \right]^{1/2}
$$  \[12\]

For compressive matrix mode, $\sigma_2 + \sigma_3 < 0$

$$
\left( \left( \frac{Y_c}{2S_{23}} \right)^2 - 1 \right) \left( \frac{\sigma_2+\sigma_3}{2S_{23}} \right)^2 - \left( \frac{\sigma_{22}\sigma_{33}}{S_{23}^2} \right)^2 + \left( \frac{\sigma_{23}}{S_{23}} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 + \left( \frac{\sigma_{13}}{S_{13}} \right)^2 + A_1 \left( \frac{\sigma_1}{S_1} \right)^2
$$  \[13\]

Stiffness reduction operations are based on Equation(s) [3]

Specifically for Hashin Tape failure,

$r_1$ depends on fiber failure

$r_2$ depends on matrix failure

$r_3 = r_1; r_4 = r_2; r_5 = r_6 = r_4$
For Hashin Tape failure, there are an additional 5 parameters which characterize moduli reduction. Information on these parameters can be found in the User’s manual for MSC Marc [32]. A parametric study was performed by Manoj [24] to determine these stiffness reduction parameters, using an FE model consisting of one element. The values of these parameters are summarized in Table 7.

Table 7. Values of Stiffness reduction parameters for Hashin Tape criterion [24]

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.6</td>
<td>0.3</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Laminated composites are known to exhibit interlaminar stresses near the free edges. These stresses develop due to elastic property mismatch between layers of the same material, or at the interface of two or more materials. Due to the presence of these stresses, a three-dimensional state of stress develops near the free edges, even though only in-plane loads are applied. In the case of a laminated composite with embedded sensor, these stresses could develop either at the interface between the sensor and bulk composite, or the interface between the resin pocket and bulk composite.

Figure 30. Description of Free Edge on the Specimen

These normal and shear interlaminar stresses have a significant effect on the failure strengths of composite materials. Any numerical analysis of failure strength must account for these interlaminar stresses, as they could impact early or delayed failure for the specimen. For example,
a two-dimensional analysis will be unable to predict the onset of delamination accurately, as it would not account for out-of-plane stresses. With the inclusion of interlaminar stresses, the same laminated composite could fail early, owing to significantly high stresses near the free-edge. Therefore, the three-dimensional analysis provides a more accurate or conservative prediction of failure strengths of composite laminates.

An attempt has been made to correctly determine the compressive strengths of composite laminates embedded with sensors and analyze the 3-dimensional stress fields around the sensor. FEA results have been formulated for failure to compare with experimental results and to better understand the stresses at the free edge near the sensor and resin pocket interfaces with the bulk composite.

Figure 31. (a) FE Model Y-Z Plane; (b) FE Model X-Y Plane
Points A, B, and C in Figure 31 are identified as critical points where stress concentrations are calculated and compared. All stress components are plotted along the path lengths through the width, ending at the free edge at points A, B, and C.

Experimental testing was performed, as per Bhasin [11], for only the $[(90/0/90)_3/90/0]$ stacking sequence specimen and FEA is performed for validation purposes of the same. In addition to that, $[0]_{22}$ stacking sequence is also studied and its results wherever necessary have been compared with previous research [11].

5.1 Stacking Sequence $[0]_{22}$

Literature reveals [21, 11] that maximum degradation of mechanical properties is observed when the sensor is placed perpendicular to the fiber direction. Hence, it is important to analyze the same, computationally. Length of the resin pocket was 1.66mm and fiber waviness was prevalent until the 7th ply for this model unless stated otherwise.

5.1.1 Thermal Loading

Thermal stresses are induced in the cool-down period after curing, when the composite cools down from the post-cure temperature to the room temperature. One of the primary causes of these stresses is mismatch of coefficients of thermal expansion. As discussed in detail in Chapter 4, the coefficients of thermal expansion for the resin pocket, the bulk composite and the sensor are significantly different. The path length to observe stresses is along the width, culminating at the free edge.

From Figure 32, it is seen that there is a concentrated tensile stress of 20 MPa at the free edge, but a largely distributed compressive stress (13 MPa) throughout the sensor-composite interface of the specimen. The two-dimensional numerical analysis by Bhasin [11] for the same
specimen predicts a fully compressive stress throughout the width but fails to consider the tensile stress at the free edge, which would eventually contribute to early failure of the specimen.

Similarly, at the root of the resin pocket, a transverse tensile stress at the free edge counterbalances the compressive stress throughout the width. This stress distribution profile could be attributed to varying mechanical behavior because of different material properties.

Figure 32. Contour Band representation of Residual Thermal Stresses in the transverse direction ($\sigma_{yy}$) for $[0]_{22}$

5.1.1.1 Residual Stress Distribution along the Thickness

Figure 32 shows a 3D stress field is present around the sensor and thermal stresses start to nullify away from the sensor in the thickness direction. A plot of transverse normal thermal stresses is shown in Figure 33, which shows the same, and only negligible stresses are observed after the 4th ply. This is because there is no change in material properties and coefficients of thermal
expansion, unlike the interface between the sensor and bulk composite, in addition to the waviness in fibers dissipating.

![Transverse Normal Stresses due to curing](image)

**Figure 33. Residual Thermal Normal Stresses ($\sigma_{yy}$) in the transverse direction due to curing.**

Along the width, interlaminar shear stresses develop in the YZ-direction to resist the relative motion of successive plies and ply-sensor interface as shown in Figure 33. This local interlaminar shear stress distribution is due to the difference in the coefficients of thermal expansion of the sensor, composite and the resin-rich region. Out-of-plane shear stress is generated because the in-plane shear stress must vanish at the free edge. It should be stated though, that in-plane stresses do not completely vanish at the free edge due to Poisson effects.

A stress singularity, or high amounts of shear stress is observed at the free edge. This stress has the ability to initiate delamination at the intersection of the interface and the free edge, as has also been seen in experiments and numerical analysis carried out by Pipes et al [19]. Similar to normal stresses, a significant reduction in shear stresses is observed away from the sensor, as the amplitudes of fiber waviness reduce.
5.1.1.2 Effect of Sensor Material on Residual Stresses

The effect of different materials was studied on the distribution of thermal stresses along the width, culminating at the free edge. Apart from the titanium based alloy sensor material that was used in the experimental testing, material properties of optical fiber, tungsten and Teflon were fed to the FE model. Maximum stresses were predictably observed for tungsten and showed good correlation with Bhasin [11].

Material discontinuity and different coefficients of thermal expansion are the primary reasons for varying stress profiles. The normal component of transverse stress due to curing is plotted in Figure 35 and the out-of-plane component of shear stress is plotted in Figure 36.

Figure 34. Residual Thermal out-of-plane Shear Stresses ($\tau_{yz}$) due to curing.
Figure 35. Effect of Sensor Material on Transverse Normal Stress due to Curing

Figure 36. Effect of Sensor Material on out-of-plane Shear Stress ($\tau_{yz}$) due to Curing
5.1.2 Compressive Loading

A linear elastic analysis was performed for the compressive load case, so no failure or contact release criteria was used. A displacement of -0.05mm in the x-direction was applied to load the bulk composite in compression. Note that the model is pre-loaded with the thermal stresses discussed in Section 5.1.1.

According to literature [17, 21, 11], a transverse tensile stress was expected at the interface of the sensor-composite laminate (Point C) and its vicinity (Point B), while a transverse compressive stress was expected at the root of the resin pocket. This results in delamination, which propagates from the sensor towards the root of the resin pocket. This finding was corroborated by simulation, as a high tensile stress was observed in the transverse direction at the sensor-composite interface, while a transverse compressive stress was observed at the root of the resin pocket.

Unidirectional composites have low transverse tensile strengths, so Point C and Point B were earmarked as areas of potential failure.

Figure 37. Contour Band representation of Thermal + Mechanical Stress in the transverse direction (σyy) for [0]_{22}
One way of determining stress criticality at Points A, B and C is to record stress concentrations. Stresses at these locations, at any point in the compression loading, when divided by the remote stress, gives the stress concentration. Stress concentrations are shown in Table 8.

Table 8. Stress concentrations in [0]22 stacking sequence

<table>
<thead>
<tr>
<th>Critical Locations</th>
<th>$K_1 = \sigma_{11}/\sigma_r$</th>
<th>$K_2 = \sigma_{22}/\sigma_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.84</td>
<td>0.098</td>
</tr>
<tr>
<td>B</td>
<td>1.32</td>
<td>-0.025</td>
</tr>
<tr>
<td>C</td>
<td>0.57</td>
<td>-0.069</td>
</tr>
</tbody>
</table>

Negative signs for stress concentrations for $K_2$ at Points B and C indicate tensile stresses due to a compressive load, a result in agreement with previous research.

If plies in a composite were not bonded to each other, they would undergo relative deformation with respect to each other. However, the reality is that plies in a composite are bonded together and resist deformation relative to one another. This resistance gives rise to the formation of a lateral normal stress, $\sigma_{zz}$. To satisfy traction free boundary conditions at the free edge, an interlaminar shear stress, $\tau_{yz}$ develops, but tends to nullify at the free edge to satisfy stress equilibrium. Interlaminar normal stress ($\sigma_{yy}$) also develops in the laminate to satisfy moment equilibrium. [35]

As a result, both normal and shear interlaminar stresses are present near the free edge of the laminate. Since all the plies are of $0^\circ$ orientation, the magnitude of interlaminar stresses is not expected to be significant. But due to the material and geometric non-linearity arising from the sensor and resin pocket, interlaminar stress distribution in the vicinity of this region will be of great interest, and influence failure. The variation of these interlaminar stresses on the free edge, from the top edge of the laminate to the midplane are plotted in Figure 38 and Figure 39.
The results for Interlaminar normal stresses at the free edge indicate the presence of high transverse tensile stresses in the vicinity of the sensor and a high compressive stress at the root of the resin pocket, which is in accordance with Shivakumar [21], Bhasin [11] and Huang et al [15].

Interlaminar shear stress, $\tau_{yz}$ at path lengths A, B and C is supposed to diminish at the free edge but it is not completely absent. It is seen though, that it is negligible as compared to the $\tau_{xy}$.
component of interlaminar shear stress, which would eventually result in the occurrence of shear failure at the root of the resin-rich pocket.

5.1.3 Progressive Failure Analysis

The load carrying capability in composite materials is maintained after the first failure has occurred. Extensive study exists and is ongoing, ranging from composite part failure initiation to complete failure. MSC Marc [32] allows progressive failure analysis with the help of gradual strength degradation. The laminate is considered linear up until the point of initial failure. The initial failure is defined by experimental data and failure strengths of components in different directions, as sourced from material datasheets [30]. These failure strengths for each lamina orientation are summarized in Table 6. There are various failure criteria options that can be used in MSC Marc, but for this study, Maximum Stress and Hashin Tape criterion are used, as they do not require any experimentally obtained interaction factors.

No testing was performed for [0]_{22} stacking sequence by Bhasin [11], therefore, there was no test data available for validation of the numerical simulations. The unidirectional laminate was studied to record the effect of the presence of sensor and the resin pocket on the composite laminate, which has already been documented in the previous sections. Another aim for studying the [0]_{22} stacking sequence was to observe the failure progression in the composite. Finally, the stress-strain curve for this analysis was compared with the findings of Bhasin’s [11] test and 2D FE model results.

5.1.3.1 Progression of Failure using Maximum Stress Failure Criterion

For this type of analysis, the failure flag and breaking contact was activated. Breaking contact resulted in release of contact as soon as failure strengths were breached within the model. Only Maximum Stress criterion was used for this stacking sequence.
Equivalent von-Mises stress of up to 78 MPa were observed before the compression load-case began.

Figure 40. Residual Stresses in the Composite due to curing

It is interesting to see that the maximum stress due to curing develops at the sensor-composite interface on the free edge of the specimen. It is necessary to evaluate the breakdown of the specimen and verify if the delamination due to compression also initiates at the sensor-composite interface.
Figure 41. Start of Compression load-case for [0]_{22} UD Laminate

The disappearance of yellow and red contour bands indicates release of contact, and hence, splitting of the composite laminate from the sensor. Due to this contact status feature, the presence of glued contact between the sensor-composite, composite-resin pocket and resin pocket-sensor is clearly shown in Figure 42.

Figure 42. Crack initiation due to compression for [0]_{22} UD Laminate
As expected, the failure initiation occurs at the interface of the sensor and the ply in contact at the free edge. Initial failure occurs at a remote stress of 542 MPa. The arrows in Figure 40 depict the direction and extent of crack propagation. Shivakumar et al [21] and Bhasin [11], in their analysis, predict crack propagation from the sensor to the root of the resin pocket, but it can be seen here that the crack also propagates in the lateral direction. Initial failure was also observed in the experiments for [(90/0/90)\textsubscript{3}/90/0]\textsubscript{s} stacking sequence specimen, and it does not occur through the whole width of the specimen. One of the most effective ways to accurately represent this phenomenon is to use solid elements for this type of analysis, as is chosen for this study.

![Crack Propagation](image)

**Figure 43. Direction of crack propagation for [0]_{22} UD Laminate**

Figure 43 shows that crack propagation occurs in both lateral and longitudinal directions, initiating from the free edge. At this point in the numerical analysis, there is complete separation between the sensor and its neighboring laminas due to excessive transverse tensile stresses which result in contact release between sensor and neighboring laminas. Continued compressive loading
would result in fiber fracture similar to the ultimate failure seen for [(90/0/90)/90/0]s stacking sequence compression test [11]. For the [0]22 specimen, ultimate failure was observed at a remote stress of 1534 MPa.

MSC Marc allows failing elements to be eroded using a given failure criterion. Element deletion was activated for failure analysis to simulate the failure process and understanding the regions where these failures occurred.

![Ultimate Failure for [0]22 stacking sequence specimen](image)

Figure 44. Ultimate Failure for [0]22 stacking sequence specimen

### 5.1.3.2 Comparison of [0]22 stacking sequence results with Bhasin [11]

All the nodes of the axially loaded face were tied to a single node and a compressive load applied to it. A fixed displacement of -0.1mm was applied in the X-direction and the specimen was loaded until ultimate failure.

The anchor node was then used to measure the reaction forces, and ultimately the average remote stress applied to the specimen. Strains were evaluated for elements on the Z-axis symmetry
plane, similar to how strain gages were placed in the experimentation process explained in earlier chapters.

Stress vs. strain curves for the \([0]_{22}\) stacking sequence laminate were then plotted and compared to the results from two-dimensional numerical analysis carried out by Bhasin [11].

![Stress-Strain curve for \([0]_{22}\) UD Laminate and comparison with Bhasin [11]](image)

Figure 45. Stress-Strain curve for \([0]_{22}\) UD Laminate and comparison with Bhasin [11]

It is observed from Figure 45 that crack initiation begins at a lower stress in three-dimensional analysis (Point A – 542 MPa). The most likely reason for this is the presence of high interlaminar stresses in the transverse direction at the free edge, because the crack initiates at the free edge. The crack then propagates in the transverse and lateral directions before the 0° lamina in contact with the resin pocket completely splits from the resin pocket at Point B.
It is interesting to note that the specimen still has a load carrying capability beyond Point B as evidenced by the stress-strain curve and corroborated by the findings of Shivakumar et al [21] and Bhasin [11].

The root of the resin pocket then fails at 1485 MPa before ultimate failure due to microbuckling at 1534 MPa. Therefore, the compressive strength of the $[0]_{22}$ laminate is estimated to be 1534 MPa. From Cytec datasheets [30], the compressive strength of the $0^\circ$ lamina is 1648 MPa. It is deduced, that due to the embedment of a sensor, there is a 7% reduction in compressive strength of the laminate. A comparison with the two-dimensional numerical analysis is summarized in Table 9.

Table 9. Comparison of compressive strengths with Bhasin [11]

<table>
<thead>
<tr>
<th></th>
<th>Initial Crack (MPa)</th>
<th>Ply Split (MPa)</th>
<th>Resin Failure (MPa)</th>
<th>Ultimate Failure (MPa)</th>
<th>%age Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raghav</td>
<td>542</td>
<td>1022</td>
<td>1485</td>
<td>1534</td>
<td>7%</td>
</tr>
<tr>
<td>Material Data</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1648</td>
<td>-</td>
</tr>
</tbody>
</table>

5.2 Stacking Sequence $[(90/0/90)_3, 90/0]_S$,

This cross-ply stacking sequence was chosen for the dual purpose of analyzing interlaminar stress distribution near the traction free edges and validating the finite element model by comparing the stress-strain curve to test data from Bhasin [11]. The failure in the test initiated near the sensor-composite interface but the exact location of failure could not be properly captured in the test due to unavailability of high speed photography. The compressive loading is discussed in the next section, which will be followed by progressive failure analysis, a discussion on
interlaminar stresses in cross-ply laminates and a comparison between the results of the FE model with test data.

### 5.2.1 Compressive Loading

The procedure followed for compressive loading of the [(90/0/90)]<sub>3</sub>/90/0s ply is the same as the [0]<sub>22</sub> laminate. A linear elastic analysis was carried out to study the interlaminar stress distribution in the vicinity of the sensor and the resin pocket.

![Figure 46. FE Model Material Properties for [(90/0/90)]<sub>3</sub>/90/0s stacking sequence laminate](image)

The stress concentrations for critical points A, B, C (as defined in Section 5.1.2) are summarized in Table 10.

<table>
<thead>
<tr>
<th>Critical Locations</th>
<th>$K_1 = \sigma_{11}/\sigma_{\text{remote}}$</th>
<th>$K_2 = \sigma_{22}/\sigma_{\text{remote}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.26</td>
<td>0.127</td>
</tr>
<tr>
<td>B</td>
<td>2.96</td>
<td>-0.023</td>
</tr>
<tr>
<td>C</td>
<td>1.36</td>
<td>-0.148</td>
</tr>
</tbody>
</table>

Investigation of interlaminar stresses for cross-ply laminates is a broad area of research. Due to Poisson’s ratio mismatch between 0° and 90° plies, and resistance to relative lateral and transverse deformations, interlaminar shear stress $\tau_{xy}$ and normal stress $\sigma_{yy}$ are developed in the laminate as shown in Figure 47. The findings of this study supplement the in-plane stresses already
documented by Bhasin [11]. In this particular figure, Z- is the thickness direction and Y- is the lateral direction.

Figure 47. Generation of Interlaminar shear stresses in a crossply laminate [8]

The interlaminar stresses observed in the \([(90/0/90)_3/90/0]\) laminate are illustrated in the following plots. All stresses are plotted at the free edge, starting from the top face coming down to half the thickness. Three different locations (A, B and C) are chosen to descriptively show the interlaminar stress distribution at the free edge.

Figure 48. Transverse Normal Stress, \(\sigma_{xy}\) at the free edge, from the top edge to the midplane
The transverse normal stress distribution at Location C is tensile in nature, and in moving towards the root of the resin pocket at Location A, more compressive interlaminar stresses are observed.

Apart from transverse normal stress, there is a presence of interlaminar shear stress, $\tau_{xy}$. Stress variations are seen at interfaces between $0^\circ$ and $90^\circ$ plies.

Figure 49. Interlaminar shear stress, $\tau_{xy}$ at the free edge, from the top edge of the laminate to the sensor-composite interface.

These findings are in accordance with the failure mode for the test and show that if delamination were to occur, it would most likely initiate at the interface of the sensor and composite, at the free edges, and would progress laterally along the width and longitudinally towards the root of the resin pocket.

5.2.2 Progressive Failure Analysis

5.2.2.1 Progression of Failure

Maximum stress and Hashin-Tape criterion were both used for the failure analysis of this stacking sequence. The initial crack occurs at the interface of the sensor and composite and tends
to propagate towards the root of the resin pocket and also laterally through the width. The propagation of failure for [(90/0/90)_s/90/0]_s stacking sequence is as shown in Figure 50.

Figure 50. Progressive Failure Analysis for [(90/0/90)_s/90/0]_s laminate
5.2.2.2 Comparison of \([(90/0/90)_3 90/0)_s\] stacking sequence results with Bhasin [11]

A similar approach as that followed for the \([0]_{22}\) laminate was also followed for the \([(90/0/90)_3 90/0)_s\] laminate and a stress-strain curve was plotted to compare the finite element analysis results to test and FEA results from Bhasin [11].

For both Maximum Stress and Hashin Tape Failure Criterion, a more brittle fracture was observed due to microbuckling, when compared to test results.

![Stress vs. Strain curves](image)

Figure 51. Stress vs. Strain curves for \([(90/0/90)_3 90/0)_s\] laminate and Comparison with test [11]

For this laminate under Maximum Stress failure criterion, it was observed that the load carrying capability after initial failure was not significant, when compared to the \([0]_{22}\) laminate. Initial failure was observed at 302 MPa and final failure at 588 MPa. For the experiment referenced
in Section 3.6, ultimate failure strength is 594 MPa. It is observed that Maximum Stress Criterion predicts the failure strength very accurately for the [(90/0/90)_3/90/0]_s stacking sequence specimen (1% error), which is within the range of experimental scatter.

Hashin-Tape failure criterion presents a more conservative solution and predicts the stress for ultimate failure at 545.6 MPa (8.2% difference)

A summary of the comparison between the finite element models and the test data is shown in Table 11.

Table 11. Comparison between Compressive strengths of Finite element models and test data for [(90/0/90)_3/90/0]_s

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Initial Cracking (MPa)</th>
<th>Ultimate Failure (MPa)</th>
<th>%age difference with test (594 MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Model (Maximum Stress)</td>
<td>302</td>
<td>588.1</td>
<td>-1.0%</td>
</tr>
<tr>
<td>Hashin Tape</td>
<td>262</td>
<td>545.6</td>
<td>-8.2%</td>
</tr>
<tr>
<td>2D Model (Maximum Stress)</td>
<td>240</td>
<td>647.0</td>
<td>9.1%</td>
</tr>
</tbody>
</table>

Overall, a more conservative solution through three-dimensional analysis is predicted in this current study. 2D numerical analysis results from Bhasin [11] predicts a compressive failure strength of 647 MPa, which is significantly higher than the compressive strength observed in the test.
Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Numerical analysis for the 5230-UD epoxy resin system was conducted, by embedding a titanium-based microwire sensor. The results of the numerical, FE analysis were compared to test results that had been conducted in the past [11].

A three-dimensional finite element analysis was conducted by effectively condensing the geometry of a coupon using octant symmetry. As a result of using symmetry boundary conditions, more than 50 hours of computational time was saved over 6 months, in conducting the numerical analysis. Two stacking sequences: [0]_{22} and [(90/0/90)_3/90/0]_3 were studied.

Residual stresses, induced in a composite laminate during the cool-down period while curing tend to introduce large interlaminar stresses at the free-edge, in the vicinity of the sensor. These stresses are a function of how far they are from the free edge, and they nullify away from the free edge. The stresses at the free edge are visibly larger as discussed in detail in Chapter 5, compared to other locations on the width, which, most likely causes failures to initiate at the free edge.

The study of effect on compressive strength of a laminate due to sensor embedment and the study of development of interlaminar stresses near the free edge were merged together to study the impact of these free-edge stresses on failure initiation and delamination in composites with embedded sensors.

Stress distributions are plotted at 3 critical locations through the thickness and along the width, to study the transverse and lateral variation of interlaminar stresses in both the stacking sequences discussed.
Stress concentrations at the sensor-composite interface (Location C), composite-resin pocket interface (Location B), and root of the resin pocket (Location A) were calculated and tabulated in Sections 5.1.2 and 5.2.2.

Progressive failure analysis was conducted to understand the progression of crack longitudinally for both stacking sequences. Finite element analysis results for the \([(90/0/90)_3/90/0]\) laminate were compared to previously conducted test results [11] and a very good correlation for compressive failure strength was observed as illustrated in Section 5.2.2.2.

To sum up, analysis of free edge stresses is very important for high-risk applications in the aerospace industry. The magnitude of these stresses varies according to stacking sequence, geometry, presence of high concentrations, loading conditions and thermal loading. Since there are too many variables, it is important to study these on practical industry problems before proceeding with full-scale component manufacturing.

6.2 Future Study

For further studies into structural health monitoring with embedded sensors and influence of interlaminar stresses on structural damage, the following recommendations could be explored in detail:

1. Analysis of sensor embedment in composite laminates away from the free-edges, resulting in resin deposition in both longitudinal and lateral directions.

2. A comparison study between layered shells and 3D hexahedral finite elements for the analysis of interlaminar stresses in laminated composites.

3. Inclusion of spatially varying fiber volume fraction in the wavy region of the composite, as volume fraction varies near the resin pocket owing to compaction.
4. Application of mixed loading to understand the influence of interlaminar stresses near the free edges of a composite.
REFERENCES


APPENDIX
Appendix A

MESH SENSITIVITY STUDY FOR [0]_{22} LAMINATE

A mesh sensitivity study was carried out to study the variance of stress magnitudes at critical locations. There were 3 different mesh densities used for this purpose.

1. Coarse Mesh – 6340 elements

Representation of Coarse mesh density for the [0]_{22} stacking sequence laminate

The coarse mesh contains 10 element columns along the width of equal element size. Presence of high aspect ratio elements near the free edge resulted in inaccurate observations of stress near the free edge, so the elements near the free-edge were made denser in the next iteration.
2. Intermediate Mesh – 10,144 elements

Representation of Intermediate mesh density for the $[0]_{22}$ stacking sequence laminate

The mesh contains 16 elements along the width. High aspect ratio elements near the free edge were made denser by inserting 6 columns of elements to replace one column from the coarse mesh. This resulted in a better representation of the variation of stress near the free-edge.
3. Fine Mesh – 25,360 elements

**Representation of Fine mesh density for the [0]$_{22}$ stacking sequence laminate**

The finest iteration mesh contained more than 25,000 elements and consisted of 40 element rows along the width. This mesh had ideal aspect ratio elements, but the use of more elements resulted in a significant computational time penalty. The region near the free edge was represented by a highly dense mesh to capture the variation in stress.

The decision to choose the appropriate mesh depended on convergence in stress at specific locations, and computational time. To compare the stresses at specific locations for the 3 different mesh sizes, Thermal interlaminar normal stress, $\sigma_{yy}$, was plotted along the width, starting from the X-Y symmetry plane of the laminate to the free-edge at the sensor-first ply interface.
Comparison of Transverse Normal Stress, $\sigma_{yy}$ for three different mesh sizes

Increasing of the density simply resulted in an increase in peak stress at the free-edge node due to the presence of a stress singularity. Therefore, to get a correct representation of the tensile transverse stresses at the free edge, the density cannot be increased further. It will simply lead to continued increase in stresses at the free-edge.

Computational time penalty is also a criteria for choosing appropriate mesh size for this analysis.

Comparison of computational times for three different mesh sizes

<table>
<thead>
<tr>
<th>Mesh Size</th>
<th>Runtime (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>12.2</td>
</tr>
<tr>
<td>Intermediate</td>
<td>13.06</td>
</tr>
<tr>
<td>Fine</td>
<td>105.9</td>
</tr>
</tbody>
</table>
From the comparison of computational time required to run a linear elastic analysis for all the mesh sizes, it is found that the intermediate mesh size resulted in an accurate representation of the stresses without inducing a significant computational time penalty. Therefore, the intermediate mesh size was chosen for this analysis.