Title
Health Monitoring of Composites with Embedded Fiber Bragg Gratings

Permalink
https://escholarship.org/uc/item/78g9t0bm

Author
Yeager, Michael J.

Publication Date
2017

Peer reviewed|Thesis/dissertation
Health Monitoring of Composites with Embedded Fiber Bragg Gratings

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy

in

Structural Engineering

by

Michael J. Yeager

Committee in charge:

Professor Michael D. Todd, Chair
Professor Charles Farrar
Professor William Hodgkiss
Professor Hyonny Kim
Professor Francesco Lanza di Scalea

2017
The Dissertation of Michael J. Yeager is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

Chair

University of California, San Diego

2017
# Table of Contents

Signature Page ........................................................................................................ iii
Table of Contents...................................................................................................... iv
List of Abbreviations .............................................................................................. vii
List of Symbols ........................................................................................................ ix
List of Figures .......................................................................................................... x
List of Tables ........................................................................................................... xv
Acknowledgements .................................................................................................. xvi
Vita ............................................................................................................................ xviii
Abstract .................................................................................................................. xxi

## Chapter 1 Introduction......................................................................................... 1
  1.1. Research Motivation ...................................................................................... 1
  1.2. Introduction to Structural Health Monitoring ............................................... 2
  1.3. Vibration based damage identification ......................................................... 4
  1.4. Fiber Bragg Gratings ................................................................................... 6
      1.4.1. Application to SHM systems ................................................................. 6
      1.4.2. Theoretical overview .......................................................................... 6
  1.5. Contributions of the Dissertation Work ....................................................... 8

## Chapter 2 Viability of Sensing Methodology....................................................... 9
  2.1. Introduction .................................................................................................... 9
  2.2. Wetted Environment Testing ...................................................................... 9
  2.3. OVB vs. VARTM ......................................................................................... 14
  2.4. Fiber Egress ................................................................................................ 17
      2.4.1. Introduction ........................................................................................ 17
      2.4.2. Proposed Design .............................................................................. 18
      2.4.3. Fabrication Procedure .................................................................... 20
      2.4.3.1. Connector Assembly ................................................................. 20
      2.4.3.2. Connector Installation ............................................................... 23
      2.4.4. Survivability Testing .................................................................... 26
# 2.4.5. Conclusions and Observations

Chapter 3 Damage Detection Scenario: Connection Damage

## 3.1. Bearing Damage

### 3.1.1. Test Article Design

### 3.1.2. Fabrication and Sensor Embedment

#### 3.1.2.1. Residual Strains and Spectral Chirping

### 3.1.3. Testing and Data Acquisition

#### 3.1.3.1. Wavelength Hopping Correction

### 3.1.4. Damage Sensitive Feature Extraction

#### 3.1.4.1. Frequency Domain

#### 3.1.4.2. Time Domain

### 3.1.5. Mahalanobis Distance Based Discrimination Framework

### 3.1.6. Hypothesis Testing

## 3.2. Fastener Loosening

### 3.2.1. Introduction

### 3.2.2. Spectral Modeling of FBGs

#### 3.2.2.1. Introduction

#### 3.2.2.2. Theory: Transfer Matrix Method

#### 3.2.2.3. Imposed Strain Field

#### 3.2.2.4. Washer Design

#### 3.2.2.5. Test Article Fabrication

#### 3.2.2.6. Experimental Validation

#### 3.2.2.7. Dual Purpose Sensor

## 3.2.3. Experimental Validation

## 3.2.4. Hypothesis Testing

Chapter 4 Damage Detection Scenario: Impact Damage

## 4.1. Introduction and Motivation

## 4.2. Test Article Fabrication and Experimentation

## 4.3. Feature Extraction

#### 4.3.1. Power Spectral Density Feature

#### 4.3.2. Cross Power Spectral Density Feature

#### 4.3.3. Time Domain Feature – AR Coefficients

## 4.4. Hypothesis Testing

#### 4.4.1. Chi-Square Distribution

#### 4.4.2. Hypothesis Formulation

#### 4.4.3. Test Results and Discussion

Chapter 5 Statistical Model Refinement

## 5.1. Introduction and Motivation
5.2. Robust Distances.................................................................................................................99
5.3. Illustrative Example...........................................................................................................100
5.4. Application to Experimental Data ....................................................................................104

Chapter 6 Damage Localization ............................................................................................106
  6.1. Introduction and Motivation ............................................................................................106
  6.2. Definition of the Feature for Localization .....................................................................107
  6.3. Imaging of the Damage Location ....................................................................................109
  6.4. Sensor Network Density ................................................................................................115

Chapter 7 Conclusions and Future Work.............................................................................121
  7.1. Conclusions ....................................................................................................................121
  7.2. Future Work ...................................................................................................................124

References ................................................................................................................................125
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>Autoregressive</td>
</tr>
<tr>
<td>ARX</td>
<td>Auto-regressive Model with Exogenous Inputs</td>
</tr>
<tr>
<td>BLWN</td>
<td>Band-Limited White Noise</td>
</tr>
<tr>
<td>BVID</td>
<td>Barely Visible Impact Damage</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Polymer</td>
</tr>
<tr>
<td>CPSD</td>
<td>Cross Power Spectral Density</td>
</tr>
<tr>
<td>FBG</td>
<td>Fiber Bragg Grating</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Domain Decomposition</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FOS</td>
<td>Fiber Optic Sensor</td>
</tr>
<tr>
<td>FRF</td>
<td>Frequency Response Function</td>
</tr>
<tr>
<td>FRP</td>
<td>Fiber Reinforced Polymer</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half of Maximum</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass Fiber Reinforced Polymer</td>
</tr>
<tr>
<td>LDV</td>
<td>Laser Doppler Vibrometer</td>
</tr>
<tr>
<td>MCD</td>
<td>Minimum Covariant Determinant</td>
</tr>
<tr>
<td>MME</td>
<td>Structural Health Monitoring</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-electro-mechanical system</td>
</tr>
<tr>
<td>MVE</td>
<td>Minimum Volume Ellipsoid</td>
</tr>
<tr>
<td>MVT</td>
<td>Multivariate Trimming</td>
</tr>
<tr>
<td>MWSM</td>
<td>Medium Weight Shock Machine</td>
</tr>
<tr>
<td>NDE</td>
<td>Nondestructive Evaluation</td>
</tr>
<tr>
<td>OGK</td>
<td>Orthogonalized Gnanadesekian-Ketternring</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>OVB</td>
<td>Oven Vacuum Bag</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead Zirconate Titanate</td>
</tr>
<tr>
<td>RD</td>
<td>Random Decrement</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Squared</td>
</tr>
<tr>
<td>SHM</td>
<td>Structural health monitoring</td>
</tr>
<tr>
<td>SPR</td>
<td>Statistical Pattern Recognition</td>
</tr>
<tr>
<td>SRSS</td>
<td>Square Root Sum of Squares</td>
</tr>
<tr>
<td>VARTM</td>
<td>Vacuum Assisted Resin Transfer Method</td>
</tr>
<tr>
<td>VBDI</td>
<td>Vibration Based Damage Identification</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS

$\lambda_B$  Bragg wavelength

$n_{\text{eff}}$  Effective index of refraction across a grating

$\Lambda_0$  Spatial period of a grating

$\rho_e$  Photo-elasticity constant of a fiber

$\varepsilon$  Strain

$a_p$  AR model coefficient

$e(t)$  Autoregressive prediction error

$\hat{S}_{\Sigma}$  Power spectral density estimate

$\omega$  Frequency

$X$  Feature vector

$\bar{X}$  Arithmetic mean of baseline feature vectors

$d$  Mahalanobis squared distance

$\Sigma$  Sample covariance

$H_0$  Null hypothesis in a binary hypothesis test

$H_1$  Alternate hypothesis in a binary hypothesis test
LIST OF FIGURES

Figure 1: Fiber Bragg gratings ................................................................. 7
Figure 2: (left) mold set-up; (middle) sacrificial material for lead support; (right) test panels in vacuum bag .......................................................... 11
Figure 3: Bending test fixture, including aquarium for wetted environment .............. 11
Figure 4: Embedded sensor performance to failure (left) and within elastic range (right) ............................................................................. 13
Figure 5: Wet vs dry performance for external sensor (left) and wet performance of embedded sensors (right) ..................................................... 14
Figure 6: Phase IB test setup (top), Carbon 1 test results (bottom left), Carbon 2 test results (bottom right) ............................................................... 15
Figure 7: Micro-bending losses .................................................................... 16
Figure 8: Plan (left), elevation (center), and exploded (right) view of connector. All measurements in inches ....................................................... 19
Figure 9: 3D Printed Connector (left) and bottom of connector (right) ....................... 19
Figure 10: Connector bottom with optical cables secured in channel with adhesive .......... 21
Figure 11: Potting the connector in epoxy ........................................................ 22
Figure 12: Fully potted connector .................................................................. 22
Figure 13: Sensor layout and connector position schematic .................................... 24
Figure 14: Connector bonded to the partially cured sub panel (left), additional 2 layers of fabric placed over the connector (center), and connector under the vacuum bag (right) ................................................................. 25
Figure 15: Panel during resin infusion (left), connector after debagging (center), and connector after break-away tab was removed. (right) ....................... 25
Figure 16: Final connector (left) and connector with patch cables affixed for interrogation (right) ....................................................................... 26
Figure 17: Medium Weight Shock Machine schematic ........................................ 27
Figure 18: Panel with shaker attached ................................................................ 28
Figure 19: Panel with bolted pedestal attached to hold additional mass ................... 29
Figure 20: Damage in panel (left) and panel with back light to reveal delaminations (right) ........................................................................................................30
Figure 21: Connector damage after blow 7 ..........................................................................................................................31
Figure 22: Top two fabric layers covering the flange of the connector........................................................................32
Figure 23: Bolted specimen sensor layout (left) and array configuration in the optical space (right) ...............................................................34
Figure 24: Generation of modal strain difference mappings ..............................................................................................35
Figure 25: Sensor layout and installation (left) and completed panel ready for cure (right) ..........................................................36
Figure 26: Bragg spectra for all arrays in test article ........................................................................................................37
Figure 27: Bragg spectra comparison, pre cure vs. post cure ............................................................................................37
Figure 28: Bragg spectra comparison, pre cure vs. post cure with spectra aligned .........................................................38
Figure 29: Testing equipment (bottom) and test setup (top) ............................................................................................39
Figure 30: Bearing damage observations: (far left) after 10,000 lb. load, no visible damage; (center left) after 20,000 lb. load, slight bearing damage; (center right) after 30,000 lb, significant bearing damage, and (far right) critical bearing damage and severe specimen elongation.........................................................41
Figure 31: Raw time history with significant wavelength hopping ......................................................................................42
Figure 32: Time history corrected via an AR model ........................................................................................................42
Figure 33: Power spectra from sensor 5 for all damage states .........................................................................................43
Figure 34: Normalized power spectra for sensor 5 – 5th peak ..........................................................................................43
Figure 35: (left) Sensor 1 Mahalanobis distance scatter plot; (center) Sensor 5 Mahalanobis distance scatter plot; (right) Sensor 8 Mahalanobis distance scatter plot ..........................................................................................45
Figure 36: Mahalanobis distances of AR model coefficients for (left) sensor 1; (center) sensor 5; and (right) sensor 8 ..................................................................................................................................47
Figure 37: Binary hypothesis test results: 50% sensor agreement (left) and 15% sensor agreement (right). Red and green represent true structural state and y-axis value represents predicted state with 0 being an undamaged prediction and 1 being a damaged prediction ........................................................................49
Figure 38: Uniform and non-uniform strains in FBGs ........................................................................................................52
Figure 39: Strain gradients of increasing intensity spanning the length of the gradient .......................... 57

Figure 40: Increased spectral broadening in reflected Bragg spectra due to imposed strain gradients.................................................................................................................. 58

Figure 41: Load case to produce desire strain profiles ................................................................................. 59

Figure 42: FE Model of composite surface with 2 traction loads (red arrows) applied .................. 60

Figure 43: Normalized strain profile in z-direction as a result of loading case in Figure 26. .......................................................................................................................... 61

Figure 44: Washer design (left) and final printed washer (right) ................................................................. 62

Figure 45: Installed washer schematic (plan view). ...................................................................................... 63

Figure 46: Installed washer schematic (cross section view). ........................................................................ 63

Figure 47: Composite layup with embedded sensors (left), and layup under vacuum before placement in curing oven (right). ............................................................................. 65

Figure 48: Reflected Bragg spectra at increasing torque levels ................................................................. 66

Figure 49: Bolt torque vs. FWHM of reflected Bragg spectra ...................................................................... 68

Figure 50: Bottom side of composite specimen with surface mounted FBG installed .................. 70

Figure 51: Test specimen in test fixture with shaker installed ................................................................. 71

Figure 52: Histogram of 100 FWHM independent measurements at a torque of 10 N-m ........................................... 72

Figure 53: Strain time histories recorded from the 2 FBG sensors from the white noise input ............ 73

Figure 54: FWHM measurement after the shaking (green line) in context of 100 previous tests ........................................................................................................ 74

Figure 55: Sensor layout (left) and naming convention and placement measurements, in inches (right) .............. 77

Figure 56: Extruded aluminum test figure ................................................................................................. 78

Figure 57: Impact locations for the test article ......................................................................................... 79

Figure 58: Testing Flow .............................................................................................................................. 80

Figure 59: Illustration of damage progression ......................................................................................... 82
Figure 60: Impact specimen after testing ................................................................. 83
Figure 61: Power spectral density feature for all 40 sensors ........................................ 84
Figure 62: Mahalanobis distances for Sensor 5 – Power spectral density feature .............. 85
Figure 63: CPSDs for baseline and undamaged cases .................................................. 87
Figure 64: Mahalanobis distances for CPSD feature for 4 sensor pairs ......................... 88
Figure 65: AR Model order vs. prediction error .......................................................... 89
Figure 66: Mahalanobis distances for all sensors: AR coefficients as the feature .......... 90
Figure 67: Baseline Mahalanobis distances for sensor pair 15 & 29 compared with a chi-square distribution with 5 degrees of freedom (implying there were 5 prominent peaks in the CPSD) ........................................ 92
Figure 68: Comparison of baseline to damaged Mahalanobis distances. The fitted chi-square distribution is given by the blue curve ................................................. 93
Figure 69: Specific hypothesis test visualization for 4 different sensor pair combinations. .......................................................... 94
Figure 70: Outcomes of varying confidence threshold selections. The solid line represents overall correct detection percentage (left vertical axis), the dashed and dotted lines represent the false-positives and false-negatives respectively (right vertical axis) ........................................... 96
Figure 71: Bivariate data with undamaged and damaged observations ............................ 101
Figure 72: Outlier detection using classical estimation for location and scatter ................. 102
Figure 73: Outlier detection using robust estimation for location and scatter .................. 102
Figure 74: Error ellipses representing the .95 quantile for different robust distances ........ 104
Figure 75: Cross prediction among sensor pairs using AR modeling ......................... 108
Figure 76: Progression of the superimposition of ellipse masks between sensor pairs .... 110
Figure 77: Localization Images for Randomly Selected Tests from the 47.25 in² Delamination .......................................................... 111
Figure 78: Damage Localization for Damage Level 7 (17.27 in²) ................................. 112
Figure 79: Damage Localization for Damage Level 8 (23.29 in²) ................................. 113
Figure 80: Damage Localization for Damage Level 9 (27.3 in²) ................................. 114
Figure 81: Damage Localization for Damage Level 10 (37.31 in²). ........................................ 114
Figure 82: Damage Localization for Damage Level 11 (39.22 in²). ....................................... 115
Figure 83: Sensor Numbering Scheme. ................................................................................ 116
Figure 84: 30 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right including S28 and S29) .......................................................... 117
Figure 85: 30 Sensors Localization for Damage levels 7-12 (from top to bottom left to right excluding S28 and S29) .......................................................... 118
Figure 86: 20 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right including S28 and S29) .......................................................... 118
Figure 87: 20 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right excluding S28 and S29) .......................................................... 119
Figure 88: 10 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right including S28 and S29) .......................................................... 119
Figure 89: 10 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right excluding S28 and S29) .......................................................... 120
LIST OF TABLES

Table 1: Shock testing matrix and results ................................................................. 30
Table 2: Test Matrix ................................................................................................... 40
Table 3: Impact methodology and accompanying delamination ............................. 81
Table 4: Hypothesis test and sensor fusion voting scheme results for the binary
detection problem. ................................................................................................. 95
Table 5: Damage detection results .......................................................................... 105
It is appropriate to begin by acknowledging my advisor, Professor Michael Todd. During my time under his leadership he has very graciously walked the line of advisor, mentor, teacher, boss, and friend. Every opportunity that has come my way in my nascent career has, in some way, stemmed from my time in his lab while under his tutelage. I am also deeply proud to have been a part of a world class institution like UC San Diego. The instruction and research opportunities I have received during my time have stretched me and grown my capacity to levels I didn’t know I could handle. The trajectory of my life and career are markedly different and I am forever grateful.

My beautiful wife deserves this degree as much as I do. I have been a student for all 6 years that we have been married and it takes a special kind of person to exercise the kind of patience and long suffering that she has shown while we have invested and sown into our future together. I often joke that I am going to go to law school once I conclude this chapter of my life. She never seems to think that is very funny.

I was very fortunate to have worked closely with Bill Gregory and Chris Key of Applied Physical Sciences throughout the entire life cycle of my research journey. They are very talented engineers and I am thankful to have had two consummate professionals to partner with during my journey. We have shared triumphs, frustrations, and a lot of time away from home together.

There are many students and postdocs that have also played an integral role in my success. Scott Ouellette, Colin Haynes, Richard Do, Zhu Mao, Daniel Whisler, and Anthony Whitaker all played integral parts in my academic journey. In particular, Anthony Whitaker and
I worked closely together for a significant portion of my work. We made a good team and I am grateful for his contributions to my research goals.

The research presented in this dissertation was funded by the Office of Naval Research, the Los Alamos National Laboratory, and the National Science Foundation.

A portion of Chapter 3 has been published in Structural Health Monitoring: An International Journal, Mike Yeager, Michael Todd, William Gregory, and Chris Key, 2016. The title of the paper is “IWSHM 2015: Assessment of embedded fiber Bragg gratings for structural health monitoring of composites.” The dissertation author was the primary investigator and author of this paper.

Another portion of Chapter 3 has been submitted for publication in the Journal of Intelligent Material Systems and Structures, Mike Yeager, Anthony Whitaker, Michael Todd. The title of this paper is “A method for monitoring bolt torque in a composite connection using an embedded fiber Bragg grating sensor”. The dissertation author was the primary investigator and author of this paper.

A portion of Chapter 4 has been submitted for publication in Advanced Composite Materials, Mike Yeager, Anthony Whitaker, Daniel Whisler, Michael Todd, Hyonny Kim, William Gregory, Chris Key. The title of this paper is “Binary hypothesis-based impact damage detection, for composite material systems embedded with fiber Bragg gratings.” The dissertation author was the primary investigator and author of this paper.

A portion of Chapter 5 has been submitted for publication in Structural Health Monitoring: An International Journal, Mike Yeager, Michael Todd. The title of this paper is “Using robust distances for feature discrimination in a damage detection scenario.” The dissertation author was the primary investigator and author of this paper.
VITA

2012  B.S.E.T. in Construction Engineering  University of North Texas

2012  B.A. in Mathematics  University of North Texas

2014  M.S. in Structural Engineering  University of California, San Diego

2017  Ph.D. in Structural Engineering  University of California, San Diego

PUBLICATIONS

*Work that has been incorporated into this dissertation

Peer Reviewed Journal Articles


Journal Articles in Progress


Fields of Study

Major Field: Structural Engineering

- Studies in Structural Health Monitoring
  Professors Michael Todd and Charles Farrar

- Studies in Structural Dynamics
  Professor Michael Todd

- Studies in Signal Processing
  Professor William Hodgkiss

- Studies in Structural Analysis
  Professors Benson Shing
ABSTRACT OF THE DISSERTATION

Health Monitoring of Composites with Embedded Fiber Bragg Gratings

by

Michael J. Yeager

Doctor of Philosophy in Structural Engineering

University of California, San Diego, 2017

Professor Michael Todd, Chair

The aim of this dissertation is to investigate a systems-level approach to the structural health monitoring (SHM) of composite laminate material systems with embedded fiber Bragg gratings (FBG). Although applicable across many structural applications, this research focuses on damage assessments for submarine components. Some of the pragmatic issues surrounding embedded FBGs are discussed including the embedment process, robustness, and egress of the embedded fiber. A design solution is presented for the egress of embedded fibers that could potentially break down barriers towards eventual commercialization of embedded FBGs. The survivability of the design is explored through mechanical shock testing.

The detectability of connection damage is explored in the form of both bearing damage and mechanical fastener loosening. Both time and frequency domain features are used for damage detection in a bolted specimen subjected to incremental bearing damage. A novel
approach to mechanical fastener preload monitoring is presented using a specialized washer design that uses a spectral shape feature for damage detection.

Impact damage assessment is performed on a representative test article. The statistical framework for final diagnosis is presented within a Mahalanobis distance based discrimination framework, and outlier analysis is then performed via a sensor-level voting scheme in the context of a binary hypothesis test. Some of the statistical inefficiencies of the traditional use of the Mahalanobis distance are addressed using robust estimations of locations and scatter as the inputs in the outlier detection. The performance of several robust distance calculations are compared to the traditional formulation. Finally, impact localization is performed with an event-agnostic algorithm and a novel imaging process as an alternative to conventional triangulation.

Current implementations of embedded FBGs in composites for SHM are limited to laboratory scenarios that address only certain components of the damage assessment process. This work provides a systems level investigation from specimen manufacturing to near field-ready damage assessment capabilities that is a step towards industrialization of embedded FBG networks for the SHM of composites.
Chapter 1

Introduction

1.1. Research Motivation

Because of their high specific strength and stiffness and the ability to be molded into complex shapes, fiber reinforced polymer (FRP) composite structures are gaining more prevalence in marine [1, 2] and aerospace [3, 4] industries. The performance benefits from composites—typically, weight reduction with increased strength, and improved thermal and acoustic properties—are challenged by a host of failure modes (delamination, disbonding, fiber breakage, matrix cracking, etc.) whose initiation and progression are not well understood and often cannot be detected by visual inspection. Although substantive research advances have been made towards damage analysis and modeling of the aforementioned failure modes in composites [5-10], research and development of damage assessment strategies are still needed
for the purposes of performance/operations optimization, maintenance planning, and overall life cycle cost reduction.

This research is motivated by a specific design objective of the US Navy to integrate composite components into submarine vessels. In addition to the aforementioned advantages of composites, they also provide a decreased radar signature and corrosion resistance, which are particularly attractive features for a submarine application. The sail, which is the vertical structure on the dorsal surface of the vessel, acts as both an ingress/egress location and a vertical stabilizer. As the Navy moves towards a composite material system for this component, overall lifecycle cost reduction continues to be a substantial focus. In service, this component could potentially be subjected to multiple failure modes including delamination damage from impacts, damage from mechanical shock, and connection damage in mechanically-fastened connections.

This necessitates the exploration of a structural health monitoring (SHM) system for the purpose of performance/operations optimization, maintenance planning, and catastrophic failure mitigation. This body of research is a first step towards implementation of a SHM system in a submarine application.

1.2. Introduction to Structural Health Monitoring

Structural health monitoring may be defined as the process of implementing a decision-enabling damage assessment strategy for structures, and it necessarily involves acquiring data while in service, extracting damage-sensitive features from the data, and assessing the condition of the structure via statistical hypothesis testing, given the inevitable noise and uncertainty in this “data-to-decision” process [11]. Assessing damage in this manner allows the cost of safe
operation to be reduced by adopting a condition-based maintenance approach. This is contrasted with the current paradigm of time-based maintenance, where such tasks are performed in accordance with a temporal schedule, irrespective of the actual needs of the structure. Unlike nondestructive evaluation (NDE), SHM systems provide monitoring without the need to remove the structure from service, which can be costly, especially in the case of submarine vessels that generally operate at significant distances from service operations at port.

Farrar et al. [12] proposed the following four-step approach for SHM systems in the context of a statistical pattern recognition (SPR) paradigm. This paradigm has been widely adopted as the most pragmatic approach to designing an SHM system.

1. Operational evaluation – The operational and environmental conditions under which the structure functions must be understood in order to determine any limitations of data acquisition. Identifying the relevant failure modes is also important during this step. Lastly, life-safety and economic justifications for an SHM system must be identified.

2. Data acquisition – Sensing modalities must be chosen in accordance with the limitations identified in the operational evaluation. Data cleansing and normalization procedures need to be identified to best separate the response of the structure due to damage from operational and environmental factors.

3. Feature extraction – Damage sensitive features must be identified that will delineate damaged data from undamaged data. An ideal feature is of low dimension and highly sensitive to damage and highly insensitive to any other structural changes.

4. Statistical model development – Statistical models are developed to assess the statistical significance of changes in features to enable decisions about the ability of the structure to continue to perform as designed.
This dissertation focuses on all aspects of this four-step paradigm in accordance with the aim of providing an inclusive, systems-level assessment of the SHM of composites with embedded FBGs.

1.3. Vibration based damage identification

Vibration-based damage identification (VBDI) has been given significant attention in the technical literature as a means to detect damage in structures at the earliest possible stage. VBDI is the process of identifying damage under the assumption that the presence of damage will change the inherent structural properties of a system and these changes will manifest themselves in the form of an altered dynamic response. The process has been intuitively understood for nearly 100 years as locomotive maintenance personnel would excite train wheels with an impact hammer and provide a damage diagnosis based on the acoustic response (using their expertly-trained ear). The ubiquitous need for assessing damage in structures across civil, mechanical, and aerospace structures has resulted in considerable attention being given to VDBI by researchers.

Exhaustive reviews of VBDI has been performed by Doebling et al. [13] and Sohn et al. [14], covering methods up to 1996 and then to 2001 respectively. A review by Montalvao et al. [15] focuses on VDBI methods for composite materials. The reader is referred to these publications for historical context.

This dissertation approaches the VBDI problem with a passive sensing approach in which the monitored structural response is excited by the inherent dynamic loading of the operational environment. Also called “output-only”, where either knowledge of or measurement
of the input loads is limited or impossible, this approach to VBDI rules out frequency response function (FRF) methods and any other method requiring a priori knowledge of the input excitation. The input excitation can be in the form of ambient operational vibration, external loads, or impact events [16]. Many researchers have looked at VBDI with impact events as the excitation source [17,18]. Nichols [19] looked at VBDI in off-shore oil platforms with the ambient sea state as the input excitation. In another civil structure implementation, Farrar et al. [20] used simulated ambient traffic-induced excitation for VBDI on a decommissioned bridge near Truth or Consequences, New Mexico. Gul and Catbas [21] employed random decrement (RD) functions to obtain the free vibration response from ambient vibration data. Brickner et al. [22] applied the frequency domain decomposition (FDD) technique [23] as an extension of the classical basic frequency domain technique, or peak picking technique, for modal identification of a car body subjected to engine vibration. Sohn et al. [24] used time series analysis to detect changes in structural conditions in a marine vessel under operational ambient loading.

For all experimentation included in this work, a pseudorandom operational environment was simulated using excitation from an electro-mechanical shaker inputting band-limited white noise (BLWN) into the system of interest. The underlying assumption is that, for a submarine application, the combination of sea-state, environmental dynamics, and engine vibration will provide an ambient excitation that can be modeled as BLWN.
1.4. Fiber Bragg Gratings

1.4.1. Application to SHM systems

Data acquisition is a foundational step of any SHM system, and all operational systems employ at least one sensing methodology to acquire the raw data that is to be mined for damage sensitive features. Traditional SHM sensing strategies include traditional strain gauges, micro-electro-mechanical system (MEMS) inertial sensors, lead zirconate titanate (PZT) transducers/actuators, accelerometers, velocimeters, laser Doppler vibrometers (LDV), and fiber optic sensors (FOS) [25]. Optical sensors and, in particular, fiber Bragg gratings (FBG), have garnered specific attention because they are light-weight, corrosion-resistant, impermeable to liquid absorption, immune to electromagnetic interference, do not provide a spark source, and are embeddable in composites [26-29]. Because of the submarine application in question, the survivability of FBGs and their ability to be embedded in composites drove the decision to employ FBGs as the sole sensing methodology in this research.

1.4.2. Theoretical overview

FBGs are a periodic modulation in the refractive index of an optical fiber that serves as an optical notch filter [30]. Figure 1 presents the internal structure and transmission and reflection spectra of an FBG.
Figure 1: Fiber Bragg gratings

As a broadband light source is passed through the filter, a narrow band is reflected back, centered at the Bragg wavelength. The Bragg wavelength is expressed as

\[ \lambda_B = 2n_{\text{eff}} \Lambda_0 \]  

(1)

where \( \lambda_B \) is the Bragg wavelength, \( n_{\text{eff}} \) is the effective index of refraction of the FBG and \( \Lambda_0 \) is the spatial period of the grating. If a uniform strain is applied across the grating, a relative change in the Bragg wavelength is observed as

\[ \frac{\Delta \lambda_B}{\lambda_B} = \left(1 - \rho_e \right) \varepsilon \]  

(2)

where \( \varepsilon \) is the longitudinal strain applied along the grating and \( \rho_e \) is the effective photo-elastic constant of the core material in the fiber [28]. The Bragg wavelength is also sensitive to temperature changes (thermal strain), but since several reliable decoupling techniques are widely known and practiced, these effects are ignored in this dissertation.
more robust exploration of the mechanics of FBGs will be presented later in the dissertation when it is employed as a design tool for a novel sensor idea.

1.5. Contributions of the Dissertation Work

The significant contributions of this dissertation are summarized as follows:

1. A systems-level investigation into the viability of embedded FBGs as a SHM solution for composite materials is conducted; this represents one of the first “design-to-data-to-decision” demonstrations of SHM using FBGs in an end-to-end application.

2. Decision enabled SHM systems are implemented on representative test structures for both bearing damage and impact-induced damage.

3. A novel method for monitoring fastener preload is presented and validated.

4. A novel egress solution is presented to bridge the gap to practice for embedded FBGs in composites.

5. Refinement of the traditional Mahalanobis distance based discrimination framework is proposed using robust estimations for location and scatter.

6. A novel impact damage localization and imaging method is presented using cross-predictive autoregressive (AR) models.
Chapter 2

Viability of Sensing Methodology

2.1. Introduction

A foundational research objective is to assess the robustness of embedded FBGs as a viable sensing methodology for a submarine application. Before an SHM system can be thought of as “field ready”, it must be able to survive and thrive within the rigors of its intended operational environment. Preliminary research thrusts of this dissertation are to assess the survivability of FBGs in a submerged environment, assess performance of embedded FBGs in various composite material systems, and develop a connector prototype for the egress of an embedded fiber.

2.2. Wetted Environment Testing

One of the attractive features of fiber optic sensors as a sensing architecture, especially for marine and submarine applications, is liquid absorption impermeability. To test the robustness of this favorable characteristic, composite specimens were tested after prolonged submersion in water. The test articles were fabricated with the GURIT Sprint WRE850T/ST94
material system and designed to a nominal thickness of 0.8 in., using 30 warps-parallel plies of material. An L-shaped mold was constructed on the mold table as shown in Figure 2 (left). This allowed the plies to be stacked up consistently through the thickness and to maintain the panel’s unity aspect ratio. During the lay-up process, the sensors were located at specific plies internal to the overall panel. Locations for the sensors were marked using permanent markers, and the fiber optic sensors were then placed at the marked locations. Micron Optics os1200™ FBG arrays were used for the internal sensors. Once the internal sensors were positioned and secured, the next ply was laid down and build-up to the overall laminate thickness continued. Once all of the plies were laid down, the test articles were prepared for vacuum bagging and subsequent cure.

A key feature in the bagging and curing of the test articles was attention to the fiber optic cable leads exiting the specimens. As part of the cure cycle, the reinforcement undergoes significant consolidation, requiring special attention for the ingress/egress of the array leads. To accommodate this consolidation for the embedded internal fiber optic sensors, extra steps were necessary during the set-up of the panel cure to help ensure that the optical lead to the sensors survived the cure. First, in order to avoid a kink in the lead as it exited the side of the panel, it was necessary to place a landing (vacuum bag sealer was used to build up a landing) to support the cable. Figure 2 (middle) shows the array lead support for one specimen prior to applying the vacuum bag. Second, Teflon tape was used to provide a resin barrier at the actual ingress/egress point to avoid infiltration into the array connectors, since the entire connector system had to be placed inside the vacuum bags in order to achieve the required vacuum. After laying up each of the panels, the uncured specimens were placed on a mold table with a G10 caul plate placed atop each to provide a smooth bag side surface. Figure 2 (right) shows each of the panels on the mold table during the bagging process.
In addition to the FBG embedded arrays, surface mounted arrays were also installed on select panels after the cure process using Micron Optics os1200™ and os3200™ arrays. The surface installation involved lightly sanding the panel in the sensor locations and cleaning with acetone to prepare a clean and uniform bonding substrate. After the fiber was placed appropriately in its designated location and temporarily fixed with tape, a two-phase mixed strain gage epoxy was applied along the roughly 0.5 in gage length of the photo-etched sensing portion of each fiber. The epoxy was then allowed to cure for 12 hours.

Figure 2: (left) mold set-up; (middle) sacrificial material for lead support; (right) test panels in vacuum bag

Figure 3: Bending test fixture, including aquarium for wetted environment
Three-point (3-pt) bend testing was selected to be the primary initial verification approach. A support spacing of 16 in. for the 0.8 in. thick panel was selected to allow the first mode of failure that would develop to be matrix cracking followed by fiber failure, each at a displacement that would preclude large deflection interaction. The test machine used for these tests is shown in Figure 3. As shown in the figure, the bottom supports for the fixture consisted of 1.5 in. diameter rounds spaced 16 in. apart. The loading head was also a 1.5 in. round directly centered between the supports. To accommodate the “wet” testing, a plexiglass aquarium-type structure was fabricated, incorporating the end fixtures. This allowed for both dry and “wet” testing to be conducted simply by filling up the aquarium and subsequently draining the aquarium. A Micron Optics SM130-700 Fiber Optic Interrogator was used as both the broadband light source and light receiver. Micron Optics’ Enlight software was used to track the peak wavelength shifts on a Dell laptop computer.

After the post-fabrication cure, it was determined that all internal sensors functioned properly, withstanding the cure temperature of 185°F for 12 hours under a full vacuum. The general testing procedure involved 6 total panels, some of which were instrumented with embedded gages and others with surface-mounted gages. Most panels were elastically loaded, and a subset was gradually loaded to failure. From all the test panels, Panel 2 was selected as an example to demonstrate the performance of the embedded fiber optic sensors in a dry environment. Panel 2 contained two internal sensors installed 7 plies from the compression side of the panel. Two elastic runs were conducted on this panel up to 5000 lbs.; these tests were followed by a test to failure of 18,800 lbs. The internal sensors survived the fabrication and were able to provide strain response as indicated in Figure 4. The figure also plots predicted strain readings from a surrogate finite element (FE) model of the test specimens and strong agreement between the model and the empirical strain data is observed.
Figure 4: Embedded sensor performance to failure (left) and within elastic range (right)

During testing, some “peak hopping” occurred, which led to the observed discontinuous strain histories seen in Figure 4. These are a consequence of the data acquisition software’s failure to accurately track central FBG reflection peaks; under load, FBGs may become chirped (suffer non-negligible strain gradients over the sensing length), which lead to overall reflection peak broadening and distortion. This effect is enhanced for embedded FBGs, where microstructure/resin interaction can lead to micro-constriction and micro-bending in the fiber. Peak hopping and micro-bending will be discussed later in the dissertation.

Two different panel sensor configurations are presented to demonstrate the performance of the fiber optics in a wet environment. Panel 5 was tested in a dry condition and in two separate wet conditions. The first wet condition involved an overnight soaking in a room temperature water bath, while the second involved an extended soak of 7 weeks. Panel 5 contained one packaged external sensor installed on the surface. Testing was conducted with the sensors located on the tension side of the beam for this comparison. As shown in Figure 5 (left), there was little change in the sensor performance due to the pre-soak environment. Post-test inspections showed that the epoxy bond of the external sensor to the laminate was starting to wear after 7 weeks in water (recall that non-marine epoxy was used for this application). Panel 3 was selected as an example to demonstrate the performance of internal sensors in a wetted
environment. Panel 3 contained three internal sensors located 7 plies from the tension surface and was soaked for the same durations as Panel 5. As shown in Figure 5 (right), no change in performance was noted from a strain response perspective.

![Diagram](image)

Figure 5: Wet vs dry performance for external sensor (left) and wet performance of embedded sensors (right)

### 2.3. OVB vs. VARTM

Typical marine platform composite construction uses glass fiber reinforced polymer (GFRP) in either a low temperature pre-preg or vacuum assisted resin transfer method (VARTM) manufacturing process. The low temperature GURIT pre-pregs, also referred to as oven vacuum bag (OVB) use a single sided film of epoxy resin on a dry reinforcement, which can be either carbon or glass. To encompass current marine applications, carbon panels were tested similar to the glass panels above to ensure compatibility for use of either reinforcement (carbon may be required to attain stiffness for frequency-driven components). Similarly, VARTM processed material has been proven as a marine environment material. Therefore, test panels were also fabricated using the VARTM method to assess the embedding of FBGs with this process.
Upon completion of an equivalent 3-pt. bend test as performed in Phase IA, results for the carbon pre-preg were similar to the results of the previous glass pre-preg tests. Figure 6 shows the sensor layout and plotted results for a selected carbon pre-preg panel. It should be noted that 5 FBG sensors were embedded in each panel, but only 4 sensors are shown in the figure. This is because the nominal center wavelength of 1 of the 5 sensors in a standard Micron Optics os1200™ array falls outside of the visible bandwidth of the fiber optic interrogator.

In contrast to the OVB specimens, the VARTM specimens did not perform satisfactorily. Post cure, it was noted that the reflected spectrum, which should reflect 4 distinct sensor peaks, only displayed 1 strong peak and the rest of the peaks fell very close to or below the noise floor altogether. This means that the interrogator is unable to reconcile peak shifts in the spectra, rendering the strain sensor useless. It is believed that this severe attenuation is the
result of an acute manifestation of a phenomenon known as micro-bending as mentioned earlier in the chapter. Because of high-frequency undulations in the composite substrate, the optical fiber is subjected to random lateral stresses along the length of the fiber, which impose small radius bends throughout [31]. These small radius bends produce an increased attenuation in the fiber known as micro-bending losses. Micro-bending couples the power from the fundamental guided mode with higher order modes that experience normal scattering and refraction, which in turn, attenuates the global power from the fiber. Figure 7 illustrates the phenomenon. More in depth analysis of bending losses in optical fibers has been performed by other researchers [32].

Figure 7: Micro-bending losses
In comparing the manufacturing differences between the VARTM and pre-preg panels, a key difference is that VARTM uses dry reinforcement before introducing resin, thus the dry reinforcement stack produces more undulation in the surface that the sensors need to conform to. For the pre-preg material with the single side of resin, the vacuum bagging process did not exhibit the same level of surface waviness as the VARTM approach, which appeared to be one of the main drivers of the micro-bending issues. The following section proposes a two-step infusion approach to the VARTM process that significantly mitigates micro-bending losses.

2.4. Fiber Egress

2.4.1. Introduction

Interrogation of an embedded array of FBGs in any practical setting requires the connection of optical hardware to the embedded fiber via standard plug and socket connectors developed by the optical fiber communications industry [33]. This necessarily involves the egress of an embedded fiber from the composite to facilitate this connection. In-plane egress is the most widely used egress method in the technical literature, and it involves the exiting of an embedded fiber at the edge of a layup between the plies. This prevents the laminate edge from being trimmed post-cure which is impractical for most non-laboratory applications. Additionally, the laminate has to be handled very carefully to not damage the fragile optical fibers exposed at the laminate edge. Reinforcement at the egress point is critical to mitigate stress concentrations on the brittle fiber and avoid breakage [34]. Free space connectors have also been suggested where a laminate with an embedded fiber with in-plane egress is trimmed exposing the cross-section of a bare fiber. An optical signal can then be monitored with an external receiver through free space [35]. This method is also impractical for most field
deployments. Out-of-plane (surface mounted) connectors have been the focus of many experimental studies because they present the most robust solution for practical deployment. Kang et al. [36] presents a review of surface mounted connectors and a working prototype. Beukema [34] presented a connector housing using a modified Diamond Micro Interface connector. Although several prototypes and ideas have been presented, few if any have been tested for robustness and survivability. This chapter presents a design that is robust enough to meet survivability standards in practice and relatively simple to install.

2.4.2. Proposed Design

One of the more significant challenges to overcome with an out of plane egress connector is the problem of resin infiltration during the vacuum and subsequent cure. Because of the delicate nature of the fiber optic cable, any resin infiltration will greatly increase the risk of breakage and the ability of the connector to be interrogated by monitoring hardware. The design presented was created through multiple iterations using a 3D printer and Acrylonitrile butadiene styrene (ABS). In practice, this would not be the material of choice or the fabrication method of choice but it provides the ability to rapidly prototype design iterations at relatively low cost. The glass transition of ABS is around 221° F so a low temperature material system was used for fabrication of composite test articles. Figure 8 presents schematics of the design and Figure 9 shows the final 3D printed design.
Figure 8: Plan (left), elevation (center), and exploded (right) view of connector. All measurements in inches.

Figure 9: 3D Printed Connector (left) and bottom of connector (right)

The connector is fabricated with a thin plate across the front façade that is designed to break away after the cure of a composite part. This break away piece provides a resin dam to prevent resin from flowing into the connector chamber during the cure. The bottom of the connector has an opening for FC/APC connector ingress and a channel for the exiting fiber optic cable(s). This hole and channel are designed to be potted with epoxy, which creates an airtight chamber that will prevent any resin infiltration during the vacuum and resin transfer.
The connector will be installed on the same ply as the embedded sensor arrays and additional plies are cut and laid over the connector chamber but on top of the flange. The connector is designed to be placed under the vacuum bag during cure, which adds little complexity to the manufacturing process.

2.4.3. Fabrication Procedure

2.4.3.1. Connector Assembly

A key component to the design of the connector is the associated fabrication procedure, which will be outlined in this section. The first step is to enclose the FC/APC connectors of the FBG arrays within the connector chamber. This is done by first inserting the ends of the arrays into the chamber through the opening on the bottom side of the connector. The connector can be scaled up in size to accommodate more arrays, but this particular iteration was sized to accommodate 2 FBG arrays. Once the connectors are inside the chamber, approximately 2 in. of excess optical cable is further inserted into the chamber. This ensures that after the break away tab is removed from the front of the connector, there will be sufficient cable to work with while installing the arrays into the final cap. A small amount of adhesive is placed over the optical cables in the channel to ensure that the cables do not slide out at all while the connector bottom is potted in epoxy. A small amount of hot glue was used in this installation. Figure 10 shows the optical cables inserted into the connector chamber.
Next, the bottom of the connector must be potted with epoxy. This is achieved by first laying a small amount of peel-ply or other non-porous material that will not stick to the epoxy. Then a quarter-sized amount of well-mixed 2-part epoxy is applied to the surface and the connector housing is placed on top of the epoxy such that the epoxy completely fills the channel and opening on the bottom of the connector. The connector is then allowed to cure for 1 hour. Figure 11 presents the potting process.
Once the epoxy has cured, the peel-ply is removed. Figure 12 shows the bottom of the fully potted connector. At this point, the chamber is completely sealed on the bottom from the epoxy and on the front because of the break away tab.

An important observation arose after fabrication with two different manufacturers of FBG arrays. Figures 10 through 12 show arrays with a black sheathing around the optical cable
from Micron Optics. This sheathing is a porous cloth sheathing susceptible to resin wicking during resin transfer. In fabrication trials, even though the connector chamber was effectively sealed, trace amounts of resin wicked up the optical fiber into the chamber making the fiber very brittle after the cure. In some cases, the fiber broke during installation of the final cap. For the fabrication of the panels to be used for survivability testing, a different sensor manufacturer named Alxenses was used. The arrays from Alxenses were coated with a plastic nonporous coating that prevented any wicking. Arrays with this type of sheathing would be suggested for these types of installations.

2.4.3.2. Connector Installation

In order to assess the robustness of the connector design, a survivability test was performed. A 46” x 46” x 3/8” panel was fabricated using 15 plies of 18 oz. glass fabric. Initially, 13 plies were laid up and infused with resin using a VARTM technique. This panel was allowed to cure, but while the panel had not fully cured, the connectors were placed and the arrays positioned so that 2 additional plies could be laid, bagged, infused, and cured to still achieve a good bond with the panel. It should be noted that earlier in the chapter it was reported that the VARTM technique produced significant attenuation in the optical fiber and rendered the sensors useless. Those coupon specimens were fully infused i.e. the sensors were positioned within a dry fabric stack and the panels were fully infused. The VARTM approach used for the fabrication of the survivability test specimen was much more successful and allowed for good sensor performance after the cure.

The panel was equipped with 2 arrays that each contained 10 serialized FBG sensors of varying center wavelengths. The “start” ends of each array were installed in one connector and the “end” ends of the arrays were installed in another connector. These connectors were placed
on opposite corners of the panel and the arrays routed and sensors positioned according to Figure 13.

Figure 13: Sensor layout and connector position schematic

The connector housings were bonded to the sub panel using 5 minute epoxy. A thin layer of well-mixed epoxy was spread on the entire bottom surface of the connector housing and then the housing was positioned on the panel. After approximately 30 minutes, the epoxy will have cured enough for further handling. Next, the final two plies of fabric are laid on top of the sub panel after a hole has been cut in the material to fit around the connector chamber but covering the flanges at the base of the connector. Peel-ply material, breather cloth, and resin
distribution media are laid before the vacuum bag is placed. The vacuum bag then covers the entire panel, including the connector housing. As the vacuum is being pulled, care must be taken to ensure that the bag fits well around the connector and does not leave any voids that will fill with resin. Figure 14 shows the installation process and Figure 15 shows the panel during resin infiltration and immediately after the vacuum bag was removed.

Figure 14: Connector bonded to the partially cured sub panel (left), additional 2 layers of fabric placed over the connector (center), and connector under the vacuum bag (right)

Figure 15: Panel during resin infusion (left), connector after debagging (center), and connector after break-away tab was removed. (right)

After the vacuum bag was removed, the break-away tab on the front face of the connector was removed, revealing the FC/APC connector leads. The leads are then attached to the cap which contains two female/female FC/APC adapters and the cap is attached to the front face of the connector with three machine screws. The final connector is shown in Figure 16.
After the cure, the connector was interrogated and all 20 embedded sensors were fully functional.

### 2.4.4. Survivability Testing

The robustness of the connector housing was explored via a shock test that was designed using a medium weight shock machine (MWSM) according to MIL-9-109D, a military specification document for qualifying Navy ship components for high impact mechanical shock. Figure 17 shows the schematic for the machine.
To conduct the test, the hammer is raised to a pre-prescribed height and released. It swings through the floor and makes contact with the bottom of the anvil plate, accelerating it upward. The test article is secured to a steel frame with a clamped boundary on all sides. The steel fixture is then secured to the anvil plate with mechanical fasteners. Because of the limited mass of the test article, a concern was that the shock event would not produce significant strains in the panel to produce any damage. For this reason a pedestal was bolted to the center of the panel. This pedestal could then have additional mass bolted to it in 150 lb. increments. This additional mass configuration would introduce damage into the panel under high impact shock.

In between impacts, the panel was actuated out of plane with an electromechanical shaker. During the excitation, the sensors were interrogated to make sure that the connector and the sensor arrays survived shock events of increasing intensity. Accelerometers were positioned on the anvil plate to measure the acceleration of the fixture during the shock event. Figure 18
shows the test setup between shock events and Figure 19 shows the mass pedestal attached to the test article.

Figure 18: Panel with shaker attached
After each impact, the panel was actuated with BLWN with a frequency band of 10Hz – 2500Hz. The excitation serves as a simulated pseudo-random operational environment and the FBGs are interrogated to ensure the functionality of the system after each shock event. The following table summarizes the test matrix and test results.
Table 1: Shock testing matrix and results

<table>
<thead>
<tr>
<th>Blow No.</th>
<th>Hammer Height (ft.)</th>
<th>Added Mass (lbs.)</th>
<th>Peak Acceleration of Fixture (g)</th>
<th>Connector Functioning Post Event?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>0</td>
<td>103.2</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>116.4</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0</td>
<td>155.2</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>87</td>
<td>162.9</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>237</td>
<td>161.7</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>2.25</td>
<td>587</td>
<td>162.5</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>5.5</td>
<td>587</td>
<td>263.1</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Low levels of damage were observed in the panel after blows 5 and 6 but significant damage was observed in the panel after the final blow. Fiber rupture, matrix damage, and delamination were observed in the panel and are documented in Figure 20. Back lighting the panel reveals the extent of the delamination around the pedestal footprint.

Figure 20: Damage in panel (left) and panel with back light to reveal delaminations (right)
2.4.5. Conclusions and Observations

Through high impact dynamic shock testing, the survivability of a proposed egress solution for embedded FBGs in composites has been confirmed. Failure of the connector would occur in one of the 3 following locations: the bond between the connector and the panel, the connector structure, or the fiber optic cables housed by the connector. It was observed that the bond between the connector and the panel maintained its integrity throughout all shock events. The fact that all sensors were still functioning after each shock event is indicative of the fact the fiber optic leads housed by the connector must have survived. The connector structure itself performed well until the final blow. The front face of the connector fractured and the housing body cracked near one of the screws that secured the front plate. The damage is presented in Figure 21.

Figure 21: Connector damage after blow 7

As previously mentioned in the chapter, ABS was chosen as the connector material because of its ability to be rapidly prototyped through 3D printing and not because of its favorable structural properties. In practice, other materials should be explored and tested that
provide better structural performance. Another potential concern of the proposed fabrication method is that the last two layers of the laminate transition from bond with the sub panel to a bond with the flange of the connector. This transition could make the area subject to delamination. Although this certainly warrants further investigation, this did not occur under the performed testing. Figure 22 shows the connector area and no visible damage is present.

![Figure 22: Top two fabric layers covering the flange of the connector](image)

The proposed design is a step forward towards the commercialization of embedded FBGs in composites for health monitoring purposes. The design is robust enough to survive high impact mechanical shock events and the installation procedure is not overly complicated. Further investigations should be made into a more suitable structural material for the connector. The current geometry of the connector could also be changed to produce a more low-profile design for smaller components.
Chapter 3

**Damage Detection Scenario: Connection Damage**

### 3.1. Bearing Damage

Bearing damage in way of bolted connections was identified as a key failure mode for assessing the integrity of a future composite submarine component. As a result, a bolted connection specimen, composite-to-metal, was designed, fabricated, and tested with FBG sensor arrays embedded during fabrication. The connection was a representative single lap shear joint, bolting the composite panel to the steel framework. A test was designed to simulate a damage detection scenario in which low levels of bearing damage were introduced via quasi-static tensile loading.

#### 3.1.1. Test Article Design

The test article was designed and fabricated with the GURIT Sprint WRE850T/ST94 material with dimensions 18” x 10” x 3/16” thick. Sensors were embedded in the locations indicated by Figure 23. Although 15 FBGs on 5 separate arrays were installed, the interrogation hardware was limited to 4 channels so array 5 was only embedded for the sake of redundancy.
Sensor configuration and orientation were chosen with the assistance of a finite element model simulating both pre- and post-damage strain fields as well as observing nodal behavior of dynamic strain modes. Sensors 2-4 were oriented diagonally to the local axis of the plate to attempt to capture both “x” and “y” strain component information in a single sensor. Sensors were also installed in non-symmetric locations to ensure the uniqueness of the information captured.

Figure 23: Bolted specimen sensor layout (left) and array configuration in the optical space (right)
An FE model was used to crudely assess which regions of the plate would be most affected by connection damage, and therefore provide insight into potential sensor installation locations. The FE model was subjected to a static tensile loading, and a map of principal stresses was derived from the simulation. Several subsequent runs were completed with a different single bolt removed from the model, and principal stress mappings were generated. Lastly, several difference maps were generated by “subtracting” the simulations with altered boundary conditions from the original simulation with the fully bolted connection. These mappings provided crude insight into how the stress paths would change in the plate with connection damage introduced. Figure 24 illustrates the FE method for generating the difference mappings.

![Figure 24: Generation of modal strain difference mappings](image)

### 3.1.2. Fabrication and Sensor Embedment

All sensors for this specimen were installed one ply below the top surface, by tacking down optical fiber with resin to hold the sensors in the appropriate position and orientation and to ensure proper routing of excess optical fiber. As with the previously detailed specimens, great care was taken with the egress of the optical cables to avoid fiber breakage at the egress point. A surface connector was not installed in this experiment because of the scope of research.
objectives, so, although the cured test article itself is robust and durable, the fiber optic leads protruding from the specimen are untreated, fragile and require delicate handling care to mitigate breakage risk. Figure 25 shows the sensors installed before the final ply (left) and after the final ply (right).

![Figure 25: Sensor layout and installation (left) and completed panel ready for cure (right)](image)

### 3.1.2.1. Residual Strains and Spectral Chirping

An important nuance that must be considered in the embedding of fiber optic sensors in composites is that the sensors will be subject to permanent residual strain fields after cure. During the fabrication of the test article it was possible to monitor full FBG spectra before and after the cure. After a vacuum bag was pulled over the part, samples of the Bragg spectra were sampled to establish a baseline spectral shape before the cure. Figure 26 gives a global view of the Bragg spectra peak strength and each sensor’s bandwidth allocation within the optical space. Figure 27 then compares Bragg spectra from before and after the cure for Array 2. There are two observations that can be made from this comparison. First, the cure introduces optical power attenuation that is a direct result of micro-bending losses discussed earlier in this dissertation. Secondly, the Bragg spectra undergo significant “chirping” during the cure that
leads to distorted spectra. Figure 28 illustrates the spectral chirping phenomenon by showing the highly symmetric and pronounced peak of the pre-cure Bragg spectrum with the dashed line, compared to a highly distorted Bragg multiple peak post cure with the solid line. The peaks have been normalized and aligned for comparative purposes.

Figure 26: Bragg spectra for all arrays in test article

Figure 27: Bragg spectra comparison, pre cure vs. post cure
3.1.3. Testing and Data Acquisition

To validate the damage detection abilities of the embedded sensor network, 90-second strain time histories were recorded for each sensor as the test article was actuated by BLWN (10-1000 Hz) transversely with an electro-mechanical shaker, intended to simulate a pseudorandom dynamic operating environment. In between each time record, connection damage was accumulated in the structure by axially loading the part with increasing loads. Finally, the part was transversely loaded with an actuator to introduce damage in a location other than the connection. A Micron Optics SM130-700 Fiber Optic Interrogator was used as both the broadband light source and light receiver, and Enlight was used to do wavelength peak tracking. A 50 lb. MB Dynamics™ electro-mechanical shaker that was powered by a MB Dynamics™ SL500VCF power amplifier actuated the structure transversely. The output voltage was sent to the shaker with a National Instruments™ cDAQ-9178 data acquisition system. Figure 29 shows a surrogate test panel secured in the test fixture with the shaker in place and all testing equipment.

Figure 28: Bragg spectra comparison, pre cure vs. post cure with spectra aligned
It is important to understand the damage progression experienced in the connection of the specimen as a result of the loading, between the vibration testing, but without removing the test specimen from the fixture after each loading. This was accomplished by loading a surrogate panel with no sensors and monitoring the incremental progression of damage. The complete test matrix is found in Table 2.
The assumption is then made that the part outfitted with the sensor arrays will experience the same progression of damage as the surrogate part. Figure 30 shows the connection damage introduced by the incremental loading. From this figure, one can see that the 40,000 lb. load could not be sustained by the test specimen, and it began to deform plastically in a bolt shear-out mode. Therefore, loading was terminated when the part experienced ~0.5 in. of total elongation. The dynamic data run performed after each static load increment lasted 90 seconds, and the first 5 seconds of the time histories were windowed off to account for transient effects and inconsistencies in the start of the (uncontrolled) shaker input. The 85-second time history was then segmented into 3-second subsections that make up individual “tests.” There were thus 28 total tests for each case, baseline, undamaged, damage level 1, damage level 2, damage level 3, damage level 4, and the transversely loaded case, making 196 total tests.
3.1.3.1. Wavelength Hopping Correction

As mentioned previously, peak hopping or wavelength hopping is a challenge that may need to be overcome when tracking highly dynamic strains with FBGs that are chirped from embedment. In this study, the raw acquired data showed significant dropouts from multiple sensors which would require correction before further processing could be performed. AR was employed to correct for lost data points. An $p$-th order AR model assumes that a current-time sensor reading may be modeled as a finite linear combination of $n$ previous readings [17]

$$x(t) = \sum_{j=1}^{p} a_p x(t-j) + e(t)$$

where $x(t)$ is the signal at time $t$, $a_p$ is the $p$th AR coefficient, and $e(t)$ is the error term. Figures 31 and 32 illustrate the implementation of auto regression as a corrective technique for wavelength hopping.
3.1.4. Damage Sensitive Feature Extraction

3.1.4.1. Frequency Domain

Damage is generally defined as changes to the material and/or geometric properties of the structure such that the structure’s intended performance is adversely affected. These changes are often observed as stiffness losses and may be detected in the frequency response of the structure, since resonant (natural) response frequencies of the structure depend heavily on stiffness. Figure 33 shows typical power spectra for a given sensor over all damage levels.
Figure 34 shows a normalized view of one of the peaks. A clear progressive shift towards lower frequencies can be observed as damage accumulates in the structure.

Figure 33: Power spectra from sensor 5 for all damage states

Figure 34: Normalized power spectra for sensor 5 – 5th peak
The chosen damage-sensitive feature, then, is a vector of frequencies that correspond to peak shifts in the power spectral density of the signal of interest when compared to a baseline,

\[ X = \begin{bmatrix} \Delta_1 & \Delta_2 & \ldots & \Delta_j \end{bmatrix} = \left[ \arg \max \left( \hat{S}_u (\omega_{0,j}) \right) \right]^T - \begin{bmatrix} \omega_{0,1} & \omega_{0,2} & \ldots & \omega_{0,j} \end{bmatrix} \] (4)

where \( \hat{S}_u \) corresponds to the power spectral density of a time history in an unknown structural state, computed via the Welch method [36] and \( \omega_{0,j} \) corresponds to the \( j \)th peak observed in the power spectral density of the baseline state as the arithmetic mean of all baseline tests. The entire spectra from 0 to 1000 Hz (Nyquist) were searched for peaks to form the initial set of baseline frequencies. In many cases, \( \hat{S}_u (\omega_{0,j}) \) does not contain a local maximum within a window centered around \( \omega_{0,j} \). In such instances, that particular peak was omitted from \( X \). So, the dimension of \( X \) is dictated by the number of peaks found in common between the baseline and all structural states within given windows defined by the nearness of sequential local maxima of the baseline spectrum.

### 3.1.4.2. Time Domain

AR models (3) predict a function value at a particular point in time as a linear combination of \( p \) past values, where \( p \) is the model order. In application to SHM, if a numerical model is generated from the structure in a known healthy state, then the ability of that model to predict accurately should decay with damage accumulation. A monotonic error calculation of the error term such as root mean squared (RMS) or square root sum of the squares (SRSS) can be used as a damage sensitive feature. For this study, the AR model coefficients, \( a \), themselves will be a multivariate damage sensitive feature vector. Many researchers have
employed this damage sensitive feature in the technical literature with Sohn et al. [24] being a notable example.

### 3.1.5. Mahalanobis Distance Based Discrimination Framework

The dimension of the multivariate feature vector is reduced to a scalar metric using the Mahalanobis distance [37] given by,

$$d_i = \left(X_i - \bar{X}\right)^T \Sigma^{-1} \left(X_i - \bar{X}\right)$$

(5)

where $X_i$ is the feature vector from an unknown structural state, $\bar{X}$ is the mean vector of training data set, and $\Sigma$ is the covariance matrix of the training set. This metric will be used to determine discordant outliers from the data sets and thus can be used to indicate a damaged structural state. Figure 35 displays representative test data from 3 of the sensors for the frequency domain feature.

![Figure 35](image)

Figure 35: (left) Sensor 1 Mahalanobis distance scatter plot; (center) Sensor 5 Mahalanobis distance scatter plot; (right) Sensor 8 Mahalanobis distance scatter plot.
Relatively stable Mahalanobis distances are observed until damage Level 3 (after 30,000 lb. axial load.), which is consistent with the damage observed in the surrogate panel without sensors (Figure 30). Low variance is also observed between tests at the same damage levels, which provides promise for the success of deviation-based hypothesis testing to be discussed later in the chapter.

For the time domain feature, the coefficients of a 27th-order AR model were generated using linear predictive coding in MATLAB. So each damage sensitive feature vector was constructed with these coefficients. An AR order optimization algorithm employing Bayesian Information Criterion (BIC) was used to define the model order, $p$. The optimum AR order for the signal ensemble was 39, but because only 28 baseline signals comprise the Mahalanobis distance sample set, the second dimension is limited to being 27. Figure 36 presents representative test data from sensors 1, 5, and 8.

The time-domain feature produces similar results to the frequency domain. The additional variance among the tests of congruent damage levels is likely due to high variability in signal-to-noise ratios among the sensors, which does not get ‘‘averaged out’’ as it does in the frequency domain.
3.1.6. Hypothesis Testing

Outlier observation via the Mahalanobis distance metric has been shown to be a potentially powerful discriminator (“detector”) of damage, but fundamentally, a quantitative statistical treatment must be employed to rigorously answer the question of whether the distance metric has changed in a statistically significant way as to indicate damage. This question is answered by hypothesis testing, and specifically, binary hypothesis testing: “Is the structure critically damaged or not?”

Thus, the question relies on a definition of criticality, which is always application dependent. In this experiment, the 20,000-lb. load level (damage level 2) began to introduce visible damage, but it was not until the 30,000 lb. load was applied that damage was observed that would warrant significant concern in a structural sense. In order to test the Mahalanobis distance–based detector, a random sample of data is collected from all undamaged cases. Recall that this would be made up of the baseline, damage level 1, and damage level 2 tests, 84 tests in all. The training set is composed of a random selection of 42 of these undamaged tests. Probability density functions (PDF) for each sensor in the training set are constructed and are assumed to follow Gaussian distributions. It should be noted that although deviations in
normality for this experiment were sufficiently small to not violate a Kolmogorov–Smirnov test, this is because of the limited sample size in the training set. A more refined statistical assumption framework will be presented later in the dissertation.

After the training set construction, the testing set is composed of all tests from critically damaged cases (damage levels 3–5) and the remaining undamaged tests not used to construct the training set. A simple discordancy test will be used to identify outliers and make decisions about the structural state according to

\[ z_i = \frac{d_i - \mu}{\sigma} \] (6)

where \( z_i \) is the outlier index; \( d_i \) is the Mahalanobis distance value being tested; and \( \mu \) and \( \sigma \) are the mean and standard deviation of Mahalanobis distances of the baseline set for a particular sensor, respectively.

The test itself is performed according to the binary hypothesis test according to:

\[ H_0 : z_i < 3 \]
\[ H_1 : z_i \geq 3 \] (7)

where \( H_0 \) is the null hypothesis that the test subject comes from a healthy structural state and \( H_1 \) is the alternate hypothesis that the test subject comes from a damaged structural state. For each test statistic that rejects the null hypothesis, one can say with 99.7% confidence (3 standard deviations under reasonably assumed normal statistical structure from central limit theorem implications) that it does not represent a feature from the damaged case.

All test data were randomly permuted, and the aforementioned hypothesis test was performed on each test statistic for each sensor. For the first test, a target of 50% sensor
agreement among all sensors (simple sensor fusion voting) for a damaged diagnosis is required. The results are presented in Figure 37 (left).

Figure 37: Binary hypothesis test results: 50% sensor agreement (left) and 15% sensor agreement (right). Red and green represent true structural state and y-axis value represents predicted state with 0 being an undamaged prediction and 1 being a damaged prediction.

For this test, 100% agreement between the predicted structural state and the actual structural state is observed (due to the finite dataset; in reality, 100% would not be observed over the structural lifetime, but the point is that the number is very close to the 99.7% target).

For the second experiment, decision-cost penalties are introduced. For structures whose failure could result in loss of life, a false negative could lead to catastrophic failure if actual damage is not addressed. A false positive would only cost the intended maintenance time or, more severely, prescribed down time of the structure that is not actually necessary. For many applications, it is highly likely that the consequence of a false negative far outweighs the cost of a false positive, so the requirement is modified to require only 15% sensor agreement. This means that if any 2 sensors of the 12 agree that a particular test statistic does not come from the undamaged PDF, a damage diagnosis will be given. Figure 37 (right) presents the results from this experiment, and a 96.8% correct prediction rate with four false positives was observed, which have been indicated with circles.
3.2. Fastener Loosening

3.2.1. Introduction

As previously mentioned, a key structural criteria for implementing composites onboard US Navy platforms regards the integrity of structural connections. Most composite attachments to legacy ship structures use mechanical fasteners, such as through bolting the composite laminate to a steel plate, using either hex head bolts (in a single shear or double shear configuration) or countersink bolts in a single shear lap joint. Monitoring the torque level in these mechanical connections is necessary to ensure that structural integrity of the connection is maintained. Standard maintenance procedures for mechanical connections currently involve time-consuming labor to conduct the necessary inspections, as well as loss of in-service time for the fleet asset. Current mitigation strategies, in addition to time based monitoring, include significant over design and redundant fasteners, which are not sustainable strategies in light of increasing demand for low-weight, high performance structures.

Numerous strategies for monitoring the health of those connections have been previously proposed in the literature. For bolted connections, vibration-based methods are attractive because they do not require special connection hardware, which may introduce highly undesirable cost increases. By monitoring and comparing signals on either side of a connection, connection loss (defined as the “damage” in this application) may be detected. Ritdumrongkul et al [38] used PZT piezoelectric transducers as actuators and sensors to detect bolt loosening via change detection of the broadband coupled sensor/host electromechanical impedance. A review of impedance-based SHM approaches was performed by Park et al [39]. Todd et al [40] demonstrated the use of properly-tuned chaotic input excitation as a robust damage detector in bolted connections. Nichols et al [41] similarly used nonlinear predictive models and their associated prediction error as a damage-sensitive feature. Fasel et al [42] developed a damage
detection strategy via a frequency domain AR model with exogenous inputs (ARX) that was analyzed with extreme value statistics, while Haynes et al [43] employed a Bayesian approach as the statistical framework for damage detection in a bolted structure.

In contrast to the aforementioned transmissible methods, which assess damage by analysis of signals interacting (or otherwise compared) across a connection, other impedance-based methods have been developed with customized or modified connection hardware. Mascaranas et al [44] explored the use of PZT enhanced washers, PZT ring stack actuators, and traditional nuts with PZT installments. Okugawa [45] introduced a smart washer composed of a thin plate and affixed PZT sensor installed below the bolt head and cantilevered over a traditional washer. Okugawa demonstrated that the natural frequency of the smart washer would change as varying bolt torque altered the boundary condition of the cantilevered washer. Yang et al [46] designed PZT ceramic washers installed in a bracket-bolt assembly for the monitoring of C-C composite thermal protection panels.

A significant amount of the relevant research employs PZT actuators as the foundational sensing methodology. This work, however, presents a solution to monitoring bolt torque via FBG optical sensors embedded in a composite substrate, and a specially designed washer. In contrast to the current impedance-based methods, the proposed approach does not require expensive connection hardware and uses a sensor that is already functioning in a different capacity as part of a greater sensor network for other SHM strategies like the one proposed by Yeager et al [47]. In order for a bolt torque monitoring strategy to be practical, the cost of the system must not surpass what is currently being spent in redundant fasteners and over design of connections if a paradigm shift is to be made.
3.2.2. Spectral Modeling of FBGs

3.2.2.1. Introduction

This method relies on a generally unfavorable characteristic of FBGs: the distortion of the spectra in the optical space as a result of non-uniform strains applied across the grading.

Figure 38: Uniform and non-uniform strains in FBGs

Figure 38 qualitatively shows the effects of uniform and non-uniform strains across FBGs. Significant research efforts have been made to model and characterize the effect of localized strain gradients on FBGs. Using a transfer-matrix approach [48], Huang et al [49] were the first to model Bragg spectra of chirped (strain-graded) FBG sensors by approximating the strain gradient as a piecewise continuous function that is constant within discretized grating lengths. After the calculation of the average period in each segment, the coupled mode theory equations are solved to reproduce the distorted Bragg spectrum. Prabhugoud and Peters [50] presented a modified local period function for significant gradients that would cause the traditional method to be non-converging. Park et al [51] demonstrated the effect of linear strain gradients of varying intensities on the reflected Bragg spectra both analytically and
experimentally. Gill et al [52] presented a genetic algorithm to reconstruct Bragg spectra based on highly complex and discontinuous strain profiles. Prabhugoud et al [53] developed an integrated formulation of the spectral response using a finite element model and a modified transfer-matrix method. Oliviera et al [54] explored the spectral response of gratings that were loaded transversely over a short region of the grating.

Researchers have also found innovative ways to employ distorted Bragg spectra in non-traditional ways to detect damage and develop SHM strategies. Okabe et al [55] detected transverse cracks in a composite laminate by examining the spectral broadening of a FBG sensor, and Takeda et al [56] proposed an intensity ratio derived from spectral distortion to detect delamination in cross-ply laminates.

This method exploits the tendency of FBG spectra to distort under non-uniform strains by controlling the locally imposed strain field in such a way as to produce monotonically increasing broadening of the Bragg spectra with increased fastener torque while inducing minimal wavelength shift. Thus, the method maintains a clearly detectable peak in the reflected spectrum that may still be tracked in the typical manner and used as a traditional uniaxial strain sensor. The theory behind the method will be demonstrated along with experimental demonstrations of feature correlation to bolt torque. Finally, it is demonstrated through vibration testing that the embedded FBG can still operate as a tradition strain sensor under the imposed distortion.

3.2.2.2. Theory: Transfer Matrix Method

Fundamentally, a Bragg spectrum’s response to strain change is dependent on the grating period, \( \Lambda \), and the core refractive index, \( n \). The effective index of refraction defining the grating may be represented by
where $\delta n_{\text{eff}}(z) = A(z) \delta n_{\text{eff}} \left\{ 1 + \zeta \cos \left( \frac{2\pi}{\Lambda_0} z + \phi(z) \right) \right\}$

(8)

is the direction down the longitudinal axis of the fiber from where is the length of the grating, is the fringe visibility, is the nominal grating period, is a grating chirp function, is the spatially averaged peak refraction index offset, and is an apodization function to suppress spectral side lobes. For these simulations a Gaussian apodization was imposed [57]

$$A(z) = \exp \left[ -s \left( \frac{z}{L} \right)^2 \right], \quad (9)$$

where is a sharpness parameter. This parameter was adjusted until the shape of the simulated Bragg spectra matched the baseline spectra of the sensors to be used for experimental evaluation.

The transfer-matrix approach allows for discretization of the grating into $M$ smaller gratings where the strain distribution is represented as a piecewise continuous function with the $i$-th grating period, $\Lambda_i$, averaged over the $i$-th grating segment,

$$\Lambda_i = \Lambda_0 \left( 1 - p_{e_i} \right) e_{i}(z), \quad (10)$$

where $\Lambda_0$ is the initial grating period under no strain, is the effective photo elastic constant of the glass fiber, and is the applied axial strain averaged over the $i$-th grating segment. The amplitudes of the forward and backward modes propagating through the $i$-th segment, denoted
by R and S respectively in the following equation, can be expressed as a function of a segment’s optical transfer matrix, $T_i$,

\[
\begin{bmatrix}
    R(z_{i-1},\lambda) \\
    S(z_{i-1},\lambda)
\end{bmatrix}
= T_i(\lambda)
\begin{bmatrix}
    R(z_i,\lambda) \\
    S(z_i,\lambda)
\end{bmatrix}.
\]

(11)

Then, the $i$-th optical transfer matrix is thus formulated

\[
T_i=
\begin{bmatrix}
    \cosh(\gamma_B \Delta z) - i \frac{\hat{\sigma}}{\gamma_B} \sinh(\gamma_B \Delta z) & -i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta z) \\
    i \frac{\kappa}{\gamma_B} \sinh(\gamma_B \Delta z) & \cosh(\gamma_B \Delta z) + i \frac{\hat{\sigma}}{\gamma_B} \sinh(\gamma_B \Delta z)
\end{bmatrix},
\]

(12)

where $\Delta z$ is the grating segment length. The coupling coefficients are given by

\[
\hat{\sigma}(\lambda) = \frac{2\pi}{\lambda} \left( n_{\text{eff}} + \tilde{\delta} n_{\text{eff}} \right) - \frac{\pi}{\Lambda_i}
\]

\[
\kappa(\lambda) = \frac{\pi \sqrt{\tilde{\delta} n_{\text{eff}}}}{\lambda},
\]

\[
\gamma(\lambda) = \sqrt{\left( \frac{\zeta \pi \tilde{\delta} n_{\text{eff}}}{\lambda} \right)^2 - \hat{\sigma}^2(\lambda)},
\]

(13)

where $\lambda$ is wavelength. The global optical transfer matrix, $T$, is the concatenation of the individual segment $T$-matrices.
\[ T = \begin{bmatrix} T_M & T_{M-1} & \cdots & T_1 \end{bmatrix}. \] (14)

The full transfer matrix formulation, then, is

\[
\begin{bmatrix}
R\left(-\frac{L}{2}, \lambda\right) \\
S\left(-\frac{L}{2}, \lambda\right)
\end{bmatrix} = \begin{bmatrix} T_M & T_{M-1} & \cdots & T_1 \end{bmatrix} \begin{bmatrix} R\left(\frac{L}{2}, \lambda\right) \\
S\left(\frac{L}{2}, \lambda\right) \end{bmatrix}. \] (15)

Because no backward traveling wave exists for \( z \geq \frac{L}{2} \), the right-side vector elements in (8) are described as \( S\left(\frac{L}{2}, \lambda\right) = 0 \) and \( R\left(\frac{L}{2}, \lambda\right) = R_{L/2} \). Clearly, \( R_{L/2} \) will be a common factor in both \( R\left(-\frac{L}{2}, \lambda\right) \) and \( S\left(-\frac{L}{2}, \lambda\right) \), so any non-zero value can be assumed for \( R_{L/2} \) [49].

Finally, peak reflectivity, \( \rho \), as a function of wavelength, can be written,

\[
\rho(\lambda) = \frac{\left| S\left(-\frac{L}{2}, \lambda\right) \right|^2}{\left| R\left(-\frac{L}{2}, \lambda\right) \right|^2}. \] (16)

Using this analytical approach, a model of a reflected Bragg spectrum is generated under any imposed strain gradient across the sensor. As outlined by Park et al [51], a linear strain gradient with a net zero strain across the gradient will reduce the peak reflectivity while simultaneously making the spectrum more and more broad band. The method purported in this work relies on this behavior but also requires that the general shape and structure of the spectrum be preserved. Park showed that severe linear strain gradients produced highly distorted spectra with multiple peaks and smeared wavelength content. In order to better
preserve the structure of the spectra, and to create a physically plausible situation with a mechanical fastener, the strain profiles in Figure 39 were chosen.

Figure 39: Strain gradients of increasing intensity spanning the length of the gradient

After applying the transfer matrix method with the strain profiles in Figure 39, the simulated Bragg spectra are presented in Figure 40.
3.2.2.3. Imposed Strain Field

The results presented in Figure 40 theoretically affirm the hypothesis that a particular strain profile can be chosen so as to exhibit control over the widening of the Bragg spectrum under increased strain magnitude. Practically, we need to create a physical situation that will impose the desired strain profiles near the fastener that is to be monitored. One such situation would be to impose two traction loads on the surface of the composite in the same direction down the length of an embedded optical fiber as shown in Figure 41.
This load state, in theory, should produce a strain curve similar to the curve at the top of Figure 41. Additionally, if the FBG sensor begins and ends directly underneath the two traction loads, then the sensor will experience something very similar to the strain profile in Figure 39. To validate this assumption, a crude FE model was created to simulate the load case as shown in Figure 42.
The model was created and meshed using hexagonal elements. The location of the 1 cm long FBG was modeled at the surface of the fiberglass plate to accurately obtain the strain profile over the length of the FBG. Additionally, a mesh control was generated at the location of the FBG, providing a finer mesh and a smooth discretized strain profile. The element width along the 1 cm gradient is 1.25 mm providing 80 elements and 80 strain values along the length of the grating. This load state produces z-direction strains as shown in Figure 43.
3.2.2.4. Washer Design

The analytically generated spectra in the previous section have provided validation that a full width at half maximum (FWHM) spectral metric could be a preload-sensitive feature for a bolted assembly under the assumed strain states. In order to further validate the method, a special washer was designed to impose the desired load case and therefore the desired strain profiles across the grating. The washer was 3D printed using an Ultimaker 2 with a nozzle diameter of 0.4 mm and ABS plastic. It is important to note that the choice of ABS as the washer material was made because of its ability to be 3D printed and, therefore, rapidly prototyped. In a practical application, investigations would need to be made into an optimal material. Creep due to temperature and loading would need to be researched since this method
relies on the washer being a force transfer mechanism. Figure 44 shows the washer design and the final printed washer.

![Figure 44: Washer design (left) and final printed washer (right)](image)

In principle, the washer would be positioned above an embedded FBG near a bolthole with the textured teeth of the washer sitting directly above the ends of the sensor. As a bolt is tightened, the clamping load produces contact friction between the bolt head and the 3D printed washer, which, in turn, imposes the desired surface tractions. Figures 45 and 46 present schematics of the proposed bolt-washer-sensor assembly.
An important consideration in the washer design was to mitigate power attenuation through the fiber by avoiding direct contact of the washer with the optical fiber. This is the
reason for the design of several concentrated loads around the fiber as opposed to a uniform line load across the fiber. Both would impose the desired strain field upon bolt tightening, but a line across the fiber would inhibit light propagation as the bolt was tightened, increasing the clamping load from the washer against the composite with the embedded FBG, and reducing the potential signal-to-noise of the FBG as well as jeopardize any “downstream” multiplexed FBGs in an array. Clearly, the through-thickness compression stress applied by the washer is sub-optimal in this study because part of the contact surface of the washer has been removed. This would result in a loss of strength of the connection, all other things being equal. In practice, the final washer design would have a larger contact surface while constraints in the resolution of the 3D printer necessitated the current design.

3.2.2.5. Test Article Fabrication

The material used to conduct the experiments was Pre-preg Style 7781 Woven E-Glass with 38% resin volume ratio with a cured ply thickness of .25 mm. To simulate a realistic bolted joint connection, the thickness of the cured laminate was designed to be comparable to the diameter of the 6.35 mm diameter bolt used. The design ply orientation used was \([0^\circ/45^\circ_3]_3\), resulting in a cured thickness of 4.925 mm. The composite was laid up and cured using an OVB technique. Figure 47 shows the layup before placement in the curing oven. The edge of the specimen with the egress of the fibers was “stepped down” by cutting each successive layer an 3.175 mm wider than the last. This provided a smooth ramped edge for the protruding fibers and minimized localized stress concentrations.

The vacuum bagging provided a constant pressure of 100 kPa. The cure cycle used was a ramp increase in temperature of 1.7°C/min up to 90°C, where this temperature was maintained for 60 minutes. After the 60 minutes, the part was cooled using the ambient air temperature
3.2.2.6. Experimental Validation

In order to validate the performance of the preload-sensitive feature, two experiments were conducted. The first experiment tested the relationship between the FWHM feature and the applied torque. The test was conducted by securing the composite specimen and installing a bolt, metal washer, 3D printed washer, lock washer and nut assembly through the composite specimen. Using a torque wrench, torque was increased from 0 N-m to 14 N-m in .5 N-m increments. At each torque level, full spectral data was acquired using a laptop computer and Micron Optics’ ENLIGHT software with a Micron Optics SM130-700 fiber optic interrogator. The interrogator has the ability to track spectral peak values at 2 KHz. In order to sample the entire Bragg spectrum instead of just a singular peak value, the sampling rate is only about 1.2Hz. Full Bragg spectra were acquired for 30 seconds so that noise can be averaged out at each torque level.
Figure 48: Reflected Bragg spectra at increasing torque levels

Figure 48 shows the averaged Bragg spectra for a selected number of torque levels. We note that the trend in the spectral shape change with increasing bolt torque is similar to the analytical simulations presented in Figure 40. Upon comparison, we note that the spectra in Figure 48 lack the perfect symmetry observed in the analytically simulated spectra in Figure 40. This is a product of the embedment process itself, and nuances in the washer orientation. As the composite specimen cures it creates residual strain fields throughout the composite as a result of subtle inconsistencies in fiber geometry and orientation, resin uniformity, and anomalies in vacuum bagging and oven cure. These strain gradients, if present across the length of a FBG, will distort the reflected spectrum [59]. Another cause of this asymmetry can be attributed to the difficulty in perfectly orienting the washer over the grating. Even a subtle misalignment will
cause the grating to experience an unbalanced strain gradient and induce spectral distortion. Recalling the simulated spectra in Figure 39, we note that, although there is spectral shape change, the grating spectrum does not shift side to side because the imposed strain field yields a net zero strain across the grating. This was not the case with the measured spectra during experimentation. As bolt torque and \( z \)-direction traction loading on the grating increased, there was not a net zero strain acting on the grating, causing it to shift laterally as it changed shape and distorted. A variety of variables could have contributed to this but the most likely is the previously mentioned orientation and position of the washer. Unless the washer is perfectly symmetric on the grating, it will produce a non-zero total strain on the grating that induces lateral shift of the Bragg spectra, even if the shape is comparable to the gradients in Figure 39. Pragmatically, however, this shift is inconsequential because the damage sensitive feature is blind to the position of the spectra in the optical space. It depends only upon the shape of the spectra via the FWHM metric. In light of this observation, the spectra in Figure 48 were aligned horizontally according to wavelength location of peak reflectivity for illustrative and comparative purposes.

At each torque level the FWHM of each averaged spectrum was calculated and plotted against the torque value. Figure 49 presents the results.
Figure 49: Bolt torque vs. FWHM of reflected Bragg spectra

We see a monotonic, and nearly linear, relationship between the FWHM feature and bolt torque, which validates the feasibility of fastener loosening detection with this method. In this experiment, the FWHM feature was calculated after many averages through time of sampled Bragg spectra with the test article unloaded (other than the clamping force of the fastener assembly. In practice, a connection would experience a wide range of dynamic loading scenarios that could induce undesirable stress distributions across the grating due to the stress concentration of the bolt hole. These stress distributions could adversely affect the FWHM feature. In the authors’ estimation, these anomalous feature measurements would be “averaged out” with full spectral sampling through extended periods of operation of the structure, but this would need future investigation. An important advantage of this proposed sensing method is the ability of the sensor to still be used as a traditional uniaxial strain sensor. An operational
scenario will be discussed next to show how this feature could be used to design a damage detection strategy on a structure in practice and validating the sensor’s dual purpose.

3.2.2.7. Dual Purpose Sensor

Employing embedded FBGs as the sensing component of a damage detection strategy for composite structures has been very successful in the literature but only in laboratory settings. Full commercialization of SHM systems with this application have been slow to develop for several reasons including lack of robustness, cost, and the complexity of the fabrication process. The proposed method for monitoring bolt torque addresses some of the aforementioned concerns. This method requires the installation of a custom washer that would be relatively inexpensive to mass-produce if commercialized. Another key advantage of this method is that it still allows the embedded sensor to operate as a uniaxial strain sensor via peak tracking of the Bragg spectra. This would allow the sensor to monitor bolt torque through full spectral interrogation while simultaneously allowing the sensor to function in an array as part of a more global vibration based SHM system. In order to validate this claim, an auxiliary experiment was performed. Using the same test specimen, a surface mounted FBG was installed in exactly the same position and orientation as the embedded sensor but on the bottom of the composite specimen as shown in Figure 50.
Because the embedded FBG is only one ply down in the layup, it is close enough to the surface to respond exactly opposite the surface mounted FBG on the bottom of the specimen when under dynamic loadings orthogonal to the surface of the composite plate. For the experiment, the composite was affixed to a test fixture positioned above a MB Dynamics electromechanical shaker as shown in Figure 51.
A plastic stinger attached the shaker to the part and a MB Dynamics SL500VCF power amplifier powered the shaker. In order to establish the sensitivity of the FWHM feature, a baseline library was generated by tightening the bolt assembly to 10 N-m of torque and then capturing full spectral data. Then the bolt assembly was loosened to approximately 3 N-m and retightened to 10 N-m to capture the same full spectral data. This process was repeated until 100 individual tests were complete giving 100 FWHM spectral measurements, each at 10 N-m of torque. Figure 52 presents a histogram of the distribution of these measurements.
Next, the electromechanical shaker was used to input 1 minute of pure white noise excitation into the system. During the vibration, the peak values of the Bragg spectra from the embedded sensor and the surface mounted sensor were sampled at 2 kHz using the Micron Optics hardware and software. Because the 2 sensors are in the same planar location on the plate but on opposite ends through the thickness, the strain time histories should be exactly opposite in magnitude of each other under an orthogonally applied forcing function. Upon completion of the vibration, the time histories were overlaid in Figure 53.
Figure 53: Strain time histories recorded from the 2 FBG sensors from the white noise input

The strain time histories show strong agreement with a subtle difference in magnitude. This difference is most likely due to the fact that the surface mounted FBG is slightly further away from the neutral bending axis than the embedded FBG that is only one ply down from the opposite surface. It is also possible that subtle errors in sensor placement or orientation could
account for the small errors. The strain time history from the embedded FBG shows no signs of “peak hopping” or “wavelength hopping” which was discussed earlier in the dissertation. With this auxiliary test we have validated that the slightly distorted spectrum created by the bolt/washer assembly leaves the spectral structure intact enough to still allow the sensor to function as a traditional FBG strain sensor.

A final consideration is to understand how sensitive the feature is to normal operational loadings. An assumption was made that 1 minute of pure white noise shaking that resulted in peak strains on the order of 50 microstrain should not cause any bolt loosening and, therefore, should not result in a significant change in the FWHM spectral measurement. So, after the shaking was completed, one final FWHM measurement was taken and placed into context of the original histogram in Figure 54.

![Figure 54: FWHM measurement after the shaking (green line) in context of 100 previous tests](image)
A portion of Chapter 3 has been published in *Structural Health Monitoring: An International Journal*, Mike Yeager, Michael Todd, William Gregory, and Chris Key, 2016. The title of the paper is “IWSHM 2015: Assessment of embedded fiber Bragg gratings for structural health monitoring of composites.” The dissertation author was the primary investigator and author of this paper.

Another portion of Chapter 3 has been submitted for publication in the *Journal of Intelligent Material Systems and Structures*, Mike Yeager, Anthony Whitaker, Michael Todd. The title of this paper is “A method for monitoring bolt torque in a composite connection using an embedded fiber Bragg grating sensor”. The dissertation author was the primary investigator and author of this paper.
Chapter 4

**Damage Detection Scenario: Impact Damage**

4.1. Introduction and Motivation

In addition to connection damage, delamination from impact damage is a possible failure mode for a composite sail component in a submarine application. Because of the nature of the operation of a submarine structure, visible inspection is not always possible to inspect for impact damage. Even when visible inspection is possible, composites are at risk for barely visible impact damage (BVID) that is the result of low velocity impacts and/or fatigue. BVID can lead to catastrophic failure with very few, if any, normal visual cues to its presence [61]. Thus, a robust SHM system for this application would also need to be able to identify impact-induced damage. To illustrate these capabilities, a representative impact specimen was created for experimentation.
4.2. Test Article Fabrication and Experimentation

The glass-epoxy pre-preg used in the fabrication was Axiom AX-3201S/EL (woven glass fiber with toughened epoxy matrix) with a target thickness of 0.5 in. (16 plies) to provide a specimen representing the intended application that may be employed in a fleet application. The 48 in. x 48 in. panel was outfitted with a network of 40 embedded FBGs with 10 sensors multiplexed on 4 separate fibers. The FBGs were placed at 6.25% of the panel thickness, closer to the surface away from the impact face, during the pre-preg layup. The panel was cured in a vacuum oven at 200 °F under constant pressure. Surrogate model finite element simulation was used to determine eigenmodes to aide in designing the placement of sensors within the laminate such that significant strain magnitudes would result from expected impact locations. Figure 55 presents the routing paths of the multiplexed FBG arrays and establishes the sensor naming convention used throughout the study.

Figure 55: Sensor layout (left) and naming convention and placement measurements, in inches (right)
A test fixture fabricated with aluminum rectangular bars was used to support the panel and introduce damage using a drop weight pendulum impact hammer. The fixture had a 44 in. x 44 in. free span and provided a clamped (fixed) boundary condition along each panel edge. The impact head was outfitted with a Piezo-based dynamic load cell for measuring impact force history and a photogate system was used to measure the actual velocity at impact. A steel cable with a pneumatic release mechanism was used to hoist the pendulum for repeatable impact energies. A surrogate, un-instrumented panel was first installed in the test fixture for system calibration and to assist in establishing damage characterization and associated energy levels. This surrogate panel and the test fixture are presented in Figure 56.

![Figure 56: Extruded aluminum test figure](image)

The instrumented specimen was installed in the frame using c-clamps to simulate a fixed-fixed boundary condition, as shown in Figure 56. On the back side, an electromechanical shaker was suspended from the frame and attached to the panel using a steel stinger rod. The
shaker was powered with an MB Dynamics power amplifier and provided the simulated pseudorandom excitation. Impact damage in the form of delamination was introduced through repeated impacts of the panel with the impact head. As repeated impacts were performed, the impact location was moved slightly to continue growing the delamination and avoid through-penetration of the panel. In between impact events, the shaker was attached to the panel and actuated for 2 minutes with BLWN. The excitation signal ranged from 10 Hz to 2500 Hz. The upper bound was governed by the Nyquist sampling limitations of the optical interrogation hardware and the lower bound was selected to exclude very low frequency components near the oscillation frequency of the suspended shaker. Each 120-second time history was windowed and segmented into 2-second tests for a total of 58 individual tests at each of the 12 discrete damage levels. Figure 57 describes the impact protocol for incrementally growing the delamination in the panel and Table 3 describes the accumulation of delamination damage in the panel.

Figure 57: Impact locations for the test article
Figure 58: Testing Flow
Table 3: Impact methodology and accompanying delamination

<table>
<thead>
<tr>
<th>Damage Location</th>
<th>Impact Number</th>
<th>Delamination Size (sq. cm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5.18</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>8.90</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>33.29</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>55.55</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>80.32</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>111.42</td>
</tr>
<tr>
<td>C</td>
<td>8</td>
<td>150.26</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>176.13</td>
</tr>
<tr>
<td>D</td>
<td>10</td>
<td>208.45</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>253.03</td>
</tr>
<tr>
<td>E</td>
<td>12</td>
<td>304.84</td>
</tr>
</tbody>
</table>

The vibration time histories induced by the shaker were recorded with a Micron Optics si155 fiber optic interrogator at a sampling frequency of 5 kHz. The testing methodology can be visualized in Figure 58 and the delamination growth following each impact has been illustrated (based on photos taken after each impact) in Figure 59. Finally, Figure 60 presents the actual test article after experimentation.
Figure 59: Illustration of damage progression
4.3. Feature Extraction

4.3.1. Power Spectral Density Feature

The same assumption that was made regarding the bolted connection specimen in Chapter 3 is made here: damage to the structure will result in stiffness loss which will change the vibration characteristics of the structure. Recall from Chapter 3 that the frequency domain feature is a vector of frequency deltas from the shift in peaks to lower frequencies (see Equation (4)). Figure 61 summarizes the results from the power spectral density peak feature.
Sensor 10, indicated with a red X on the figure, was lost during fabrication and was inoperable for the duration of testing. It is difficult to glean too much useful information from Figure 61 but it shows the global success of the feature, which is worth noting. All 39 operable sensors show the Mahalanobis distance being correlated with the delamination area. The horizontal axis in the figure is the test number. Recall that there are 6 baseline tests and 12 different damage levels giving 18 total test groups with 58 individual tests within each damage level for a total of 1044 individual tests. Figure 62 presents the results for just sensor 5, making visualization easier.
4.3.2. Cross Power Spectral Density Feature

Although the power spectral density feature used up to this point in the dissertation performs well within the context of these experiments, it is not without its shortcomings. In general, it will not be robust to a generalized input excitation. If the power spectrum of the input excitation is flat (which is the case in these experiments), then the feature will perform as expected, but without knowledge of the input, it is impossible to know for sure if peak shifts in the power spectral density of the response are due to damage or due to changes in frequency content of the input. A practical example in the context of this research could be that the operation of the engine of a submarine vessel introduces a strong harmonic component to the ambient excitation acting on the vessel. If that harmonic component shifts in frequency because of a change in operation of the engine, it could be perceived as damage by the SHM system.
even though no damage has occurred ("false positives"). So clearly there is a need to have a more robust frequency domain feature. This concern was outlined in detail by Farrar et al. [20], and a solution was proposed via a modified frequency domain feature using the cross power spectral density (CPSD) estimates for pairs of sensors. The CPSD is defined as

\[
\hat{S}_{xy}(\omega) = \frac{2}{N} E \left[ X^*(\omega) Y(\omega) \right]
\]

where * denotes the complex conjugate. Here, \( E [ \cdot ] \) is an overlapping average operator. From this definition it is clear that two measured responses will only be correlated at the resonant frequencies of the structure. This feature alteration does not change the rest of the damage detection strategy. The shifts in peaks of the CPSD will be the damage sensitive feature vector and that multivariate feature vector will be mapped to a scalar metric through the Mahalanobis distance for discrimination.

For illustration, Figure 63 presents representative CPSD curves for a random sensor pair. A baseline CPSD is shown in blue and the CPSD from the fully damaged case (47.25 sq. in. delamination) is shown in red and clear shifts to lower frequencies can be noted. In this particular case, the feature vector for this sensor pair is of dimension 5 because of the 5 prominent peaks.
Figure 63: CPSDs for baseline and undamaged cases

Because sensor pairs are being used to generate the spectra and there are 40 sensors (though only 39 are operable), there are 780 possible sensor pair combinations. So another advantage of using the CPSD as the foundation for the damage sensitive feature is that it provides a much broader space, so to speak, to search for damage sensitive features. Searching all 780 sensor pairs, however, is computationally expensive and overly redundant for the purpose of this study so a random permutation of 100 sensor pairs was generated as the set of time histories that were used to generate all CPSDs. The following figure presents the results for 4 randomly selected sensor pairs.
Figure 64: Mahalanobis distances for CPSD feature for 4 sensor pairs

In Figure 64, the data points to the left of the solid vertical line are from baseline (undamaged) tests, and the dashed vertical lines represent the different damage levels.

4.3.3. Time Domain Feature – AR Coefficients

Similar to Chapter 3, time series analysis is employed to have a more robust library of features that can be used to design a holistic SHM system. AR modeling will be used as it was previously. The AR model order must first be determined before subsequent analysis can begin. As mentioned in Chapter 3, an appropriate model order is important because too low of an order may not be able to fully capture the underlying physics of the data, but too many terms will
over-fit the model (e.g., capture noise characteristics), yielding a model that may not generalize to other time histories. A more intuitive approach to determining the model order was used during this test. AR models of varying model orders were generated for a particular baseline time history for each sensor. Then these models were used to predict another baseline time history of the same sensor. At lower model orders, the model will not generalize the capturing of inherent physical processes to other baseline time histories. At excessively high model orders, the model gets fitted to the noise of the original baseline time history and becomes a progressively worse predictor of other time histories. If AR model order is plotted against the resulting prediction error of the model there will be a global minimum at the optimum AR order as expressed in Figure 65.

![Figure 65: AR Model order vs. prediction error](image)

After performing this procedure for all sensors and multiple tests, it was determined that the optimum model order was near 150. Once the model order has been determined, the AR models must be generated for all sensors and tests and the Mahalanobis distance calculated.
Recall that the AR coefficients themselves are the multivariate damage sensitive feature. So each feature vector is made up of 150 elements. Figure 66 presents the results of this procedure for all 40 sensors.

![Figure 66: Mahalanobis distances for all sensors: AR coefficients as the feature](image)

As with the frequency domain features, the AR coefficients show strong correlation to increasing delamination area.

### 4.4. Hypothesis Testing

In Chapter 3, distributions of Mahalanobis distances for the undamaged bolted specimen were assumed to be normally distributed. This is, in reality, a poor assumption but it allowed for the full detection process from data to decision to be carried through. For this test, a
more appropriate statistical model is developed. In this section, Mahalanobis distance distributions from the CPSD feature will be used to carry out the hypothesis testing.

4.4.1. Chi-Square Distribution

An important underlying assumption is that the feature vectors that are extracted from the raw time histories are multivariate normal. If this is true, then the squared Mahalanobis distance will follow a chi-square distribution with $p$ degrees of freedom [62] where $p$ is the dimension of the feature vector:

$$x \sim N_p(\mu, \Sigma) \Rightarrow d \sim X^2_p$$

where $x$ is the multivariate feature vector of dimension $p$, $\mu$ and $\Sigma$ are the mean and covariance of the sample, $d$ is the collection of Mahalanobis distances and $X^2_p$ is a chi-square distribution with $p$ degrees of freedom. This assumption is validated by plotting a histogram of the baseline Mahalanobis distances for a given sensor pair and overlaying a chi-square distribution of the appropriate degrees of freedom. Figure 67 shows this for the pair of sensors 15 and 29. It is evident that the Mahalanobis squared distances follow a chi-square distribution, which strongly supports the assumption of Gaussianity for the feature vectors.
4.4.2. Hypothesis Formulation

Given this statistical model, a detection hypothesis test may be constructed. In this study, “critical damage” was defined to be the lowest level of damage (1.86 cm² delamination). Figure 68 shows the baseline data compared to the smallest damage level, including the chi-square distribution applied to the baseline; the filled points are being tested (compared) against the open circles via the test

\[ H_0 : d_i \in X^2_p \]
\[ H_1 : d_i \notin X^2_p \]  \hspace{1cm} (19)

where “0” indicates the null hypotheses and “1” indicates the alternate hypothesis. The hypothesis test is applied to each of the 100 sensor pairs in consideration independently (since the number of degrees of freedom can change from pair to pair in accordance with cross spectral...
peak identification), and then a simple voting scheme may be employed across the network to arrive at a final decision.

Figure 68: Comparison of baseline to damaged Mahalanobis distances. The fitted chi-square distribution is given by the blue curve

Figure 69 shows a number of different sensor pair comparisons, for illustrative purposes. For the indicated sensor pair number, the baseline histogram and corresponding chi-square model are shown, along with testable data points (shown in red as well). In any binary hypothesis test, the decision of which hypothesis to select depends upon a threshold that must be set, and this threshold depends on the application; in this test, a 95% confidence was selected, resulting in the individual black dashed lines drawn upon each distribution in Figure 69.
Figure 69: Specific hypothesis test visualization for 4 different sensor pair combinations.

Considering each possible sensor pair means that there will be 100 true/false test results for each potential outlier, as the experiment was set up using 100 random sensor pair combinations. The simple sensor fusion strategy is a voting scheme in which if a majority (>50) of the sensor pairs choose an outlier, then the point is labeled an outlier, and the null hypothesis is rejected. If a point, in reality, comes from a damaged structural state but is labeled undamaged, a false-negative is the result. A false-positive implies the opposite: that a data point is actually from an undamaged structure but is given a damaged assignment. Finally, a blind test is conducted to assess the performance of the SHM algorithm. A random assortment of 290 baseline data points is used to create the baseline chi-square distribution, leaving 58 data points that are, in reality, undamaged and 58 points that came from the damaged structure. The
The aforementioned binary hypothesis then attempts to accurately discern between damaged and undamaged data points.

### 4.4.3. Test Results and Discussion

The results after final sensor fusion via voting are shown in Table 4. The first row represents results for the binary test as stated, i.e., detecting the lowest damage level. No false negatives were reported, and about 11% false positives, which is consistent with the statistical model threshold. The same baseline was also applied to some higher damage levels, and the results are shown on subsequent rows. For any delamination 33.29 cm$^2$ and larger, there was 100% correct classification.

<table>
<thead>
<tr>
<th>Delamination Area (sq. in.)</th>
<th>Correct Prediction Percentage</th>
<th>False Negatives (Out of 116)</th>
<th>False Positives (Out of 116)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.288</td>
<td>0.897</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>0.803</td>
<td>0.914</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>1.38</td>
<td>0.983</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5.16</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4: Hypothesis test and sensor fusion voting results for the binary detection problem.

It is important to note that the damage detection scenario constructed in this experiment attempts to model an unsupervised learning scenario in which the probability distribution functions of the damaged Mahalanobis distances would be unknown. In this type of application
the decision threshold will be established somewhat arbitrarily as it was for this experiment. Figure 70 presents the prediction results along with the false-negatives and false positives for a range of potential threshold choices.

![Figure 70: Outcomes of varying confidence threshold selections. The solid line represents overall correct detection percentage (left vertical axis), the dashed and dotted lines represent the false-positives and false-negatives respectively (right vertical axis)](image)

According to the figure, a decision threshold of around 83% would appear to be the best choice for a decision threshold because it yields the best prediction results and minimizes the occurrences both the false-negatives and false-positives. It is important to remember, however, that in many SHM applications, a false-negative diagnosis will have significantly higher life safety implications than a false positive (and thus, consequences). This practical consideration justifies the more conservative choice of 95% as the decision threshold used in this experiment.

A portion of Chapter 4 has been submitted for publication in *Advanced Composite Materials*, Mike Yeager, Anthony Whitaker, Daniel Whisler, Michael Todd, Hyonny Kim,
William Gregory, Chris Key. The title of this paper is “Binary hypothesis-based impact damage detection, for composite material systems embedded with fiber Bragg gratings.” The dissertation author was the primary investigator and author of this paper.
Chapter 5

Statistical Model Refinement

5.1. Introduction and Motivation

So far, the Mahalanobis distance has been used extensively to create a discrimination framework for damage identification in composites. Recalling the formulation of the Mahalanobis distance (5), the inputs are a test vector of interest, and then the statistical location and scatter of the training data set. In the SHM technical literature, the statistical location and scatter have historically been estimated as the arithmetic multivariate mean of the baseline data (location) and the sample covariance of the baseline data (scatter). It has been observed by Filzmoser et al [63] (among others) that this formulation produces a kind of circular dependence in that the Mahalanobis distance attempts to identify outliers but it is formulated by quantities that are sensitive to the same outliers.
5.2. Robust Distances

The mitigation technique proposed here is to employ robust estimations of location and scatter in the training data set to be used in the formulation of the Mahalanobis distances. Many robust estimators have been explored by other researchers. The pioneering work was proposed by Gnanadesikan et al [64] who developed multivariate trimming (MVT) in which a robust estimation of the covariance was calculated by removing a subset of objects with the highest Mahalanobis distances iteratively until convergence of the covariance. The estimator is not good for all applications because the breakdown value is heavily dependent on the dimensionality of the data. Rousseeuw [65] proposed the minimum volume ellipsoid (MVE) method that seeks to find the smallest ellipsoid that encompasses a subset of the data. Although it has a 50% breakdown value it is computationally inefficient and was eventually replaced by another metric of Rousseeuw’s [66] called the minimum covariance determinant (MCD). The MCD has a 50% breakdown value but additionally, efficient algorithms exist for its computation including the FAST-MCD [67], making it more desirable for practical application. The orthogonalized Gnanadesikan-Ketering (OGK) estimator proposed by Marrona et al [68] is extremely efficient at the expense of affine equivariance. The Olive-Hawkins method uses both the Devlin-Gnanadesikan-Kettering (DGK) attractor [69] and the Median Ball Attractor (MBA) [70] in its formulation. Although there are many other proposed estimators in the literature, the MCD, OGK, and Olive-Hawkins methods will be compared against the classical formulation in this chapter.
5.3. Illustrative Example

In order to assess the performance benefits of using robust estimators the Mahalanobis distance distributions from the CPSD feature from the impact panel in Chapter 4 will be used. Recall from that discussion that the Mahalanobis distances of the undamaged panel follow a chi-square distribution with \( p \) degrees of freedom, where \( p \) represents the dimensionality of the feature vectors and stems from the number of prominent peaks in the CPSD estimates.

In order to establish an intuitive understanding of the potential gain of using robust estimators, it is beneficial to limit the feature space to two dimensions for visual interpretation. So in this preliminary exploration, only the first two peaks of the CPSDs between sensor pairs are tracked to generate the feature vectors. Figure 71 presents data from a representative sensor pair. Each data point represents the frequency deviation in the first two spectral peaks of the CPSD for a given sensor pair compared to a baseline measurement for undamaged (open circles) and damaged (filled circles) structural states. The two ellipses correspond to a .95 quantile of the distribution of Mahalanobis-squared distances calculated using different estimates for location and scatter. The solid ellipse was generated using the classical estimates for location.
and scatter, namely, the sample mean and the sample covariance. Assuming the filled circle data points were feature vectors from an unknown structural state (damaged or undamaged), a binary hypothesis test would be constructed according to (19) where “0” indicates the null hypotheses and “1” indicates the alternate hypothesis. Visually, this may be interpreted as any data point that falls outside of the ellipse would be classified as an outlier and given a damaged diagnosis. It is observed that the baseline data set in Figure 71 contains several extreme values on the right side of the plot that effectively “stretch” the error ellipse and include several points that actually come from the damaged structure. This is a phenomenon known as masking, where the presence of outliers in the baseline data causes true outliers from the damaged structure to be given a false negative diagnosis. The dashed ellipse was constructed using the MCD estimations of location and scatter and it is observed that this ellipse is less influenced by some of the extreme values of the baseline data. Every solid circle data point that
is between the two ellipses can be thought of as data points that would have been incorrectly diagnosed had the classical estimations of location and scatter been used. Figures 72 and 73 illustrate the potential benefit of using robust distances in the context of the binary hypothesis test.

Figure 72: Outlier detection using classical estimation for location and scatter

Figure 73: Outlier detection using robust estimation for location and scatter
In Figures 72 and 73, the plots on the right show the robust distances from the undamaged structure and the robust distances from the damaged structure. Overlaid in green is the PDF of a chi-square distribution for 2 degrees of freedom and the horizontal dashed line depicts the .95 quantile. The points shaded in yellow in both figures would be correctly identified as outliers. It is clear from the figures that using a robust estimate for location and scatter has favorable potential impacts on the detection of damage. Using robust distances, 32 out of 58 total outliers were identified as opposed to only 16 of 58 using the classical formulation.

In addition to comparing the detection performance of distances using robust and classical estimations for location and scatter, another goal of this study is to assess the performance of different robust estimators. The MCD, OGK, and Olive-Hawkins estimators will be used in a comparative performance study. Figure 74 presents the error ellipses from classical estimation-based distances and the three robust estimators.
5.4. Application to Experimental Data

To assess the performance of the formulations, a damage detection scenario is simulated using the full dimensionality of the data. The set of 348 individual baseline feature vectors was randomly permuted and a subset of 290 feature vectors was used to calculate the Mahalanobis distances for the binary test. This leaves 58 feature vectors that are, in reality, undamaged and 58 feature vectors from the lowest damage level (1.86 cm\(^2\) delamination) that will be tested. Ideally, the test will be able to perfectly distinguish between damaged and undamaged feature vectors.

Out of the 780 possible sensor pair combinations only 100 pairs were considered because of the computational cost and excess redundancy. A decision-level voting scheme is the final diagnosis mechanism; if more than 50\% of the sensor pairs reject the null hypothesis, then a “damaged” diagnosis is given. Table 5 presents the results from the full damage detection scenario.
The results show a non-trivial improvement in detection performance using robust estimations of location and scatter when calculating the Mahalanobis distances. All robust estimations performed the same in the sense of overall correctness but the OGK and Olive-Hawkins estimations minimized the number of false negatives. This implies that these two estimations are slightly more exclusive regarding the subset of baseline feature vectors used in the estimation of location and scatter. In most SHM applications where life-safety is a factor, the consequences of a false negative far outweigh the consequences of a false positive so more restrictive estimations are probably preferred.

A portion of Chapter 5 has been submitted for publication in *Structural Health Monitoring: An International Journal*, Mike Yeager, Michael Todd. The title of this paper is “Using robust distances for feature discrimination in a damage detection scenario.” The dissertation author was the primary investigator and author of this paper.
Chapter 6

Damage Localization

6.1. Introduction and Motivation

To this stage, only damage detection has been addressed in the preceding chapters. For obvious reasons, the ability to localize damage is an equally valuable feature of a robust SHM system especially in a large composite structure where BVID would be hard to find by visual inspection. Damage localization has been a significant research focus for SHM researchers. In the case of plate-like structures like the ones in consideration in this dissertation, researchers have developed numerous strategies for damage localization. In the case of impact source localization, conventional triangulation techniques based on time of flight (TOF) of elastic waves has been in practice for many years. A thorough review of acoustic source localization techniques has been performed by Kundu [71]. Impact localization in isotropic plate-like structures has been well researched with several successful implementations with the foundational work performed by Tobias [72]. This problem is less complex than the case of anisotropic plate-like structures because the wave speed is directionally dependent. Specifically employing FBGs, Betz et al [76] proposed a configuration of a pair of rosettes of 3 FBGs each
for damage localization. Hiche et al [77] developed a strain amplitude based method for impact localization and Frieden et al [78] employed FBGs in the traditional Lamb-based triangulation framework.

The aforementioned methods detect and localize impacts, but do not necessarily speak to whether or not said impacts produced damage in the structure. Here a method is proposed that would be coupled with the preceding damage detection strategies to localize damage after it has been detected.

6.2. **Definition of the Feature for Localization**

This strategy employs time series analysis in the form of AR modeling across sensor pairs in the context of a new imaging algorithm. This error term in (3) is the foundation of construction of the damage sensitive feature used for localization. For all possible sensor pairs, the AR coefficients from the first sensor in the pair are used to predict the other sensor in the pair and the prediction error is calculated for both the baseline and the damaged cases as illustrated in Figure 75.
Recall that an array of 40 sensors implies that there are 780 possible sensor combinations. The feature used for localization, then, is the ratio of the prediction errors between the baseline and the damaged case for every possible sensor pairs such that:

\[
\delta_p = \frac{\text{RMS}\left[ e_{p,\text{damaged}}(n) \right]}{\text{RMS}\left[ e_{p,\text{undamaged}}(n) \right]}
\]  

(21)

where \( p \) is the index for all possible sensor pairs and \( \text{RMS}[\cdot] \) is the root mean square of the error. The underlying assumption is that the performance of the prediction, regardless of how good or bad, should be relatively unchanged between the undamaged and damaged cases if both sensors are far removed from the damage. If one of the sensors in the pair is close to the damage, local dynamic anomalies will degrade the performance of the AR model in the damaged prediction and push the ratio higher than unity.
6.3. Imaging of the Damage Location

Imaging of the localized damage can be performed according to,

\[
I_{\text{damaged}}[i,j] = \sum_{i=1}^{p} \delta_i^p M_{\theta}^p - \sum_{i=1}^{p} M_{\theta}^p
\]  

(22)

where \( M_{\theta}^p \) is an elliptical image mask where the foci are the two sensors in a given sensor pair, \( i \) and \( j \) are the pixel indices, \( p \) is the number of pairs, and \( \delta_p \) is the damage sensitive feature (21). Figure 76 illustrates the imaging methodology. For every sensor pair, an ellipse mask of all ones is generated for the pixels contained by that mask. Where two ellipses overlap, for instance, the pixel would have a value of two, etc. This is continued until all 780 (only 741 sensor pairs were used because of the inoperable sensor 10) ellipses are super imposed on one another shown in the bottom right of Figure 76.
After the full stack of ellipses is generated, another stack is generated, but the individual masks are weighted by the prediction error ratio $\delta_p$. This will skew the image slightly towards the damage and simple image subtraction will reveal the location of the damage. Figure 77 shows the localization results for the most extreme damage case: the 47.25 in$^2$ delamination.
An important clarification is needed regarding the interpretation of the localization images. The nature of the localization feature is qualitative in nature and, therefore the imaging must be interpreted qualitatively. The area of red coloration, for example is not indicative of the size of the delamination, or of the intensity of the damage. It is tempting to draw more conclusions from the image than are actually there. The image simply gives a qualitative estimation of the location of the damage after it has been decided that damage exists. While the localization imaging performs well for the largest delamination, its performance degrades as the damage severity decreases. Below damage level 7 (17.27 in² delamination), the localization
algorithm is unable to localize with any consistency. Figures 78 through 82 show selected localization images for damage levels 7 – 11 (17.27 in$^2$ – 39.22 in$^2$).

Figure 78: Damage Localization for Damage Level 7 (17.27 in$^2$).
Figure 79: Damage Localization for Damage Level 8 (23.29 in$^2$).
Figure 80: Damage Localization for Damage Level 9 (27.3 in$^2$).

Figure 81: Damage Localization for Damage Level 10 (37.31 in$^2$).
Figure 82: Damage Localization for Damage Level 11 (39.22 in²).

6.4. Sensor Network Density

The figures in the preceding section suggest that the accuracy of the localization is greatly influenced by the size and/or the severity of the damage. Another important consideration is sensor network density. It is important to quantify the ability of the localization algorithm to perform with varying levels of sensor network density. To assess this, only a subset of sensors was used during processing to simulate a less dense sensor network. Several randomized simulations were conducted in which a random collection of sensors was generated for 30, 20 and 10 sensors. The localization algorithm was performed with only those sensors. Figure 83 presents the sensor numbering scheme used to generate the randomized sensor subsets along with the damage location indicated by the diamond shapes.
Sensors 28 and 29 seem to be very critical for good performance which is not surprising considering their to the damage. In instances where sensors 28 and 29 were excluded from the sensor network, the localization algorithm provided less correlated results to the damage, even in more dense networks. Conversely, if all of the sensors in close proximity were included in the localization attempt, the results were very good, even in more sparse networks. This leads to the conclusion that the damage sensitive feature is only sensitive in close proximity to damage. So a more sparse sensor network leads to a higher probability that damage is not close to any sensors.

The Figures 84 through 89 present the results from the localization simulations with reduced sensors used in the algorithm. The damage location is marked but the white diamonds while the sensors used in the simulation are shown as white x’s. The simulations that are
presented were chosen because of the presence or absence of Sensors 28 and 29 as these are the most relevant cases for discussing performance of the localization algorithm.

Figure 84: 30 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right including S28 and S29)
Figure 85: 30 Sensors Localization for Damage levels 7-12 (from top to bottom left to right excluding S28 and S29)

Figure 86: 20 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right including S28 and S29)
Figure 87: 20 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right excluding S28 and S29)

Figure 88: 10 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right including S28 and S29)
Figure 89: 10 Sensors Localization for Damage Levels 7-12 (from top to bottom left to right excluding S28 and S29)
Chapter 7

Conclusions and Future Work

7.1. Conclusions

The research in this dissertation provides a systems-level investigation into the health monitoring of composites using embedded fiber Bragg gratings. Experimentation has, in general, been conducted on representative test articles in an attempt to bring SHM with embedded FBGs closer to commercialization. Although applicable across other applications, the research was specifically tailored towards submarine components to meet the needs of continued innovation within the US Navy. The reason for choosing optical sensors as the sensing methodology and an in-depth exploration of the motivation behind the body of work was discussed in Chapter 1, along with a review of structural health monitoring.

In Chapter 2, we investigate the pragmatic viability of embedded FBGs as a sensing methodology in a submarine application. First, a wetted environment test was conducted to assess the ability of FBGs to function under differing levels of liquid absorption. Then, tests were conducted to determine how the composite manufacturing method and material affects FBG performance. Three-point bend tests were performed for GFRP and CFRP specimens for
OVB and VARTM process. The sensors performed well except for the panels manufactured with a VARTM technique. It was determined that the consolidation of a fully infused VARTM process introduces micro-bending into the fiber which greatly attenuates optical transmission. Lastly, a novel surface mounted connector design was proposed that provides a method of egress for embedded fiber while also not introducing significant complexity into the manufacturing process. The robustness of the connector was assessed via a high impact mechanical shock test in which the connector was still optically viable after withstanding multiple dynamic shock events. Test articles with the embedded connectors were manufactured using a two-step VARTM process which meets Navy specifications and also mitigates the micro-bending observed in other VARTM panels.

In the first part of Chapter 3, a damage detection system is developed to detect low levels of connection damage in the form of bolt bearing damage using a network of embedded FBGs. Both frequency and time domain features were employed to perform the detection and a binary hypothesis test was constructed to assess the decision making ability of the system. Later in Chapter 3, a novel bolt preload monitoring method was proposed using a specially designed washer and an embedded FBG near a bolt hole. The method provides strong correlation between bolt torque and the damage sensitive feature while still allowing the FBG to be used as a traditional strain sensor as part of a great damage detection scheme.

The main focus of Chapter 4 was to apply the damage detection system from Chapter 3 to an impact damage detection scenario. A large impact panel with 40 embedded FBGs was subjected to incremental delamination through repeated impacts with a weighted pendulum. Further refinement to the statistical model for feature discrimination was made and the system was able to detect very small defects in the panel.

Chapter 5 explores further statistical refinement by addressing the robustness of the Mahalanobis distance. By using so-called robust distances to compute the statistical location
and scatter of a baseline sample population, significant improvement in damage detection ability was observed. The technique was applied to the impact panel and compared to the performance of the classical formulation of the Mahalanobis distance which uses sample mean and sample covariance as the estimates of location and scatter.

Lastly, Chapter 6 presents a novel imaging technique for localizing impact damage when the impact event was unobserved. Using weighted ellipse masks between sensor pairs, damage was localized in the impact panel. A sensor density study was performed to assess the ability of the method to localize damage with fewer and fewer sensors.

A list of the main contributions made in this dissertation is as follows:

- Assessment of embedded FBGs as a pragmatic sensing solution for the health monitoring of composites in a submarine application.
- Design and validation of a novel surface-mounted egress solution that was tested for survivability in a high impact mechanical shock experiment.
- “Design-to-data-to-decision” demonstrations of an SHM system for monitoring connection damage and impact damage were presented in the context of representative test structures.
- A novel method for monitoring fastener preload using a specially designed, 3D printed washer was presented and validated.
- Robust Mahalanobis distance estimations were explored and compared to the classical formulation used in the SHM literature.
- A novel impact damage localization and imaging method was presented using cross-predictive AR models.
7.2. Future Work

This research attempts to bridge the gap between the laboratory and commercialization of embedded FBGs for the health monitoring of composites, there are still issues that must be addressed before full scale commercialization will be possible.

Further refinement needs to be made to the embedded connector at the egress point of an embedded array of FBGs. This research presents only a proof of concept with a less-than-optimal material. Further exploration into the appropriate manufacturing material and further design improvements should be made before the connector is industrially viable. Additionally, although wetted environment testing was conducted, the connector itself was never tested in an underwater environment. In the application the Navy has in mind, the connector would be on a non-pressurized component and would be submerged in water. A quick test should be performed to ensure that this does not hinder interrogation.

In this work, a passive sensing approach to SHM was taken in which excitation of the system comes from the operational environment. In all test cases, a simulated pseudorandom operational loading was simulated with BLWN through an electromechanical shaker. Although the CPSD feature in Chapter 4 should be robust to the system input, different input spectra should be explored to ensure that is the case. Also, a significant consideration in this type of application would be temperature compensation. A submarine vessel would undergo significant temperature gradients at varying sea depths. This body of work ignores all temperature effects because several techniques in the technical literature have been proposed and validated. However, further research should explore how temperature compensation techniques can be integrated into this work.
References


