Incorporation of Fiber Bragg Grating sensors in additive manufactured Acrylonitrile butadiene styrene for strain monitoring during fatigue loading

by

Doug Munghen

A thesis submitted in conformity with the requirements
for the degree of Master of Applied Science
Graduate Department of Applied Science and Engineering
University of Toronto

© Copyright by Dougy Munghen 2021

Incorporation of Fiber Bragg Grating sensors in additive manufactured Acrylonitrile butadiene styrene for strain monitoring during fatigue loading

Doug Munghen

Master of Applied Science

Graduate Department of Applied Science and Engineering
University of Toronto

2021

Abstract

This study investigates the characteristics of Fiber Bragg Grating (FBG) sensors with respect to their feasibility for use in additive manufactured materials under fatigue loading. This was done through tensile fatigue testing of both standard Acrylonitrile butadiene styrene (ABS) specimens and ABS specimens containing FBG sensors. These sensors were incorporated into the material using two different techniques: inserting and embedding. Comparing fatigue test results between the specimen types showed that incorporating the FBGs into the material affected fatigue life differently depending on the load level, while also increasing the variation in fatigue life between specimens. The strain measurements of the embedded FBGs were seen to more closely resemble results from finite element simulations than were the measurements of the inserted FBGs, thus proving embedding to be the superior technique.

Acknowledgments

First, I would like to thank Professor Kamran Behdinan for giving me the opportunity to study at the University of Toronto. The past 21 months have been an extraordinary learning experience and your counsel has been a tremendous benefit to this research.

I thank Dr. Vincent Iacobellis for his guidance in research, writing and testing. Having someone to help guide me through this degree has made things much smoother than otherwise would have been.

I thank my parents who have always pushed me to better myself. Your love in support has done more for me than I think I will ever know.

I thank my friends for keeping my spirits high while keeping me down to earth during these challenging times. Special thanks to Davis McClarty, for the bible states, “As iron sharpens iron, so one man sharpens another”.

Lastly, I would like to thank the health care workers who have sacrificed so much during the past year and without whom this research would likely not have been possible.

Table of Contents

Acknowledgments.....	iii
Table of Contents	iv
List of Tables	vi
List of Figures	vii
List of Appendices (if any)	ix
1 Introduction	1
1.1 Motivation.....	1
1.2 Outline.....	2
2 Literature Review	3
2.1 Fiber Bragg Gratings.....	3
2.1.1 Background	3
2.1.2 Structural Health Monitoring Applications	4
2.1.3 Temperature Sensing Applications	12
2.1.4 Biomedical Applications.....	14
2.1.5 Other Applications	17
2.2 Additive Manufacturing.....	19
2.2.1 Fatigue of Additive Manufactured Materials.....	19
2.2.2 Additive Manufactured Materials and Fiber Bragg Gratings	22
3 Experimental Methods	25
3.1.1 Study Methodology.....	25
3.1.2 FBG Connectorization and Polishing Process	27
4 Results and Discussion.....	28
4.1.1 Tensile Testing.....	28
4.1.2 Fatigue Testing.....	28
5 Conclusions	35

6 Future Work	35
References	37
Appendices (if any)	42
Copyright Acknowledgements (if any)	43

List of Tables

Table 4-1: Static testing results of standard and through hole specimens	28
Table 4-2: Fatigue testing average number of cycles.	29
Table 4-3: Number of cycles for each specimen type at 600 N load level	33
Table 4-4: Comparing change in strain during loading between specimens and Finite element model.....	34

List of Figures

Figure 2.1: Fiber Bragg Grating's principle of operation	3
Figure 2.2: FBG response as function of strain	4
Figure 2.3: Cantilever beam grating locations	5
Figure 2.4: Embedded FBG Locations inside of Wing.....	5
Figure 2.5: Loaded wing during testing	7
Figure 2.6: Full-scale fatigue test set-up.....	8
Figure 2.7: Experimental setup of turbine blade	9
Figure 2.8: Coupon with surface mounted FBG sensors in a cross pattern	10
Figure 2.9: High temperature FBG specifications	12
Figure 2.10: Longitudinal FBG array anchored on the femur fixed using a plate fracture implant	15
Figure 2.11: Schematic representation of polymer FBG array in cork insole for gait pattern measurements.....	16
Figure 2.12: Factors in additive manufacturing with effects on fatigue strength	22
Figure 3.1: Specimen design and layer types.....	25
Figure 3.2: Three steps of FBG embedding procedure. From left to right: half printed specimen, place FBG and glue, print second half of specimen	26
Figure 3.3: Injecting epoxy into the FC connector	27
Figure 4.1: Number of cycles until failure vs. Tensile stress level.....	29
Figure 4.2: Fractured specimens: on the left is the standard specimen and on the right is the specimen with the through-hole.....	31

Figure 4.3: Time vs. Displacement (MTS) vs. Strain (FBG) at 600 N load level	32
Figure 4.4: Time vs. Displacement (MTS) vs. Strain (FBG) Additional embedded FBG test specimens.....	33

List of Appendices (if any)

1 Introduction

Additive manufacturing, also known as 3D printing, creates a structure by printing individual layers of material on top of each other until the desired shape forms. Compared to subtractive manufacturing, this technique offers unique benefits such as reduced tooling costs and the ability to produce complex component geometries [1]. These factors have made 3D printing popular in the aerospace and biomedical industries, specifically as a prototyping tool [2]. 3D printed materials have even advanced to the point where they are now beginning to be considered for selection in components that undergo service loads [3].

Along with additive manufacturing, the past two decades have also seen a rise in what is known as "smart materials". These materials possess inherent sensing capabilities, making them useful for structural health monitoring (SHM) in civil and aerospace applications [4]. A technology that has aided in the creation of these materials is Fiber Bragg Gratings (FBGs). FBGs consist of a periodic grating structure at the core of a single-mode fibre. This grating is able to reflect certain incident light depending on changes in temperature and strain of the fiber. Thus, by tracking the changes in the wavelength of the reflected light, one can measure the change in temperature or strain. This allows FBGs to be used as sensors for structural, medical, and chemical applications for measuring vibration, temperature, strain, and impact. They have particular benefits over traditional sensors including light weight, small size, good sensitivity, good long-term stability, corrosion resistance, and immunity to magnetic and electromagnetic interferences [5].

1.1 Motivation

Although much research has been conducted on the static properties of additive manufactured materials, much less has been done on the dynamic mechanical properties [1]. Likewise, FBGs have more recently begun to be embedded in additive manufactured plastics materials such as PLA and ABS [2], [6]–[9], however, embedding FBGs into 3D printed materials needs further investigation to view the reliability of these sensors when embedded and under dynamic loads. A study has thus been developed to evaluate the performance of these sensors for this specific application. This is done through fatigue testing and data analysis comparing results between different test specimen types both with and without the incorporation of FBGs.

The objectives of this thesis are as follows:

- Characterize dynamic properties of Acrylonitrile butadiene styrene (ABS)
- Compare fatigue life results of specimens with and without FBGs
- View measurement performance of FBGs under fatigue loading
- Compare strain measurements between different FBG incorporation techniques

1.2 Outline

This thesis begins with a literature review of fiber Bragg gratings and additive manufacturing. Next the methodology used for testing is described, followed by the results and discussion. Conclusions are then made followed by potential future work on these topics.

2 Literature Review

2.1 Fiber Bragg Gratings

2.1.1 Background

Fiber Bragg gratings (FBGs) are a type of optical sensor with many uses such as signal processing, communication, as well as temperature, and strain detection [10]. First developed in the 1980s, FBGs consist of a periodic grating structure at the core of a single-mode fibre. Fabrication occurs by exposing the fiber to a pattern of intense laser light, causing a permanent periodic change in the fiber's refractive index [11]. The internal periodic structure of the fiber causes certain incident light to be reflected while letting the rest pass through as seen in Figure 2.1. The wavelength at which the light reflects is known as the Bragg wavelength. This wavelength is determined by Equation 1, shown below, where λ_B is the Bragg wavelength, n_{eff} is the index of refraction, and Λ_B is the period.

Equation 1: Bragg Wavelength Equation

$$\lambda_B = 2n_{eff}\Lambda_B$$

Since the index of refraction and the period of the FBG change with temperature and strain, as seen in Figure 2.2, changes in the Bragg wavelength can be used to find changes in these parameters. This principle makes FBGs a useful sensing technology in the field of engineering.

Figure 2.1: Fiber Bragg Grating's principle of operation [4]

Figure 2.2: FBG response as function of strain [11]

These sensors can be used for structural, medical, and chemical applications since they can sense vibration, temperature, strain, and impact. They work well because they are light, have a small size, good sensitivity, good long-term stability, corrosion resistance, and are immune to magnetic and electromagnetic interferences [5]. FBGs can be surface mounted or due to their small size and compatibility with common polymeric materials, they can be easily embedded inside a structure without inducing significant weakening of the material.

2.1.2 Structural Health Monitoring Applications

One field where FBGs are seeing more and more use is structural health monitoring (SHM). These sensors are suited to this area since they allow for real-time dynamic measurements when embedded in or added to the surface of a structure. The incorporation of FBGs gives a structure a built-in capacity for sensing changes in temperature, strain, etc., essentially enabling the material to be what is known as a “smart structure” [12]. Many different applications of FBGs fall under SMH including vibration/shape monitoring, fatigue measurements, and damage detection.

Vibration sensing and structural shape monitoring using an FBG array on a cantilever beam were done by Davis et al. [13]. To obtain an acceptable dynamic range for strain measurements 3 FBGs were surface mounted on the 96cm long aluminum beam as described in Figure 2.3. Since the location of the sensors affects the measured response, the sensors were placed at the nodal points of the beam’s first 3 mode shapes. Vibration monitoring was achieved by individually interrogating each sensor, leading to results that closely matched the theoretical mode shapes.

Shape monitoring was carried out using real-time data acquisition and an algorithm that related strain levels, trail functions, and boundary conditions, again leading to accurate results.

Figure 2.3: Cantilever beam grating locations [13]

FBGs were embedded in a wind turbine blade for SMH and cure monitoring by Bang et al. [14]. During the course of curing, the section of the blade containing the FBGs was placed in an oven while the sensors were connected to an external interrogator. Modal vibration monitoring was also performed, and the results produced by FEA and FBGs were in good agreement. The small size and lightweight of the FBGs were stated as being beneficial in this type of testing. The sensor layout is shown in Figure 2.4.

Figure 2.4: Embedded FBG Locations inside of Wing [14]

Panopoulou et al. used FBGs for dynamic strain measurements as well as modal analysis of composite structures [12]. Sensors were mounted in a network pattern to allow for structural damage identification. The exact configuration was determined using Finite Element modeling by placing sensors such that the highest strain field would be along the optical fibre axis. An electromechanical shaker was used to excite the structure while damage was simulated by locally

varying the mass. The methods used proved to be successful, thus showing the usefulness of FBGs for SHM.

Position and displacement sensing were done using a pair of FBGs by Nazeer et al. [15]. The sensors were fixed to a cantilevered aluminum beam while an actuator applied the deflections. An optical sensing system and an interrogator were used to measure displacement and strain, respectively. Experimental and analytically calculated values showed that through further calibration good accuracy in results can be achieved using this method.

Employing FBGs as strain sensors for deflection estimation of a two-dimensional structure was examined by Di Palma et al. [16]. FBGs were distributed within a multilayer symmetric panel consisting of a central aluminum honeycomb, bonded on the top and bottom to layers of epoxy glass. The panel was placed on metal supports at each end and loaded with weights up to 6 kg while strain was measured. The strain values were converted to deflections through an estimation theory based on classical beam theory and used to create a map of the deflections for the entire panel. This method was shown to be accurate by comparing the measured deflections with those estimated through theory.

Krebber et al. viewed the behaviour of FBGs embedded in a composite during fatigue testing [17]. A tensile test machine was used to load specimens at a frequency of 5 Hz. A total of 2,000,000 cycles were conducted with 5 quasi-static cycles done after each 50,000-cycle interval to view the performance of the FBG sensor. The FBGs performed well and inconsistencies in the measurements were thought to be caused by bonding issues between the FBGs, their coating, and the matrix material. Temperature testing was also done which showed that the strain sensing abilities of the FBG array were unaffected by temperature changes.

Detecting damage evolution in polymeric composites using embedded FBGs was investigated by Shin & Chiang [5]. Test coupons were made of carbon fiber epoxy laminate with a centre hole and FBGs embedded in the axial loading direction between the central 0-degree laminate. Fatigue testing was completed at a frequency of 4 Hz using an MTS servo-hydraulic test system between 1.5 and 15 kN. Ultrasonic C-scan images were taken at 0, 10,000, 60,000 and 100,000 cycles to view where the damage that had occurred and how it affected the individual FBGs. Results showed that the placement of the FBGs affects the data outputted since the amount of wavelength shift that occurs is related to the amount of damage in the surrounding area.

Costa et al. performed static and dynamic tests on a quarter scale model of a T38 composite wing with embedded FBG sensors [18]. A finite element model of the wing was used to position the sensors in the areas with the highest strain values while maintaining a low rate of change of strain with distance. Static loading was done by placing a weight on the tip of the wing while it was in a cantilever position, shown in Figure 2.5, and dynamic loading was done using an impact hammer. The sensors array appeared to monitor the loads correctly with the results showing a high level of accuracy.

Figure 2.5: Loaded wing during testing [18]

The fatigue response of a composite laminate material was investigated using embedded fiber Bragg gratings by Keulen et al. [19]. The FBG sensors monitored strain energy release rate which was combined with previous loading history to make predictions of the remaining life of test specimens. Flat composite specimens were used for fatigue testing performed at 4 Hz using hydraulic MTS equipment. The recorded strain levels closely matched those measured with an extensometer during the fatigue experiments. The predicted remaining useful life based on the FBG sensor was also in good agreement with the actual calculated remaining useful life, showing that embedded FBGs are suitable for use during fatigue testing.

Damage monitoring in composites under fatigue loading utilizing FBGs was examined by Kocaman et al. [20]. FBGs were embedded to view local changes in strain and temperature which could not be obtained by external sensors. Fatigue testing was done using an MTS test frame at a frequency of 4 Hz to avoid overheating. The use of FBGs showed large differences in local and global strain behaviour of the composites and a significant change in temperature before failure meaning these sensors can be used to predict the onset of failure.

FBGs are susceptible to breaking when exposed to certain environments and cannot always be embedded into structures due to manufacturing complexity and cost. For these reasons Zhu et al. investigated the use of FBGs encapsulated into CFRP packaging for SHM in composite wind turbine blades[14]. This concept was first validated by viewing the strain transfer efficiency of the packaged sensors compared to theoretical values. This was done by attaching FBGs to a cantilever which was loaded so that strains can be measured. The packaged FBGs were shown to have a strain transfer efficiency of almost 95%. Next, a full-scale fatigue test was carried out using the packaged FBGs to measure strain as seen in Figure 2.6. Typical strain gauges were also placed in the same spots for comparison. Results showed that the strain gauges tended to degrade over the 16-day test period while the FBGs did not. This effect was most prevalent further from the root of the blade. It was also noted that the strain gauges showed asymmetric behaviour when comparing compressive and tensile strain while the FBGs did not.

Figure 2.6: Full-scale fatigue test set-up [14]

Di Sante reviewed recent advances and applications of fiber optic sensors for structural health monitoring [4]. Applications included strain-based deformation shape reconstruction, strain monitoring in wing structures, life-cycle monitoring of l-shaped parts, detection of debonding in composite patches and lap joints, impact and several other types of damage detection, and use in smart composites.

The performance of distributed embedded FBGs and strain gauges for damage detection in wind turbine blades were compared by Sierra-Pérez et al. [21]. The turbine blade was set up in a cantilever position shown in Figure 2.7 and loads simulating those seen in service were applied linearly while measurements were taken at suitable levels. The distributed sensing arrangement

proved to be ineffective however the FBGs still performed well and showed advantages when compared to strain gauges such as requiring fewer wires and having a longer life.

Figure 2.7: Experimental setup of turbine blade [21]

Tan et al. used FBGs to monitor hard impacts on a pantograph-catenary system that is used in the traction power supply system of electrified railways [22]. Due to the FBGs immunity to electromagnetic fields, they are perfect for this environment and can be embedded in the system's contact strip. Strain data was collected in real-time during operation to observe whether impacts exceeded safe levels. The collected data is stored for long term comparisons to detect where maintenance is needed.

Barely visible impact damage on composites can grow and lead to failure. Therefore methods of damage detection and location are needed for these materials. Goossens et al. investigated such a method using FBG sensors [23]. Damage testing was done on 5 different CFRP materials using an INSTRON CEAST 9350 Drop Tower Impact test. The damage was measured by surface mounted or embedded FBGs. The surface-mounted sensors were packaged in GFCP and high-density polyethylene, forming what is known as a strain measurement wire. These wires, which can be seen in Figure 2.8, were attached to the material specimen in a cross pattern. This layout has been shown to withstand in-flight conditions and has the capability of being automated due to its simplicity. The damage was detected through changes in the fiber Bragg wavelength or the Pearson correlation coefficient. Test results showed that the mounted fibers were more accurate and provided better precision than those which were embedded. Since embedded FBGs also

cannot be repaired the researchers recommended that more attention be given to surface-mounted FBGs over embedded ones.

Figure 2.8: Coupon with surface mounted FBG sensors in a cross pattern [23]

Hammond et al. used FBGs to conduct modal analysis on a marimba bar (musical instrument)[24]. 6 sensors were mounted on the bar using Kapton tape and a musician struck the bar. The first mode of the bar was successfully reconstructed through a 6-step process. This process is as follows: (1) measure the wavelength spectrum, (2) extract the strain for each FBG, (3) convert the strain into a localized curvature and bend angle vector, (4) identify a mode from its corresponding resonance frequency (5) extrapolate the measurement to get the curvature and torsional along the whole length of the marimba bar for that particular mode, and (6) use differential geometry to reconstruct the mode shape from the curvature and torsion functions and calibrate the measurement. For higher modes to be reconstructed a higher density of sensors must be used. The results showed good agreement with FEA simulations as well as results from a scanning laser Doppler vibrometer.

Tsuda et al. have investigated ultrasound detection using fiber Bragg gratings and its application to damage detection [25]–[27]. The presence of damage can be identified when the detected ultrasonic signal deviates from the reference signal of undamaged structure [25]. FBGs are advantageous for this application since they are a wavelength encoding sensor, thereby making the sensor self-referencing, rendering it independent of fluctuating light levels and the system immune to source power and connector losses that plague many other types of fiber-optic sensors.

FBG ultrasonic sensing systems can be classified into two types with either a broadband light source or a tunable laser source which are explained well in the paper. In short, both systems use the variation of the reflected light caused by a Bragg wavelength shift to detect ultrasonic waves. The systems were tested and compared to a piezoelectric sensor through impact detection tests and sensitivity tests.

To evaluate ultrasound detectability ultrasonic waves were detected at several ultrasonic source–sensor intervals by an FBG sensing systems mounted on carbon-fiber-reinforced polymers thin plates. Ultrasonic waves propagating through thin plates are referred to as the Lamb waves. The same was done for another thin plate specimen with visible damage introduced by a ball that was dropped.

Results showed that wave velocity measured from experimental results agreed well with that estimated theoretically. Both FBG sensing systems possessed ultrasonic sensitivity high enough for practical use. Compared with the broadband light systems, the tunable laser system had higher sensitivity to ultrasonic wave. Ultrasonic propagation through the damaged area divided into two routes: straight propagation and bypass around the damaged area. FBG sensors in either system can detect respective waves propagated in different route whereas piezoelectric sensors cannot distinguish between them. FBG sensors in combination with the tunable laser system prove to be an alternative of conventional piezoelectric sensors in ultrasonic inspection of composite structures.

Choi et al. surface mounted FBGs to a composite wind turbine blade to measure the blade tip deflection by long term monitoring [28]. Bragg wavelength shifts were obtained and transformed to strains. The tip deflection was determined by the finite difference method with the measured FBG strains. To measure the strain accurately with temperature variation, temperature compensated FBG sensor probes were fabricated with two fiber Bragg gratings molded in one package to achieve different strain and temperature sensitivities.

For preparation of the blade load test the blade had FBG sensor probes and electrical strain gauges installed at 1 m intervals through the length of the web. The blade was tested using static loads using three load saddles and a spreader bar on the blade in order to add a load similar to that of wind pressure. Results showed the blade tip deflections calculated from the FBG strains were well fitted with the deflections measured from linear variable differential transformers,

showing that strain sensing using FBG sensor probes installed in the wind turbine blades can be a useful solution.

Zeng et al. studied the application of FBG sensors in damage monitoring of sandwich composite L-joints, which aims to reveal the interface damage between the glass fiber reinforced polymer skin and the foam core [29]. Measurements by numerical simulation and surface mounted strain gauges were found to be less sensitive to internal damage, proving the great significance of embedding fiber Bragg grating sensors to monitor interface damages of sandwich.

Using FBGs for structural health monitoring in a masonry railway bridge was examined by Alexakis et al. [30]. A bridge that was over 150 years old at the time had deteriorated due to increased use over time. When the bridge underwent extensive repairs in 2015 a vast fiber optic sensor network was integrated as well. This was the first time FBGs had been used in a masonry rail bridge for SHM. The FBGs measured the dynamic deformation of the bridge and this data was used to track the strain distribution over an extended period. The generated strain distribution closely matched the visual deterioration of the bridge showing the usefulness of this method.

2.1.3 Temperature Sensing Applications

FBGs ability to sense changes in temperature is commonly used in industry. They are now being utilized in high temperature sensing for manufacturing equipment, fuel combustion machinery, large diesel engines in trains, post fire structures, as well as oil and gas and geothermal industries [31]. Cavillon et al. reviewed high and ultra-high temperature FBG sensors, which are defined by operating temperatures below and above 800 °C, respectively. A summary of different types of FBGs and their operating temperatures is shown in Figure 2.9.

Grating type	Maximum temperature of operation (°C)
Type Ia	~700 (~1 h)
Regenerated Femtosecond Type II fs-IR	~1295 (10 min) ~1000 (150 h)
Sapphire fs-FBG	~1600 (~6 h)

Figure 2.9: High temperature FBG specifications

High temperature strain measurements are an issue since typical FBGs can only be used for long durations at temperatures sub-300°C. This has led to the development of new FBG types such as type-I gratings, type-II gratings, and a regenerated fiber Bragg gratings (RFBG). Proper packaging and attachment of the FBG are also necessary to guarantee the sensors will not degrade with increasing temperature. The development of a strain sensor for high temperature applications was described by Tu et al. [32]. This sensor was metal-packaged and based on a RFBG for applications up to 540°C. The sensor was characterized through high temperatures tensile tests and numerical simulations were also done using finite element analysis. The tensile tests were done using a P91 steel specimen with the metal packaged RFBG mounted on by way of electrical resistance spot welding. Test was completed at 100°C, 200°C, 300°C, 400°C, 500°C and 540°C, using an MTS universal testing machine with a furnace. Results showed that these sensors have good potential for high temperature strain measurements however improvements must first be made since there was still prevalent strength degradation.

Other research on high temperature FBG includes that by Canning et al., who tested phosphosilicate FBGs which exhibited stability up to 600°C [33]. Laffont et al. used RFBGs up to 610°C in a tubular furnace while Ecke et al. showed the usefulness of FBGs at cryogenic temperatures [34], [35].

Ghazanfari et al. describes an extrusion-based additive manufacturing process which embeds sapphire optical fiber sensors in ceramic components during part fabrication [36]. This allowed the fibers to be fully integrated into the part so that many problems of traditional embedment can be avoided. Ceramics and sapphire fibers both have great material properties for high temperature applications.

Unjacketed sapphire fibers of 5 cm length and 125/250 μm diameter were placed in a tank and then covered with a ceramic paste which was extruded at controlled flowrates through a circular nozzle. This process was automated and is known as the “Ceramic On-Demand Extrusion process”. The part is fabricated in a layer-by-layer fashion by repeating the layered deposition followed by layered radiation drying with a liquid surrounding the already deposited layers. Six alumina blocks were fabricated and five sapphire fibers of the same diameter were embedded in each block. Three of the blocks had fibers of 125 μm diameter embedded in them while the other

three contained 250 μm fibers. 2 of the part were freeze dried while others were humid dried in an environmental chamber.

The attenuation of signals through the embedded fibers was measured along with the flexural strength of the parts. The results of microscopy, attenuation tests, and mechanical tests indicate that as the diameter of the fibers and relative density of the parts increase, it becomes more challenging to successfully embed the fibers. Nevertheless, for smaller fibers (125 μm diameter) the parts and the embedded fibers are functional. Thus, they could potentially be used to measure the strains in the parts generated by thermal and/or mechanical loads.

Li et al. used ultrasonic welding to embed nickel-coated fiber Bragg gratings in aluminum [37]. Testing of different fiber coatings as well as different base metals was done to see which combination worked best in the ultrasonic welding process. This process works through positioning a fiber in a small slot on the base metal. Another metal foil placed on top creating a sandwich structure. When pressure and ultrasonic vibration are applied, friction breaks up the surface oxide, interlocking, diffusion, and plastic deformation occurs within two metal foils. Then the foils are bonded due to inter-diffusion and mechanical mixture and mean-while the fiber is embedded in the metal during the welding process. Testing showed that aluminum is the most appropriate metal and that fibers should be chemical electro plated before embedment to protect them.

The strain response of the embedded FBGs were tested by applying tensile loads to the aluminum samples. A computer controlled instron-1186 and the FBG Network Analyzer were used for controlling the loading process and recording the strain of the aluminum sample. A linear relationship was seen between the FBG wavelength and applied strain indicating there was no debonding. The proposed method for ultrasonic embedding of metal coated FBG will lead to multiple promising applications in the area of safety monitoring for the industry of aerospace and automobile manufacturing.

2.1.4 Biomedical Applications

The use of FBGs in the biomedical field is widening due to their previously stated advantages as well as their ability to perform spatially quasi-distributed measurements. Using FBGs for strain

measurement in fractured bones was looked at by Najafzadeh et al. [38]. Two FBG arrays were attached to a synthetic femur bone which had been fractured at a 30-degree angle and reassembled using a plate fracture implant as seen in Figure 2.10. The first array was anchored longitudinally using 5 FBG sensors while the second array used 7 sensors and was fastened in a coil shape. Compressive loading tests were performed as the bone's displacement was measured. Results showed higher strain values closest to the fractured region signifying that this area should be most closely monitored. It was also shown that the longitudinal sensors worked better than those fastened in a coil shape.

Figure 2.10: Longitudinal FBG array anchored on the femur fixed using a plate fracture implant [38]

Theodosiou & Kalli looked at the recent applications of FBG sensors made from cyclic transparent optical polymer fibers (CYTOP) [39]. FBGs were used in the development of a wearable exoskeleton to assist in physical rehabilitation. FBGs were inserted into shoe soles as seen in Figure 2.11 to track gait patterns from which diseases can be detected. FBGs flexibility made them useable for the development of soft robotic applications. An example of this is their use in a smart walker platform where they were used to monitor the device's condition, the user's intended motion, the user's gait cadence, and possibly map the structure's environment. FBGs also have the potential to be used as ultrasound sensors due to their optical characteristics being a good match for acoustics in liquids.

Figure 2.11: Schematic representation of polymer FBG array in cork insole for gait pattern measurements [39]

The advantages of FBG sensors have been recognized by the medical industry and thus FBGs are becoming more frequently used for medical applications. Examples include diagnostic imaging, measuring deflection of needles, applied for inside blood vessels, in smart fabrics to measure cardiac and respiratory rhythms, vital signs like heart rate, blood pressure, body temperature, respiratory status, and level of consciousness [40]. Bonafino et al. used FBGs to monitor heartbeat by attaching them to a subject's brachial artery using medical tape [41]. The system consisted of an interrogator with a sampling rate set at 1 kHz, which permitted collection of the peak wavelength shift. A dopant in the fiber's core meant that the fibers were very sensitive and thus able to cause wavelength shifts with only a heartbeat.

Correia et al. used FBG sensors to maintain the optimum pressure between medical devices and human tissue [42], [43]. Contact between a medical device and tissue accounts for approximately a third of damage to soft tissue in hospitals. An FBG was embedded into a polymer patch which was calibrated for transverse load by placing a known weight on the top of the patch and recording the reflection spectrum using an interrogator. The sensor was tested by using it in an endotracheal tube where it was shown to correctly monitor pressure in a 3D printed model tracheal wall.

2.1.5 Other Applications

Huang et al. looked at using FBGs for dynamical measuring of several parameters in industrial hydraulic piping [44]. FBGs' ability to withstand harsh conditions along with their lightweight and small size makes them ideal for this environment. Although normally used to measure strain and temperature, by connecting spring sensing elements FBGs can also be used to measure things such as pressure, acceleration, and flow rate. By using a network of different FBG sensors, data collection becomes easier as does combining different types of data. Experiments used twelve FBG sensors to measure the clamping looseness of a hydraulic pipe as well as strain, temperature, pressure, and acceleration. A vibrator was used to excite the pipe while an interrogator was used to monitor wavelength shifts in the sensors. This experiment showed good agreement between the FBGs and standard sensors, with FBGs having a better signal to noise ratio. The FBGs were also able to obtain signals in the time, frequency, and modal domains which is useful for structural health monitoring of the pipe as well as measure clamping looseness in the pipe.

FBGs can be applied to the geotechnical field for water content monitoring in soil. This was studied by Mehravar et al. who inscribed FBGs in polymer optical fiber and inserted them into soil samples [45]. These fibers have an affinity for water which causes them to swell leading to a shift in the Bragg wavelength. Testing was conducted by inserting the sensor in soil samples with different water contents and viewing the accuracy of the measurement. Initial results looked promising however, for this method to be useful at very low water contents further research is required.

Railway signaling facilitates are used for train detection and train control to maintain safe separations among the trains. This can be done using axle counting methods. With the introduction of electrification in railways, the rails are often used to carry the traction return current. Track circuits are also subject to operation failures in hostile environment, such as the areas susceptible to flooding. For these reasons Wei et al. developed a remote FBG sensing for train axle counting [46]. FBGs are suitable to this task since they are immune to electromagnetic interference.

FBG sensors were installed on rails to measure the strain change of the rails, which momentarily deform when a train passes. ANSYS Multiphysics software was employed to simulate the levels

of rail deformation when a train is standing by the rail so that the most appropriate positions for the sensors could be found. The maximum deformation of the track was found at its head of the rail where the train wheel stands. To validate this, an experiment was been carried out in the laboratory to measure the strain change at various positions of the rail induced by passage of a test train. The tests showed the head of the rail with horizontally installed sensors was the most sensitive for measurements. Since it is not practical to install FBG sensor on the head of the rail because of safety considerations, it was placed at the rail foot which had the second highest strain levels.

In field testing was done and axles could be successfully counted by counting strain signal peaks. Train speed can also be derived from two consecutive peaks in the signal, together with the inter-axle length. To smoothen the signals for peak detection, the signals are first low-pass-filtered with a cutoff frequency of 10 Hz. The system was tested for 6 months and had no malfunctions or performance degradation.

FBG sensors and a rotary optical coupler were used to study the mechanical properties of a rotating shaft [47]. These are used to replace strain gauges attached with slip ring or telemetry which have commonly been used to measure performance in driveshaft abuse tests. Unlike strain gauges, FBG sensors enable researchers to observe load distribution at different sections of the shaft with a centimeter gap.

Temperature and static tests were completed along with rotational tests. The rotational tests of a shaft were completed using a lathe. An FBG sensor was mounted on the shaft and connected to a rotary optical coupler which remained stationary. The rotary optical coupler was linked to the optical circulator which receives broadband light. The optical circulator reads the reflected wavelength which can be visualized on PC. Testing was done at speeds of 25, 50 and 75 rpm. Results of the rotational shaft test were not given seemingly due to errors caused by a difference in the size of FBG core and the rotary optical coupler.

The use of FBG sensors for SMH of wind turbine blades has been discussed through several examples. One issue that may arise from the method is the amount of space required for the system components such as the interrogator, wireless unit, and battery [48]. Since these parts must be placed on something stationary, smaller wind turbines may not been large enough to hold all of this equipment. To combat this issue Chen et al. investigated the use of a fiber optic

rotary joint (FORJ) to transmit the optical signals from the FBGs to the interrogator. Testing was done by measuring the strain response of a 600 W small scale wind turbine which was compared to measurements from the traditionally used IMote2 wireless system. The data from the two methods matched well showing the new system utilizing the FORJ has as potential in field use.

These space constraints were also seen by Wen et al. for their testing of model floating wind turbines [49]. For this reason, they incorporated a FORJ into the sensing system used to monitor the turbine's performance. The FBG-FORJ was carefully incorporated into the turbines nacelle design such that it would not disturb the delicate mass properties of this structure. Testing was done to validate the sensing system by way of static loading tests, hammer tests, blade rotating tests, and dynamic loading tests. Results showed that this sensing system is proficient in measuring blade loads and is a feasible monitoring technique.

2.2 Additive Manufacturing

2.2.1 Fatigue of Additive Manufactured Materials

Potential applications of 3D printed elastomers include integrated shock absorption components, integrated grips, living hinges, gaskets, and other flexible components that traditionally utilize the unique properties of elastomers. However, the flaws and voids caused by the layer-by-layer fabrication process in many AM processes may significantly reduce the fatigue life of printed elastomers, since fatigue failure in elastomers is the result of the propagation of small tears present in the specimen due to manufacturing.

There is some research on the fatigue properties of AM parts, but the literature is scarce. For this technology to be used as a manufacturing process, rather than just a prototyping tool, more research on the fatigue properties of AM components is needed. More et al. seek to fill a gap in the literature by characterizing the fatigue life of a direct 3D printed elastomer, and the multi-material interface [50].

The authors performed fatigue testing of multiple elastomeric specimens fabricated with the Objet Polyjet process. The fatigue testing specimens were designed according to the ASTM standard and consisted of a modified dog bone shape to fit into a set of special elastomer grips due to the lateral shrinkage of elastomeric specimens under high strains. Fatigue specimens contained 1 or 2 materials with the multi-material specimens having 2 possible interfaces.

Specimens were mounted and tested in an MTS Tytron 250 Microforce Testing System with a 250N load cell. After the specimens were mounted and the maximum extension was determined for the desired strain, the specimens were tested in a loading and relaxation cycle until complete part failure. Results of the testing gave some clear insights such as there being no evidence to support the hypothesis that the multi-material interface has a fatigue life that is inferior to the normal material's fatigue life. Future work on the characteristics of printed elastomers could involve compressive fatigue characteristics, the effect of build orientation, the effects of surface finish, the effect of part ageing, and the effect of strain rate.

In the work of Zhang et al. [51], a systematic characterization is conducted on the mechanical properties of 3D-printed ABS components. Specifically, tensile, fatigue and creep properties and how they are affected by printing orientation. Focusing on fatigue properties, testing was conducted using a rotary tester to employ a cantilever load on a plunger shaped specimen. Results also showed a steep decrease in the number of cycles to failure when the load was increase from 30 N to 60 N.

Ezeh et al. quantitatively reviewed the understanding of the fatigue behavior of additively manufactured polylactide [52]. A number of data sets were selected from the technical literature and statistically re-analyzed in terms of S-N curves to define a reference value both for the negative inverse slope and the endurance limit extrapolated at $2 \cdot 10^6$ cycles to failure. In terms of stress-strain response, the mechanical behavior of AM PLA is seen to be predominantly brittle, with the level of ductility varying as the printing direction changes. Conclusions made from this research include the mean stress effect in fatigue can be modelled by simply using the maximum stress in the cycle as well as printing direction appearing to have little effect on the overall fatigue behavior of AM PLA, and thus the stress/strength analysis can be performed effectively by treating this polymer as a homogenous, isotropic and linear-elastic material.

Further Research by the author investigates the fatigue behavior of AM PLA by post-processing a large number of data both generated by running ad-hoc experiments and taken from the technical literature [53]. In particular, attention is focused on the way raster orientation and non-zero mean stresses affect the overall fatigue behavior of AM PLA. The authors investigated the mean stress effect in fatigue of AM PLA by testing a large number of un-notched specimens. Using a standard electric fatigue table that was modified for these specific experimental trails

fatigue results of 3D-printed PLA test specimens were produced. Results showed that is that max stress can be used for certain specific materials to assess the effect of load ratios, R , larger than -1. For 3D-printed PLA the mean stress effect in fatigue can effectively be accounted for by simply performing the fatigue assessment in terms of max stress.

Work by Frascio et al. looks at the fatigue behavior of one class ABS [54]. Fatigue tests were completed using a Schenk PK103 fatigue testing machine which was modified to apply plane bending load to bar shape specimen containing a lateral semi-circular notch. Three different build directions were investigated to study the directionality fatigue behavior under the same nominal bending stress. A load cell was added to the system to continuously monitor the true applied load, with the bending load being applied in displacement control, at 25 Hz frequency. Six sets of specimens were tested, two for each build direction, one under bending moment with $R = 0$ and one under bending moment with $R = -1$. Results showed a clear effect of the stress ratio on endurance but a limited effect from the build direction. Investigating the samples with the longest endurance at each tested stress level, it was apparent that they have both external surface and cross section smooth and well packed.

Hassanifard et al. analyzed several studies to view the effects of part build directions or raster orientations on the strain-life fatigue parameters of 3D printed plastic materials manufactured through FDM [55]. Ramberg-Osgood stress-strain curves from the other studies were utilized through a strain-based approach to fatigue to give homogenized and quantitative information to help in the design of AM parts. This analytical strategy identified several useful trends in the fatigue properties of 3D printed plastic materials, such as the fatigue behavior of 3D printed materials in different build directions or raster orientations was found to be noticeably different.

Jap et al. investigated the effect of raster orientation on the static and fatigue properties of filament deposited ABS polymer [3]. AM has a large number of process parameters, all of which have the potential to impact the mechanical properties of the finished part as seen in Figure 2.12.

Figure 2.12: Factors in additive manufacturing with effects on fatigue strength [3]

Results from the authors fatigue tests showed that for a given stress level, the raster orientation has a great impact on the fatigue life of the component. Evaluation of the models for a constant stress, say 16 MPa, shows the $-45^{\circ}/45^{\circ}$ raster specimen to have more than twice the fatigue life of the equivalent $0^{\circ}/90^{\circ}$ raster specimen.

2.2.2 Additive Manufactured Materials and Fiber Bragg Gratings

Kousiatza et al. embedded FBGs along with thermocouples into the middle-plane of the composite structures for simultaneous monitoring of both residual strains and temperature profiles developed during the building procedure [56]. The fabricated specimens were subjected to thermal cycling and based on the derived FBG recordings, the composites' coefficients of thermal expansion (CTEs) were evaluated. Finally, the effect of fiber orientation and type on the induced temperature profiles, residual strains and thermal expansion behavior were identified.

Experimental results indicate that the fiber type and orientation strongly influence the process generated temperature profiles and residual strains. It is also shown that significant changes in the obtained slopes of the thermal strains-temperature graph are exhibited when the applied temperature, throughout the heating cycle, exceeds the composite samples and in the temperature range of 80–100 °C. Furthermore, the conducted experiments clearly demonstrate the FBG sensors' ability to accurately determine the in- and post-process induced residual strains, as well

as the thermal expansion behavior of FDM-fabricated continuous fiber reinforced thermoplastic composites.

Zubel et al. embedded polymer optical fiber Bragg gratings (POFBGs) into an FDM-manufactured sensing patches [57]. The sensing patches contained a POF embedding channel, whose bottom was at the neutral axis of the beam region. Once the channel had been fully made glue was deposited within and the FBG was inserted. The fiber was moved back and forth along the channel multiple times to assure that it was at the bottom of the channel. The fiber was then mounted with tape on temporary supports at both fiber inlets, and the glue was allowed to cure for 15 min before the supports were removed and the printing process was resumed.

Deterioration of grating characteristics were seen mostly due to the temperature of the printing nozzle and bed. To overcome these two changes were made: the structural material was changed to polylactic acid (PLA), which prints at nozzle and bed temperatures of 230 °C and 50 °C, respectively; the channel depth was increased to 750 μm , allowing for a thicker glue layer isolating the fiber from the nozzle temperature and a shorter POFBG was used to avoid differential chirping due to uneven strain. Using this modified approach, the grating withstood printing, and there was no observable change to the shape of the response peak.

The strain response of the sensing patch was measured by clamping down one side of the structure and using a translation stage on the other. Unexpectedly, strain sensitivity of the patch which was some 3.5 times lower than usual values found in the literature, possibly due to the glue shielding a bigger part of the stress exerted on the POF. The thermal stability of the embedded POFBG was also shown to be an issue.

Fang et al. embedded FBGs in an equal-strength cantilever to thoroughly investigate the strain variation while it was loaded; and comparison was carried out between the measured and theoretical results to verify validity and reliability of embedded FBG sensors in monitoring health of 3D printing structures [58]. A 3D printer printed out the lower part of the test sample according to the design requirements and then FBG sensors were equipped in a square groove to continue printing and finally produce the test sample. FBG sensors were mounted in parallel to the cantilever during the printing process. The FBGs were not coated to ensure compatibility with the substrate however they were encapsulated by ND353 glue. The cantilever was step loaded to the corresponding levels by rotating the hand wheel, then the corresponding readings

were recorded in the dynamometer and the wavelength at the reflective center of the FBG. Such tests were carried out for 3-5 times. Load vs. strain graphs showed good agreement with theoretical values. It was confirmed that FBG sensors embedded inside a 3D printing structure may be utilized to measure internal strain accurately and effectively.

Zelený et al. examined the reliability and response of an FBG sensor embedded in a structure fabricated by a 3D printer [59]. The concept of 3D printing promises to be a good host for FBGs; the printing can be stopped in the middle of the process and a fiber with a FBG sensor can be easily placed and glued into the specially shaped slot. After that, the following layers are printed to confine the fiber sensor. In addition, the 3D printing offers a high design freedom of the final shape and dimensions of the structure which is not achievable by the conventional techniques.

A prototype structure was printed to verify that a fiber sensor embedded by 3D printing can measure mechanical strain. The response of a fiber Bragg grating is tested and evaluated under the loading tests. It was designed to be thin and flat to provide high elasticity being necessary for easier straining. The prototype structure was printed during the three basic steps: 1. bottom part with the groove for the sensor to be placed is printed 2. printing process is interrupted and fiber with the inscribed FBG is placed into the groove. The FBG sensor is fixed by glue along its length promising better response in the strain during a measurement 3. the final layers that confine the fiber sensor are printed.

The structure was glued onto the surface of a wooden beam specimen which is exposed to a 4-point flexural test, ensuring that the grating is strained uniformly with the timber sample along the propagation axis. Comparison between the experimental results and those predicted by theory match well however the slopes of the Force vs. Strain graphs vary by around 8%, implying that calibrating the FBG sensor may be necessary. The temperature and humidity influence on the measured values is neglected in this test, because of the nearly constant environment in which the measurement is performed. However, for a long-term measurement, where the temperature changes are higher than about ± 5 °C, an external or internal temperature compensation is required. In addition, using the sensor in different temperature conditions would require recalibration.

3 Experimental Methods

This section details the experimental methods used to characterize the dynamic properties of ABS, see how these properties are affected by the introduction of FBGs, and also measure the performance of FBGs under fatigue loading. A description of the connectorization and polishing process for the FBGs is also included.

3.1.1 Study Methodology

Test specimens were manufactured in a MakerBot Replicator 2X FDM 3D printer using MakerBot's True White ABS filament. The printer bed was covered with blue painter's tape and set to a temperature of 115°C while the filament was extruded at a temperature of 240°C. The filament, which had an original diameter of 1.77mm, was extruded at a speed of 30mm/s for the first layer, 40mm/s for outlines, and 60mm/s for the infill. The infill density was set to 80%, as this was the highest level at which printer jams did not frequently occur. An 80% density was also used in works by [8], [60], [61]. With a nozzle diameter of .4mm, the layer height was set to .3mm as this was the height that allowed for the fastest printing without frequent jams. The infill pattern was selected as hexagonal, consisting of straight lines printed in the horizontal direction and hexagons printed in the vertical direction, as seen in Figure 3.1. Two shell layers were used, each with a thickness of .3mm. The specimen design was that of ASTM standard D7791, with the thickness raised so that the testing machine could properly grip the specimen. The .stl file was given a thickness of 7.2 mm; however, specimens had an average thickness of around 7 ± 0.2 mm.

Figure 3.1: Specimen design and layer types

Specimens made to contain an FBG were printed using the same parameters with the addition of a .1mm hole through the specimen's length. The FBG was incorporated either by embedding it

during the printing process or inserting it into the specimen afterward. Differences between the measurements of these embedding techniques can be seen in the results section.

Static tensile tests were completed to view the proportional limit of the material. These tests were done on an MTS universal testing machine following ASTM standard D638 – 14. Five tests of each specimen type were completed with a loading strain rate of 5 mm/s. From the static tests, the load levels for tensile fatigue tests were selected. Tensile fatigue tests were first run on the standard specimens at load levels of 800, 600, 400, and 200 N. Specimens were tested under sinusoidal axial loading at a frequency of 2 Hz with a stress ratio (R) of 0.1. The same testing procedure was then completed on specimens that had an FBG sensor inserted after printing. For these two cases, 4 specimens were tested at each load level for a total of 32 tests. Additional fatigue tests were completed on specimens containing FBGs that were embedded during the printing process. These specimens were specially constructed to allow for maximum strain transfer between the specimen and the FBG. This construction was done by following a procedure similar to the one found in [60], with the following steps: print half of a specimen, position the FBG sensor in the through-hole while keeping it under tension and glue the FBG in place with super glue, and finally print the second half of the specimen. A diagram of this procedure can be seen in Figure 3.2.

Figure 3.2: Three steps of FBG embedding procedure. From left to right: half printed specimen, place FBG and glue, print second half of specimen

The FBG sensors collected strain data at a rate of 10 Hz using a SmartScan SBI FBG Interrogator, connected to a computer equipped with SmartSoft for SmartScan SBI software. A model of both specimen types was constructed in ANSYS workbench, and the response to testing loads was simulated and compared to FBG data to see how well they match.

3.1.2 FBG Connectorization and Polishing Process

The FBGs used during all tests were from ITF Technologies and were single-mode apodized, 80um cladding fibers. The FBGs came without any end connectors and thus had to go through a connectorization process and polishing process. The process began by submerging the FC/APC connectors in isopropyl alcohol for a few minutes and after letting them completely dry. After gently cleaning the end of the fiber with isopropyl alcohol, the fiber is tested to see if it fits into the connector and the length of exposed fiber is sufficient for connectorization. After this fit is confirmed, the fiber is removed, and an epoxy is inserted into the connector using a syringe. Enough epoxy is used so that a small bead appears on the outside face of the connector ferrule as in Figure 3.3.

Figure 3.3: Injecting epoxy into the FC connector [62]

Next, the connector is pushed onto the fiber while slowly rotating the connector. Breakage is checked for by sliding the connector back and forth, ensuring that the protruding fiber moves in and out of the connector. The end of the connector must have a sufficient bead of epoxy to support the end of the fiber during polishing. A short section of scrap fiber is ideal for applying epoxy because it is rigid enough and large enough to pick up a small bead of epoxy; at the same time, it is flexible enough to minimize the danger of breaking the fiber that protrudes through the connector. At this stage, the fiber must be left overnight so that the epoxy can cure.

After the epoxy has cured the fiber must be lightly scored the fiber just above the epoxy bead, making sure the cutting edge of the scribe is held perpendicular to the protruding fiber. Ideally, the scribe should make contact with the fiber about one fiber diameter above the epoxy. Cleaving

occurs next by gently squeezing the fiber tip and pull along the mechanical axis of the fiber. Next the fiber protruding from the surface of the epoxy bead is hand polished using a sheet of 30 μm polishing film. Afterwards, a polishing plate and polishing disc are used with 30 μm , 6 μm , 3 μm and 1 μm polishing film to fully polish the connector end. After connector passes a quick inspection, it is ready to use.

4 Results and Discussion

4.1.1 Tensile Testing

A summary of the static tensile test results for both the standard specimens and those with the through-hole for the FBG can be seen in Table 4-1. The average ultimate tensile strengths (UTS) were seen to be between 10-12 MPa for the 2 specimen types. This average is lower than what is found in the literature however, these findings range widely from 15 MPa to 45 MPa [1], [3], [51], [54]. This is thought to be caused by several factors such as infill density, infill pattern, and raster orientation. Interestingly the average maximum sustained load was higher for the specimens with the hole which contained less material. This is likely linked to the printing characteristics, with one theory being that the filament surrounding the hole acts like a stiffener bar to strengthen the specimen. This stiffening effect is a result of area around the FBG hole being the only vertically deposited filament layer in the entire specimen and is deposited in a denser pattern than the rest of the specimen.

Table 4-1: Static testing results of standard and through hole specimens

Specimen Type	Average Max Load (N)	Average UTS (MPa)	Standard Deviation (MPa)
Standard	925.20	10.36	0.34
Through Hole (FBG)	1021.44	11.36	0.88

4.1.2 Fatigue Testing

From the tensile test results, the maximum load level for the fatigue testing was selected to be 800 N, since it was clear both kinds of specimens would be able to sustain cyclic loading at this

level without immediate fracture. The fatigue test results from all load levels can be seen in Figure 4.1, which shows the standard specimens' results versus those of the specimen with a through-hole containing an inserted FBG.

Figure 4.1: Number of cycles until failure vs. Tensile stress level

In comparison with other literature sources, these specimens fail at lower stress levels which is in line with what was seen in the tensile tests. It should still be noted that fatigue test results also range widely between sources. As can be seen from the graph, the standard specimens had slightly longer fatigue lives at the lower loads, while the specimens with the through-hole and inserted FBG were seen to have longer lives at higher loads. This can also be viewed numerically by looking at the results in Table 4-2. The percentage difference in the number of cycles for the through-hole specimen in comparison to the standard specimen is negative for the lower two load levels and positive for the higher two. The standard deviation of the number of cycles shows that

at three out of four load levels, the variation in the number of cycles is between 80-160% greater for the specimens with the through-hole and inserted FBG.

Table 4-2: Fatigue testing average number of cycles.

Load Level (N)	Average Number of Cycles			Standard Deviation	
	Standard Specimen	Through Hole Inserted FBG Specimen	Percentage Difference	Standard Specimen	Through Hole Inserted FBG Specimen
200	212500.00	152299.50	-28.33	34762.26	62527.71
400	8551.75	6758.25	-20.97	1079.40	787.39
600	1204.50	3288.25	173.00	190.89	493.55
800	325.75	328.25	0.77	44.61	82.65

Figure 4-2 shows one fractured specimen of each type along with its fracture surface. These two specimens correspond to the most common breakage for each specimen. All specimens experienced brittle fracture without any necking. The standard specimen can be seen to have a nearly uniform fracture with the different layers breaking at almost the exact same spot in the x-direction. The specimen with the through-hole has a more irregular surface, with the filament directly around the hole fracturing at a slightly different point than the rest of the surface. This is caused by the material in this area being deposited in a different and denser pattern than the rest of the specimen. This would seem to support the idea that the filament surrounding the through-hole acts to strengthen the entire specimen, since it may contribute to slowing crack propagation. Furthermore, the fact that this material makes this specimen less homogeneous than the standard specimen may explain why the through-hole specimens have much higher variation in the number of cycles to failure.

Figure 4.2: Fractured specimens: on the left is the standard specimen and on the right is the specimen with the through-hole

The performance of the FBGs for strain monitoring was examined by plotting the displacement data from the MTS machine with the FBG strain data. Figure 4.3 shows this comparison from tests at the 600 N load level using a specimen with an inserted FBG, as well as from an embedded FBG.

Figure 4.3: Time vs. Displacement (MTS) vs. Strain (FBG) at 600 N load level. In the top graph the FBG is inserted and in the bottom graph it is embedded.

Between the two specimen types, results varied substantially. Even though these two specimens underwent the same loading and had very similar fatigue lives, the specimen with the inserted FBG showed strain changes of around 10 ustrain per cycle compared to almost 2500 ustrain for the embedded FBG. This is due to the inserted FBG being less secure in the host material than the embedded FBG. Although inserting the FBG allows it to be reused for multiple tests, Figure 4.4 demonstrates that the strain response is too low for this technique to be viable. The embedded specimen exhibited much more promise since the FBG produced strain levels which were more stable while also better matching simulation data. Thus additional specimens with embedded FBGs were fatigue tested under the same loading conditions. These specimens were constructed using the process previously detail to allow for maximum strain transfer between the specimen and the FBG. The results of two additional embedded FBG specimens are shown in Figure 4.4.

Figure 4.4: Time vs. Displacement (MTS) vs. Strain (FBG) Additional embedded FBG test specimens

The results from these tests compared well with those of the original embedded specimen, as they showed a much greater strain response than the inserted FBGs. Thus, these results corroborate the idea that embedding is superior to inserting the FBG. Consistency between the two specimens in Figure 4.4 is not particularly high with the strain ranges differing by around 5500 μ strain. This is due to slight variations in the embedding process due to slight changes in adhesive thickness and layup as this process was completed by hand.

Table 4-3 displays the fatigue results of the three specimen types at the 600 N load level. This is the only load level embedded FBGs were tested at since they cannot be reused once glued in the

specimen. The results show that the embedding process may have some effect on the specimens' fatigue life. The variation in the number of cycles is also higher for the embedded specimens, perhaps showing that the glue has an influence on the consistency of the specimen.

Table 4-3: Number of cycles for each specimen type at 600 N load level

Load Level (N)	Average Number of Cycles			Standard Deviation		
	Standard Specimen	Through Hole Inserted FBG Specimen	Through Hole Embedded FBG Specimen	Standard Specimen	Through Hole Inserted FBG Specimen	Through Hole Embedded FBG Specimen
600	1204.50	3288.25	2584.33	190.89	493.55	837.10

To view the validity of the strain measurements, the data from the embedded FBGs was compared with a finite element (FE) model constructed in ANSYS Workbench. Table 4-4 shows the average change in strain during loading for different specimens and from the FE model. The measurements of the embedded FBGs are more similar in magnitude to the FE model than those from the inserted FBG. This has been previously been mentioned in work done by Liacouras et al. [63]. No damage in the sensor was observed during the fatigue testing prior to fracture of the specimen.

Table 4-4: Comparing change in strain during loading between specimens and Finite element model.

Specimen Type	Change in Strain During Loading (μ strain)
Inserted (Average)	50
Embedded #1	1000
Embedded #2	2000
Embedded #3	7500
Embedded #4	2000
Finite Element Model	2800

5 Conclusions

The properties of additive manufactured ABS and FBG sensors were both characterized in this study. This was done by tensile fatigue testing under differing specimen and sensor configurations as identified in section 2: standard, containing an inserted FBG sensor and containing an embedded FBG sensor. Results showed that the incorporation of the sensor altered the specimens' fatigue life differently for high and low load levels. The through-hole was seen to increase the variation in the number of cycles until failure by 80-160% in three out the four load levels. FBG strain measurements showed that although the insertion technique allows for the sensor to be reused, the results produced lacked stability and were more than 50 X less than the results of finite element simulation. Embedded FBG specimens displayed a strain response 20-150 X larger than the inserted FBGs, indicating they were better incorporated into the host material. The measurements from the FBG sensors matched the results from finite element simulation of the test specimens undergoing tensile loading.

These findings demonstrate that FBG sensors are a valuable tool for strain monitoring in additive manufacturing ABS. The combination of these two technologies may benefit industry in the future by allowing for a more accessible way to create smart materials. Additional research in this area may include optimizing the FBG embedding process as well as viewing how raster orientation or other printing characteristics affect the FBG strain response and specimen fatigue life.

6 Future Work

This investigation provides a potential starting point for more future work. First and most obviously is the optimization of the FBG embedding process. While the one showcased in the study was shown to be of some utility, improvements could lead to greater practicality for the application of embedded FBGs.

Second the is viewing the effects of different raster orientations on the FBG measurements, the embedding process and fatigue life. The same could be done for other printing parameters such as infill density and layer height.

The application of embedded FBGs under high frequency loading could be a possible avenue for research. The sensors on measured data at a rate of 10 Hz in this study which is nowhere near 2.5 kHz capability of the sensors possess. This could be utilized for very high cycle high frequency fatigue testing in particular.

The application of FBG sensors for full-scale fatigue testing is another interesting area. The networking and multiplexing capabilities of FBGs can allow for distributed fiber optic strain measurement systems as demonstrated by Davis et al. [64].

Many other applications of FBGs exist such as composite curing [14], temperature sensing [31]-[37], and biomedical implants [38] to name a few. In the biomedical field the idea of using FBGs to track human motion through wearable technologies could also be an area to explore [39][61].

References

- [1] C. W. Ziemian and R. D. Ziemian, “Residual strength of additive manufactured ABS parts subjected to fatigue loading,” *International Journal of Fatigue*, vol. 134, p. 105455, May 2020, doi: 10.1016/j.ijfatigue.2019.105455.
- [2] A. Leal-Junior *et al.*, “Fiber Bragg Gratings in CYTOP Fibers Embedded in a 3D-Printed Flexible Support for Assessment of Human–Robot Interaction Forces,” *Materials*, vol. 11, no. 11, p. 2305, Nov. 2018, doi: 10.3390/ma11112305.
- [3] N. Jap, G. Pearce, and A. Hellier, “The effect of raster orientation on the static and fatigue properties of filament deposited ABS polymer.” 2019.
- [4] R. D. Sante, “Fibre Optic Sensors for Structural Health Monitoring of Aircraft Composite Structures: Recent Advances and Applications,” p. 48, 2015.
- [5] C. S. Shin and C. C. Chiang, “Fatigue damage monitoring in polymeric composites using multiple fiber bragg gratings,” *International Journal of Fatigue*, p. 7, 2006.
- [6] W. Yan, S. Ma, H. Wang, and X. Zhang, “Fiber Bragg grating online packaging technology based on 3D printing,” *Optics & Laser Technology*, vol. 131, p. 106443, Nov. 2020, doi: 10.1016/j.optlastec.2020.106443.
- [7] C. Hong, Y. Zhang, D. Su, and Z. Yin, “Development of a FBG Based Hoop-Strain Sensor Using 3D Printing Method,” *IEEE Access*, vol. 7, pp. 107154–107160, 2019, doi: 10.1109/ACCESS.2019.2933568.
- [8] C. Hong, Y. Yuan, Y. Yang, Y. Zhang, and Z. A. Abro, “A simple FBG pressure sensor fabricated using fused deposition modelling process,” *Sensors and Actuators A: Physical*, vol. 285, pp. 269–274, Jan. 2019, doi: 10.1016/j.sna.2018.11.024.
- [9] G. T. Kanellos, G. Papaioannou, D. Tsiokos, C. Mitrogiannis, G. Nianios, and N. Pleros, “Two dimensional polymer-embedded quasi-distributed FBG pressure sensor for biomedical applications,” *Opt. Express*, vol. 18, no. 1, p. 179, Jan. 2010, doi: 10.1364/OE.18.000179.
- [10] Q. Wu, Y. Okabe, and F. Yu, “Ultrasonic Structural Health Monitoring Using Fiber Bragg Grating,” p. 26, 2018.
- [11] “FBG Principle.” . (n.d.). Retrieved from <https://fbgs.com/technology/fbg-principle/>
- [12] A. Panopoulou, T. Loutas, and D. Roulias, “Dynamic fiber Bragg gratings based health monitoring system of composite aerospace structures.” 2011.
- [13] M. A. Davis, A. D. Kersey, J. Sirkis, and E. J. Friebele, “Shape and vibration mode sensing using a fiber optic Bragg grating array,” p. 8, 1996.
- [14] P. Zhu *et al.*, “Alternating strain response of fibre Bragg grating sensors embedded into carbon fibre composites for wind blade health monitoring,” p. 5, 2019.

- [15] N. Nazeer, R. M. Groves, R. Benedictus, H. Delft, and H. Delft, "Simultaneous position and displacement sensing using two fibre Bragg grating sensors," p. 9, 2019.
- [16] P. D. Palma, G. Palumbo, M. D. Pietra, V. Canale, A. Iadicicco, and S. Campopiano, "Fiber Bragg Gratings strain sensors for deflection estimation of a two-dimensional structure," p. 8, 2019.
- [17] K. Krebber, W. Habel, T. Gutmann, and C. Schram, "Fiber Bragg grating sensors for monitoring of wind turbine blades," Bruges, Belgium, May 2005, p. 1036. doi: 10.1117/12.623635.
- [18] J. M. Costa *et al.*, "Fiber-optically sensorized composite wing," San Diego, California, USA, Apr. 2014, p. 906213. doi: 10.1117/12.2057943.
- [19] C. J. Keulen *et al.*, "Prediction of fatigue response of composite structures by monitoring the strain energy release rate with embedded fiber Bragg gratings," *Journal of Intelligent Material Systems and Structures*, p. 11, 2016.
- [20] E. S. Kocaman, E. Akay, C. Yilmaz, H. S. Turkmen, I. B. Misirlioglu, and M. Yildiz, "Monitoring the Damage State of Fiber Reinforced Composites Using an FBG Network for Failure Prediction," p. 19, 2017.
- [21] J. Sierra-Pérez, M. A. Torres-Arredondo, and A. Güemes, "Damage and nonlinearities detection in wind turbine blades based on strain field pattern recognition. FBGs, OBR and strain gauges comparison," *Composite Structures*, vol. 135, pp. 156–166, Jan. 2016, doi: 10.1016/j.compstruct.2015.08.137.
- [22] M. Tan, N. Zhou, J. Wang, D. Zou, W. Zhang, and G. Mei, "A real-time impact detection and diagnosis system of catenary using measured strains by fibre Bragg grating sensors," *Vehicle System Dynamics*, vol. 57, no. 12, pp. 1924–1946, Dec. 2019, doi: 10.1080/00423114.2018.1556396.
- [23] S. Goossens, T. Geernaert, Z. Sharif Khodaei, E. Karachalios, D. Saenz-Castillo, and F. Berghmans, "Barely visible impact damage detection and location on composite materials by surface-mounted and embedded aerospace-compatible optical fibre Bragg grating sensors," in *Optical Sensing and Detection VI*, Online Only, France, Apr. 2020, p. 17. doi: 10.1117/12.2559262.
- [24] A. Hammond, L. Shumway, and C. Hurlbut, "Modal analysis using fiber Bragg gratings." 2018.
- [25] H. Tsuda, "Ultrasound and damage detection in CFRP using fiber Bragg grating sensors," *Composites Science and Technology*, vol. 66, no. 5, pp. 676–683, May 2006, doi: 10.1016/j.compscitech.2005.07.043.
- [26] J.-R. Lee and H. Tsuda, "A novel fiber Bragg grating acoustic emission sensor head for mechanical tests," *Scripta Materialia*, vol. 53, no. 10, pp. 1181–1186, Nov. 2005, doi: 10.1016/j.scriptamat.2005.07.018.

- [27] H. Tsuda, J.-R. Lee, Y. Guan, and J. Takatsubo, "Investigation of fatigue crack in stainless steel using a mobile fiber Bragg grating ultrasonic sensor," *Optical Fiber Technology*, vol. 13, no. 3, pp. 209–214, Jul. 2007, doi: 10.1016/j.yofte.2006.12.003.
- [28] K.-S. Choi, Y.-H. Huh, I.-B. Kwon, and D.-J. Yoon, "A tip deflection calculation method for a wind turbine blade using temperature compensated FBG sensors," *Smart Mater. Struct.*, vol. 21, no. 2, p. 025008, Feb. 2012, doi: 10.1088/0964-1726/21/2/025008.
- [29] H. Zeng, R. Yan, L. Xu, and S. Gui, "Application study on fiber Bragg grating sensors in damage monitoring of sandwich composite joints," *Jnl of Sandwich Structures & Materials*, vol. 22, no. 5, pp. 1542–1563, Jun. 2020, doi: 10.1177/1099636218789621.
- [30] H. Alexakis, A. Franza, S. Acikgoz, and M. DeJong, "Structural Health Monitoring of a masonry viaduct with Fibre Bragg Grating sensors," p. 8, 2019.
- [31] M. Cavillon *et al.*, "Overview of high temperature fibre Bragg gratings and potential improvement using highly doped aluminosilicate glass optical fibres," *J. Phys. Photonics*, vol. 1, no. 4, p. 042001, Aug. 2019, doi: 10.1088/2515-7647/ab382f.
- [32] Y. Tu, L. Ye, S.-P. Zhou, and S.-T. Tu, "An Improved Metal-Packaged Strain Sensor Based on A Regenerated Fiber Bragg Grating in Hydrogen-Loaded Boron–Germanium Co-Doped Photosensitive Fiber for High-Temperature Applications," *Sensors*, vol. 17, no. 3, p. 431, Feb. 2017, doi: 10.3390/s17030431.
- [33] J. Canning, K. Sommer, and M. Englund, "Fibre gratings for high temperature sensor applications," *Meas. Sci. Technol.*, vol. 12, no. 7, pp. 824–828, Jul. 2001, doi: 10.1088/0957-0233/12/7/313.
- [34] G. Laffont, R. Cotillard, and P. Ferdinand, "Multiplexed regenerated fiber Bragg gratings for high-temperature measurement," *Meas. Sci. Technol.*, vol. 24, no. 9, p. 094010, Sep. 2013, doi: 10.1088/0957-0233/24/9/094010.
- [35] W. Ecke, I. Latka, T. Habisreuther, and J. Lingertat, "Fiber optic grating sensors for structural health monitoring at cryogenic temperatures," San Diego, California, Apr. 2007, p. 653002. doi: 10.1117/12.717755.
- [36] A. Ghazanfari, W. Li, and M. Leu, "Advanced ceramic components with embedded sapphire optical fiber sensors for high temperature applications," 2016.
- [37] Y. Li, W. Liu, Y. Feng, and H. Zhang, "Ultrasonic embedding of nickel-coated fiber Bragg grating in aluminum and associated sensing characteristics," *Optical Fiber Technology*, vol. 18, no. 1, pp. 7–13, Jan. 2012, doi: 10.1016/j.yofte.2011.09.004.
- [38] A. Najafzadeh *et al.*, "Healing Assessment of Fractured Femur by Strain Measurement using Fibre Bragg Grating Sensors," p. 6, 2019.
- [39] A. Theodosiou, "Recent trends and advances of fibre Bragg grating sensors in CYTOP polymer optical fibres," *Optical Fiber Technology*, p. 11, 2020.

- [40] Z. Liu and H.-Y. Tam, “Industrial and medical applications of fiber Bragg gratings (Invited Paper),” *Chin. Opt. Lett.*, vol. 14, no. 12, pp. 120007–120011, 2016, doi: 10.3788/COL201614.120007.
- [41] J. Bonefacino *et al.*, “Ultra-fast polymer optical fibre Bragg grating inscription for medical devices,” *Light Sci Appl*, vol. 7, no. 3, pp. 17161–17161, Mar. 2018, doi: 10.1038/lsa.2017.161.
- [42] R. Correia *et al.*, “Highly sensitive contact pressure measurements using FBG patch in endotracheal tube cuff,” Limerick, Ireland, May 2016, p. 99161F. doi: 10.1117/12.2236859.
- [43] R. Correia *et al.*, “Optical fibre sensing at the interface between tissue and medical device,” Perth, Australia, Apr. 2017, p. 103400X. doi: 10.1117/12.2269811.
- [44] J. Huang, Z. Wang, and Z. Zhou, “Multi-parameter dynamical measuring system using fibre Bragg grating sensors for industrial hydraulic piping.” 2018.
- [45] M. Mehravar, H. Yang, W. Zhang, and D. J. Webb, “Ground-water monitoring using polymer optical fibre Bragg gratings,” in *Seventh European Workshop on Optical Fibre Sensors*, Limassol, Cyprus, Aug. 2019, p. 132. doi: 10.1117/12.2541326.
- [46] Chu-liang Wei *et al.*, “A Fiber Bragg Grating Sensor System for Train Axle Counting,” *IEEE Sensors J.*, vol. 10, no. 12, pp. 1905–1912, Dec. 2010, doi: 10.1109/JSEN.2010.2049199.
- [47] E. Cuandra, N. Z. A. Bakar, and G. A. Mahdiraji, “Mechanical performance characterization of rotating shaft using fibre Bragg grating sensors,” Selangor Darul Ehsan, Malaysia, 2020, p. 020007. doi: 10.1063/5.0001439.
- [48] Y. Chen, Y. Q. Ni, X. W. Ye, H. X. Yang, and S. Zhu, “Structural health monitoring of wind turbine blade using fiber Bragg grating sensors and fiber optic rotary joint,” San Diego, California, Apr. 2012, p. 834534. doi: 10.1117/12.914961.
- [49] B. Wen, X. Tian, Z. Jiang, Z. Li, X. Dong, and Z. Peng, “Monitoring blade loads for a floating wind turbine in wave basin model tests using Fiber Bragg Grating sensors: A feasibility study,” *Marine Structures*, vol. 71, p. 102729, May 2020, doi: 10.1016/j.marstruc.2020.102729.
- [50] J. P. Moore and C. B. Williams, “FATIGUE CHARACTERIZATION OF 3D PRINTED ELASTOMER MATERIAL,” p. 15, 2012.
- [51] H. Zhang *et al.*, “Tensile, Creep, and Fatigue Behaviors of 3D-Printed Acrylonitrile Butadiene Styrene,” *J. of Materi Eng and Perform*, vol. 27, no. 1, pp. 57–62, Jan. 2018, doi: 10.1007/s11665-017-2961-7.
- [52] O. H. Ezeh and L. Susmel, “On the fatigue strength of 3D-printed polylactide (PLA),” *Procedia Structural Integrity*, vol. 9, pp. 29–36, 2018, doi: 10.1016/j.prostr.2018.06.007.

- [53] O. H. Ezeh and L. Susmel, "Fatigue behaviour of additively manufactured polylactide (PLA)," *Procedia Structural Integrity*, vol. 13, pp. 728–734, 2018, doi: 10.1016/j.prostr.2018.12.121.
- [54] M. Frascio, M. Avale, and M. Monti, "Fatigue strength of plastics components made in additive manufacturing: first experimental results," *Procedia Structural Integrity*, vol. 12, pp. 32–43, 2018, doi: 10.1016/j.prostr.2018.11.109.
- [55] S. Hassanifard and S. M. Hashemi, "On the strain-life fatigue parameters of additive manufactured plastic materials through fused filament fabrication process," *Additive Manufacturing*, vol. 32, p. 100973, Mar. 2020, doi: 10.1016/j.addma.2019.100973.
- [56] C. Kousiatza, D. Tzetzis, and D. Karalekas, "In-situ characterization of 3D printed continuous fiber reinforced composites: A methodological study using fiber Bragg grating sensors," *Composites Science and Technology*, vol. 174, pp. 134–141, Apr. 2019, doi: 10.1016/j.compscitech.2019.02.008.
- [57] M. G. Zubel, K. Sugden, D. Saez-Rodriguez, K. Nielsen, and O. Bang, "3D printed sensing patches with embedded polymer optical fibre Bragg gratings," Limerick, Ireland, May 2016, p. 99162E. doi: 10.1117/12.2237495.
- [58] L. Fang, T. Chen, R. Li, and S. Liu, "Application of Embedded Fiber Bragg Grating (FBG) Sensors in Monitoring Health to 3D Printing Structures," *IEEE Sensors J.*, vol. 16, no. 17, pp. 6604–6610, Sep. 2016, doi: 10.1109/JSEN.2016.2584141.
- [59] R. Zelený and J. Včelák, "Strain Measuring 3D Printed Structure with Embedded Fibre Bragg Grating," *Procedia Engineering*, vol. 168, pp. 1338–1341, 2016, doi: 10.1016/j.proeng.2016.11.367.
- [60] N. Reggiani Manzo, G. T. Callado, C. M.B. Cordeiro, and L. C. M. Vieira Jr., "Embedding optical Fiber Bragg Grating (FBG) sensors in 3D printed casings," *Optical Fiber Technology*, vol. 53, p. 102015, Dec. 2019, doi: 10.1016/j.yofte.2019.102015.
- [61] H. Cheng-Yu, Z. Ahmed Abro, Z. Yi-Fan, and R. Ahmed Lakho, "An FBG-based smart wearable ring fabricated using FDM for monitoring body joint motion," *Journal of Industrial Textiles*, p. 152808371987020, Aug. 2019, doi: 10.1177/1528083719870204.
- [62] Thorlabs, *Guide to Connectorization and Polishing Optical Fibers*. 2013.
- [63] P. C. Liacouras, G. T. Grant, K. Choudhry, G. F. Strouse, and Z. Ahmed, "Fiber Bragg Gratings Embedded in 3D-Printed Scaffolds," *NCSLI Measure*, vol. 10, no. 2, pp. 50–52, Jun. 2015, doi: 10.1080/19315775.2015.11721724.
- [64] C. Davis, M. Knowles, N. Rajic, and G. Swanton, "Evaluation of a Distributed Fibre Optic Strain Sensing System for Full-Scale Fatigue Testing," *Procedia Structural Integrity*, vol. 2, pp. 3784–3791, 2016, doi: 10.1016/j.prostr.2016.06.471.

Appendices (if any)

Copyright Acknowledgements (if any)