Structural Health Monitoring of Composite Structures: A Review

By

Jacob Pessin

……

Submitted in partial fulfillment

of the requirements for

Honors in the Department of Mechanical Engineering

UNION COLLEGE

June 9, 2019

ABSTRACT

PESSIN, JACOB Structural Health Monitoring Methods of Composite Structures

Department of Mechanical Engineering, June 2019.

ADVISOR: Professor Cortez

Structural health monitoring has the potential to allow composite structures to be more reliable and safer, then by using more traditional damage assessment techniques. Structural health monitoring (SHM) utilizes individual sensor units that are placed throughout the load bearing sections of a structure and gather data that is used for stress analysis and damage detection. Statistical time based algorithms are used to analyze collected data and determine both damage size and probable location from within the structure. While traditional calculations and life span analysis can be done for structures made of isotropic materials such as steel or other metals, composites are highly orthotropic in nature. Composites must then be analyzed experimentally for more reliable results of the current damage state, or in-situ with SHM. Current research focuses on utilizing both piezoelectric sensor actuator pairs for damage detection, as well as fiber and particle based sensors for strain state awareness. While each method has its drawbacks due to incidental discontinuities reducing structural properties or difficulty in implementation and accuracy, SHM is vital for the successful wide spread implementation of composite structures. Piezoelectric based acousto-ultrasonic based sensor networks are ideal for damage detection and localization but are difficult to imbed within composites and can reduce their properties. Fiber and particle based strain sensors are ideal for detection of deformation and stress state, but are difficult to repair and to detect damage of the structure.

Table of Contents

LIST OF TABLES III

LIST OF FIGURES IV

CHAPTER 1 1

BACKGROUND ON STRUCTURAL HEALTH MONITORING 1
1.1 INTRODUCTION 1
1.2 BACKGROUND 2

CHAPTER 2 8

METHODS OF DAMAGE RECOGNITION AND DATA AQUISITION 8
2.1 DATA PROCESSING ALGORITHMS 11
2.2 STRESS STATE DATA ACQUISITION 14

CHAPTER 3 22

COMPARRISON OF STRUCTURAL HEATLTH MONITORING METHODS 22
3.1 ADVANTAGES OF SENSOR ARRAYS 23
3.2 DRAWBACKS OF VARIOUS METHODS 25

CHAPTER 4 27

DISCUSSION OF EFFECTIVENESS AND UTILITY 27

CHAPTER 5 32

CONCLUSIONS, RECCOMENDATIONS, & APPLICATIONS 32

REFERENCES 34

List of Tables

TABLE 1. CLASSIFICATION OF SHM SYSTEMS BASED ON RELIABILITY QUANTIFICATION AND HOW THE SYSTEM WILL OPERATE BASED ON A PERIODIC AND AN AUTOMATIC MONITORING SCHEME[2]....................12

List of Figures

FIGURE 1. FLOW CHART FOR SHOWING THE ORGANIZATION OF VARIOUS MATERIAL TESTING PROCEDURES, WITH A FOCUS ON STRUCTURAL HEALTH MONITORING AND ITS IMPORTANT ASPECTS........8
FIGURE 2. BASIC DIAGRAM FOR THE PROCESS OF STRUCTURAL HEALTH MONITORING OF A PART, FROM THE DEVELOPMENT OF THE SENSOR AND ANALYSIS METHODS TO DAMAGE ESTIMATES AND UPDATES FOR THE REMAINING LIFE OF THE STRUCTURE [1]........10
FIGURE 3. HEAT MAP OF A STRUCTURE GENERATED FROM DATA GATHERED FROM AN SHM SYSTEM[4].........13
FIGURE 4. SCHEMATIC REPRESENTATION OF STRUCTURAL HEALTH MONITORING (SHM) PRINCIPLES AS THEY APPLY TO THE PROCESS OF HEALTH MONITORING USING PIEZO ELECTRIC SENSORS [2]. 14
FIGURE 5. PROCESS OF THE GENERATED EAVE FROM THE ACTUATOR PRODUCING A TRANSMITTED WAVE THAT IS RECEIVED BY THE SENSOR AND ANALYZED. 15
FIGURE 6. EXPERIMENTAL SETUP OF SEVERAL SENSOR-ACTUATOR TEST PIECES, WITH THE SENSORS AND ACTUATORS MERELY TAPED ONTO THE OUTSIDE OF THE TEST PIECES[2]. 16
FIGURE 7. MICROFABRICATED STRETCHABLE NETWORK CONCEPT: MICROFABRICATE COMPLETE INTEGRATED NETWORK (BOTTOM LEFT), STRETCH NETWORK (BOTTOM CENTER), AND DEPLOY NETWORK INTO STRUCTURE (BOTTOM RIGHT)[3]. 17
FIGURE 8. STRETCHABLE PIEZOELECTRIC SENSOR NETWORK STRETCHED FROM ITS ORIGINAL SIZE (A) AND EMBEDDED IN A CARBON FIBER PLATE (B) [3]........18
FIGURE 9. EXAMPLE OF THE NANO-FIBER/PARTICLE SHM APPROACH, UTILIZING CHANGES IN RESISTIVITY FOR SHM 20
FIGURE 10. EXAMPLE OF A LASER BASED SHM SYSTEM THAT UTILIZED THE DIFFRACTION OF A LASER BEAM TO MEASURE THE STRAIN AND THUS THE PRESENT STRESS IN A SYSTEM[6]....21
FIGURE 11. CYCLE OF SHM FROM THE SENSING OF THE CURRENT PART STRESS STATE, TO THE CONTROL TO ALTER THE STRESS STATE[3]. 22
FIGURE 12. IMPLEMENTATION OF A SENSORS NETWORK IN A COMPOSITE MATERIAL[7] 23
FIGURE 13. PRESENT SHM SYSTEM USED IN AIRCRAFT WITH INTERCONNECTED PIEZOELECTRIC SENSOR SYSTEMS[1].........28
FIGURE 14. SCHEMATIC ILLUSTRATION OF COMPOSITES WITH INTEGRATED FLEXIBLE SENSOR MATRIX FOR IN SITU LIFE CYCLE MONITORING[4]. 31

Chapter 1

BACKGROUND ON STRUCTURAL HEALTH MONITORING

1.1 Introduction

Structural health monitoring is the passive or active procedure of determining the stress and strain states of a structure in order to detect and locate sites of damage. This system of monitoring can take several forms, but in general focuses on the implementation of sensor units that are able to detect the location and magnitude of a defect within the structure on a time scale basis, differentiating the process from non-destructive testing. Intelligent structures is what comes to mind when one considers the applications of structural health monitoring [1]. A structure that is actively monitored on a constant basis for defects and damage will be able to be utilized more efficiently and effectively for its specific application. There is considerable attention for the application of structural health monitoring as it pertains to the structural health of composite parts and larger composite structures.

Composite materials allow for the integration of sensing technology within the material structure of the system, leading to numerous advantages and hurdles that need to be overcome before widespread implementation is possible [2]. Many of the issues with implementing a structural health monitoring system are related to the complexity of the algorithm necessary to interpret the sensing data obtained from the sensor unit. Another issue relates to the process of interpreting stress and strain data into likely locations of damage and intensity of the damage detected [1]. With regards to the sensor system itself, there are difficulties in implementing a system that is both lightweight and does not impede the structural integrity of the part through its implementation [2]. The methodologies presented later in this paper seek to solve either one of these two problems through novel implementations of sensor units and the development of clever algorithms based on a probability, time based analysis of the sensor data.

1.2 Background

Structural health monitoring itself as a technology has evolved over the years and has been important to engineers and designers when planning for how long a part or structure might last. For most structural applications the life span and working period of anything that is made is finite and real world structures are prone to conditions that are difficult to monitor in a laboratory set up [3]. Historically structural health monitoring has involved visual inspections of structures over the course of their life span in order to determine damage and when repairs and replacement might be necessary. This primitive nature of the health monitoring of structures and critical load bearing parts has led to the implementation of failure criteria. Calculations and estimations of the cyclical loading of forces on a structure help to determine the lifespan of the various components of a structure.

Properties for the structure are obtained in a laboratory setting, in which elastic modulus and tensile strength, along with the brittle nature of the structure is taken into account for its estimated lifespan. A factor of safety is always included in this estimation as it is difficult to accurately portray environmental conditions and how they will affect the structural integrity of any component over the course of its service life. This can lead to over or under estimations for the full service life of a part, leading either to catastrophic failures of a structure before its estimated service, or a part being replaced while it might have years of service life still left.

Most modern day implementations of structural health monitoring involve the use of spread out sensor units on a structure, and are mainly utilized in bridges and other critical load bearing structures where constant observation of the structure would be too costly or time consuming, yet failure of the structure could lead to severe loss of life. This is prevalently seen in bridges in Hong Kong, where there are stress and strain monitoring system in place along many of its bridges. This includes the Wind and Structural Health Monitoring System (WASHMS) in place along the Tsing Ma, Ting Kau, Kap Shui Mun and Stonecutters bridges [4]. This sophisticated system utilizes sensory system for obtaining structural data, data acquisition system for collecting the data from the sensors, and centralized computing systems for analyzing the collected data utilizing a form of statistical time series assessment in order to measure stress and detect where damage might have occurred. The sensors that are utilized on all of the bridges include accelerometers, strain gauges, displacement transducers, level sensing stations, anemometers, temperature sensors and dynamic weight-in-motion sensors. This real world example of actual structural health monitoring uses many of the same principles and approaches that would be used when conducting a structural health monitoring regime on composite systems and structures [4].

Structural health monitoring of composites is of particular interest to engineers and scientists as it would allow for more precise and in depth monitoring of aerospace grade parts and industrial components. This includes applications in components for satellites and rockets, as well as fighter planes, commercial jets, and wind turbine blades. An accurate implementation of structural health monitoring would allow for more accurate knowledge of the current stress state as well as accumulated damages that have occurred in the part or structure [5]. This combined with statistical analysis of the damage index for the part as well as current and cyclical loadings will allow for a more accurate duration of service life. Which corresponds to a less conservative factor of safety for the structure. This can lead to major improvements in cost savings for maintaining aircraft and wind turbines, as well time savings on repairs and the current methods of visual inspections to verify the integrity of parts and structures [1]. This paper will look at the two sides necessary for an effective structural health monitoring system. The first being the sensor system for the collection of the data from various critical points of the part or structure. The next being the data processing system that utilized complex algorithms and signal processing to convert the sensor input data into real time stress times, along with damage location and intensity.

1.3 Methodologies

The primary purpose of this paper is to present several methods for structural health monitoring as it applies to the health diagnostic purposes for composite parts and structures. Exploratory methods for the algorithm component of the health monitoring system will be presented and compared to each other in terms of ease of implementation and efficacy as proven through simulation and experimentation. Several methods for sensor integration into the composite structure will also be presented and assessed. There are two broad categories for sensor implementation of the composite structures, embedded sensors within the material itself and sensors that are adhered after manufacturing of the composite structure and lie on its surface. Both of the categories presented have advantages and disadvantages as it pertains to decreased material performance and accuracy for damage detection. Additionally is important to determine the severity of cracks that have occurred. Ideally a system will be created that is able to be easily integrated in a variety of composite layups and has enough resolution and accuracy to obtain accurate state of stress data from the material in real time that is able to be processed by the statistical algorithm and be analyzed for damage location and severity.

There will be several related, yet distinct in their approach, methods for the statistical algorithm of pattern recognition and analysis in this paper that will be compared and contrasted to one another, as well as a summary given for how each of them operates. The first methods utilizes a statistical time based method in order to perform reliability calculations on both simulation and experimental data from an acousto-ultrasonic based structural health monitoring system [6]. The next method utilized a sequential probability ratio test framework for the analysis portion of the structural health monitoring procedure. This was tested with a vibrational based sensor technique for the health monitoring, and works on assessing the probability that damage has occurred based on the experimental data obtained from the sensor unit [6]. The next method is similar to the other two presented yet is a statistical time series technique based on a modeling method of the system and again uses statistical analysis for determining damage detection given a certain location on the structure [7]. Another method presented utilizes differences in voltage potential across a sensor and how it changes over time to calculate the likelihood that damage has occurred in a given region of the structure [8]. Most of these methods use statistics to detect the probability of damage having occurred in a given region of the structure, yet differ in the specifics of the algorithm utilized and its approach given the different types of sensor apparatuses tested on the structure.

One of the more varied and interesting components of a structural health monitoring system is the physical sensor apparatus that is utilized for data collection purposes. The most common set up that is used is a piezoelectric system that deforms according to aggregated stresses in the structure. These translate into voltages produced by the piezoelectric sensor which can be transformed into a deformation and used for damage detection [1]. Another method is similar but uses a pair of piezo electric actuators and collectors for a sensor unit. The actuator produces a waveform that is picked up by the collector. The collected waveform is analyzed in comparison to the waveform produced by the emitter actuator, thus allowing for an algorithm to be implemented and help detect the location and degree of damage that has occurred [7]. Other systems utilize more novel approaches that integrate nanotechnology or flexible sensors in the sensing system. One such method utilizes a flexible printed circuit board for housing the sensor units, while another uses a flexible network of sensors that can be either imbedded or attached to the surface of a composite structure [2]. Other techniques utilize nanowires and nanoparticles as the sensing units that are able to obtain better resolution that other systems and impede less with the structural properties of the composite structure [9]. Another interesting approach to the sensor technology is a “strain paint” that can be applied to the surface of the structure easily post processing [3]. Lastly a sensor method involving the use of lasers is explored for detecting disbonds and crack growths in composite materials [10]. These methodologies for data processing of the structural health monitoring system and for implementing sensor units into a composite structure are critical for producing health monitoring systems that are both reliable and accurate.

Chapter 2

METHODS OF DAMAGE RECOGNITION AND DATA AQUISITION

Structural health monitoring can be broken down into two main components, the processing algorithm that takes in sensor data and outputs likelihood of damage having had occurred as well as damage magnitude, as well as the particular sensor system that is used for the monitoring purposes, figure 1.

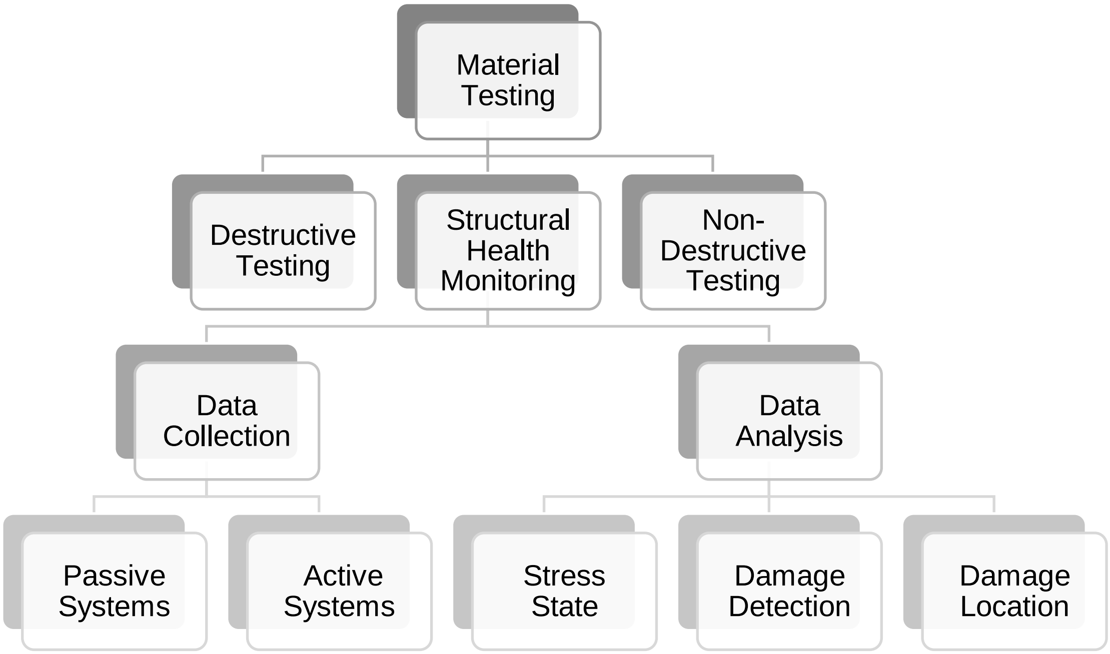

Figure 1. Flow chart for showing the organization of various material testing procedures, with a focus on structural health monitoring and its important aspects.

Structural health monitoring (SHM) is but a subset of the larger field of material testing and simulation, and is promising in its ability to help save costs and reduce down time for maintenance of parts (figure 1). To this end there has been no shortage of research in health monitoring systems for a variety of structures and parts, with a particular focus given to composites, due to the complex nature of their stress states and failure modes. Failure analysis for more simple isotropic structures is easier to do in a laboratory set up with basic simulation tools as the material properties are more uniform than that of composites [11]. This allows for destructive and non-destructive testing to be utilized so that a service life for the part or structure can be calculated [7].

While basic maintenance and service must be given to these simpler structures, their more predictable nature allows for them to be implemented with less complex analysis techniques and instrumentation. Composite parts and structures have a myriad of desirable characteristics, ranging from their excellent strength to weight ratio, tunable properties, ease of molding to complex shapes, and high toughness. The drawback and main concern with composites, which makes them a necessary candidate for structural health monitoring, however is their orthotropic nature [12]. Modeling and predicting the failure modes as well as damage locations of composite structures is much more difficult than more traditional isotropic materials, such as metals. SHM is a complex process that starts from the development of sensor technology to the implementation of adaptive structures as seen in figure 2.

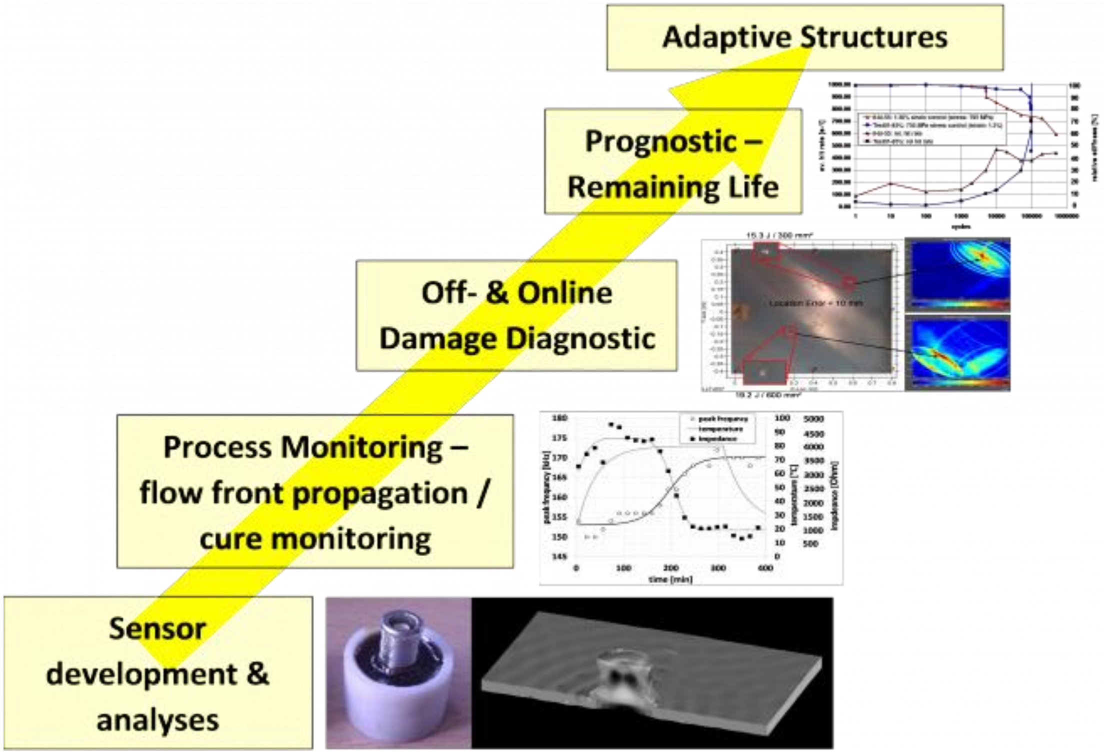

Figure 2. Basic diagram for the process of SHM of a part, from the development of the sensor and analysis methods to damage estimates and updates for the remaining life of the structure [13].

Structural health monitoring would allow for damage prediction and stress state analysis of these more difficult to model composite parts and structures [7]. The orthotropic nature of composites means that their properties are not the same in all directions. Defects in the layup as well as loadings in non-material directions can cause complex stress states. Out of plane shear stresses can cause delamination damage to occur far before actual damage to the fibers or the ply's of the composite material might form. Figure 2 shows the basic outline of the process of structural health monitoring and how it can be used to gather data on the current damage state of a composite part, as well as where damage has occurred. This estimation of damage along with data on the current stress state of the structure allows for an additional estimation of the remaining service life of the part [14]. Damage also helps show if any additional maintenance would be necessary to keep the structure functional and help prevent a catastrophic failure. All of this culminates in composite structures that are able to adapt to environmental loads and conditions more effectively than those without structural health monitoring systems, as well as require less maintenance from employees. This leads to decreased costs in long term operation of structural health monitoring system along with advantages in increased safety, longevity of parts, and preemptive failure analysis. The implementation of "intelligent" structures in the future can be able to relieve stresses and even repair damage on their own without human interference [15]. The focus of the following sections of this report will be on outing several methods used in data processing of the structural data from the sensor units, as well as methods for obtaining and collecting data through several implementations of novel sensor arrays.

2.1 Data Processing Algorithms

While the sensors are able to collect data on the current stress and damage state of a part, post processing of the data is important for determining damage size and location. The data is also necessary for calculating the remaining service life and maintenance of a structure. Several different types of algorithms are utilized for processing the data, and while not the focus of this paper, are crucially important in the process of SHM, table 1.

Table 1. Classification of SHM systems based on reliability quantification and how the system will operate based on a periodic and an automatic monitoring scheme [6].

	S-SHM (Scheduled	**A_SHM (Automatic)**
Known Damage Location (KDL)	The system will only interrogate periodically a known "hotspot" location. *(similar to NDE)*	The system will continuously interrogate a known "hotspot" location.
Unknown Damage Location (UDL	The system will periodically interrogate the entire structure for damage.	The system will continuously interrogate the entire structure for damage.

A summary of SHM schedules can be seen in table 1, which outline how an algorithm will operate in order to determine both damage location and magnitude [6]. The core of many of the algorithms used in SHM is a comparison of healthy and unhealthy state data for a given composite structure. A statistical time based methodology can be used in structural health monitoring systems in order for reliability calculations to be done for determining the damage index [8]. This type of methodology involves the use of time scale measurements taken from the composite structure. The data can then be utilized along with a statistical analysis in order to determine the likelihood of damage having occurred at a specific location, as well as the magnitude of the damage, figure 3.

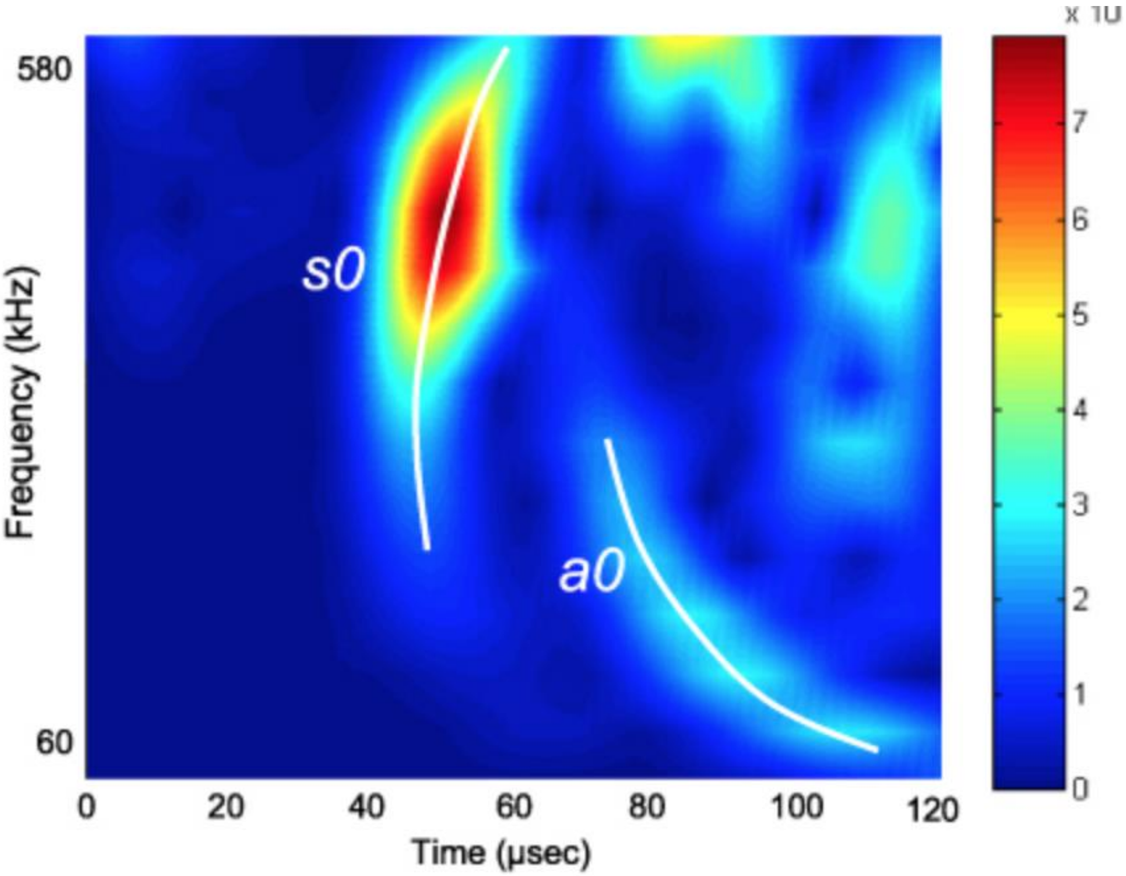

Figure 3. Heat map of a structure generated from data gathered from an SHM system [1].

A basic outline of a heat map generate from a SHM system can be seen in figure 3. This helps to show how the algorithms and processing techniques are able to analyze the raw data from the sensors and generate damage location and magnitude indexes for the composite materials [16]. While some algorithms may differ in the specifics of how each processes the stress input data, all that output damage detection are based in the statistical likelihood of detecting damage and its magnitude [11]. Other SHM systems only monitor the current stress and strain state of the structure, and thus process the data from the sensors and converts it into deformations in the structure and the corresponding loads.

2.2 Stress State Data Acquisition

The primary and most widely utilized technique for data acquisition in structural health monitoring systems, not just limited to composite parts, is the use of piezoelectric sensors, and piezoelectric sensor-actuator pairs figure 4.

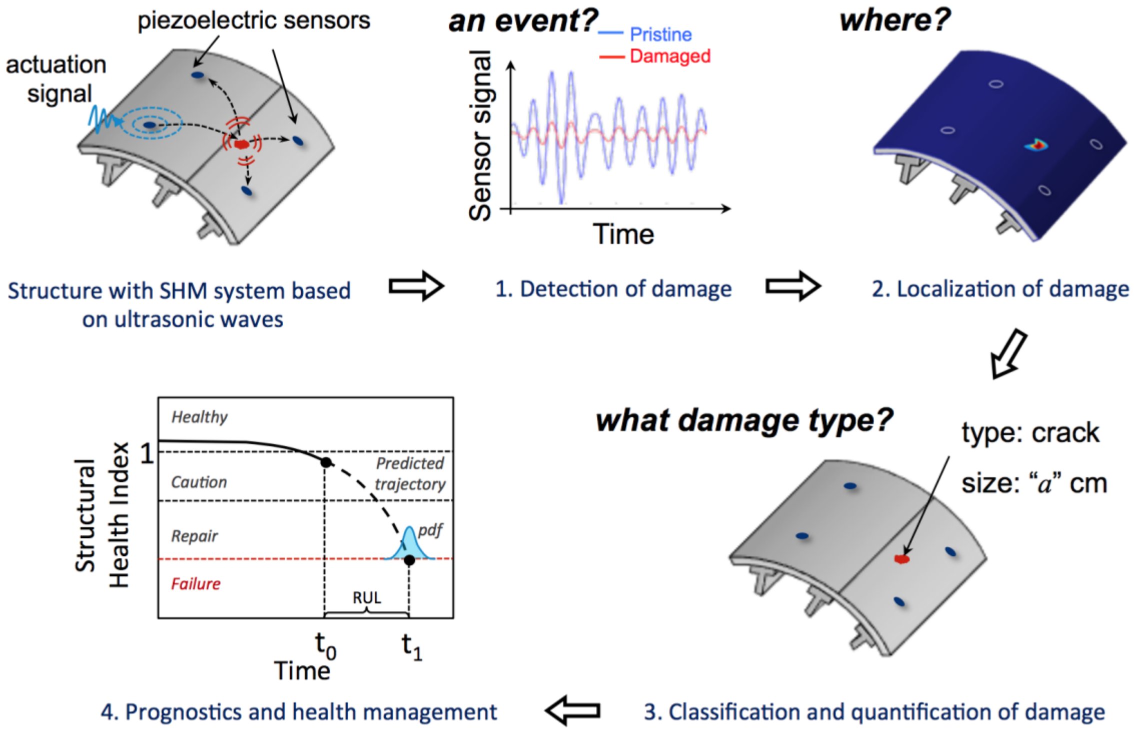

Figure 4. Schematic representation of structural health monitoring (SHM) principles as they apply to the process of health monitoring using piezo electric sensors [6].

The process for structural health monitoring using piezo electric sensors is the most well established method and is utilized on many health monitoring systems, not just limited to composite materials and structures. The general schematic for SHM of a part that utilizes piezoelectric sensors is outlines in figure 4. The process starts with a detection of damage from surrounding sensors to the damage site, which is then interpreted to find its location and size, and then analyzed to see how the damage affects the remaining life expectancy of the part [11]. Figure 5 helps to show the methodology for damage detection using piezoelectric sensors.

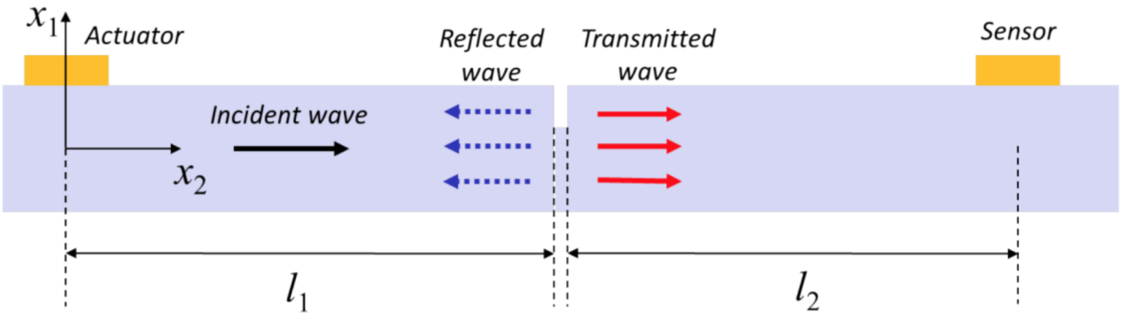

Figure 5. Process of the generated wave from the actuator producing a transmitted wave that is received by the sensor and analyzed [6].

The implementation of the piezoelectric actuator-sensor network and how it can detect damage is actually a relatively easy to understand process, albeit quite complicated to implement. Across the structure, pairs of sensors and actuators are placed such that the actuator outputs a known waveform through the part, and the sensors pick up the waveform and any distortions that have happened to it as its traveled through the part, with the basic schematic of this setup shown in figure 5 [6]. When damage or an unknown defect occurs in the structure, a waveform that was generated by the actuator will become distorted. By utilizing multiple sensors the damage size and location can be inferred from the received waveform when compared with the original output signal [6]. Certain properties and set material propagation parameters need to be known and analyzed before the implementation of a piezoelectric sensor system. This is especially true when applied for composite parts and structures, as composites are orthotropic in nature. Stresses through the lamination and the curing process can create air pockets, residual cracks in the matrix, and un wetted fibers. These factors alter the propagation properties of the material significantly from the ideal [17]. When computer simulations are utilized as well to predict SHM procedures and damage detection it is difficult yet essential that defects in the part "healthy" state is known [6]. Tests must be done initial to determine what the received wave will look like in the structure in its healthy state. This is done so that changes in the received wave can be analyzed from data sent by multiple sensors to determine the aforementioned stress state and damage state of the structure, figure 6.

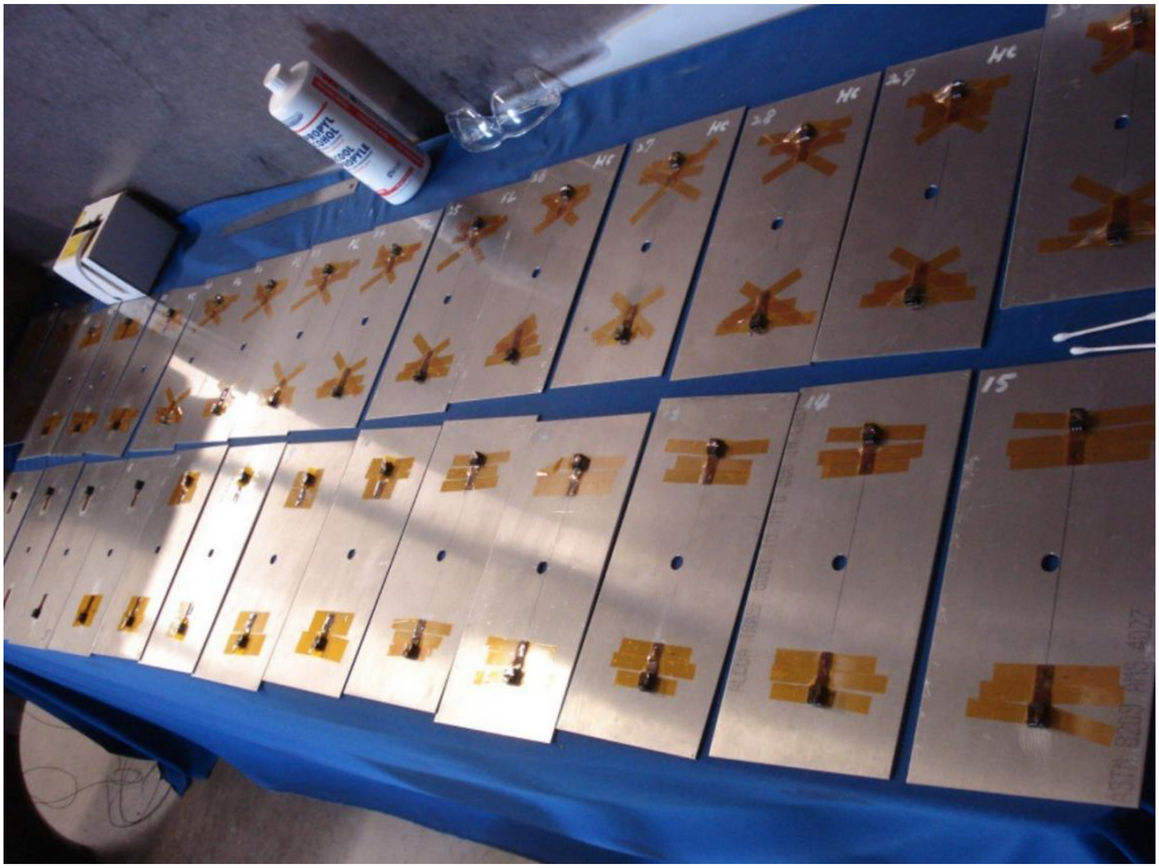

Figure 6. Experimental setup of several sensor-actuator test pieces, with the sensors and actuators merely taped onto the outside of the test pieces [6].

While the arrangement and setup of the piezoelectric sensors can vary based on the method and application, the basic operation of the system remains quite similar when utilizing these types of sensors. A basic setup of a piezoelectric sensor network can be seen in figure 6, which basically demonstrates how in the simplest way the piezoelectric sensors are attached to the surface of the part [5]. Multiple studies that focus on the control algorithms for processing the data from the sensor units utilize piezoelectric sensors due to the body of knowledge and ubiquitous nature of the technology. More exotic sensor technology integration can be used due to the ease of implementation in composites, figure 7.

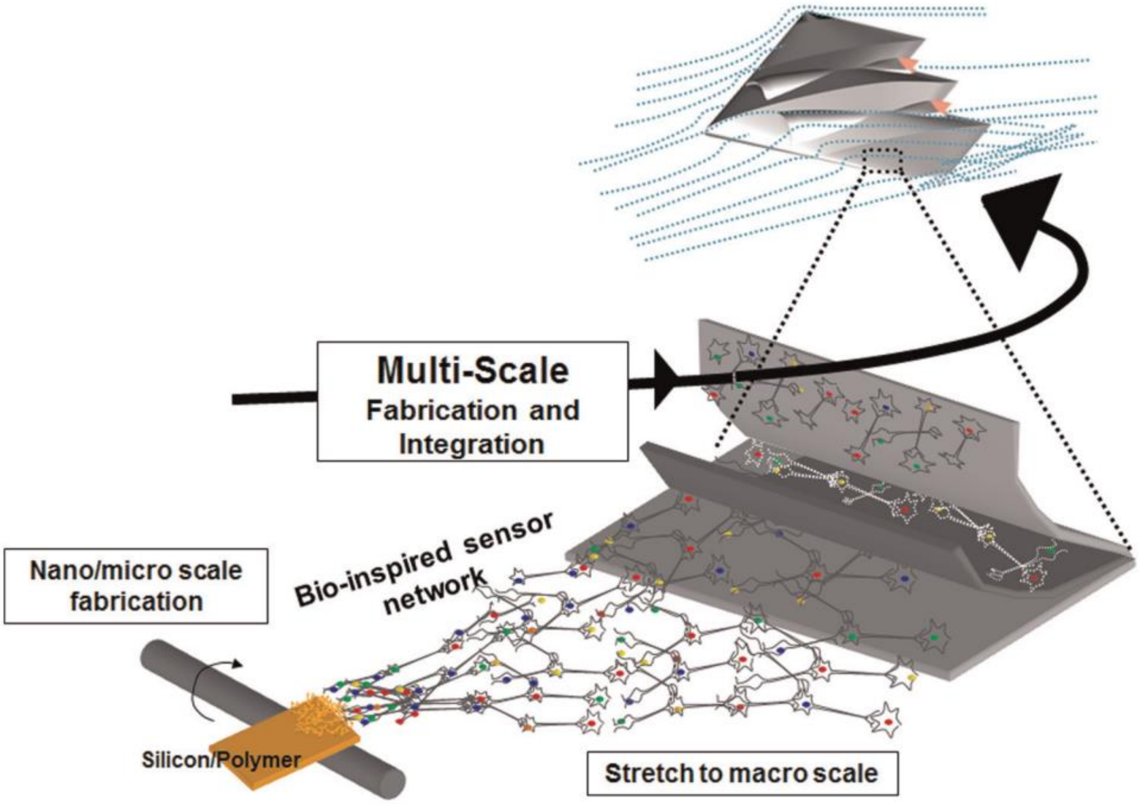

Figure 7. Microfabricated stretchable network concept: microfabricate complete integrated network (bottom left), stretch network (bottom center), and deploy network into structure (bottom right) [5].

The main advantage that composite materials present for the implementation of these SHM technologies adapted for other materials, is the ability for the sensor networks to be imbedded within the composite structure itself. This can provide numerous benefits when it comes to resolution and accuracy of damage detection [5]. When damage occurs in a composite the most common failures modes are through cracking of the matrix and through delamination of the plys. An integration of a sensor network within a composite structure can be seen in figure 7. The sensor network embedded in the composite part allows for a more detailed and accurate analysis of the current stress and damage state. From this data an analysis of the interplanar shear stresses between the plys can occur, figure 8.

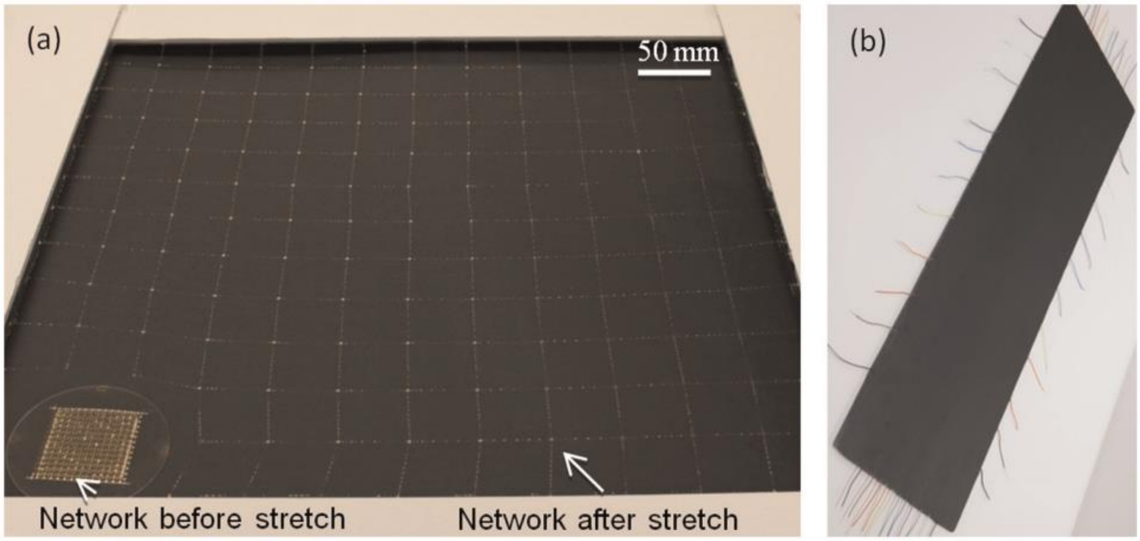

Figure 8. Stretchable piezoelectric sensor network stretched from its original size (a) and embedded in a carbon fiber plate (b) [5].

Piezoelectric sensors are well tested in their ability to detect and locate damage that has occurred in many different kinds of structures, and are especially applicable to composite ones as well. Embedded sensors, as seen in figure 8, can give advantages in regards to composite monitoring during the manufacturing process as well [5]. This crucial information for a composite structure's health state even before the implementation of the part can help predict how the structure will act under loading and over time. When an epoxy based composite cools the matrix and fibers, which have different poisons ratios, will contract at different rates. This results in cracking in the matrix and can in some cases result on delamination or even fiber damage as well. An in-situ monitoring system would allow for this damage to be located and assessed based on its severity [6]. While not the only type of sensor that is utilized, piezoelectric sensors have advantages for their accuracy and lightweight nature, ideal for SHM purposes.

The next category of sensors types that are used for SHM purposes are less well researched yet have promising implications for how SHM can be tailored towards composite materials. This included the implementation of nanoparticles and nano-wires within and applied to composites that have sensor capabilities for determining the current stress state of the structure [18]. Conductive films can also be implemented post-processing of the structure for accurate strain measurements, figure 9.

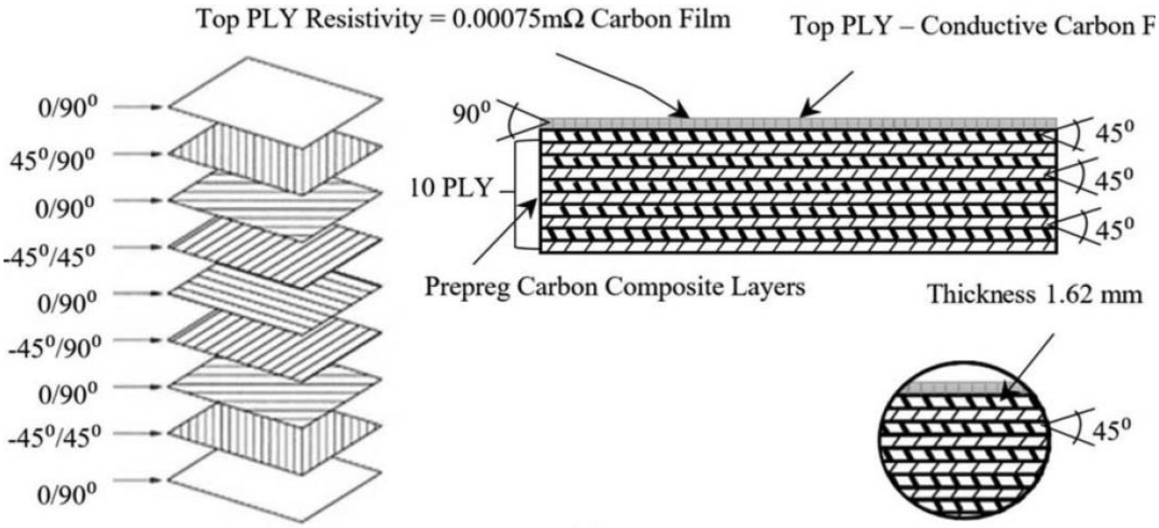

Figure 9. Example of the nano-fiber/particle SHM approach, utilizing changes in resistivity for SHM [3].

The premise of these sensors is that they are able to operate as a change in the deformations of the composite structure will alter the state of the sensors as well. This change in deformation acts like a common strain gauge and alters the base resistance of the "wires" in the material as seen in figure 9. This then corresponds with a change in stress and damage that might have occurred in the part [19]. There are also more novel based sensor systems that utilize light or sounds as the SHM sensor units. As seen in figure 10, a method of a laser based monitoring system used in conjunction with a strain paint can actively monitor the strain faced in a composite part over time.

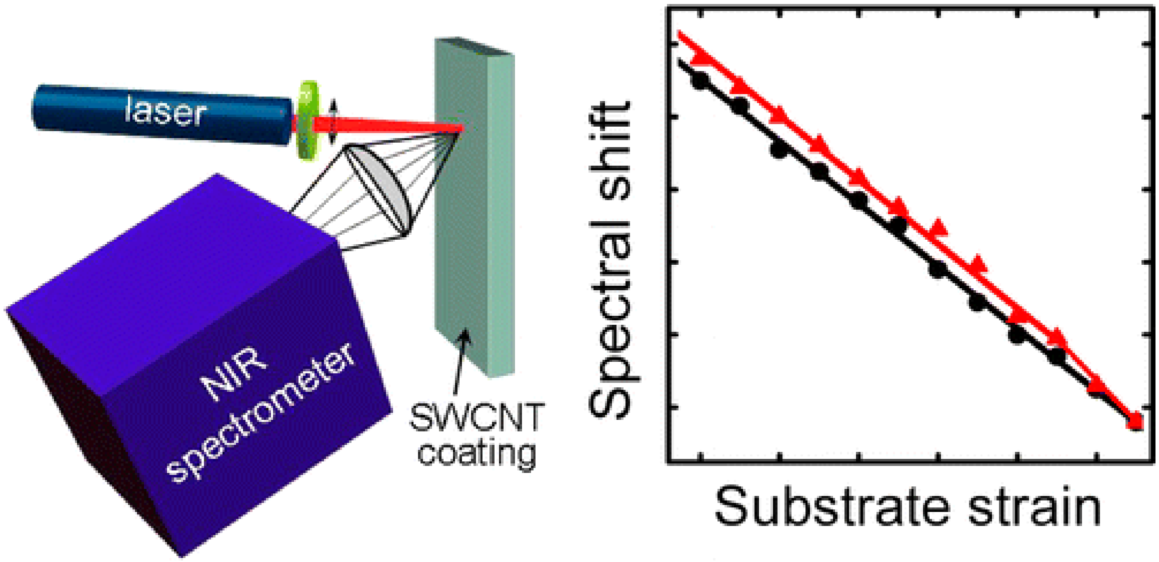

Figure 10. Example of a laser based SHM system that utilized the diffraction of a laser beam to measure the strain and thus the present stress in a system [3].

When a laser is shone at the strain paint on the part or structure a spectrometer is able to read the refracted light and determine the current strain state. While this method is not solely tailored for composite parts, it does allow for extensive monitoring of the current stress state, which like many of the other methods discussed is crucial for SHM of composite parts [3]. As stated previously the orthotropic nature of composite parts requires that they need SHM methods for more accurate predictions for service life and damage analysis for intelligent structures.

Chapter 3

COMPARRISON OF STRUCTURAL HEATLTH MONITORING METHODS

Previously the procedures for collecting data to be analyzed from composite structures for structural health monitoring was discussed. However, each of the methods for data collection has drawbacks and advantages over others for different applications. These methods all follow a similar broad methodology as outlined in figure 11.

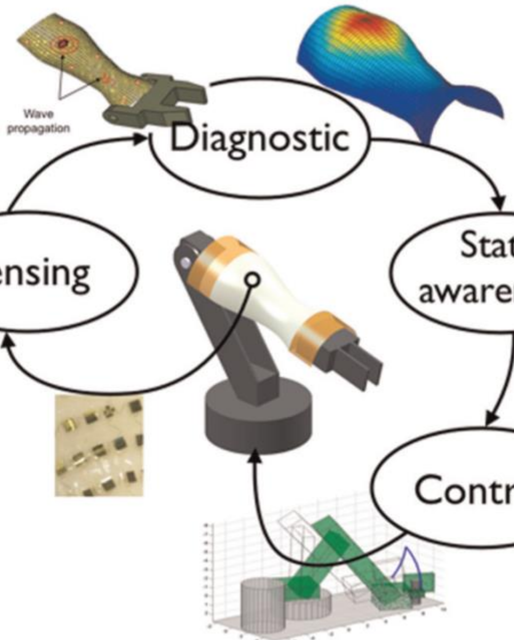

Figure 11. Cycle of SHM from the sensing of the current part stress state, to the control to alter the stress state [5].

Figure 11 shows how the process of sensing to awareness and control can be done with SHM, with each of the different sensing methods having advantages over the others in terms of their application [5].

3.1 Advantages of Sensor Arrays

An important aspect for some implementations of structural health monitoring is the implementation of sensors that are able to determine damage location as well as the magnitude of the incurred damage without manual control or interference, figure 12. Piezoelectric sensors, along with acousto-ultrasonic methods have advantages over other methods as it pertains to damage detection and location analysis [14].

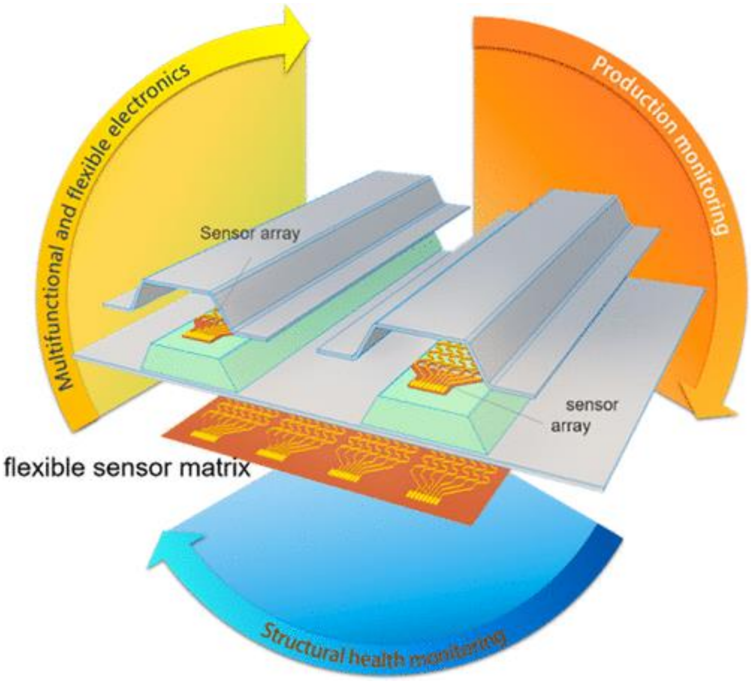

Figure 12. Implementation of a sensors network in a composite material [2].

The method for embedded piezoelectric sensor arrays can be seen in figure 12, which is particularly good at damage location detection and magnitude of damage in composite materials. As described above, the piezoelectric sensor-actuator pairs as well as acousto-ultrasonic sensor methods rely on the use of a propagating waveform in order to detect damage within a structure [1]. The advantages of these methods are that the wave is able to penetrate within the material to provide detection capabilities for damage that cannot even be seen at the surface level.

The nanowire and nanoparticle methods have advantage for detecting deformations and stress states, as well as with integration with composite structures. Many of the methods that use some form of a resistive sensor unit are great at detecting strain within a structure, and thus the stress and loads being applied [2]. In certain applications this information can be used to alter the loading of the structure if it is discovered that the stress resultants are higher than expected and the loadings need to be changed before permanent damage occurs to the structure. Composite materials by nature can have the sensor systems easily embedded within them due to the nature of their manufacturing process. These sorts of resistive sensors are easy to integrate within as they are very thin and do not impede the normal material performance of the composite structure, and are quite resilient to deformations and strain on the composite [19].

The laser based method for strain measurements of the surface of the composite has the advantage of being easily deployed for already existing structures. The only alteration to the composite is the application of the aforementioned “strain paint”, and the installation of the laser emitter and spectrometer for recording deformations in the material [3].

3.2 Drawbacks of Various Methods

The biggest drawback of piezoelectric sensors is how when imbedded within a composite, they can cause detrimental changes to the original material properties of the structure. The piezoelectric sensors act as discontinuities within the composite structure and can disrupt the plys of the structure during curing and after when used in load and the environment [18]. This effect is caused due to the introduction of a much weaker material, the piezoelectric sensors, which creates breaks in the fiber arrays. This creates stress concentrations in the material which can lead to premature failure of the composite structure and undue weight added to the structure, further decreasing the efficacy of its material properties [10].

While resistive based sensors are easily integrated within composite structures, these type of sensor system are in general unable to provide detailed information on cracks and any delamination that can occur in the composite material [17]. Resistive sensors such as those derived from nano-particles and nano-wires are great at obtaining data on the deformation of a composite and are great at in-situ monitoring of composite, yet do not have the capability for specific damage detection like the wave propagation based sensors do.

The laser based sensor has a drawback in its ability to gather information from within the object. While this sensor system can gather surface level strain data it has little damage detection capabilities and cannot gather data from within the structure itself, where the strain paint is not applied. This creates limits to the utility of the data in terms of long-term damage estimated for the structure and remaining service life [3].

SHM methods and sensor units each have their own advantages and disadvantages when it come to their applications for certain SHM practices. It is most important that the user and designer of a composite structure consider their needs when choosing a SHM sensor unit, and may even need multiple to fit their full list of requirements to ensure the long term health of a composite system.

Chapter 4

DISCUSSION OF EFFECTIVENESS AND UTILITY

As presented in the previous chapters, it can be seen that there are a variety of ways that structural health monitoring can be implemented and used for both damage detection and for calculating the stress and strain states of a structure. This chapter will cover in depth the effectiveness of the various sensor methods for collecting data based on damage detection and stress states. The circumstances in which these system might be used for SHM purposes of structures will be covered as well [19]. Figure 13 shows the implementation of a piezoelectric based SHM system used on an airplane. With aerospace technologies utilizing more and more composite parts and structures, it is becoming even more important for complex and comprehensive SHM system to be utilized.

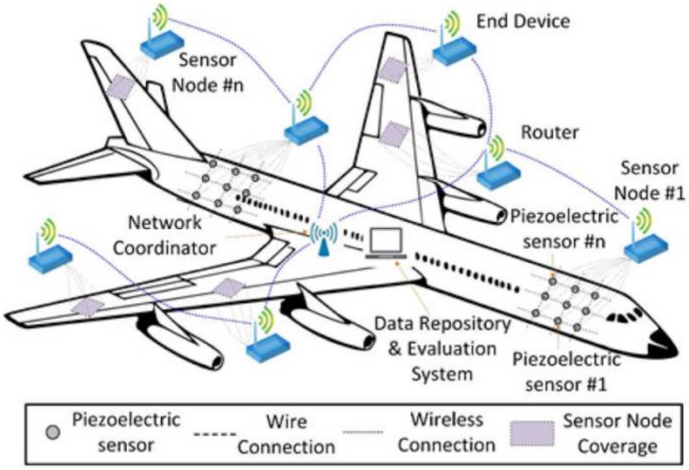

Figure 13. Present SHM system used in aircraft with interconnected piezoelectric sensor systems [20].

A large part of the research that is being done on varying sensor apparatus', as well as on new sensor technologies, is how effective these sensors are for collecting useful data. Sensors need to be both accurate and holistic in their collection methods. The very reason that new SHM techniques are being developed is due to the current state of SHM in composites and other aerospace structures. For composite materials it is necessary for sensor systems to be able to gather data across the whole of the composite structure and not just at certain points along the structure that are predetermined to be areas of stress concentrations. While this method can work well for metals and other isotropic materials, composites do not behave as reliably or predictably as other types of materials [12]. Due to their orthotropic nature and prepotency to accrue matrix cracking and defects in the laminate, stress resultants can behave in quite unpredictable ways. Since stress and damage can occur in areas where it is not predicted, and thus would not have the required sensor density, in composite structures it is possible that stress concentrations and damage can go unnoticed, and lead to catastrophic failure. Thus the future of effective sensor systems will require systems than can be implemented across an entire composite part or structure, whilst not interfering with the material properties [12].

In terms of piezoelectric sensors, the research that has been done in expandable sensor system is promising for a SHM array that benefits from the damage detection capabilities of piezoelectric sensors [1]. The work that had been done on this sort of piezoelectric sensor network has been inspired from nature, and how the nervous systems forms an active detecting network across living organisms. This system also lends itself way to large scale manufacturing as the sensor arrays can be fabricated in a relatively small space, and then expand to full size afterwards to cover and entire composite structure [5]. This type of structure can also easily embedded within a composite system and integrated well with existing composite designs. Intelligent structure optimization and SHM capabilities for damage detection and lifespan analysis of the structure can be done with an embedded sensor system [19].

In terms of the other category of fibrous and nano-particle based sensor systems, some of the better systems are able to be embedded within the composite matrix and require little other external instrumentation [2]. While there are some novel systems for detecting strain and thus the resultant stresses on a structure, they tend to require additional instrumentation. More devices can weigh down on the structure and cannot be easily used to monitor that entire structure consistently. An example of this is a strain paint sensor system that utilizes a laser source and a spectrometer for accurate strain measurement of a composite part [3]. This technique while proven to be accurate require additional heavy instrumentation that cannot be easily implemented for real structures in-situ, and would be better suited for non-destructive testing rather than SHM. Other fiber based sensor systems actually utilize similar carbon fibers to that used in many types of common graphite based composite structures, yet have its own obstacles to implementation [9]. The work that has been done in this area have not yet created fibers that can be implemented in graphite based composites, as the sensor fibers themselves are also graphite [19], and can only be implemented in non-conductive composite materials.

One of the most promising application of embeddable sensors for SHM of composites is a flexible fiber based sensor system that can be placed inside of the composite even during the layup process. This not only allows for structural health monitoring of the material post processing, but would allow for monitoring the curing process of the epoxy matrix of the structure as well [2]. This would be quite effective at providing some preliminary parameters on what the current damage and stress state of a composite part is after curing. For all composites the curing process is exothermic and when the part cools back down to operating temperature there is stress that builds up in the part. Stress accumulation is due to the uneven thermal expansion of the polymeric matrix binding material and the more rigid reinforcing fibers [17]. Figure 14 shows how these flexible circuits can be integrated in composites and be used for health monitoring during the curing process and after for more conventional SHM.

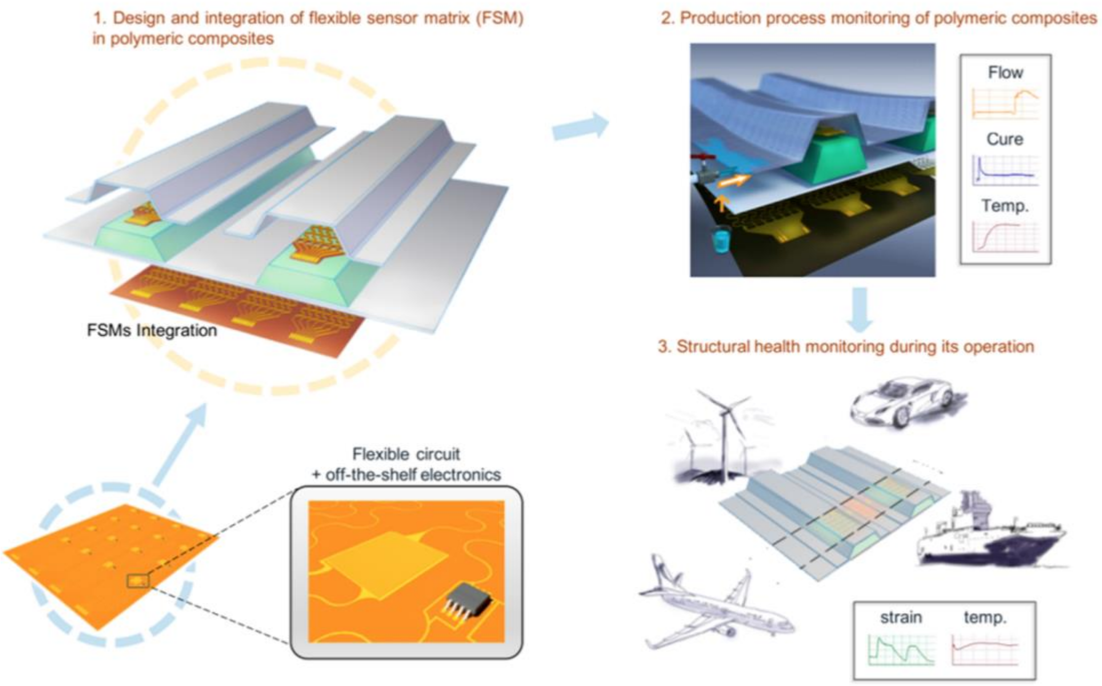

Figure 14. Schematic illustration of composites with integrated flexible sensor matrix for in situ life cycle monitoring [2].

Another advantage that the fibrous and nanoparticle based embeddable sensor system have over some larger systems is that they do not impede the material performance of the composite to the degree that some of the larger sensor system do [2]. Any discontinuity in a composite can lead to a decrease in ultimate yield strength and the resilience and toughness of the structure. Some of the larger piezoelectric sensor systems have this sort of problem if they are imbedded within the composite structure [5]. Decreasing sensor size is an effective way to mitigate this problem, which the thin and spread out fiber based sensor systems excel at.

Chapter 5

CONCLUSIONS, RECCOMENDATIONS, & APPLICATIONS

SHM is an important technology and is critical for the optimized use of composite materials in structures and even smaller parts. Previously in this paper, focus was placed on the methods of data analysis for damage detection and stress state awareness, as well as they various sensor systems and techniques for collecting said data. Now some context will be given to these different sensor systems, and how they can be applied and used in real world applications for structural health monitoring of composite parts.

Current applications for SHM are mostly limited to large civil engineering projects, such as bridges and skyscrapers, as well as aerospace and aeronautical applications [4]. SHM can be and should be utilized in many more applications that involve the use of composite materials. Future applications can be implemented in civilian vehicles that are using more and more composite materials, and can benefit from the sensing technology SHM provides. As discussed previously in this paper, SHM, while adding cost and complexity to a part or structure, has several benefits as well. Structural health monitoring decreases maintenance costs and can prolong the service life of a structure by mitigating the need for excess factors of safety for the loadings of these parts. It also allows for the implementation of "intelligent structures" that are state aware and can notify when critical damage has occurred or when the loading on the part is at dangerous levels that could lead to catastrophic damage.

SHM is a diverse an powerful tool that allows for engineers and designers to gather more data and be more aware of the damages that occur in composite structures, as well as design better composite parts. The nature of composite materials means that we need to be much more complex in predicting the properties of said structure. This differs from isotropic materials like metals, and as such SHM provides useful insights on the current stress state and damage index of the structure. While the different sensor systems are useful for different applications, it is evident that to create a holistic understanding of the current state of a composite structure, a combination of sensor arrays should be used. Piezoelectric sensors are great at damage detection while resistive based fiber sensors are great at detecting strain and stress. In conclusion, structural health monitoring system are vital for determining the current damage state of composite systems, relying on data acquisition and processing system for collecting stress state data and analyzing for statistical likelihood of damage detection.

References

[1] Ihn, J. and Chang, F., 2004, "Detection and Monitoring of Hidden Fatigue Crack Growth Using a Built-in Piezoelectric Sensor/Actuator Network: I. Diagnostics," Smart Materials and Structures," **13**, pp. 609-620.

[2] Yang, Y., Chiesura, G., Plovie, B., Vervust, T., Luyckx, G., Degrieck, J., Sekitani, T. and Vanfleteren, J., 2018, "Design and Integration of Flexible Sensor Matrix for in Situ Monitoring of Polymer Composites," ACS Sensors, **3**(9), pp. 1698-1705.

[3] Withey, P., Vemuru, V., Bachilo, S., Nagarajaiah, S. and Weisman, B., 2012, "Strain Paint: Noncontact Strain Measurement Using Single-Walled Carbon Nanotube Composite Coatings," Nano Letters, **12**(17), pp. 3497–3500.

[4] Dascotte, E., Strobbe, J., and Tygesen, U., 2013, "Continuous Stress Monitoring of Large Structures," International Operational Modal Analysis Conference, Guimarães, pp. 2-10.

[5] Salowitz, N., Guo, Z., Roy, S., Nardari, R., Li, Y., Kim, S., Kopsaftopoulos, F. and Chang, F., 2014, "Recent Advancements and Vision Toward Stretchable Bio-Inspired Networks for Intelligent Structures," Structural Health Monitoring," **13**(6), pp. 609-620.

[6] Vishnuvardhan, J., Kopsaftopoulos, F., Li, F., Lee, S. and Chang, F., 2016, "Damage Detection Sensitivity Characterization of Acousto-Ultrasound-based SHM Techniques," Structural Health Monitoring, **15**(2), pp. 143-161.

[7] Kopsaftopoulos, F. and Fassois, S., 2015, "A Vibration Model Residual-Based Sequential Probability Ratio Test Framework for Structural Health Monitoring," Structural Health Monitoring, **14**(4), pp. 359-381.

[8] Kopsaftopoulos, F. and Fassois, S., 2010, "Vibration based health monitoring for a lightweight truss structure: Experimental assessment of several statistical time series methods," Mechanical Systems and Signal Processing, **24**(7), pp. 1977-1997.

[9] Bowland, C., Nguyen, N. and Naskar, A., 2018, "Roll-to-Roll Processing of Silicon Carbide Nanoparticle-Deposited Carbon Fiber for Multifunctional Composites," ACS Applied Materials & Interfaces, **10**(31), pp. 26576–26585.

[10] Nguyen, N., Gupta, N., Ioppolo, T. and Ötügen, M., 2009, "Whispering Gallery Mode-Based Micro-Optical Sensors for Structural Health Monitoring of Composite Materials," Journal of Material Science, **44**(6), pp. 1560–1570.

[11] Giurgiutiu, V., 2011, "Piezoelectric Wafer Active Sensors for Structural Health Monitoring of Composite Structures Using Tuned Guided Waves," Journal of Engineering Materials and Technology, **133**(4), pp. 1-6.

[12] Liu, Y. and Kumar, S., 2014, "Polymer/Carbon Nanotube Nano Composite Fibers–A Review," ACS Applied Materials & Interfaces, **6**(9), pp. 6069-6087.

[13] Scheerer, M., 2015, "Process- & Structural Health Monitoring," from https://www.aac-research.at/en/process-usage-monitoring/.

[14] Aggelis, D., Barkoula, N., Matikas, T. and Paipetis, A., 2012, "Acoustic structural health monitoring of composite materials," Composites Science and Technology, **72**(10), pp. 1127-1133.

[15] Quaegebeur, N., Micheau, P., Masson, P. and Castaings, M., 2012, “Methodology for Optimal Configuration in Structural Health Monitoring of Composite Bonded Joints,” Smart Materials and Structures, **21**(10), pp. 1-11.

[16] Xu, B., Senesi, M. and Ruzzene, M., 2010, “Frequency-Steered Acoustic Arrays: Application to Structural Health Monitoring of Composite Plates,” Journal of Engineering Materials and Technology, **133**(1), pp. 011003-011006.

[17] Luo, S. and Liu, T., 2014, “Graphite Nanoplatelet Enabled Embeddable Fiber Sensor for in Situ Curing Monitoring and Structural Health Monitoring of Polymeric Composites,” ACS Applied Materials & Interfaces, **6**(12), pp. 9314–9320.

[18] Yan, L., Hong, C., Liu, J., Du, B., Zhou, S., Zhao, G., Hu, P. and Zhang, X., 2018, “Multifunctional Thermal Barrier Application Composite with SiC Nanowires,” ACS Applied Materials & Interfaces, **10**(33), pp. 27955–27964.

[19] Alarifi, I., Alharbi, A., Khan, W. and Asmatulu, R., “Carbonized Electrospun Polyacrylonitrile Nanofibers as Highly Sensitive Sensors in Structural Health Monitoring of Composite Structures,” Journal of Applied Polymer Science, **133**(13), pp. 43235-43242.

[20] Aliabadi, M. and Khodaei, Z., 2018, "Structural Health Monitoring for Advanced Composite Structures Computational and Experimental Methods in Structures," World Scientific Publishing Europe Ltd., **8**, pp. 288.