AN EXPERIMENTAL RESEARCH TO INVESTIGATE THE UTILITY OF FIBER OPTIC ACOUSTIC SENSORS FOR COMPOSITE HEALTH MONITORING
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SUMMARY

Fiber optic sensors are the current area of focus for researchers involved in developing Non-Destructive testing (NDT) methods for composite health monitoring. The ability to offer numerous advantages over their traditional counterparts such as no electromagnetic interference, wide temperature operating ranges, capability of embedding the sensor in the structure, have led to the uprising of fiber optic sensors. Composite materials which are increasingly being used in market areas such as aeronautics, automotive and wind turbine blades undergo complex failure mechanisms. Accurate knowledge of such failure modes can allow for more efficient maintenance philosophies and thereby further extending life cycles of these structural components. There exists a promising marketplace for reliable fiber optics based sensing systems to form the basis of serving such functionalities. It has also led Optics11 B.V. to determine the potential of its ZonaSens optical measuring system for composite health monitoring purposes. Hence forming the framework of this project and the main research question i.e. What is the performance of the ZonaSens optical acoustic measuring system when implemented for composite health monitoring purposes in terms of reliability and accuracy? An experimental research based approach followed during the project was limited to the study on diagnosis of damage in composite materials using the measuring system.

To begin with, two NDT methods namely, frequency modal analysis and Acoustic Emission (AE) monitoring were studied. Fiber optic sensors have shown capability to provide reliable damage related information using propagation of acoustic waves in the structure. They have been used to detect wide range of micro-structural failures such as matrix cracking, fiber breakage, delamination and fiber matrix debonding. ZonaSens optical measuring system due to its high sensitivity and dynamic range is also termed capable of being an acoustic emission sensing system for composites. Frequency modal analysis relies on examining the vibrational response of the system through an initial external vibration to detect damage. The dependency of physical properties of the structure on the vibrational response forms the basis of this technique. Experimental setups were created and vibrations were introduced into carbon fiber based composite samples in undamaged and damaged situations. Monitoring of frequency spectrums after post processing of the data revealed altered characteristics in damaged specimens. It was especially in the ultrasonic range, pertaining to presence of local
damage in the laminates. Detecting the presence of delamination was the most interesting situation whereby; clear frequency shifts were seen corresponding to the hypothesis.

The measurements were substantiated by performing tests on different samples while using a reliable setup. Effect of different optical fiber configurations on the quality of signal was also noted. Whereby, the effect of microbending of the fiber leading to optical loss was correlated to the degraded quality of the signal. To analyze real time damage propagation in composites, samples were brought under increasing loads until failure using different test setups. Post processing of the logged data provided record of acoustic emissions during linear increase of load. Frequency and time-amplitude based clustering analysis provided in literature was used to characterize damage events due to matrix cracking and fiber breakage. The reliability of the measurements was confirmed by performing tests on different samples and relating data to the physical damage mechanism. The effect of damaging of the embedded optical fiber on the quality of the obtained data was also analyzed.

The evaluation of ZonaSens optical measuring system for the above-mentioned NDT methods highlighted the potential of the system for composite health monitoring. The high sensitivity of the system allows for diagnosing local damage in composite using vibrational analysis. Furthermore, damage events prior to final failure were also analyzed using the system during continuous AE monitoring. Data substantiation by comparison of results with literature and performing multiple tests showcases the reliability and accuracy of the measurements and thereby the system. Limitations arising from different optical fiber configurations and its degradation (bending/breaking) during damage progression have a considerable influence on the feasibility of the system for practical applications. Hence with developments in these aspects, ZonaSens optical measuring system will be capable for use in NDT methods for composite health monitoring purposes, specifically for damage diagnosis.

Some recommendations arising from the tests include integration of Fiber Bragg Gratings (FBGs) forming the sensing zone inside the composite laminate. It is to be able to eliminate any sensitivity to surrounding noise sources. Furthermore, ability to use a higher sampling rate than the present (750 kHz) and a detailed clustering analysis can allow for characterizing events due to delamination and fiber-matrix debonding occurring during damage progression. Implementation of multiple zones in the laminate can also provide the prospect of
locating the origin of damage. At last, finding new means of integrating the optical fiber in the laminate which can protect it from immediate damage can be very useful when implementing the system for practical applications.
1. INTRODUCTION

This chapter describes the research framework of this project which has been carried out to fulfill the requirements of the final graduation assignment within the aeronautical engineering programme at Inholland University of Applied Sciences (Delft, The Netherlands). The graduation project has been carried out at Optics11 B.V., a company based in Amsterdam, The Netherlands. Optics11a spin-off from Vrije Universiteit (Amsterdam) is a young engineering company which is involved in the manufacturing of optical fiber sensing systems (Optics11, 2017). The assignment proposed by the company involves investigating the utility of fiber optic acoustic sensors for composite health monitoring (for full description see Appendix A: Description of the assignment) (Optics11, 2017). The boundaries and scope of this project are described in section 1.4 of this chapter. Finally, description of the report structure is given in section 1.5.

1.1 Including the background and problem analysis

The role of fiber optic sensors for composite health monitoring in different industrial applications has seen an upward trend. Composite health monitoring is a subject of utter importance due to the complexities involved in predicting damage growth and life time of such materials. Existing sensor systems used in various Non-Destructive Testing (NDT) techniques for composite health monitoring fall behind fiber optic sensors in various scenarios. Fiber optic sensors offer no electromagnetic interference with wide temperature operating ranges and capability of embedding in the structure. Therefore, researchers in academia have developed sensors based on fiber optics and have shown potential to provide indications of matrix cracking, delamination and fiber breakage both in real time and offline analysis. Accurate knowledge of such failure modes can allow one for more efficient maintenance philosophies and thereby further extending life cycles of composite components. It has applications in different market segments such as aeronautics, wind turbine blades, automotive and more. Leading aircraft manufacturer, Airbus has expressed interests in introducing fiber optic sensors for SHM purposes in all its newer aircraft in the future. Hence development of reliable fiber optic
sensor systems for composite health monitoring applications is a promising marketplace. Optics11 B.V., company based in Amsterdam wants to introduce its patented fiber optic based remote sensing platform called ZonaSens in composite health monitoring. The product has shown its worth in hydrophone applications; however, its readiness for composite damage diagnosis is undetermined. It is therefore of utmost importance to perform testing and experimentation with ZonaSens optical measuring system on composites which can allow for determining the reliability and accuracy of this sensing platform. (Sante, 2015) (Francis T.S. Yu, 2002) (Charles R. Farrar K. W., 2007) (Gardner Business Media, Inc. , 2008) (Arora, Project Plan version 2.0, 2017).

Based on the above-mentioned reasoning, the main and sub research questions of the project can be set up. It is described in the next section of this chapter.

1.2 Main and sub research questions

The main and sub research questions arising from the previous section of this chapter are stated below. (Arora, Project Plan version 2.0, 2017)

What is the performance of the ZonaSens optical acoustic measuring system when implemented for composite health monitoring purposes in terms of reliability and accuracy?

To answer the main question, the following sub-questions are to be answered first.

1. What kind of experiments will be performed (e.g. experiments leading to initiation of failure modes in composite samples /external disturbances on the samples)?
2. What kind of information can be derived from signal processing and analysis related to the internal state of the samples during experiments?
3. Are there ways to validate the results obtained from the measurements, if yes, what are they and what is the accuracy of results?
4. What is the feasibility of ZonaSens measuring equipment when implemented for practical applications in composites?
1.3 Method of investigation

To answer the above-mentioned questions in the given time frame, a pre-defined method of investigation must be followed during the complete project duration. The work scope is to be covered by the author in an independent manner with technical advice from the engineering personnel at the company. The outline of the method of investigation is showcased below.

A literature study will be conducted to determine the prospects of the experiments. It also includes understanding the existing research studies conducted in this field. It will then be followed by an experimental research encompassing testing and data analysis. Following such a path can then allow for setting up conclusions determining the feasibility of ZonaSens optical measuring system for composite health monitoring applications. It will be followed by giving recommendations for continuing this research. The research methodology adopted during this project is also showcased in Figure 1.

![figure 1](image)

**Figure 1:** Overview of the research methodology adopted during the project.

1.4 Boundaries and scope of the project

The activities which are to be covered during the research phase mainly involve performing a literature study to define the theory behind the experiments which are to be conducted, manufacturing and testing composite samples with integrated fiber optic sensors, signal processing and analysis. Since the work scope around such
activities can be very wide which can lead to deviations from the project capacity, certain limitations are defined in this section to set realistic goals. (Arora, Project Plan version 2.0, 2017)

**Do’s**

- Defining the NDT techniques which are to be used for evaluating ZonaSens optical measuring system is an important aspect of this project.
- Analyzing results and conclusions given in literature which relate to such NDT techniques for this subject (composites integrated with fiber optic sensors) is within the scope.
- Understanding the sensitivity of the measuring equipment and cause of variations in the nature of the obtained signals are within the scope.
- Performing experiments with fiber optic sensors integrated in different configurations is within the scope.
- **LabVIEW** is to be utilized during the project for signal processing and analyzing results. Other software sources that are to be used for such purposes include **Origin** (for data analysis and graphing) and **Microsoft Excel**.
- Performing spectral analysis (computing spectrograms, power spectrums and Fourier transformations) is within the scope.
- Ensuring a reliable test setup (pertaining to test standards ISO/ASTM) during experimentation. An example of the test configuration used during the research is showcased in Figure 2.

![Figure 2: Example test configuration pertaining to ASTM standards used during the research.](image)
Don’ts

• The project does not involve optimizing the production process of composites integrated with fiber optic sensors. Since this aspect is out of the market portfolio of the company.
• No changes are to be made into the internal configuration of the interrogator and human machine interface belonging to the ZonaSens optical measuring system.
• Complex composite manufacturing methods are not to be used during the project.
• Complex shapes of composite samples are not to be used during the project.
• Use of finite element analysis is out of the scope.

1.5 Structure of the report

The outline of the report is as follows. Chapter 2 firstly describes the literature study conducted during the project. It includes background of concepts related to fiber optics, ZonaSens, composite health monitoring techniques, integration of fiber optics and composites which are essential for this project. This chapter also provides familiarity with NDT techniques for which ZonaSens will be evaluated. It is followed by explanations on the setup of experiments, background of the data analysis process and discussion of the results from the tests conducted concerning frequency modal analysis in chapter 3. Chapter 4 includes a similar division of sections as chapter 3 but regarding another NDT technique called Acoustic Emission (AE) monitoring. It is followed by verification and discussion of results in chapter 5 and final conclusive interpretations from the previous sections of the report in chapter 6, whereby the research questions are answered. Finally, the recommendations arising from this experimental study are described in chapter 7 of this report.
2. ANALYSIS OF THE LITERATURE AND CONCEPTS TO BE UTILIZED DURING THE PROJECT

As mentioned in the introduction chapter of this report, the project aims to investigate the utility of fiber optic acoustic sensors (ZonaSens) for composite health monitoring purposes. To perform this experimental research, knowledge of concepts and recent findings from academia related to this project has to be acquired. This chapter aims to describe the fundamental background of fiber optics and its principles which are utilized in this project (see section 2.1). An insight into the importance of composite health monitoring and the currently used techniques is given in section 2.2. It is followed by information on two NDT methods namely; frequency modal analysis and Acoustic Emission monitoring which are to be evaluated during the project to determine the performance of the ZonaSens optical measuring system (see section 2.3 and 2.4 respectively). Furthermore, a review on integrating fiber optic sensors in composites is also given in section 2.5 of this chapter. This is followed by a short conclusion of the literature research in section 2.6.

2.1 Background of fiber optics

The integration of fiber optics with composites is the key highlight of this project. It is thereby important to acquire background knowledge of aspects related to both fields which are to be practically utilized during the testing phase. The following section covers the initial subject i.e., fiber optics. This section is divided into three sub-sections namely, principle, structure and applications of fiber optic cables (see section 2.1.1), application of fiber optic sensors and their advantages over conventional sensors (see section 2.1.2), Fiber Bragg Gratings and its use in Michelson interferometry principle for ZonaSens optical measuring system (see section 2.1.3).

2.1.1 Principle, structure and applications of fiber optic cables

Optical fibers which are inhomogeneous structures strictly designed for creating a closed space in which light can propagate form the basis of fiber optic technology. The fibers which are mainly composed of glass (usually
(silica) can be differentiated into many types depending on their composition and size, such as single mode and multimode fibers. These types are differentiated based on modes of light they can support for propagation. Fiber optic cables follow a usual construction which consists mainly of a core, cladding and a polymer jacket. Core is the region where light is propagated and it has higher refractive index than the surrounding medium which is called the cladding. The difference in the refractive index and the material used in the buildup of core and cladding can decide the amount of propagation losses if the principle of total internal reflection of light is not fulfilled. Single mode fibers which are also used in this project have core diameter in the range of $5 \, \mu m$ and a cladding diameter in the range of $125 \, \mu m$. Since the fiber itself is very delicate, external protection is required to prevent any mechanical or environmental stress. A polymer coating followed by a buffer and a jacket is usually incorporated for protection of the fiber. The external coatings cause an increase of the total diameter of the construction to a few millimeters. Figure 3 gives an illustration of the construction of fiber covered by a polymer jacket (coating). (Paschotta, Fibers, n.d.) (Paschotta, Fiber optics, n.d.) (Alexis Méndez, 2007)

![Figure 3: Construction of a fiber illustrating the core where light is propagated. The core is surrounded by medium with higher refractive index called the cladding. A polymer jacket is also shown which is used for protection of the glass fiber.](image)

Fiber optic cables are used in a number of applications including the communication systems for transmitting digital data in a fast and an efficient manner, in fiber optic sensors for detection of stress, strain, temperatures in industrial applications, medium of transporting laser light etc. (Paschotta, Fiber optics, n.d.) Fiber optic cables for sensor applications are of prime interest to this project. More information on fiber optic sensors is given in sub-section 2.1.2 of this chapter.
2.1.2 Application of fiber optic sensors and their advantages over conventional sensors

Fiber optic sensors are typically based on the devices which use the principles incorporating fibers for transmission of light. Such sensors are used for measurement of temperatures, mechanical strains, displacements, vibrations, pressure, acoustics, accelerations, and rotations. (Paschotta, Fiber-optic Sensors, n.d.) The use of fiber optic sensors has seen an upward trend for the applications mentioned earlier due to decreasing costs and increasing advancements offering advantages over the traditional sensing equipment. (Francis T.S. Yu, 2002)

The major advantages of fiber optic sensors over other traditional sensors (accelerometers, piezo based sensors, strain gauges etc.) are as follows (Paschotta, Fiber-optic Sensors, n.d.) (Francis T.S. Yu, 2002).

1. No electromagnetic interference to surrounding electronic equipment and immunity to disturbances from other electrical devices.
2. Safety of use in dangerous surroundings such as high voltage environments, explosive environments etc.
3. Wide temperature range in combination with being chemically passive.
4. Light weight and high sensitivity.
5. Careful construction of setup can lead to none or minimal loss of information.

Different approaches are used for the development of fiber optic sensors with majority of them based on Fiber Bragg Gratings (FBGs) as point sensors (explained in section 2.1.3). Other approaches involve use of fibers in principles of interferometry such as in Fabry-Pérot interferometers, in scattering principles such as Raman scattering, Brillouin scattering, and Rayleigh scattering for distributed sensing purposes and different multiplexing techniques for Quasi-distributed sensing purposes. Explanations on use of FBGs and optic fibers in such interferometry and scattering principles are out of the scope of this report. However, one principle which involves use of FBGs in interferometric fiber sensors where they act as reflectors to measure phase shifts is important to elaborate. It is because this principle is used in the ZonaSens measuring equipment (Paschotta, Fiber-optic Sensors, n.d.).
2.1.3 Fiber Bragg Gratings and its use in Michelson interferometry principle for ZonaSens optical measuring system

FBGs comprise of an optical fiber where a certain core region is exposed to periodic or aperiodic change in refractive index. This periodic modulation can be caused by exposing the region with UV light. The change in refractive index causes reflection of light propagating in the fiber for which the Bragg condition is satisfied. The reflection of light of a certain wavelength \( \lambda_B \) from the grating region depends on the effective index of refraction \( n_{\text{eff}} \), Bragg period \( \Lambda \) of the grating and is given by the following equation. (Manjusha Ramakrishnan, 2016) (Paschotta, Fiber Bragg Gratings, n.d.) (Sante, 2015)

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

An overview of the principle of operation of a FBG is illustrated in Figure 4 (Manjusha Ramakrishnan, 2016).

Due to presence of local deformation in the grating resulting from external strain or changing temperatures, there occurs a shift in the Bragg wavelength (see lower section of Figure 4). By monitoring this shift in wavelength, physical quantities can be calculated. The positive or negative shift depends on the expansion or contraction of the FBG. It is also important to differentiate between the shifts in wavelength occurring due to temperature and strain (Manjusha Ramakrishnan, 2016). FBGs have been used in the monitoring of strain, temperature and detecting damage in composite materials as single point sensors. Literature has shown that
tests conducted with such sensors on composites have been performed in both embedded and on-surface state (it implies that FBGs are attached on the surface of the composite specimen) (Fucai Li, 2009).

FBGs used in the ZonaSens equipment do not serve as sensors themselves, but acts as mirrors for the incorporated Michelson interferometer based sensor. Interferometers which fall under the category of phase modulated sensors measure optical phase difference between two light waves (Alexis Méndez, 2007). The useful information is extracted after the superimposition of different light waves. The optical device utilizes an input light beam which is separated into two beams using a beam splitter. After that some of the beams are exposed to external physical influences and are then later recombined. The resulting beam is then used to understand the effects causing any difference in the characteristics of the individual light beams (Paschotta, Interferometers, n.d.). Due to the high sensitivity of such sensors, they have been used to monitor acoustic emissions in composite materials for damage detection purposes (Laurent Rippert, 2002).

Michelson interferometer uses a single beam splitter for separating and recombining beams reflected from mirrors. Depending on the number of outputs required, the configuration of the beam splitter can vary. For e.g. the recombination of beams can occur on a different location on the beam splitter; if more than one or a different output is required. Different configurations of a typical Michelson interferometer are also shown in Figure 5 (Paschotta, Interferometers, n.d.). One of the arms after the beam splitter (BS) is referred to as the reference arm and other as the measuring arm.

![Figure 5: Different configurations of Michelson interferometer depending on the number and type of outputs required.](image-url)
In the ZonaSens equipment, at the end of the reference arm a FBG of a certain wavelength is used (a broadband fiber mirror is also sometimes used and it will reflect light waves of all wavelengths). The measuring arm consists of FBGs which are separated by fiber optic cable. The cable between the FBGs forms the sensing zone in this setup. Therefore, FBGs in this case do not serve as sensors but as mirrors. Any perturbations due to external influences in the in-between fiber optic cable will result in changes in the distance between the FBGs of the measuring arm. By comparing the interferometric signals, the changes in the optical path length between the FBGs can be precisely measured. (Optics11 B.V., 2016) (Sielecki A., 2017). This allows one to acquire much more detailed information regarding the influences of the external effects on the surfaces where the measuring zone is attached. The schematic of the ZonaSens measuring setup is illustrated in Figure 6 (Optics11 B.V., 2016).

Figure 6: (Above) ZonaSens optical measuring system in operation, (Below) schematics of the system showcasing the reference arm, measurement arm and the sensing zone.
The ZonaSens controller shown in Figure 6 forms the main component of the setup which consists of devices for processing of the information acquired by the sensing zone using the Michelson interferometer setup. The controller box has ports for connections to the computer, power supply and the two interferometric fibers (reference arm and measuring arm). The software coupled to the ZonaSens hardware allows for setting parameters for data acquisition, diagnostics, recording data for post processing and visualizing real time data.

The nature of the system provides the capability to measure very high frequencies up to 1 MHz and a large sensing region provides soaring sensitivity. This ability gives ZonaSens an advantage over other sensing equipment such as point based FBGs, piezoelectric sensors etc. Hence acoustic waves of higher frequencies and any minute structural displacements can be measured by this optical system. Such capabilities to visualize and quantify acoustic events have opened possibilities for applying this technology for SHM purposes for composites. More information on need for composite health monitoring and use of acoustic emissions for damage diagnostics in composites is given in the following sections of this chapter.

### 2.2 Composite health monitoring techniques

Structural Health Monitoring (SHM) is referred to as the process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure. Damage here relates to the changes which adversely affect the performance of the structure (Charles R. Farrar K. W., 2007). Monitoring of structures can allow for improving the life cycle of a component by application of more efficient maintenance philosophies. SHM techniques have gained huge interests in applications where composite materials are used. This is driven by the increasing use of composites especially based on carbon fiber and glass fiber in applications areas such as aircraft, automotive, construction, wind turbine blades etc. Furthermore, use of composites for critical components in such applications has also seen an upward trend. Composites are affected by varying external environmental conditions, perturbations which can lead to initiation of damage which may not even be visible. Therefore, it is important to monitor composites during their operational life for damage diagnosis. Information from such diagnosis can relate to the presence of damage and may even provide location and extent of damage (Manjusha Ramakrishnan, 2016). Furthermore, crucial information on prediction of failure can also be obtained through SHM (Seth S. Kessler, 2001).
Various NDT methods have been developed for composite health monitoring purposes in the previous decades. To name a few: vibration-based analysis, Acoustic Emission (AE) monitoring, X-ray radiography, thermography, eddy currents monitoring, A- and C-scanning ultrasonic inspection techniques, acousto-ultrasonics and low frequency methods. Due to the inherent characteristics of the composite materials, no technique can fully identify all types of damage (existence of multiple defect geometries in composites). The difference arises on the prospect of accuracy and extent of damage detection. Furthermore, for many techniques there exists the limitation of not being able to perform in-situ measurements due to size limitations of the equipment (Manjusha Ramakrishnan, 2016) (Staszewski, 2001) (Baillie, 1999.)

Research dictates that fiber optic sensors are accumulating interests for condition monitoring and damage diagnostics due their compact size and many other advantages over traditional sensors (see section 2.1.2). One of the most interesting advantages is their capability to embed in the structure. Fiber optic sensors have shown capability to provide reliable damage related information in composites in NDT techniques involving propagation of mechanical vibrations. Detection of acoustic emissions by fiber optic sensors is one of the prime areas of interest. It can be used to detect wide range of micro-structural failures such as matrix cracking, fiber breakage, delamination and fiber matrix debonding (M. Giordano, 1998). Majority of the research in the field of detecting acoustic emissions with fiber optic sensors in composites has involved FBGs and interferometry based sensors. The aim has been to replace currently used piezoelectric based acoustic emission sensors (Baillie, 1999) (Manjusha Ramakrishnan, 2016) (L. Rippert, 2000).

ZonaSens optical measuring system due to high sensitivity and dynamic range is also termed capable of being an acoustic emission sensing system in composites. Of the previously mentioned NDT techniques, frequency methods and AE monitoring are areas where ZonaSens can play a role for acoustic emission detection system. However, experiments are needed to be performed to determine the quality of results and hence the performance. More information on the background of these two NDT methods is given in sections 2.3 and 2.4 of this chapter.
2.3 Literature review

Frequency modal analysis which falls under the category of modal-based damage detection techniques has been used in industry for structural damage detection. Modal parameters (frequencies, mode shapes and modal damping) are categorized as functions of the physical properties of a structure. Thereby, any changes in the physical properties will cause changes in these parameters. Such parameters are analyzed by examining the vibrational response of the system. In other words, this vibration based damage detection system uses changes in the structural characteristics to detect, characterize and locate damage in structural and mechanical systems. Modal analysis has been put forward as a powerful tool for global damage detection from simple to complex structures. It offers several advantages over other NDT techniques. These are found below (C. Sujatha) (Hanno Niemann, 2010) (Charles R. Farrar S. W., 1997) (Seth S. Kessler, 2001).

1. The vibration analysis allows for assessing the condition of the entire structure.
2. It is not required to have access to the complete structure.
3. The technique has proved to be cost effective and relatively simple to implement when compared to other NDT methods.
4. Deriving damage related information from the data obtained is easy.

In this technique, the structure is excited by ambient energy through an external shaker or an embedded actuator (such as based on piezo transmitters) and the dynamic response of the structure is measured by sensing systems such as strain gauges, piezo transducers, accelerometers or laser vibrometers. Different types of excitation signals have been mentioned in literature such as burst random, burst chirp, sinusoidal linear sweep, sine dwell, white noise etc. Besides the principle of measurement, the response is also dependent on the amount of sensing points and the location of sensors. The illustration showcasing the principle of this technique is given in Figure 7 (Hanno Niemann, 2010) (Seth S. Kessler, 2001).
As mentioned earlier, modal parameters are functions of the physical properties of the structure. These are mass, damping and stiffness. Damage to a structure will decrease mass and stiffness and will increase damping ratio locally (Y. Zou, 2000). Any such changes in the physical parameters have been correlated to damage occurrence (onsets of cracks, loosening of a connection) in the structure. Use of modal analysis especially related to examination of natural frequencies for damage detection in composites is reported in literature. It offers the advantage of convenient measurements and high accuracy (Hanno Niemann, 2010) (Charles R. Farrar S. W., 1997). Natural frequencies which are determined from the characteristic equation (dependent on the boundary conditions) of the structure is mathematically related to the Young’s modulus (E), second moment of inertia (I) and mass (m) by its multiplication with the ratio \( \left( \frac{EI}{m} \right)^{0.5} \). Any effect on the stiffness of the structure due to damage affects the ratio, thereby resulting in a change (typically decrease) of the natural frequencies of the structure (Seth S. Kessler, 2001).

Measurement of lower frequency modes (< 2 kHz) has been the dominant measurand in the frequency analysis. This is mainly due to the limitations posed by the sensing systems to measure high frequencies and the requirement of more energy to initially create high energy excitations. Lower frequency modes are related
to the global condition of the system. Therefore, any shifts in the frequencies in lower modes can provide an indication of the existence of damage in the structure. Most literature has reported a 5-10% decrease of resonance frequencies for damaged specimens when compared to intact specimens. For example, a study conducted by Kessler et al. (Seth S. Kessler, 2001) on graphite/epoxy panels gave clear resonance reductions when the samples were analyzed for different damage types. A result from their study showcasing frequency plot from the intact specimen and the delaminated specimen is given in Figure 8. For instance, the peak near 50Hz in Figure 8 has moved towards left for the case with delamination in the composite specimen. Furthermore, detection of damage using frequency shifts has been associated with the capability to perform precise measurements to derive reliable conclusions regarding presence of damage. (Charles R. Farrar S. W., 1997)

It has been repeatedly mentioned in the literature to carry out further research to measure high frequency modes of the structures. Since these modes are associated with local responses of the structure and carry the most detailed information of the damage present. Furthermore, increased ability to detect multiple frequency

![Figure 8: A result from the study conducted by Kessler et al. showcasing clear shifts in the lower frequency modes in the delaminated specimen when compared to the intact specimen.](image)
shifts can also provide spatial information of damage. Since presence of damage at many locations will lead to
different combinations of changes in frequencies, especially at higher modes (Charles R. Farrar S. W., 1997)
(Seth S. Kessler, 2001).

The eligibility of the ZonaSens for the sensing arm of this NDT technique must be tested. The high sensitivity
of the measuring zone between FBGs may provide interesting information regarding frequency modes which
when analyzed for intact and damaged specimens can reflect presence of damage in composites. Another
technique for which the performance of ZonaSens must be tested is the Acoustic emission monitoring.
Opposite to the above-mentioned technique, AE monitoring is used for analyzing the real-time response of
the structure. More information on this technique is given in section 2.4 of this chapter.

2.4 Acoustic Emissions from composite laminates

Acoustic Emission (AE) can be defined as a transient elastic wave generated by the rapid release of energy
within the material. In response, the sensor generates a signal which is related to the wave and is called the
AE signal (Azadeh Keshtgar, 2013). The discontinuities in the structure release energy in the form of elastic
waves when subjected to loading or stress. These stress waves are usually of the order of high frequencies
which are detected by sensors and transformed into interpretable signals. Currently AE monitoring in
structures is dominated by ultrasonic transducers which can detect acoustics of the order 20 kHz to 1 MHz.
Accuracy of measurements form such sensors depend on the number of sensors and signal interrogation
system. The interrogation systems which can detect acoustic signals can define the nature of the acoustic
source event depending on the amplitude, frequency and speed. An illustration of a typical acoustic emission
monitoring process is shown in Figure 9 (Department of Mechanical engineering, Vrije Universiteit Brussel)
(Department of Mechanical engineering, Vrije Universiteit Brussel).
Advantages offered by AE monitoring compared to other NDT techniques are listed below. (Baillie, 1999)

1. The technique can detect propagation of minute cracks.
2. AE monitoring provides the advantage of real time diagnosis of the system i.e. while the structure is still in service.
3. While monitoring, no external energy is released into the structure.
4. Knowledge of location of sensor is not important, since AE examination is non-directional.
5. Size of the structure does not pose a limitation.
6. Dynamic processes associated with damage initiation and material degradation can be monitored.

Significant amount of research has been performed within the academia for monitoring of AE for failure processes in composites. The superiority of AE monitoring over other NDT techniques for identification of damage is illustrated in Table 1 (Ding, 2010). It can be seen that with implementation of AE monitoring, it has been possible to diagnose different types of damage mechanisms in composites.
Several researchers have tried to qualitatively categorize the damage modes caused by AE events. This involves mainly relating parameters such as amplitude and frequency to different damage modes. Such analysis can provide discrete information on the type of damage in the composite material. Other parameters which have also been studied include duration of the events, number of events and energy analysis. Extensive surveys conducted by Ying Ding on AE parameter analysis carried out by different researchers reveal that there are contradictions in the conclusions related to amplitude analysis (Ding, 2010). Some researchers claim high amplitude events are related to matrix cracking and low amplitude events are related to fiber cracking, however some claim the opposite. The possible reason dictated is the use of different materials or specimen configuration. A survey on AE frequency analysis (relating different damage types to different frequency contents) conducted by Ying Ding on works of different authors provides good agreements between conclusions. These are listed below (Li Li S. V., 2015) (Ding, 2010).

1. Relating low frequency events to matrix cracking (< 140 kHz)
2. Relating medium frequency events to fiber/matrix debonding, fiber pull out (200 kHz to 300kHz)
3. Relating high frequency events to delamination/ fiber breakage (> 300kHz (may go up to 400 kHz))

Even though considerable amount of research on AE parameter analysis and frequency analysis has been done, some literature puts it insufficient for extracting features from AE signals. Time-frequency analysis has been termed as powerful solution to non-stationary problems, which can be applied to composite health monitoring processes. A time-frequency distribution gives distribution of total energy of the signal at time and frequency points and thereby provides an alternative approach to conventional Fourier based methods. Such methods provide time variation of spectral quantities which implies allowing for reconstructing the whole failure and relating it to the real damage process in time. It also allows for pointing out any sudden changes in

<table>
<thead>
<tr>
<th>Damage Type</th>
<th>AE</th>
<th>Ultrasonic C-scan</th>
<th>Radiography</th>
<th>Microscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Fracture</td>
<td>Possible</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Delamination</td>
<td>Possible</td>
<td>Yes</td>
<td>Yes</td>
<td>At edges only</td>
</tr>
<tr>
<td>Matrix Cracking</td>
<td>Possible</td>
<td>No</td>
<td>Yes</td>
<td>At edges only</td>
</tr>
<tr>
<td>Debonding</td>
<td>Possible</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1: Composite damage identification capabilities of various NDT techniques
the properties of the specimen (Robertson, 2007). Such characteristics which can be extracted from AE monitoring have led to the upsurgence of this NDT technique for health monitoring of composites. The two main research areas have been the focus of development i.e., advanced sensors for AE monitoring and signal processing/analysis (discussed above). The involvement of fiber optic sensors has been the result of it.

Embedding of fiber optic cables which constitute a part of the fiber optic sensors in composites has been reported. Acoustic emissions which are related to the propagation of mechanical waves in the material lead to the local bending of the fibers. Bending of fiber also leads to coupling of some propagation and radiation modes. Proper signal interrogation further can allow for extracting transient features from the measured optical signal. These features can be related to stress waves due to different damage modes such as matrix cracking, delamination etc. (Laurent Rippert, 2002) (L. Rippert, 2000). Simulation of acoustic emissions due to damage in composites for experimental purposes has been conducted by carrying out tensile and fatigue tests by different researchers. It has allowed researchers to analyze and describe acoustic events in a controlled manner. Composites material types which are mainly selected during such experiments are either based on carbon fiber or glass fiber. Different research papers reveal that the range and accuracy of results is highly dependent on the signal interrogation system and the data processing program. MATLAB and LabVIEW are the two main post processing software which have been utilized by researchers for performing spectral analysis of the recorded data (M. Wevers, 2000) (V. Arumugam, 2011) (Li Li S. V., 2015) (Laurent Rippert, 2002).

As mentioned earlier, embedding of optical fibers in composites forms a key constituent of different type of fiber optic sensors. Majority of literature related to development of sensing systems has involved testing with embedded fibers; however, some researchers also opt for on-surface integration. Integration of optical fibers with composites is also required for performing different experiments during this project. However, finding the optimal manufacturing method is out of the scope. Many researchers in academia have reported conclusions arising from embedding of optical fibers in composites. Background knowledge related to this subject is also viable for this project as it can improve the quality of the experiments. The following section of this chapter reports the same.
2.5 Review of technical issues and associated performance

The embedding of fiber optic cables or FBGs in composites forms a crucial part of the experimental research which is carried out in the field of composite health monitoring using Fiber Optic Sensors (FOS). Embedding of FOS in composites allows one to protect the sensing region against external environment and provides increased sensitivity to the internal architecture of the composite specimen. Surface mounting of fiber optics for composite monitoring is reported less in the literature for AE and frequency analysis. Even though the process of surface mounting the FOS is less challenging and is faster, it is practiced not as much of due to the fragility of the optical fibers. Also, this aspect of integration of FOS with composites is application dependent. With surface mounting of optical fibers, the means of adhesion play a significant role in the transfer of vibrations and strain to the fiber from the composite during excitation. This aspect has then lower significance with embedded optical fibers (Geert Luyckx, 2011) (Sante, 2015).

Embedding of fibers in composites also has its shortcomings. Optical fibers serve as a disturbance in the internal architecture of the composite structure. This is mainly due to size differences (Standard optical fibers have diameter of the order of 250 \( \mu \) m (with coating) and composite fibers are of the order of 5-10 \( \mu \) m (for carbon fibers)). These can lead to formation of resin rich regions around the optical fibers causing an irregularity in the internal structure of the composite. An illustration showcasing the cross-section of a fiber optic cable in different types of composite specimens is given in Figure 10 (Sante, 2015).

![Figure 10: Cross-section of a fiber optic cable in a composite specimen with (a) unidirectional (b) cross-ply and (c) woven fabric internal architectures.](image)

Furthermore, the manufacturing process of composites with embedded FOS can lead to deviations in the spectral sensitivity of the sensors. This is due to the presence of residual strains acting on fibers due to the
partial release of internal stresses during heating and cooling processes while manufacturing. Hence existence of such non-uniform strain fields can have effect on the spectral response of embedded sensors especially for strain measurements. However, for damage detection purposes (as for this project) literature states that effect of distortions in the spectral response does not have any considerable effect on the conclusions (Sante, 2015).

As mentioned above, presence of optical fibers in the internal architecture of composites has a negative influence on the mechanical properties of the material. Various research studies have been conducted to quantify the effect of this degradation mechanism on parameters such as fracture toughness, stiffness, compressive/tensile strength etc. of composites. As it can form the basis for creating reliable failure prediction methodologies (Manjusha Ramakrishnan, 2016). Majority of research dictates that embedding of optical fibers parallel to the reinforcement fibers does not have any significant reduction in the strength of composites. This is especially the case with optical fibers with very small diameters. Orientation of optical fibers in different directions relative to reinforcement fiber can have influence on the static strength of composite laminates and can lead to presence of 'defect centers' in the material. Other factors that have influence on the overall strength of the laminate include thickness of the laminate and the protective coating of the optical fiber. Some research studies also dictate that if the density of optical fibers in composites is low, it may have insignificant influence on mechanical properties of the laminates (Geert Luyckx, 2011) (Manjusha Ramakrishnan, 2016). Hence the level of certainty on the scope of influence of optical fibers on the mechanical properties of composites has different views from researchers in this field.

As mentioned earlier, the coating of the optical fiber also influences the properties of the laminate. It has been reported in literature that slippage of the optical fiber in the composite material may also occur. Possible solutions that have been tested include, embedding of optical fibers in the laminate without a coating (thereby stripping the coating before the manufacturing process) or using optical fibers that have properties which are similar to the resins used in composite material. The first method has encountered various issues due to handling difficulties. The second method however has seen some success with coating materials such as polyimide. This also allows for reduced damage due to handling and increased transfer of strain from the material to the optical fiber. Furthermore, use of polyimide coating allows for a clean interface from with the
surrounding resin. Figure 11 gives an illustration of a polyimide coated optical fiber in a thermoplastic composite part (Udd, Winz, Kreger, & Heider, 2005).

Apart of the above-mentioned concerns and conclusions from several authors, the most widely documented technical issue regarding integration of optical fibers in composites is the possibility of fiber breakage at ingress/egress points. Such locations are critical due to the presence of sharp pressure gradient resulting in severe bending of optical fiber (Sante, 2015). Different approaches have been used in literature to tackle this problem, such as use of custom fiber connectors at the edges, use of hypodermic tubes, plastic tubes (usually made of Teflon), embedded connectors etc. Figure 12 gives an illustration of two widely used ingress/egress connection methods (Sante, 2015). Use of any method requires the proper sealing of the connections to prevent any outer flow of resin during the laminate manufacturing processes and avoiding any sharp curvature of the fiber to prevent any optical loss (Udd, Winz, Kreger, & Heider, 2005) (Manjusha Ramakrishnan, 2016). One research paper also suggests eliminating the connection points by implementing wireless transmission of data using embedded sensors to external data reading point (Geert Luyckx, 2011).
Figure 12: Use of Teflon tubing (LH) and custom connectors (RH) for making end connections of fiber optic cables in composites.

The dependence of the type of manufacturing method and the level of human interference on the process can also have influence on the quality of the laminates, positional accuracy of the fibers, strength and reliability of the end connections. The two most common manufacturing methods that employed are hand layup and prepreg layup methods. The hand layup method involves stacking of reinforcement fibers (dry) and applying matrix (example by resin infusion technique) in between them followed by curing and shaping. While the latter involves stacking of pre-impregnated plies (matrix material already in the plies). The curing process can be performed at room temperature or using an autoclave (for accelerated heat and pressure) (Gardner Business Media, Inc., 2014) (Manjusha Ramakrishnan, 2016). Furthermore, attachment of optical fiber during any manufacturing process requires slight pre-strain on the surface of the ply to prevent any unintentional bending of fiber. As previously mentioned in section 2.4 although discrete research towards optimizing the structure and production means of the composite specimens is out of the scope of this report, knowledge of aspects related to the manufacturing strategies and procedures concerning the integration of optical fibers in composites can offer a technical advantage towards improving the quality of the experiments.

2.6 Conclusions from the literature review

ZonaSens optical measuring through its large bandwidth and high sensitivity offers an advantage of retrieving very detailed acoustic information from the fiber optic sensing region (Optics11 B.V., n.d.). This capability of ZonaSens provides an opportunity to discover the potential of this technology for composite health monitoring purposes. SHM which is practiced in many industries especially which involve composites has been increasingly implemented to improve the life cycle of components. Developing techniques and equipment to accurately monitor composite structures for detection of damage has been an area of research. Use of fiber optic sensors
in composite health monitoring has been a result of this drive to replace existing sensors as they offer several advantages. Research has shown that the characteristics of ZonaSens equipment seem suitable to be evaluated for two NDT methods for damage detection in composites. These are frequency modal analysis and AE monitoring. Several researchers have experimented integration of FOS in composites to obtain damage information from composites using these techniques. The integration of FOS in composites although carries several challenges and is on a developing trend within the industry, it aims to provide precise information on presence of damage when compared to traditional sensors.
3. DAMAGE DIAGNOSIS IN COMPOSITE SPECIMENS USING FREQUENCY MODAL ANALYSIS

The use of frequency modal analysis for composite health monitoring is an interesting subject for researchers involved in the development of equipment for NDT techniques. As mentioned in the section 2.3 of this report, resonance modes of composite specimens carry an imprint of the material’s health. This when analyzed in intact and damaged scenarios can provide useful information for deciding on the condition of a composite component. ZonaSens optical measuring system through its capabilities of high sensitivity and large bandwidth has the potential for measuring more accurate vibrational response from composite specimens.

To determine this potential, reliable experimental setups must be created. It involves production of composite specimens with integrated fiber optic cable constituting the sensing zone. A method of reliably inducing damage along with a technique of producing excitations through an external source on the specimens is also required. Different types of damage scenarios will be created. At last, data analysis tools must be set-up for accurately understanding the behavior of resonance modes which are expected to provide indication of damage in the specimen.

The following sections of this chapter aim to extensively cover the above-mentioned areas of action. Section 3.1 provides information on the experimental setup which will be necessary to implement when performing measurements. It includes information on the method of creating excitations in the laminates, preparation of the first batch of composite samples with integrated fiber optic cables and setup of the data analysis tools. It is followed comparison of the resonance modes of undamaged composite laminates in section 3.2. It is followed by description of procedures adopted to induce different types of damage and the results from the measurements. Section 3.3 showcases the same for the four-point bending test, section 3.4 provides information on the impact test, section 3.5 provides information on the behavior of the resonance modes after a series of drilling tests and section 3.6 provides information on delamination tests. At last, section 3.7 provides the conclusions from the study conducted in this chapter.
3.1 Set-up of the constituents of the experimental setup

The sub-sections within this section aim to describe the constituents of the experimental setup required prior to testing and performing measurements. Sub-section 3.1.1 describes the method utilized for creating vibrations in the composite laminates. Sub-section 3.1.2 provides an overview of the manufacturing process and specifications of the first batch of laminates. It is followed by explanation of the data-analysis tools required to visualize frequency spectrums in sub-section 3.1.3.

3.1.1 Method of creating excitations in the composite specimens

As mentioned in section 2.3 of the report, it is important to have a reliable source of creating vibrations on the composite specimens. The ability to replicate the setup of the vibrational source is critical for performing comparisons in between different conditions of a composite specimen and between different composite specimens. The latter can be used to study the effect of different optical fiber configurations in similar composite specimens.

Therefore, through means of external vibrations, resonant frequencies of the composite laminates can be obtained (These are the frequencies at which the maximum amplitude vibrations occur) (Incorporated Research Institutions for Seismology, 2014). These are dependent on the physical parameters of the object and can also be referred to as the natural frequencies of the system which are the properties of the system. Therefore, if a composite laminate encounters external vibrations, which correspond to one of its natural frequencies, it will start vibrating at that moment with higher amplitude. This moment is referred to as the occurrence of resonance. Hence it is also important for the vibrational source to generate excitation with a range of frequencies as it can allow for picking up different resonance modes of the composite laminates. Furthermore, generating excitations of higher frequencies is also a critical requirement as it can allow for studying the behavior of higher resonance modes. To meet the above-mentioned requirements, an ultrasonic bender has been used (shown in Figure 13). This vibration transmitter has a resonant frequency of 1.7 MHz and a maximum input voltage of 100Vp-p (Volt Peak to peak) (PUI audio Inc., 2016).
Furthermore, a sinusoidal frequency sweep has been chosen as the type of excitation signal. It provides the capability to control the range of frequencies depending on the setup as opposed to white noise. Furthermore, initial tests conducted with white noise excitation signal did not provide any information on the resonance modes of the composite laminates. It can be related to the low amplitude of the vibrations which constitute the white noise signal. To generate the frequency sweeps, RIGOL DG4102 Arbitrary waveform generator with maximum output voltage of 20Vp-p has been used. Output characteristics of the signal generator are however not adequate to drive the piezoelectric bender. Therefore, an amplifier must be integrated into the circuit to generate optimal input conditions for the piezo. These are mainly higher voltage amplitude and drive frequency. For this setup, a module based miniature high voltage amplifier, PDm200B has been used (shown in Figure 14) (PiezoDrive, 2017).

![Figure 14: PDm200B amplifier required to drive the ultrasonic bender.](image)

The amplifier can operate on different input DC voltages (12, 24 and 48) and provides a gain of 20. The output types can be varied between high-speed and low noise. For this study, the high-speed output which provides a higher signal bandwidth has been chosen. Furthermore, the amplifier has a power bandwidth of 63 kHz at 100Vp-p output load which limits the overall range of frequency spectrum that can be analyzed (PiezoDrive, 2017). Therefore, output voltage from the amplifier has been limited to 60Vp-p by controlling the input signal to obtain larger output bandwidth. Furthermore, EST 150 power supply has been integrated to provide ±12V input voltage to the amplifier.
The above-mentioned settings and equipment provide the basis for creating an excitation signal through the ultrasonic bender on the composite laminates. The laminates are based on carbon fiber. More information on the preparation of the specimens is given in sub-section 3.1.2 of this chapter.

### 3.1.2 Preparation of composite laminates and integration with external apparatus

The composite laminates to be used for performing experiments in this research have been manufactured using carbon fiber prepregs (for material details refer to Appendix B: Specifications of carbon fiber prepreg used for manufacturing samples during the experimental study). (Hexcel Composites, 2013) The reason for choosing this material is based on its availability and the simplicity involved in the manufacturing process. Furthermore, autoclave based curing process has been utilized. It provides the convenience of manufacturing multiple samples at one instance. Three composite samples have been manufactured in the first batch using the autoclave curing process. The stacking sequence utilized during this process is [0]8. The reason for choosing the unidirectional layup is to limit the variations in the experiments. Furthermore, it provides the basis for understanding the effect of different optical fiber configurations.

Two samples were embedded with SMF28e optical fiber (covered with low temperature polymer coating) and one sample embedded with SM1250 (covered with high temperature polyimide coating). The optical fibers during the manufacturing process were placed between 4th and 5th ply. The configuration and size of samples is showcased in Figure 15 (Arora, Manufacturing plan, 2017).

![Figure 15: Optical fiber configuration and size of samples (1st batch) manufactured using autoclave based curing manufacturing process.](image)
The loop configuration of the optical fiber increases the total length of the fiber inside the specimen thereby increasing the sensitive region (constituting a sensitive zone located between two FBGs). Furthermore, an increased spatial distribution provides the possibility of obtaining more detailed information of the resonance modes. The low density of the fiber is also not expected to create extensive degradation in the internal architecture of the composite specimens. The fiber at ingress/egress points was protected using high temperature tape which was applied on both sides (upper and lower). An approximate 2 cm of tape was also inserted inside the specimens to prevent any effect due to the movement of resin during the curing cycle.

![Image: Use of high temperature tape to prevent any unintentional movement of optical fiber at the ingress/egress points.](image)

The conditions operative during the curing cycle are showcased in Table 2. These conditions are also utilized to manufacture more samples for experiments to be discussed in the later sections of this report.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Time</td>
<td>3 hours + 40 minutes</td>
</tr>
<tr>
<td>2.</td>
<td>Temperature</td>
<td>185º C</td>
</tr>
<tr>
<td>3.</td>
<td>Pressure</td>
<td>6.9 bar</td>
</tr>
</tbody>
</table>

*Table 2: Details of the autoclave curing cycle used for manufacturing samples.*

**Observations after the curing cycle:** It was revealed that due to high prevalent temperature, melting of polymer coating of the exposed SMF28e optical fiber occurred (showcased in Figure 17) (refer to Batch 1, Appendix B: Visuals from the autoclave based composite laminate manufacturing process for more images).
However, the fiber inside did not suffer any damage (checked using a visual fault locator). Therefore, it is feasible to use these samples for experiments which are discussed in the following sections of this chapter.

![Figure 17: Melting of the polymer coating constituting the SMF28e optical fiber observed after the autoclave curing process.](image1)

Before proceeding to the experimenting stage, it is necessary to create a reliable means for clamping the ultrasonic bender on the laminates. Thereby, a simple spring based clamp has been fabricated which can support the bender at the edge of the laminate (see Figure 18). A firm contact between the bender and the laminate is also necessary for optimal transfer of vibrations from the former to the latter. Furthermore, to maintain similarities between test setups involving different laminates, the location of the excitation source has been fixed at the middle of the laminate’s edge in the lengthwise direction.

![Figure 18: Mechanism for obtaining a firm contact between the excitation source and composite laminate.](image2)

Furthermore, fiber optic pigtails are utilized in terminating the end connections of the fibers originating from the laminates. The end connections then can be used for connecting the FBGs resulting in the formation of the sensitive zone of the ZonaSens optical measuring system. Apart from the mechanical integration of the different components of this setup, method of obtaining accurate frequency spectrums of the laminates
resulting from an external vibrational excitation is also required. The tools necessary for such examination are described in sub-section 3.1.3 of this section.

3.1.3 Set-up of the data analysis tools for monitoring frequency spectrums

The ability to record a time-based measurement from the Human Machine Interface (HMI) of the ZonaSens optical measuring system can allow for obtaining time dependent variation of the resonance modes using different post processing tools. LabVIEW, a renowned signal processing software designed for building measurement and control systems has been utilized to perform post processing of the recorded measurements from the HMI (National Instruments, 2017).

The concept of Short-time Fourier Transform (STFT) which relies on classical Fourier analysis has been utilized. The Virtual Instrument (VI) performing this operation in LabVIEW performs Fourier Transforms (FT) on consecutive sections of the signal. The window length defined by the user along the signal of interest is used to perform the FT. Hence by breaking up the signal into many periodic sections using window functions such as Hanning, a STFT is obtained. The window function is applied to reduce the effect of spectral leakage arising due to the existence of non-integer number of periods in the section of the signal (Robertson, 2007) (National Instruments). The width of the chosen window function for performing the analysis acts as a limitation for time and frequency resolutions. A wide window provides a good frequency resolution and a poor time resolution and vice versa. Since the aim is to obtain more accurate frequency information, a large window width is chosen for the current analysis (window length of 8192 samples for experiments within this chapter). The function extracted from the STFT contains frequency spectrums for each time which are averaged characteristics for the specified time interval within the window length (Robertson, 2007). The time interval chosen between two spectra is 30 milliseconds (ms). The spectral map which is a Three-Dimensional (3D) representation of the frequency spectra as a function of time can be represented in different formats. The colormap representation which is adopted for this research showcases the signal power distribution using different colors. Such analysis can allow for visualizing the energy of the system as a function of time (National Instruments Corporation, 2009). Therefore, by performing the above mentioned STFT operation on the signal (which is recorded concurrently when the frequency sweep through the ultrasonic bender is applied), very detailed information of the resonance modes of a composite laminate can be logged. The next step is to extract
these modes from the background noise picturized in the colormap. This operation can be performed by
translating the time axis along the line of frequency sweep (which exists at a slope) in the colormap and
thereby extracting the frequency and amplitude coordinates for plotting them separately. Hence providing
plots with distinctive information regarding resonance modes which are reliable and easy to compare in
different scenarios. The LabVIEW block diagram build to perform such operations is showcased in Appendix
D: LabVIEW block diagram for post processing of data recorded during frequency modal analysis.

Apart from the frequency-time analysis, result of the classical FT can also be obtained in LabVIEW.
Furthermore, the HMI of ZonaSens also provides the prospect of exporting the real time recorded FFT of the
signal. It provides the opportunity to compare the information obtained from both sources for reliability. The
HMI of ZonaSens provides different options when recording FFT. This includes averaging type, number of
averages, scale and the type of windowing function. In addition, the user is also required to define other pre-
processing terms before recording any measurement. This includes, sampling rate, number of samples to read
and type of filtering. More detailed information on the chosen requisites is given in the following sections of
this chapter along with the information from the experiments.

3.2 Comparison of resonance modes of the undamaged composite laminates

It is evident that composite samples manufactured from the similar process, with same materials under alike
conditions may differ in properties. This is especially the case when automated means of prepreg layup are
not employed. However, it is interesting to compare the resonance modes of such samples. It can provide with
information on the reliability of signal, range of modes which can be excited using the current setup and any
similarities or differences in the position of these modes. Performing such a comparison requires having
equivalence in the setup of the experiment, signal generation settings, pre-processing settings in the HMI.
Table 3 showcases the chosen parameters.
Signal generator settings

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Type of excitation</td>
<td>Sine sweep</td>
</tr>
<tr>
<td>2.</td>
<td>Sweep time</td>
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</tr>
<tr>
<td>3.</td>
<td>Frequency range</td>
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</tr>
<tr>
<td>4.</td>
<td>Amplitude</td>
<td>3Vp-p</td>
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</table>

HMI settings

<table>
<thead>
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<th>S.No.</th>
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<th>Value</th>
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<tr>
<td>2.</td>
<td>Samples to read</td>
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</tr>
<tr>
<td>3.</td>
<td>Reference FBG wavelength</td>
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</tr>
<tr>
<td>4.</td>
<td>Laser ref (1) power</td>
<td>4 mW</td>
</tr>
<tr>
<td>5.</td>
<td>Measurand FBG wavelength</td>
<td>1550 nm</td>
</tr>
<tr>
<td>6.</td>
<td>Laser (2) power</td>
<td>12 mW</td>
</tr>
</tbody>
</table>

Boundary conditions of the composite laminates: Free-Free

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
</table>
| Boundary conditions of the composite laminates: Free-Free

The chosen sampling rate has been based on the Nyquist frequency theorem. Furthermore, due to the presence of a large sensitive zone, the effect of disturbances from the external environment (noise of electrical equipment and surroundings), temperature drift and laser noise (between 100 Hz to 1 kHz) can cause difficulty in distinguishing resonance modes of the laminate from other sources at lower frequencies. Hence the frequency sweep is initiated from 2 kHz (Sielecki A., 2017). The upper limit of the sweep has been fixed at 120 kHz, it is due to the occurrence of distortion in the extraction of current by the piezo at very high frequencies. The reason for setting a very high value of power for the second laser is discussed below.

A test conducted with similar signal properties and sampling parameters on another composite laminate with embedded optical fiber in the straight configuration (optical fiber running parallel to the fibers of the carbon laminate), gave a better-quality signal than a curved configuration at lower specified power of the lasers. This
has been related to the microbending of the optical fiber in the latter case (see Figure 19) (L. Rippert, 2000). Microbending can lead to optical losses causing decrease in the strength of the signal which can be diagnosed in the HMI of the ZonaSens. Microbending concept can be utilized for performing strain and temperature calculations but it is a hindrance for the research related to frequency modal analysis. Because the total length of the fiber inside the composite laminate is not very large in the present situation, this problem can be solved by increasing the power of the laser (see Table 3; HMI settings). The effect becomes more pronounced when a very large length of the fiber is affected by microbending and increasing the power of the laser does not have a considerable effect on the strength of the signal anymore.

![Figure 19: The perpendicularity of the optical fiber with respect to the carbon fibers of the composite laminate causes unintentional microbending leading to optical loss.](image)

Therefore, through careful electrical integration of the systems and implementation of the parameters mentioned in Table 3, signal was recorded concurrently when the frequency sweep was initiated. Through post-processing in LabVIEW, colormaps are obtained for each of the laminates. Figure 21 showcases an example of a colormap obtained for a laminate ((1) in this case) for the first 30 seconds of the signal. In addition, Figure 20 showcases an example configuration of the laminate with the excitation source clamped to its surface.
Figure 20: Example configuration of a laminate whereby the excitation source is clamped on its surface to generate vibrations.

Figure 21: Colormap representation of the STFT performed on the signal recorded using the HMI.

The line of frequency sweep in Figure 21 contains information on the resonance modes of the laminate. This when analyzed for all three laminates separately and for the complete length of the signal can provide data for comparison. Figure 22 showcases graphs for the resonance modes of the three laminates.
Figure 22: Comparison of the resonance modes of three composite samples with same configuration and setup (Range: 2 kHz – 30 kHz)

As seen from Figure 22, the noise floor of the signals from the three laminates is in correspondence. This in combination with a comparable absolute excitation level of the resonance modes from different laminates gives an indication that the data reflected may truly correspond to the internal state of the laminates. It provides basis for comparing the location of resonance modes and their corresponding behavior. Furthermore, it showcases the reliability of the system to generate repeatable conditions for recording and analyzing the data. For the range of frequencies showcased in Figure 22, it can be concluded that many resonance peaks exist and with laminates (1) and (2) having higher amplitudes compared to laminate (3). Furthermore, a frequent correlation between the resonance peaks from different laminates can be seen (at 9 kHz, 11 kHz, 15 kHz, 18 kHz, 29 kHz). A closer look reveals that there are similarities in the general location of the modes. It is also interesting to note that after an approximate 30 kHz point, the amplitude of the resonance modes appears to drop considerably. Furthermore, there appears to be more correspondence of the location of the peaks for higher modes especially for laminates (1) and (3) (see Figure 23).
Figure 23: Comparison of the resonance modes of three composite samples with same configuration and setup (Range: 48 kHz – 90 kHz)

As seen from Figure 23, the correspondence in the absolute amplitudes and location of resonance peaks between laminates (1) and (3) is impressive (at 50 kHz, 55 kHz, 65 kHz, 70 kHz, 75 kHz, 82 kHz). However, between laminates (1) and (2), (2) and (3), a closer look reveals that main difference arises from the high Q-factor of the resonance peaks belonging to laminate (2). But the general location of the peaks remains similar (such as at 82 kHz). It is notable to be able detect and see similarities in the resonance modes of different laminates even in the ultrasonic range. The next step is to be able to detect changes in the resonance modes due to presence of global or local damage. To create such scenarios, various tests are conducted to replicate damage (in different forms) in the laminates. The first test that has been conducted is called the four-point bending test. The aim during this test is to bring the laminate to certain load levels in steps and perform measurements at those load levels. More information on this test and the corresponding results is mentioned in section 3.3 of this chapter.
3.3 Detection of local damage during four-point bending test

The setup of the four-point bending test has been utilized to bring a composite laminate under different loads. It is interesting to examine the behavior of the resonance modes when the laminate is under a certain stress level, which has the capability to deform the internal architecture of the laminate due to creation of a possible local damage (such as minute cracks or delamination). During this test, composite laminate labeled (1) from section 3.2 was utilized. The following sub-sections provide details of the test procedure (in sub-section 3.1.1) and discussion on the results obtained (in sub-section 3.3.2).

3.3.1 Procedure and details of the four-point bending test (quarter point)

The test setup was created in accordance with ASTM standard (Designation: C393-00) to maintain the reliability of the measurements. The test configuration of two-point load (quarter point) was chosen (see Figure 24). (ASTM International, 2000)

![Figure 24: Two-point load (Quarter point) configuration chosen for conducting the four-point bending test.](image)

But the purpose of the intended test was different from what is specified in the guidelines of the test standard. During the test, the sample was brought to a pre-load of 5N and load was increased to 105N with a speed of 100N/min. Upon reaching 105N, the load was maintained and a frequency sweep measurement was carried out. The position of the specimen was not hindered since all connections and positioning of the piezo was done prior to initiating the test. The test was continued and the sample was brought to a load of 205N and then 305N in a similar manner with speed of 100N/min. Frequency sweep measurements were performed at
both loads. Figure 25 showcases the position and state of the composite laminate at an instance when the load is increasing.

![Figure 25: Position and state of the composite laminate (1) when the load is increasing.](image)

The sample was then brought to the upper force limit, in this case 350N and then the test was finished. Another test was conducted to bring the laminate under a higher load level. During this test, the laminate was brought from a preload of 5N to 505N with a speed of 500N/min. A frequency sweep measurement was then performed at 505N load. The sample was then brought to rest by taking it first to the upper force limit (in this case 520N). Another frequency sweep measurement was performed with the sample not being under any load. All measurements were performed with settings described in Table 3. This measurement was performed to examine any permanent changes that might have occurred in the specimen during the application of separate loads. Since the ultimate strength of the laminates that were manufactured is unknown, maximum load which was applied during this test was kept to 520N. The load graphs obtained from the test program for both cases are shown in Figure 26.
3.3.2 Discussion of the results obtained from the measurements performed at separate load levels

The data logged during the measurements when treated with the same post processing procedure can be used to obtain detailed information regarding resonance modes at different load levels. Such characteristics are to be compared with the laminate in undamaged situation and with resonance modes at different loads. Figure 27 and Figure 28 showcases graphs containing frequency spectrum of the laminate in undamaged situation and at different load levels.

Figure 26: Load curves for both tests conducted using the four-point bending setup.
Figure 27: Comparison of frequency spectrums of composite laminate (1) at separate load levels obtained from the four-point bending test (Range: 2 kHz – 30 kHz)

Figure 28: Comparison of frequency spectrums of composite laminate (1) at separate load levels obtained from the four-point bending test (Range: 48 kHz – 90 kHz)
Apart of the comparable noise floor indicative from the graphs in Figure 27, the general replication of peaks depicts similar global conditions at different load levels. Examination of the graph with No damage vs. At 205N load indicates that characteristics of the mode at 15 kHz have not changed. Lower modes at around 9 kHz and 12 kHz have become more pronounced. Furthermore, for the higher resonances in the showcased range (at 18 kHz, 21 kHz, 24 kHz, 27 kHz, 29 kHz) it is seen that there is either damping of the resonance modes or an increase of the Q-factor. These provide an indication of the changed characteristics of the laminate. Extending the comparison to the cases with loads of 305N and 505N, it is seen that decrease of the absolute amplitudes of the peaks have occurred. Furthermore, the Q-factor has increased as the load has increased (for higher modes). However, it is difficult to define a trend in the location of the peaks, which is the most important factor. Besides, it is not clear that if the behavior of the modes at increasing load levels is due to the altered internal architecture of the composite laminate or from a poor mechanical coupling of the piezo with the laminate’s surface, due to increase in the bending. For resonance modes in the higher range (between 48 kHz - 90 kHz depicted in Figure 28), there is a similar trend in the modes with increasing load levels. Yet again, the position of the modes does not follow any trend. This is reflected by the resonance mode near 82 kHz which also showcases an exception in the absolution excitation level of the mode. Furthermore, interestingly this mode also appears to move towards right in the graph (indicative of rise in resonant frequency) which is incomprehensible.

Sound of slight cracking was heard when the load was being increased to 505N. The sound and visual recording of the test provided a conclusive proof of this damage. Hence, it is also interesting to compare the frequency spectrums of the undamaged state and the state after the test (see Figure 29 for the plots).
The first indication which the comparison provides is the change in absolute amplitude of the modes present around 8 kHz, 25 kHz and 30 kHz. This implies that amplitude ratios of concurrent resonance peaks have changed. However, there is no movement with respect to the location of the modes. For the higher range (above 40 kHz) a similar behavior exists. But increase of Q-factor of the modes is depictive of the presence of damage on a local scale.

To conclude, examination of the resonance modes in different situations (at separate load levels and after the test) reveals that there exist visible characteristics which point to the existence of local damage in the composite laminate. However, to derive a conclusive trend from the test is difficult. It specifically applies for the location of the resonance modes. It can be related to inability of the current fiber optic configuration to attain such detailed information when the damage imparted to the laminate is very small. Possibly such indications are visible with the presence of different forms of damage. To further continue this investigation, analysis of the impact damage test is given in section 3.4 of this chapter.
3.4 Detection of damage after an impact test

The drop impact tower has been utilized to impart damage into the composite laminate (2). The drop of weight on the laminate can lead to fiber breakage, delamination, cracking and their combinations. This test can be used to make a visual account of the damage which can be related to the results. The following sub-sections provide details of the test procedure (in sub-section 3.4.1) and discussion on the results obtained (in sub-section 3.4.2).

3.4.1 Procedure and details of the impact test

The drop impact tower utilized during the test aims to meet ASTM test standards (Designation: D7136). (Faturohim, 2016) But the purpose of the intended test was very different and did not aim to find the damage resistance of the laminate. The laminate was carefully placed in the test setup with the side of ingress/egress points slightly out of the clamp to prevent any damage. The impactor was dropped on the laminate with the anti-rebound function activated. This is to prevent the impactor hitting the laminate twice (setup of the plate prior to clamping is shown in Figure 30).

Figure 30: Setup of the drop tower prior to clamping the plate and closing the safety door. The composite plate can be seen resting on the metal surface with the impactor (in black) above it.
Further details of the test are given in Table 4.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Weight of impactor</td>
<td>1530.7 g</td>
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<tr>
<td>2.</td>
<td>Height of drop</td>
<td>0.14 m</td>
</tr>
<tr>
<td>3.</td>
<td>Velocity of the impactor just before impact</td>
<td>1.66 m/s</td>
</tr>
<tr>
<td>4.</td>
<td>Kinetic energy of the impactor just before impact</td>
<td>2.1 J</td>
</tr>
</tbody>
</table>

Table 4: Details of the impact test performed on composite laminate (2).

The damage imparted on the plate is showcased in Figure 31.

![Figure 31: Damage imparted to the laminate using the drop tower as seen from the naked eye and from a magnified view.](image)

Frequency sweep measurements were performed before and after the test using the settings described in Table 3 (except the upper range of frequency sweep changed to 110 kHz and sampling rate was changed to 220 kHz).

3.4.2 **Discussion of the results obtained from the measurement performed after the impact test**

Post processing of the logged data provides frequency spectrums to compare the excited resonance modes in undamaged and damaged scenarios. Figure 32 showcases the same for the range 2 kHz to 40 kHz. The frequency spectrum of the laminate obtained after the impact test appears to be drastically damped when compared to the undamaged situation. The signal appears to be just indicative of noise except for three
resonance peaks which are visible between 15 kHz and 20 kHz, and around 30 kHz (no other resonance modes appear in the total spectrum). The characteristics of frequency spectrum in the damaged situation are related to the possible redistribution of stress around the optical fiber which increased the severity of the microbending effect when the impact occurred. However, the sensitivity of the system was high enough to detect the prominent resonance modes after the impact. It is recommended to perform the impact test again with a different embedded optical fiber configuration to validate the above described conclusion. Drilling tests have been further conducted on composite laminate (3). The analysis of the results and the details of the test are given in section 3.5 of this chapter.

![Graph showing frequency spectrum comparison](image)

**Figure 32:** Comparison of frequency spectrums of composite laminate (2) before and after impact test (Range: 2 kHz – 40 kHz). Left scale on the vertical axis corresponds to the frequency spectrum of the no damage case.

### 3.5 Detection of damage induced after series of drilling tests

The degree of damage created by drilling in the composite laminate (3) is maximum from the previously discussed cases. Hence it is safe to assume that characteristics of the frequency spectrum will contain more information (compared to the previous cases) which can be reflected upon the created damage. The following
sub-sections provide details of the test procedure (in sub-section 3.5.1) and discussion on the results obtained (in sub-section 3.5.2).

### 3.5.1 Procedure and details of the drilling tests

Two holes of diameter 3.5mm were drilled into the laminate. The distance between the holes was set to be 7cm (configuration of the plate also showcased in Figure 33).

![Configuration of holes (diameter of 3.5mm and separated by 7cm) drilled into composite laminate (3).](image)

Frequency sweep measurements were performed at three instances, before the test, after drilling the first hole and after the second hole using the settings described in Table 3 (except the upper range of frequency sweep was changed to 100 kHz and sampling rate was changed to 200 kHz due to use of a different software (HMI) version).

### 3.5.2 Discussion of the results obtained from the measurements performed after the drilling tests

Post processing of the logged data provides frequency spectrums to compare the excited resonance modes in undamaged and damaged scenarios. Since the overall condition of the specimen changes after drilling the first hole, it has been chosen to compare the second damaged situation only with the last condition (specimen with one hole). Figure 34 showcases the same for the range 2 kHz to 30 kHz and Figure 35 showcases the frequency spectrum for the range 40 kHz to 80 kHz.
The most interesting information for this damage scenario lies in the higher frequency range, i.e. in Figure 35. It is because of the difficulty to differentiate the resonance modes in the lower frequency range. However, the modes in the lower range appear to have changed characteristics. Notice the mode in Figure 34 for the case, No damage vs After 1st hole at 15 kHz, which has damped after first damage. This trend of damped characteristics continues after 20 kHz which is indicative in Figure 35. The change in the location of the peaks...
is still difficult to determine. It is interesting to note that the characteristics of the modes after the second damage situation appears to be very like first damage situation. The region of the modes does not change and an increase of Q-factor is seen for some modes. The altered characteristics in the frequency spectrums are more pronounced due to a higher damage level than discussed in section 3.3. The last damage scenario which has been covered within this domain is delamination in composites. It is a complex failure mechanism which is difficult to detect and can occur on a very local scale and thereby is of very interesting nature to this research. Ability to detect internal defects which are not visible on a global level can provide crucial information for damage diagnostics. More detailed information on the frequency analysis performed to detect delamination is given in section 3.6 of this chapter.

3.6 Detection of delamination in composite laminates

To be able to compare delaminated laminates with their corresponding intact one, a new batch (2nd) of carbon-fiber based composite samples was prepared. The manufacturing process type, prepreg specifications, stacking sequence is similar to the previous batch (discussed in section 3.1.2). However, the optical fiber type and the configuration used while embedding are different. This is due to the availability of optical fiber with better properties (minimum bend radius of 5mm). A total of 5 laminates were manufactured, with three laminates containing peel-ply patches for inducing delamination (For visuals refer to Batch 2, Appendix b: Visuals from the autoclave based composite laminate manufacturing process). The sizes of patches were in an increasing order i.e. 2x2 cm (D1); 3x3 cm (D2); 4x4 cm (D3). The fourth sample was like the first three samples but without any delamination. Figure 36 showcases the optical fiber configuration used for the first four samples along with the position and different sizes of peel-ply patches placed between the third and fourth prepreg of first three specimens (D1, D2 and D3).
The fifth specimen was embedded with a polyimide coated fiber having minimum bend radius of 3 cm. It is to be utilized for further testing. The conclusion obtained from the comparison of resonance modes of undamaged composite laminates with similar configuration in section 3.2 provides the basis for comparing different laminates within this sub-section.

Observations: Optical fiber at one of the end points of the laminate (D1) with 2x2 cm peel-ply patch was damaged. It prevented for making connections with the fiber optic pigtails. The possible reason has been accounted to an impact either during transportation of laminates or due to pressure from the edge of the Teflon sheet resting above the laminate during curing cycle. Furthermore, the good signal quality obtained from the other laminates at low laser power corresponds to the parallel configuration of the optical fiber with the carbon fibers.

The signal generator and HMI settings used for performing the frequency measurements are shown in Table 5.
Signal generator settings

<table>
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<th>S.No.</th>
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<th>Value</th>
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<td>1.</td>
<td>Type of excitation</td>
<td>Sine sweep</td>
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<td>2.</td>
<td>Sweep time</td>
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<td>3.</td>
<td>Frequency range</td>
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<td>Amplitude</td>
<td>3Vp-p</td>
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</table>

HMI settings

<table>
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<th>Parameter</th>
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<td>2.</td>
<td>Samples to read</td>
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<td>3.</td>
<td>Reference FBG wavelength</td>
<td>1540 nm</td>
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<tr>
<td>4.</td>
<td>Laser ref (1) power</td>
<td>6 mW</td>
</tr>
<tr>
<td>5.</td>
<td>Measurand FBG wavelength</td>
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</tr>
<tr>
<td>6.</td>
<td>Laser (2) power</td>
<td>6 mW</td>
</tr>
</tbody>
</table>

Boundary conditions of the composite laminates: Free-Free

Examination of the data obtained from the frequency sweep measurements provided clear indication of the presence of damage in laminates D2 and D3. Resonance modes above 16 kHz showcase measurable changes in the modes which can be quantified. Furthermore, the mode characteristics of the delaminated laminates correspond to each other especially in the higher range. Distinctive frequency shifts of certain higher modes are also visible for the delaminated laminates when compared to the reference case. Table 6 showcases change in location of three higher modes.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Reference (Hz)</th>
<th>D2 (Hz)</th>
<th>% decrease</th>
<th>D3 (Hz)</th>
<th>% decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>30975</td>
<td>30675</td>
<td>0.97</td>
<td>30650</td>
<td>1.05</td>
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<tr>
<td>2.</td>
<td>46325</td>
<td>45950</td>
<td>0.81</td>
<td>46000</td>
<td>0.70</td>
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<tr>
<td>3.</td>
<td>77100</td>
<td>76875</td>
<td>0.29</td>
<td>76825</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table 5: HMI and signal generator settings used for performing frequency sweep measurements on the second batch of laminates.

Table 6: Relative decrease of resonance peaks in delaminated laminates when compared to reference laminate.
The repeatable decrease of frequency at higher modes corresponds to the hypothesis mentioned in section 2.3. However, an approximate decrease of 5-10% in the location of modes is not present when analyzing the frequency spectrums. An example of behavior of the second resonance mode mentioned in Table 6 is showcased in Figure 37.

![Figure 37: Comparable frequency shifts observed for delaminated laminates when compared to the reference laminate. Furthermore, increase of absolute amplitude of the peak with increasing degree of delamination is also seen.](image)

As higher resonance modes provide an indication of the induced damage, it is also interesting to perform an analysis on the lower modes of these laminates to look for any trends which may also point to existence of damage. Thereby, an energy analysis has been performed for sections of excited modes below the ultrasonic range (≤ 20 kHz). The area under curve representing the FT can provide the energy content within the band of frequencies present in the original time-based signal. Table 7 showcases the magnitude of the energy content between chosen frequency bands.
<table>
<thead>
<tr>
<th>Range (Hz)</th>
<th>3000-8500</th>
<th>8500-12000</th>
<th>12000-16000</th>
<th>16000-20000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>23427</td>
<td>7923</td>
<td>25440</td>
<td>15961</td>
</tr>
<tr>
<td>D2</td>
<td>39324</td>
<td>19577</td>
<td>34454</td>
<td>13830</td>
</tr>
<tr>
<td>D3</td>
<td>18491</td>
<td>10538</td>
<td>20144</td>
<td>6016</td>
</tr>
</tbody>
</table>

Table 7: Energy (magnitude) of resonance modes within specified frequency ranges for reference and delaminated laminates.

Examination of energy content of resonance modes between different bandwidths does not provide comparable information. The energy content for D2 laminate is maximum for the first three limits, followed by the reference and D3 laminate (in this order). The behavior can be related to the intrinsic properties of the laminates but cannot provide information of damage. The last case (frequency bandwidth 16 kHz – 20 kHz) appears to relate to the decrease of energy content with corresponding increase of damage. However, from the overall energy analysis, a conclusion relating to damage diagnosis is difficult to set up. It is due to presence of conflicting trends. It can be related to extreme sensitivity of the equipment which does not allow for differentiating modes in the lower spectrum.

3.7 Conclusions from the frequency modal analysis

The study conducted in the previous sections of the current chapter revealed interesting results about the composite damage diagnostic capability of ZonaSens optical measuring system. The ability to provide detailed information of resonance modes in the ultrasonic range highlighted the intrinsic nature of the system and the large sensitive zone embedded in the composite specimens. The comparable noise floor of the signals and location of frequency peak regions from three similar laminates showcased correspondence. A qualitative insight into the frequency spectrums obtained before and after the application of different loads on a composite specimen reveals that there exist visible characteristics which point to the existence of local damage in the laminate. These correspond to the change in absolute amplitudes of certain modes. However, to derive a conclusive trend from the test is difficult. It specifically applies for the location of the resonance modes. It can be related to inability of the fiber optic configuration to attain such detailed information when the damage imparted to the laminate is very small. Apart from damage diagnostics, signal quality degradation due to perpendicularity of the optical fiber in relation to the carbon fiber of the laminate was observed. It has
been related to the unintentional microbending effect induced on the optical fiber. The effect was confirmed by comparing signal quality from samples with fiber optic cable placed parallel to the carbon fiber. Another test conducted whereby, impact damage was induced to a laminate showcased a totally different behavior. The frequency spectrum obtained after the test was indicative of sole presence of noise and three resonance modes. The characteristics have been related to the possible redistribution of stress around the optical fiber which increased the severity of the microbending effect when the impact occurred. However, the sensitivity of the system was high enough to detect the prominent resonance modes after the impact. It is recommended to perform the impact test again with a different embedded optical fiber configuration to validate the above described conclusion. With the increase of damage induced by drilling holes into a laminate, damping of higher resonance modes has been reported. Another test whereby delaminated samples were compared to an intact sample, frequency shifts (percentage decrease between 0.3 to 1%) for the higher resonance modes were seen. The comparable nature of the modes belonging to laminates with pre-induced delamination is interesting to note. It confirms the reliability of the measurements. The repeatable decrease of frequency at higher modes corresponds to the hypothesis; however, an approximate decrease of 5-10% in the location of modes is not present when analyzing the frequency spectrums. The results from the energy analysis performed on reference and damaged (delaminated) laminates does not provide conclusive information due to presence of conflicting trends. It again portrays the need to monitor changes in the resonance modes present in the ultrasonic range for detecting damage with ZonaSens optical measuring system.
4. VISUALIZING DAMAGE PROGRESSION IN COMPOSITE SPECIMENS USING AE MONITORING

An examination of altered internal characteristics due to presence of damage in composite laminates by monitoring the change in the features within the frequency spectrums is an important aspect of offline analysis. Whereby, the specimen needs to be externally excited and must be taken out of service. An alternative NDT technique which has the potential to overcome this limitation by providing real-time composite health monitoring capability is AE (Acoustic Emission) monitoring. As mentioned in section 2.4 of this report, AE monitoring provides the opportunity to interpret and visualize the ongoing dynamic processes such as crack propagation and material degradation in the component. ZonaSens optical measuring system through its capabilities of high sensitivity and large bandwidth has the potential for measuring real-time damage information of the composite laminates under load. However, at present the system is only capable of recording single or continuous sets of real time signal which can be post processed through data analyzation software such as LabVIEW (as used for experiments conducted within previous chapter).

To determine this potential, reliable experimental setups must be created. It involves use of composite samples produced for tests conducted within last research domain and production of new samples based on requirements of the experiment. Furthermore, a reliable means of inducing damage is necessary for tracking the failure mechanism. At last, data analysis tools must be set-up for accurately understanding the behavior of signals which can be related to the damage phenomenon. The following sections of this chapter aim to cover the above-mentioned areas of interest. Section 4.1 describes the set-up of the tools required to analyze the data to be obtained from the experiments. Section 4.2 provides description of the four-point bending test conducted to monitor acoustic events during the failure progression and the corresponding discussion of results. Section 4.3 provides description of tensile tests conducted on samples for AE monitoring and discussion on the corresponding results. At last, section 4.4 provides conclusions from the experiments conducted within this study.
4.1 Set-up of the data analysis tools for monitoring time-frequency spectrums

The overall procedure for monitoring acoustic emissions has been adapted from the LabVIEW program created for the previous set of experiments. Therefore, the concept of STFT is utilized yet again because of its capability to provide accurate time related frequency information. Refer to sub-section 3.1.3 for detailed information on how this process is carried out. As for the previous experiments, more detailed frequency information is required, thereby a large window length of 16384 samples is chosen. Furthermore, time interval between two spectra has been decreased to 25 ms. In addition to visualizing peak frequencies of acoustic emissions during a load increase on the specimen; a feature which allows for displaying an averaged FT of the signal for a specified interval has been introduced. Furthermore, the program also gives the prospect of displaying a FFT for the signal for an instance in time. High pass signal filtering is also introduced to interpret the characteristics of the signal in the amplitude-time graph. For analysis, the data has broken down into consecutive sections of signal (of 5 seconds each). It is due to a large sampling rate which is to be utilized during the experiments. The LabVIEW block diagram build to perform such operations is showcased in Appendix E: LabVIEW block diagram for post processing of data recorded during AE monitoring.

4.2 Monitoring of spectra resulting during four-point bending test

Composite samples with embedded optical fiber in direction parallel to the carbon fiber of the laminate have been utilized (2nd batch of laminates including delaminated and reference specimens). Three samples have been used for tests within the current section to obtain an optimal measurement. However, only the details from the final experiment are discussed. It is because, from the initial tests it was concluded that in quarter point loading (see Figure 24), configuration of the upper loading points and distance between lower loading point was not optimal. However, measurements were taken, and results were noted. The specifics of the final test and discussion on the obtained results are given in sub-sections 4.2.1 and 4.2.2 respectively.

4.2.1 Procedure and details of the test
The setup of the four-point bending test (standard details mentioned in sub-section 3.3.1) has been used to bring laminates under increasing linear load until final failure. The standard guidelines have been implemented for only constructing a reliable setup of the experiment. The test configuration of two-point load (third point) was chosen whereby the distance between the upper load points is reduced to one-third, preventing too much flexure of the laminate. During the test, the sample was brought to a pre-load of 5N followed by an increasing load with a speed of 50N/s. A force shutdown threshold of 10% of Fmax was set. Figure 38 showcases the position and state of composite laminate while increasing load. The load graph obtained from the test program is shown in Figure 39.

Figure 38: Position of the laminate on the setup during increasing load. Note the reduced distance between the resting points and different configuration of upper load points when compared to Figure 25.
Figure 39: Load curve for the test conducted using the bending setup to initiate failure in the specimen (D2). X-axis specifies the time during which the load (on Y-axis) was increased, depicting the linear behavior. The drop in the load indicates crack and then ultimate failure.

The ZonaSens optical measuring system was connected to the optical fibers originating from the laminates. Continuous sections (length: 30 seconds) of signal were recorded simultaneously during the increase of load on the specimen. The HMI settings utilized during the test are shown in Table 8.

<table>
<thead>
<tr>
<th>S.No.</th>
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</tr>
</thead>
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<td>Measurand FBG wavelength</td>
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<tr>
<td>6.</td>
<td>Laser (2) power</td>
<td>6.84 mW</td>
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<tr>
<td>7.</td>
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</tbody>
</table>

Table 8: HMI settings for performing simultaneous measurement during load increase on the specimen.
The above chosen sampling rate can allow for interpreting peak frequencies in the signal up to 375 kHz according to the Nyquist theorem. It gives the possibility of recording acoustic emissions arising from damage events resulting in higher peak frequencies.

4.2.2 Discussion of the results obtained from the measurement performed during the load increase

The larger width of the specimen compared to the upper load points led to stress concentrations on the laminate. It was also witnessed during the initial tests with other samples. The presence of stress concentrations at the edges of upper loading point becomes severe with increasing load. Due to the unidirectional nature of the fibers, this effect leads to splitting of the matrix in the longitudinal direction. With increasing load, the crack is transferred along the length of the specimen leading to total failure (hence separating into pieces). The matrix splitting phenomenon occurred during tests conducted on all samples. It was to ensure the repetitiveness of the failure mechanism. Figure 40 showcases the location where the laminates broke, corresponding with the above given explanation. Examination of the broken edge of the laminate showcases some fiber breakage at certain locations. It has been related to the slight misalignment of the prepregs in the laminate (hence not being perfectly at 0° with respect each other).

![Image](image_url)

**Figure 40:** Occurrence of splitting of matrix at edge of the loading points due to excessive stress concentration at this location. The propagation of the crack in the longitudinal direction pertains to the construction of the laminate.

Post processing and analysis of the logged data reveals that the most interesting damage information is in the approximate last two seconds of the signal before failure. The instantaneous crack growth and propagation in
the longitudinal direction which occurred during the test is also visible in the colormap. No trace of any damage mechanism is seen before the final events. Figure 41 showcases the AE events in the last five seconds of the second segment of the signal. The presence of events with peak frequency of 375 kHz (which is the maximum limit for this case) is seen. Appearance of higher amplitudes at the top of the graph for such events point to the fact they may even surpass 400 kHz. AE events with such high peak frequencies have been related to fiber breakage in literature. As mentioned before, breakage of fiber along the direction of crack was also seen in the microscopic examination of the laminate. These AE events are immediately followed by events with lower peak frequencies which fall into the category of matrix cracking (< 140 kHz (refer to section 2.4)).

Examination of amplitude-time graph for the final events also show correspondence with typical signals recorded by researchers relating AE signals to different damage mechanisms in composites (refer to (Gorman, 2011)). The signal belonging to the events occurring between 25.02 – 25.25 seconds is showcased in Figure 42. The event appears to be a superimposition of different damage mechanisms leading to a complex waveform. The initial high frequency component in the event occurs in 0.98 ms followed by low frequency events occurring in approximate 9.54 ms. The high amplitude and low duration event has been related to the fiber breakage. The shorter duration of such an event can be related to the faster speed of sound in the fiber
compared to matrix. (Gorman, 2011) The change in the background noise after approximate 26 seconds into the test indicates optical loss due to damage/breaking of the fiber (sensor) (see Figure 41). However, the dominant events pertaining to matrix cracking are still visible in the time-frequency domain. A drop in the absolute amplitude of the signal after this instance is seen in the time-amplitude graph. It has been related to the disturbance in the calibration mechanism due to optical loss.

![Graph of AE signal](image)

**Figure 42:** AE signal belonging to the event occurred between 25.02 – 25.25 seconds showcased in Figure 41.

Various researchers have also performed tensile tests on composite samples to continuously monitor crack growth using AE during loading. (M. Wevers, 2000) (L. Rippert, 2000) (Laurent Rippert, 2002) (Baillie, 1999) Tensile tests offer the prospect of a slow damage growth leading to appearance of AE events (damage initiation) long before failure, as opposed to the bending test of unidirectional laminates (where crack initiation led to instantaneous damage). Furthermore, with the direction of optical fiber parallel to the load direction and carbon fibers, the sensitivity towards detecting AE due to propagation of longitudinal cracks is also expected to increase. Section 4.3 provides details of the tests and the corresponding results.
4.3 Monitoring of spectra on unidirectional laminates

The size of composite samples utilized for previous experiments is unsuitable for conducting tensile tests. Samples of lower cross-section area are required to be able to reach an ultimate tensile load below 200kN (upper force limit of the testing machine). Therefore, four carbon-fiber based unidirectional samples (prepreg stacking sequence: [0]6) of dimensions 29cm x 4.2 cm x 1.14 mm have been manufactured (for visuals, refer to Batch 3, Appendix C: Visuals from the autoclave based composite laminate manufacturing process) (Fiber optic cable with low bend radius was embedded). Initial tests were conducted to optimize the operating parameters and configuration of the setup. The specifics of the final test and discussion on the obtained results are given in sub-sections 4.3.1 and 4.3.2 respectively.

4.3.1 Procedure and details of the test

The test setup was created in accordance with ASTM standard (Designation: D3039/D3039M-14) to maintain the reliability of the measurements. (ASTM International, 2014) All recommended guidelines mentioned in the publication were followed during the test. The specifications of the test are mentioned in Table 9.

<table>
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<td>2.</td>
<td>Force shutdown threshold</td>
<td>80 % $F_{\text{max}}$</td>
</tr>
<tr>
<td>3.</td>
<td>Grip to grip separation during start</td>
<td>100 mm</td>
</tr>
<tr>
<td>4.</td>
<td>Hydraulic pressure at the grips</td>
<td>140 bar</td>
</tr>
</tbody>
</table>

*Table 9: Specifications of the tensile test procedure*

Initial tests showcased that presence of teeth of the circular grips which hold the specimen lead to localized stress concentrations on the samples causing premature failure. Hence both ends of the specimen were covered with sand paper to prevent early unintentional damage. Figure 43 showcases the final configuration of the specimen.
Figure 43: Configuration of the specimen during the tensile test. Also pictured are the ingress/egress points of the optical fiber from the laminate.

The tensile load curve obtained during the test is showcased in Figure 44 (The graph only displays a limited segment of the curve after reaching the ultimate load). Furthermore, the details of the HMI settings utilized during the test to perform the synchronous signal measurement through ZonaSens are given in sub-section 4.2.1 of this document.
Figure 44: Load curve for the tensile test conducted to initiate failure in the specimen (F3). X-axis specifies the time during which the load (on Y-axis) was increased, depicting the linear behavior.

4.3.2 Discussion of the results obtained from the measurement performed during the increase of tensile load on the specimen

Unidirectional laminates when loaded with forces in longitudinal direction experience breakage at the lower of matrix fracture strain or the fiber fracture strain. Laminates used in this research contain epoxy matrix which falls into the category of low strength brittle matrices, hence making it more probable to fail earlier than the fiber during tensile loading (Pilling, 2006). It was observed after that test that long splitting occurred in the gage (area between the grips) after originating from the inside of upper grip. Examination during and after the test also revealed that cracks were present in the longitudinal direction originating from the upper grip (see Figure 45). The slow propagation of cracks which occurred during the test is interesting since it will not lead to immediate damaging of the optical fiber.
The first AE events in the time-frequency spectrum appear at 83.3% of the ultimate tensile load. These events/hits mark the onset of the damage processes in the laminate (Bohse, 2004). The first event appears as a superimposition of different events. Since presence signal with high amplitude is seen, which can be related to the cracking of matrix but the peak frequency of the event is 275 kHz which prevails from other damage mechanism (see Figure 46). It is difficult to specify the other damage mechanism which brings high frequency component into this event. The amalgamation of events is also visible in the time-amplitude graph, which cannot be correlated to a typical signal of matrix breaking or fiber fracture.
The above showcased event is followed by multiple events with low peak frequency events (< 100 kHz) relating to matrix cracking until first load drop on the specimen around 110 seconds into the test (refer to Figure 44). The appearance of matrix cracking events during spectral analysis corresponds with the theoretical prediction of an initial matrix failure prior to reaching ultimate tensile load. Furthermore, when the matrix fails, the deflection (strain) experienced by the fiber remains same causing it to experience the same stress as it was prior to matrix failing. Hence with increasing strain on the specimen, the fibers continue to stretch until attainment of fiber failure strain which determines the ultimate tensile load on the specimen. (Pilling, 2006) However, it is interesting to note that examination of spectral map does not reveal any acoustic emissions pertaining to any damage or breakage of fibers during the attainment of ultimate tensile load. Further increase of tensile load until the specified shutdown threshold (80% of Fmax) causes longitudinal deflection of the specimen until total failure. Further analysis of the data reveals the instance where damage occurs to the fiber causing alteration in the background signal (see Figure 47). The extent of damage however existed until a point where obtaining a signal containing damage information was still possible. However, it also had certain implications on the quality of information obtained, as explained below.
Figure 47: Change in the characteristics of the background signal as seen in the time-frequency domain due to damaging of the optical fiber. This instance between 0-0.2 seconds occurs in the 8th segment of the signal recording.

The examination of the signal in the amplitude-time domain corresponding to the events occurring after the damaging of the optical fiber during the loading process showcase unwanted disturbances, which lead to degradation of signal characteristics such as amplitude, duration, rise time etc. It can be related to possible polarization fading and imperfect calibration procedure in the measuring system due to signal attenuation. However, it is interesting to notice that the frequency information in the degraded signal is retained but only the time-amplitude related data is not usable anymore. With increasing deflection, the optical fiber also experiences a stretch which causes fading of the signal at certain locations in the frequency-time domain (see Figure 48). With increasing damage to the optical fiber, it becomes difficult to pick acoustic events with lower amplitudes and lower peak frequencies. However, high frequency damage events such as fiber breakage are still visible (see Figure 48). Presence of such characteristics does not allow for deriving a possible mechanism which can be related to the growth of damage in the specimen while the strain on the fibers was increasing. Similar signal characteristics were also seen for different samples tested under similar conditions, allowing for reliably deriving this conclusion. Furthermore, appearance of high frequency acoustic events provides the indication that events are originating from the sample itself and does not appear from other background sources and thereby is much higher to relate to any ambient acoustic noise.
As mentioned earlier, since the aim is to be able to monitor growth of damage in a composite component, an ability to perform detailed clustering of data based on multi-parametrical descriptors related to both time and frequency features is required (Li Li Y. S., 2016). Since using the current analysis it cannot be said that at what rate damage is growing and where is the limit. Event classification based on peak frequency and amplitude has limited ability to provide information on damage mechanisms, especially related to delamination, fiber-matrix debonding or occurrence of simultaneous events. It is because several contrasting links have been specified in different studies. In addition, the presence of degraded signal due to damaging of the optical fiber poses a limitation in the current analysis. It provides an indication of scenarios on the quality of information that will be obtained when fiber damage occurs in a composite component in service. Hence a robust means of embedding the optical fiber in the component is required, which prevents it from getting immediately damaged, thereby making it feasible for relating physical mechanisms to cluster event classification (Li Li Y. S., 2016).
4.4 Conclusions from the tests conducted

The study conducted in the previous sections of the current chapter revealed interesting results regarding continuous damage detecting capability of ZonaSens optical measuring system for composite materials. The ability to use a very high sampling rate (750 kHz) provided the opportunity to record AE events originating from fiber breaks indicating serious damage to the material. Furthermore, appearance of high frequency acoustic events provides the indication that events are originating from the sample itself and cannot be related to any ambient acoustic noise. Comparison of the physical damage imparted to the laminate during the bending test with clustering of damage with frequency and time-amplitude features of an AE signal showcase correspondence. In addition, comparison of obtained signal characteristics with typical signals found from theory confirms the reliability of the data. However, it particularly applies for signal obtained prior to damaging of optical fiber. It has been confirmed by conducting tensile tests on samples of different size. Whereby, the frequency information in the degraded signal is retained but only the time-amplitude related data is not usable anymore. Furthermore, changes in the background signal from the optical fiber is seen due to being stretched/damaged or rubbed against internal fractured surfaces of the laminate (leading to polarization fading and signal attenuation). In addition, AE events marking the onset of damage processes during the tests have been seen. The physical explanations of damage progression in samples during different tests also correspond with the nature of events as seen in the time-frequency domain. However, detailed clustering of AE signal parameters with different damage mechanisms is required to be able to identify intermediate events such as fiber-matrix debonding, delamination and events occurring at same time. Consideration also must be given to the embedding means and configuration of optical fiber in the laminate which prevents immediate damage to the fiber. Hence, providing qualitative damage related information for a large segment of composite component’s service life.
5. VERIFICATION AND DISCUSSION OF RESULTS

The results obtained from the study conducted in chapters 2, 3 and 4 provide a range of results which present the basis for answering the main research question of this thesis. In this chapter, the verification means of the core results which have been obtained has been established. These are discussed below.

1. The first major result relates to finding specific applications areas for ZonaSens within NDT methods for composite health monitoring. These are frequency modal analysis and Acoustic emission monitoring. Experimental setups pertaining to these techniques were created which allowed for evaluating the performance of the measuring system. The result has been verified by assessing literature relating to use of fiber optic sensors in composites. Different sources have been considered to derive reliable information. Refer to sections 2.2, 2.3, 2.4 and 2.6 for more detailed information on this result.

2. Following up from the literature study, the next major result relates to sensing of resonance modes in the ultrasonic range. The capability to record these modes through ZonaSens highlights the high sensitivity offered by the system. Monitoring of changes in resonance modes in the ultrasonic range has been highly recommended in literature, since it provides the prospect of assessing local damage in the material. The measurements were verified by performing tests on different undamaged specimens which provided comparable results. Refer to sections 3.1 and 3.2 for more detailed information on this result.
3. Attainment of characteristics which pertain to existence of notable damage in the laminate has been an interesting outcome of experiments performed within NDT method relating to frequency analysis. Clear and distinctive frequency shifts for resonance modes in the ultrasonic range for delaminated laminates were noted. For other damage types, to derive a conclusive behavior is difficult. The result has been verified by making different samples with similar damage (in increasing order) which then showcase expected behavior when compared to the undamaged sample. Furthermore, nature of the result complied with the overall hypothesis of the first NDT method assessed during the project. Refer to sections 3.6 and 3.7 for more detailed information on this result. The reliability of the overall measurements has been confirmed by use of standard electronic equipment, test benches, ASTM standards, controlled process from preparation of samples to final analysis of data, fixation of sample configuration (batch wise) and use of reliable data processing and analysis tools. Refer to sections, 3.1, 3.3, 3.4, 3.5, 3.6, 4.2 & 4.3 for more detailed information on use of software tools, equipment and standards during this study.

4. Acoustic emission visualization during damage progression in composite laminates is an important result relating to AE monitoring obtained using ZonaSens. Furthermore, events relating to onset of damage also showcase the high sensitivity of the measuring system to pick up information relating to internal damage. Resemblance of obtained signal characteristics with typical AE events arising from fiber breakage and matrix cracking verifies the true nature of AE events. Furthermore, use of post-processing concepts recommended in the literature to derive information, controlled loading mechanisms and correlation of AE events with the physical damage mechanism also highlights the
reliability of the measurements. Refer to sub-sections 4.2.2 & 4.3.2 for detailed information on this result.

5. The last result pertains to the limitations discovered during the experimental study. These correspond to signal quality degradation which has the potential to cause difficulties in analyzing data and deriving conclusions from measurements. The limitations arise from the method of integration of fiber optic cables in the composite laminate. These have huge impact on the use of ZonaSens for practical applications. Verification has been done by testing of samples with different embedded fiber optic configuration and comparing signal characteristics obtained while performing measurements on different samples exposed to similar test conditions. Refer to sections 3.2, 3.6, 4.2 and 4.3 for reasoning behind these limitations.
6. FINAL CONCLUSIONS FROM THE EXPERIMENTAL STUDY

To decide on the performance of ZonaSens optical measuring system for composite health monitoring purposes, two different Non-Destructive Testing (NDT) methods namely, frequency modal analysis and Acoustic Emission (AE) monitoring were taken into consideration. Several researchers have experimented integration of different fiber optic sensors (FOS) in composites to obtain damage information using these techniques.

For the former technique, experiments were conducted to monitor change in the behavior of resonance modes of composite specimens embedded with fiber optic cables. The ability to provide detailed information of resonance modes in the ultrasonic range highlighted the intrinsic nature of the system and the large sensitive zone. A qualitative insight into the frequency spectrums obtained before and after the application of different loads/impact/drilled holes/delamination on composite specimens revealed that there exist visible characteristics which point to the existence of local damage in the laminate. The information derived from the data analysis showcase change in absolute amplitudes of certain modes, comparable noise floor level, and damping of several modes after the application of damage. The most interesting observations were made with the delaminated samples whereby, comparable behavior of resonance modes and frequency shifts (decrease between 0.3 to 1%) of delaminated specimens compared to the reference laminate was seen. The ability to monitor the latter observation has been the focus area of the research within frequency analysis. Its
correspondence with the theoretical background showcases the reliability of the experimental setup and the measurements. Furthermore, attainment of similar resonance mode behaviors for undamaged samples with similar configuration also provides the basis for repeatability and accuracy of measurements.

Among experiments conducted to monitor acoustic emissions during damage progression in composites, four-point bending and tensile load was applied on specimens conforming to ASTM test standards (some deviations during the application of the former). This along with the information regarding the type of experiments conducted for the former NDT method answers the sub-question, *What kind of experiments will be performed (e.g. experiments leading to initiation of failure modes in composite samples /external disturbances on the samples)?* Using AE monitoring events originating from matrix splitting and fiber breaks were analyzed prior to final failure, in addition to marking onset of damage. Comparison of such signal characteristics with literature and the physical damage mechanism showcased correspondence. Furthermore, appearance of peak frequencies near 300 kHz substantiated the origin of events from the sample itself. The provision of information related to altered characteristics in the damaged samples from the former technique (changed absolute amplitudes, frequency shifts, similar noise floor level form different measurements) and information on events related to onset and progression of damage from the latter technique leads the answer to the sub-question, *What kind of information can be derived from signal processing and analysis related to the internal state of the samples during experiments?* Furthermore, the means of validating the results as discussed above provides the answer to the sub-question, *Are there ways to validate the results obtained from the measurements, if yes, what are they and what is the accuracy of results?*
In terms of feasibility for practical applications, several limitations encountered during the research may downgrade the data analysis part of the damage monitoring process. It includes signal quality degradation when fiber optic cable is embedded perpendicular to the fibers in the laminate causing unintentional microbending. The effect can become more pronounced over a large length of sensing region in bigger composite components. Furthermore, damaging of the optical fiber during damage progression in the composite leads to altered signal characteristics, which makes it uninterpretable in time-amplitude domain and increases difficulty in differentiating events in the time-frequency domain. In addition, results from experiments also dictate that usable frequencies are in the ultrasonic range, because the system is too sensitive to the ambient noise which can alter the signal characteristics in the lower frequency range. But the ability to accurately monitor higher frequencies can give an upper edge to the system by detecting damage which may not be feasible for other measuring systems. It collectively provides the answer to the last sub-question i.e. ‘What is the feasibility of ZonaSens measuring equipment when implemented for practical applications in composites?’

To conclude, ZonaSens optical measuring system has the capability to provide detailed and reliable damage related information in composite materials. However, it may not be possible to detect very little local damage when comparing resonance modes in damaged and undamaged specimens. The system has the potential to make repeatable measurements which are easier to differentiate from the noise originating from surrounding sources due to the higher frequency range in which it can operate. For AE monitoring, the system seems very suitable only if the limitation arising from the damaging of optical fiber is taken into consideration. Hence by collectively considering the answers to all sub-questions, and the information given above, ZonaSens optical measuring system carries the potential to serve as the sensing arm of different NDT methods used in
composite health monitoring with a reliable and accurate manner of providing information. It provides the answer to the main research question of this experimental study i.e. *What is the performance of the ZonaSens optical acoustic measuring system when implemented for composite health monitoring purposes in terms of reliability and accuracy?*
7. RECOMMENDATIONS FOR FURTHER RESEARCH

During execution of this research, the author encountered certain prospects related to the experimental setups which can be improved, data-analysis tools which are interesting to implement for further research and new focus areas of research with ZonaSens for composite health monitoring. Recommendations pertaining to these subjects are mentioned below.

• The impact test conducted to monitor changes in the resonance modes provided an unexpected outcome. It is recommended to perform the test again with a different embedded optical fiber configuration to validate the obtained conclusion.

• It will be interesting to embed the FBGs forming the sensing zone also inside the specimen. It provides the possibility of eliminating noise from surrounding sources.

• Integration of two sensing zones in a planar laminate can allow for setting up post processing tools to find location of damage in the sample.

• It is recommended to perform experiments for monitoring AE emission with fiber optic cable attached to the specimen in a manner which prevents it from immediate damage.

• Implementing detailed clustering analysis can provide information on the rate of growth of crack/damage in a sample. It can also provide tools to classify events due to fiber-matrix debonding and delamination, which were presently difficult to categorize solely based on peak frequencies specified in literature.
BIBLIOGRAPHY


Sielecki, A. (2017, March 1). Sources of noise in ZonaSens affecting measurements in the lower frequency range . (C. Arora, Interviewer)


### Physical Properties - HexPly 8552 UD Carbon Prepregs

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<td>Nominal laminate density</td>
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### Mechanical Properties - HexPly 8552 UD Carbon Prepregs

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Appendix B: Visuals from the autoclave based composite laminate manufacturing process

Batch 1
Batch 2
Batch 3
Appendix C: LabVIEW block diagram for post processing of data recorded during frequency modal analysis
Appendix D: LabVIEW block diagram for post processing of data recorded during AE monitoring