Durability of Piezoelectric Wafer Active Sensors (PWAS) for Health Monitoring of Composite Structures

A thesis submitted in fulfilment of the requirements for the degree of Master of Engineering (Aerospace Engineering)

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April 2016
Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

_____________________
Geoffrey Richard Thomas
10 April 2016
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Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISC-SHM</td>
<td>Aerospace Industry Steering Committee on Structural Health Monitoring</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Standard Test Method</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fibre Reinforced Plastic</td>
</tr>
<tr>
<td>CVM</td>
<td>Comparative Vacuum Monitoring</td>
</tr>
<tr>
<td>EM</td>
<td>Electro-Mechanical</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
</tr>
<tr>
<td>PWAS</td>
<td>Piezoelectric Wafer Active Sensor</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead Zirconate Titanate, Pb(Zr$<em>x$Ti$</em>{1-x}$)O$_3$</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SHM</td>
<td>Structural Health Monitoring</td>
</tr>
</tbody>
</table>
Abstract

The aim of this Masters of Engineering (MEng) - Aerospace thesis was to investigate the durability of Piezoelectric Wafer Active Sensors (PWAS) for the health monitoring of composite structures.

One significant challenge faced by the aviation industry is the cost and time associated with maintaining aircrafts, in particular, aging airliners. Structural Health Monitoring (SHM) is a possible approach to reduce the high cost of inspection and maintenance. SHM involves the integration of sensors into a structure and setting up a diagnostic system to provide continuous monitoring of its health and to detect damage when it occurs. Among available SHM technologies, PWAS are one of the most promising due to their ability to detect various types of damage over large regions. However, before SHM systems can be fully utilised in aerospace structures several questions need to be answered, in particular, concerns about their long-term durability and survivability. In the open literature, only a few studies can be found that have addressed the durability of PWAS used in composite laminates. After a comprehensive literature review, three specific areas were identified as warranting further investigation, namely, static and fatigue loading, impact events and numerical modelling.

For the experimental investigation, a carbon fibre/epoxy composite host was chosen with PWAS bonded to the surface and/or embedded in the mid-plane of specimens. A method for embedding the PWAS into the composite laminates was successfully developed. The performance of the sensors under different external loading was then monitored using the capacitance, output voltage and electro-mechanical impedance of the sensors. Visual inspection, as well as SEM analysis was also conducted after each test.

Static and fatigue four-point bending tests were performed to study the durability of PWAS under tensile and compression strain. Both the surface-bonded and embedded sensors were used in these experiments. The behaviour of PWAS under compression strain was different from that of the tensile one. Those sensors subjected to compression strain suffered from cohesive failure under both static and fatigue testing. This was evident with an increase in their capacitance value. Under static testing, those PWAS bonded to the
tensile surface of the host composites exhibited an initial increase in the capacitance followed by almost no change at higher strain levels. Under fatigue loading, the PWAS subjected to tensile strain performed much better than those under compression loading. Only minor debonding was observed in these sensors before any major signs of damage to be identified in the PWAS. It is noteworthy that the capacitance of the embedded sensors was not sensitive to their debonding, while delamination at the Kapton interface was detected by monitoring the electro-mechanical impedance of the sensors.

The effects of impact events on surface-bonded and embedded PWAS was also investigated. Due to their brittle nature, both composites and PWAS are extremely susceptible to impact loading, which for the case of aircrafts could be caused by events such as bird strikes, hail or tyre debris. Tests were conducted with the impact load directly over the PWAS and at a designated distance away, with different impact energy levels. Results showed that sensors bonded on the back face or embedded into the composite could survive impact energies up to 7 joules, after which significant changes in their performance, as well as physical cracking, was found to occur. Multiple impacts were also applied to specimens, which showed that embedded sensors are able to survive a greater number of impacts before exhibiting any signs of degradation. When impacts were applied at a small distance from the sensor, only PWAS bonded to the top surface of the host composite were degraded, with visible damage occurring to the composite well before any degradation to the bonded sensors on the back face or embedded.

The final part of this investigation was focused on numerical modelling, in particular, developing a methodology to distinguish between sensor degradation and structural damage. The numerical model consists of a 3D representation of a free PWAS and a host composite laminate with a bonded sensor while the impedance for both cases was analysed. Findings were compared with the experimental results and good agreements attained for both instances. Using the bonded model as a base, three modes of damage were then investigated which included, debonding of the sensor, structural damage with delamination in the composite and a crack in the PWAS. The results showed that the imaginary part of impedance is highly effective in distinguishing damage between the sensor and structure. The slope of the impedance curve was increasing by progressive debonding of the sensor while a reduction in the slope was observed after introducing a crack to the PWAS. For the
delamination case, no change to the imaginary part of impedance was identified, however, the 1st resonant frequency for the real part of impedance became distorted.

The Master's thesis concludes with a summary of the major finding from this investigation and provides several recommendations for future research into PWAS durability.
1. Introduction

1.1. Background and Rationale for the Research

1.1.1. Ageing aircrafts

The issue of ageing aircraft is currently a major challenge facing the aviation industry. Thanks to the use of through-life extension methods and improvements in design, the average age of aircrafts continues to rise, with many planes now beginning to surpassing their original design life. Although helping to reduce acquisition cost for airlines, older aircrafts however, require greater emphasis on maintenance to ensure their structural integrity and to help maintain a high level of safety for passengers.

A good example of an accident involving an older aircraft was Aloha flight 243 which took place in 1989. This accident involved a Boeing 737-200 which had been in services for 19 years and had experienced over 89,000 flight cycles \[^1\]. As a result of fatigue and corrosion, part of the roof of the fuselage separated from the structure during mid-flight, as seen in Figure 1-1. Miraculously there was only one casualty as a result of this accident; however, this serves as a stark reminder of what can occur if damage goes undetected during maintenance checks.
According to the International Air Transport Association (IATA), around 13% of the total operating costs for airlines in 2010 were associated with maintenance of their aircrafts, as illustrated in Figure 1-2. It has also been said that for every 10 years in service, the cost to maintain any aircraft increases by roughly 15% \(^3\). As traditional aerospace metals are now being replaced with composite materials, it is more than likely these costs are going to increase further.

**1.1.2. Composite materials**

The use of composite materials in aircraft structures has grown dramatically in recent time, as seen in Figure 1-3, and is replacing traditional metallic materials such as aluminium. The major benefits of using composites over metals include a higher specific stiffness, greater specific strength and lower density, meaning that composite structures can be significantly lighter and more fuel efficient. Composites are also corrosion resistant, have excellent fatigue properties and can be easily tailored to produce more aerodynamic and efficient structures \(^4\). Some good examples of the extensive use of composites in aerospace include Boeing 787 Dreamliner and the Airbus A350 \(^5, 6\).

![Figure 1-3- Aircraft percentage weight made from composite materials \(^7\)](image)

Although being lighter and stronger than aluminium, using composites does come with some drawbacks. Apart from being significantly more expensive to manufacture,
composites introduce new and complex modes of damage which need to be properly understood before they can be fully integrated into a structure. Some of these damage modes include delamination between laminar plies, fibre fracture, fibre micro-buckling and matrix cracking. Composites in particular are vulnerable to impact damage, which is due to the brittleness of their constituents [4].

For aircrafts, the most impact events are caused by hail, tire debris, bird strike and tool drops during maintenance. Depending on the impact energy, this can result in matrix cracking, delamination and fibre breakage. Barely Visible Impact Damage (BVID) caused by low-velocity impacts is especially a major concern in aviation as it often results in delamination under the surface that cannot be seen easily with the naked eye. These delaminations can radiate through the thickness of the structure and significantly lower its load carrying capabilities. As a result, structures are often over-designed and require extensive Non-Destructive Testing (NDT) to maintain their integrity.

1.1.3. Non-destructive testing

NDT has been the traditional method used for evaluating the integrity of a structure. Generally, it is performed both during the manufacturing process for detecting any material defects and in service for detecting damage to the structure caused by operations. As depicted in Figure 1-4, aircrafts are under different levels of stress during flight and can be sustain to damage in numerous locations, which require checking at various intervals during their lifetime. By using NDT techniques, the size, location and type of damage can be determined; and from this information, engineers can assess the structure's integrity and determine if corrective action is required.
The most common NDT methods used in aerospace include visual inspection, ultrasonic, eddy current radiography and thermography, with each method having its own advantages and limitations. Given the type of damage that can be detected varies for each method, a combination of two or more methods are generally required to ensure all modes of damage are accurately detected. A summary of the NDT methods can be seen in Table 1-1, which includes the type of damage they can detect, together with their advantages and limitations.

### Table 1-1: Summary of NDT methods

<table>
<thead>
<tr>
<th>Damage type</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection</td>
<td>• Fatigue cracks&lt;br&gt;• Delamination&lt;br&gt;• Visible impact&lt;br&gt;• Surface defects&lt;br&gt;• Corrosion</td>
<td>• Requires no complex equipment&lt;br&gt;• Inexpensive&lt;br&gt;• Little training needed</td>
</tr>
<tr>
<td>Ultrasonics</td>
<td>• Fatigue cracks&lt;br&gt;• BVID&lt;br&gt;• Delamination</td>
<td>• Well established and commonly used&lt;br&gt;• Can detect small damage&lt;br&gt;• Good depth range</td>
</tr>
<tr>
<td>Eddy current</td>
<td>• Fatigue cracks</td>
<td>• Detect small cracks&lt;br&gt;• Inexpensive</td>
</tr>
<tr>
<td>Radiography</td>
<td>• Fatigue cracks&lt;br&gt;• BVID&lt;br&gt;• Delamination&lt;br&gt;• Corrosion</td>
<td>• Fast monitoring&lt;br&gt;• Good depth range</td>
</tr>
<tr>
<td>Thermography</td>
<td>Fatigue cracks</td>
<td>BVID</td>
</tr>
<tr>
<td>--------------</td>
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</table>

### 1.1.4. Structural health monitoring

Structural Health Monitoring (SHM) is a relatively new and promising technique for detecting damage in structures, which could reduce the reliance and need for NDT. As defined by the Aerospace Industry Steering Committee on Structural Heath Monitoring (AISC-SHM), SHM is "the process of acquiring and analysing data from onboard sensors to evaluate the health of a structure" [8]. Commonly compared to the human nerves system, as shown in Figure 1-5, SHM systems use a series of sensors located on all parts of a structure which are continuously monitoring and checking for any changes in the structure’s performance. Once damage develops to a critical size, maintenance would then be scheduled to repair the structure.

One of the biggest problems with NDT is that it can be a time consuming and costly process, not ideal in an industry which continually strives to keep cost to a minimum. For commercial aircrafts, it has been said that around 44% of all on-aircraft maintenance man-hours are spent inspecting the entire aircraft for damage [10]. Where for the military, some aircraft can require more than 10 hours of maintenance for every flight hour [11]. As SHM systems would be permanently attached to the structure, this should result in a significant reduction in the need for NDT and reduce the overall cost of the maintenance. By implementing a comprehensive SHM system, it has been estimated that the airlines could reduce maintenance cost by as much as 20% [9].
Introducing SHM onto aircraft will also have a variety of other benefits. In the short term, by already knowing where damage is located, it should reduce costs and maintenance times, meaning airlines can have their aircraft back in operation quicker. Although not being a primary objective, SHM should also increase the level of safety as the damage can be detected when it occurs and an aircraft could be taken out of services if it becomes critical. In the long term, SHM could shift maintenance schedules from a time-based method to condition based, whereby maintenance is only conducted when damage is known to have occurred. It could also help to extend the operating life of aircrafts and assist in improving designs by reducing damage tolerance. Although introducing SHM will result in an increase in the manufacturing costs of an aircraft, in the long term its benefits would appear to far outweigh the initial expenditure.

Current monitoring systems (strain gauges, etc.) and systems which determine flight parameters (speed, temperature, etc.) are already extensively used on structures[12]. However, these are limited by the type of data they can gather and rely on historical data to predict the status of any possible damage. SHM systems, on the other hand, acquire and analyse data from onboard sensors to evaluate the actual health of the structure [13].

Some examples of current SHM systems being developed include Comparative Vacuum Monitoring, Fibre Bragg Grating and Ultrasonic wave methods. An overview of the principles of these systems and how they detect damage is provided in the next section of this chapter.
1.1.5. Types of SHM systems

**Comparative Vacuum Monitoring (CVM)**

One type of SHM technique which has seen considerable attention in recent times is Comparative Vacuum Monitoring (CVM)\(^ {\[14,15\]}\). This technique relies on a sensor to be either bonded to a metallic or embedded in a composite structure and can be used to detect surface cracks or delamination. The principle behind the sensor is that it consists of a series of long, narrow galleries (bubbles) which alternate between low pressure and ambient pressure, as shown in Figure 1-6. When a crack breaks through two adjacent galleries, this will result in a change in pressure and can be detected by a pressure sensor. Utilising this technique, one can then determine the size and location of the damage. This method is relatively simple to implement; however, it relies on a crack to propagate in the location of the sensor, as such it is more suited for monitoring critical areas and not an entire structure.

![Figure 1-6- Example of CVM sensor\(^ {\[16\]}\)](image)

**Fibre Bragg Grating**

Fibre Bragg Grating (FBG) is another SHM technique and is well suited for monitoring large regions of a structure\(^ {\[9\]}\). Similar to fibre optic cable, FBG utilises glass fibres to transmit light through a cable network. Using a process called grating, strain in particular regions can be then measured by observing any changes in the lights frequency as it passes through the grating. Although this technique can be used to monitor large sections, it is limited by the type of damage it can detect as it relies on a local strain to occur. Also, for the damage to be detected, it needs to be within close proximity to one of the gratings in the fibre for it to be detected.
Ultrasonic Wave Methods

Ultrasonic wave methods, specifically using Piezoelectric Wafer Active Sensors (PWAS), are another promising technique and are the main focus of this research. Some of their advantages include low cost, light weight, ability to detect a variety of damage types in a large area, acting as an active/passive sensor, and have been shown to have little to no effect on the structure's mechanical properties [17-20]. A more detailed description of the principles behind PWAS (propagating wave methods) and how they can be used to detect damage in structures can be found in the next chapter of this thesis.

1.1.6. Regulations and certification of SHM systems

The failure of any subsystem on an aircraft can have catastrophic consequences, which is why strict standards are currently in place to regulate the design, durability and survivability of certain aircraft components [21]. Before an SHM system could be fully integrated into mainstream use, it needs to comply with regulations and standards for their durability and integration. While most work into SHM has been focused on detecting structural damage and aspects of their durability, currently gaps exist regarding standards for implementing SHM, which will need to be addressed in the near future.

![Figure 1-7- Framework for SHM systems standards](image)

The topic of certifying an SHM system has been discussed by Kessler [21] and Chambers [22]. Both studies present a similar notion that the framework for certifying a system will come from existing standards for civil and military aircrafts. As SHM systems involve sensors, software and are integrated into the aircraft, they suggest a combination of structural
design and environmental standards will be required. A graphical representation of this framework can be seen in Figure 1-7, which included the relevant standards, such as DO-160E, ASTM and other equivalent military standards. These standards include a variety of appropriate durability tests which can be conducted and the most important of these have been summarised in Table 1-2.

Table 1-2- SHM durability tests$^{[22]}$

<table>
<thead>
<tr>
<th>Environment</th>
<th>Testing type</th>
<th>Additional Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Temperature</td>
<td>At max. Operating temperature</td>
<td>85°C for 2hrs</td>
</tr>
<tr>
<td>Low temperature</td>
<td>At min. Operating temp</td>
<td>-55 °C</td>
</tr>
<tr>
<td>Thermal shock</td>
<td>High ramp rate</td>
<td>-85 °C – + 85°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>65°C and 95% RH</td>
<td>Pure water (no salt)</td>
</tr>
<tr>
<td>Fluid susceptibility</td>
<td>Both Oil and water based fluids</td>
<td>Eg, Fuel, oil, water</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromechanical interference</td>
<td>-</td>
</tr>
<tr>
<td>Static strain</td>
<td>Large tensile and compressive strain</td>
<td>-</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Below material fatigue strain levels</td>
<td>-</td>
</tr>
<tr>
<td>Low-velocity impact</td>
<td>Barely visible and visible</td>
<td>-</td>
</tr>
<tr>
<td>Vibration</td>
<td>-</td>
<td>Defined by DO-160E</td>
</tr>
</tbody>
</table>

The Aerospace Industry Steering Committee on Structural Heath Monitoring (AISC-SHM) was also established in 2006, which was in reaction to some who felt that Airbus A380 and Boeing 787 programmes had missed out on the opportunity of utilising SHM technologies. Comprising of leading industry organisations, regulatory bodies and academia, its main aim is to assist in the implementation of SHM for aerospace vehicle structures $^{[23]}$. Following its establishment, the committee released its first publication in 2013 entitled "Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircrafts" $^{[24]}$, a summary of which was published by Foote $^{[13]}$. This document addresses a number of areas, including essential aspects of SHM requirements, validation & verification and certification. Although not going into specific details about the certification of an SHM system, this document is an important starting point and will greatly assist industry in the process of SHM implementation.
1.2. Research Aims and Objectives

The main aim of this Masters project was to assess the durability and long term survivability of PWAS surface-bonded and embedded in a carbon fibre composite laminates. As identified in the literature review chapter, a majority of research into PWAS so far has been focused on the detection of damage in structures. However, before any SHM system, particularly PWAS, can be fully integrated into mainstream use, further investigations including durability under operational conditions are required. Given most work has been focused on metallic structures, composite materials are another area which warrants further study. Composites have the added benefit in that apart from being able to bond the sensors to the surface, the PWAS can also be embedded into the composite structure where they are likely to be protected from certain mechanical and environmental effects.

Before defining the objectives of this project a detailed review of current publications was undertaken, to determine the state of the art of PWAS and to identify any important gaps which warrant further investigations. From this critical review the major objectives of the project were developed and include:

- Develop a methodology for embedding PWAS in composite specimens.
- Determine the effects of impact and fatigue loadings on PWAS and identify threshold levels that PWAS can survive without damage/degradation.
- Develop a 3D numerical model which accurately represents a PWAS integrated with composite structure.
- Using the numerical model, investigate how various modes of damage influence PWAS performance, so as to help identify vitiations between structural damage and PWAS degradation.

Undertaking this research will help to gain a greater understanding of PWAS durability, especially when integrated with composite materials. Consequently, it can assist in the process of introducing them into mainstream use both in aerospace and various other industries.
1.3. Overall Structure of the Thesis

The thesis comprises of a literature review, manufacturing methodology, numerical modelling and experimental testing.

Chapter 2 is presenting the literature review, which summarises the main theory behind PWAS and the detection of damage in structures. This is then followed by an extensive review of durability studies already undertaken and identifying any research gaps. Finally, investigations into numerical modelling are reviewed, which also discusses any opportunities to further development.

Chapter 3 describes the materials and methodology used for the manufacturing of the specimens. It also explains how the PWAS performance was monitored and includes a statistical analysis showing the consistency of the PWAS performance.

Chapters 4 and 5 are reporting the experimental studies, which includes the fatigue and impacts experiments. Each chapter comprises of a methodology, test matrix, a discussion of the results and conclusions.

Chapter 6 includes the numerical modelling of PWAS, which begins with a free PWAS and then moves onto a bonded sensor. This is then followed by an investigation into the effects of sensor bond quality, delamination in the composite and cracked PWAS has on their performance.

Finally, Chapter 7 is the conclusion chapter, which summarises the main findings from this research and includes recommendations for future studies.
2. Review of PWAS Theory and Literature

2.1. Introduction

Currently, there are a variety of SHM technologies available for detecting damage in structures. For this investigation, systems based on Piezoelectric Wafer Active Sensors (PWAS) were chosen. Implementing these sensors is one of the most promising and versatile methods given their ability to detect numerous types of damage in structures over a large region.

In this chapter, topics related to the piezoelectric theory and previous research undertaken will be discussed. This includes the basic principles of the piezoelectric effect and methods which can be used for damage detection in structures. A review of the methods for integrating PWAS within host structures, followed by a comprehensive literature review regarding their durability is presented. Finally the chapter concludes with an overview of numerical modelling using piezoelectric materials and in particular investigations implementing the EM impedance method.

2.2. Piezoelectric Effect

Piezoelectricity is a term used to describe the coupling of a material’s mechanical and electrical properties. First discovered in 1880 by Pierre and Jacques Curie, the word piezoelectricity comes from the Greek word piezein, "to press". They discovered that when a piezoelectric material is subjected to a force, the resulting deformation of the material caused an electric charge to be generated on its surface, which is known as the piezoelectric effect. This phenomenon also occurs inversely, known as the inverse piezoelectric effect, where an electric voltage applied to a piezoelectric material causes it to mechanically deform \(^\text{[25, 26]}\).

Piezoelectric material can either occur naturally in nature or can be synthetically produced. Piezoelectric Crystals are the natural form and include materials such as Quartz, Rochelle salt, and EDT (Ethylene Diamine Tartrate). These crystals however only possess weak piezoelectric property, which is why for industry applications synthetic piezoelectric ceramics are most often used. Some examples include Barium Titanate (BaTiO3) and Lead Zirconate Titanate (PbZrTiO3), commonly referred to as PZT \(^\text{[25]}\).
Piezoelectric ceramics are polycrystalline ferroelectric materials and have a perovskite crystal structure (electric dipole), an example of which can be seen in Figure 2-1. Adjoining dipoles then form regions with local alignment called domains. This alignment gives a net dipole moment to the domain, thus creates a net polarization \[^{25}\]. Neighbouring domains in the ceramic are however randomly aligned resulting in a total overall polarization of zero. The process of aligning, or poling, is achieved by applying a strong DC electric field to the material, which is conducted at elevated temperatures which helps to accelerate the poling process. Once the electric field is removed the domains then maintain this alignment and the ceramic has a permanent polarization. An illustration of this can be seen in Figure 2-2.
Although polarized, the ceramics can be returned to its original state, which is known as depoling. This process can occur in numerous ways including, by applying a strong electrical field in the opposite direction to polarization or subjecting them to high temperature. The temperature at which the domains are able to move freely and lose their alignment is known as the "Curie" temperature. This temperature depends on the type of material and can vary from 180-360°C. Generally it is advised the maximum operating temperature for the piezoelectric material is half of that of the Curie temperature, which is to ensure its piezoelectric properties do not degrade over an extended period of time.
2.3. Piezoelectric Properties and Material Selection

When it comes to selecting a type of piezoelectric material, there are several factors which need to be considered which include the intended application of the sensor and the working environment.

Generally piezoelectric materials can be classified into two groups, soft or hard materials [25]. Soft piezo materials exhibit a higher piezoelectric constant and electromechanical coupling factor, higher permittivity, lower Curie temperature and are more susceptible to depolarization. These properties make them more suitable for sensing applications such as accelerometers, microphones and pressure sensors. Hard piezo materials where else generally have, low dielectric loss, a higher Young’s modulus and are harder to dipole. This makes them ideal for high-power applications including motors, actuators and transducers.

2.3.1. Electromechanical coupling coefficient

The electromechanical coupling coefficient, \( k_{xy} \), is used as an indicator for how effective a piezoelectric material can convert mechanical energy into electrical energy, or vice-versa [26]. The first subscript (x) denotes the direction which the electrodes are applied, and the second subscript (y) denotes the direction along which the mechanical energy is developed. This coefficient can be defined as:

\[
K_{xy} = \sqrt{\frac{\text{Mechanical Energy Stored}}{\text{Electrical Energy Applied}}} \quad \text{EQ. 1}
\]

2.3.2. Dielectric constant

The dielectric constant \( \varepsilon \), also known as permittivity, is the dielectric displacement of the piezoelectric ceramic material per unit electric field. This can be either given as \( \varepsilon^t_{xy} \) which is the permittivity at constant stress or \( \varepsilon^s_{xy} \) the permittivity at constant strain. Often it is expressed as the relative dielectric constant, \( K^T \), which is the ratio of the amount of charge it can store relative to the absolute dielectric constant \( \varepsilon_o \), \( 8.85 \times 10^{-12} \text{ farad / meter} \).

\[
K^T = \frac{\varepsilon}{\varepsilon_o} \quad \text{EQ. 2}
\]
Using the dielectric constant the Capacitance, \( C \), for a given type and size of sensor can then be calculated:

\[
C = \frac{K_{xy} \varepsilon_0 A}{h} \quad \text{EQ. 3}
\]

where, \( A \) is the area of the material and \( h \) is its thickness.

### 2.3.3. Piezoelectric constants

The piezoelectric charge constant, \( d_{xy} \), relates the polarization generated with the mechanical stress applied, or alternatively the mechanical strain experienced with an electric field is applied. For strain-dependent applications (actuator) the charge constant is a good indicator for the suitability of a piezoelectric material.

The piezoelectric voltage constant, \( g_{xy} \), denotes the electric field generated by a piezoelectric material per unit of mechanical stress applied or, alternatively, is the mechanical strain experienced by a piezoelectric material with an electric displacement applied. For sensing applications the voltage constant is an important property when determining the suitability of a piezoelectric material.

### 2.3.4. Frequency constant

The frequency constant, \( N \), is used to determine the resonant frequency of PWAS. The resonant frequency is the frequency at which minimum impedance occurs, which is a complex ratio of the voltage to the current for an AC circuit. For a PWAS disk there are two resonant frequencies. The first is the Radial Mode, which relates to the diameter of a circular disk. When the frequency further increases the next resonant frequency is the Thickness Mode, which relates to the thickness of the disk.

\[
\text{Resonant Frequency, Radial mode } f_r = \frac{N_p}{D} \quad \text{EQ. 4}
\]

\[
\text{Resonant Frequency, Thickness mode } f_r = \frac{N_T}{h} \quad \text{EQ. 5}
\]

where, \( N_p \) is the Frequency constant (planar), \( N_T \) is the Frequency constant (thickness), \( D \) the diameter of a circular disk and \( h \) its thickness.
2.4. Damage Detection Using PWAS

PWAS can be used in a variety of ways for the detection of damage in thin-walled structures, depending on the type, size and location of the damage. As a transmitter, bonded PWAS utilise the $d_{31}$ piezoelectric coupling to generate an in-plane strain in the structure. This in turn can be used to create high-frequency ultrasonic waves, also known as Lamb waves \[17\].

As a receiver, PWAS utilises the same coupling to convert ultrasonic waves in a structure back into an electrical signal. Using Lamb waves one can then determine if any damage exists in the structure, for example delamination, cracks, corrosion and several other types of damage \[17\]. For the damage to be detected, the wavelength used needs to be smaller than the damage size, or damage needs to significantly alter the stiffness of a large enough region of the structure \[19\]. In this section, the two main techniques used for detecting damage will be discussed, which includes elastic waves (propagating Lamb waves) and the electro-mechanically (EM) impedance method (standing Lamb waves).

2.4.1. Propagating Lamb waves

Lamb waves, also known as guided plate waves, are a type of ultrasonic wave that remain guided between two parallel surfaces \[27\], with their principles well documented in a number of publications \[26, 28, 29\]. An example of the two types of waves is illustrated in Figure 2-3, which can be either symmetric or anti-symmetric and have different velocities depending on their frequency.

![Figure 2-3- Lamb wave modes](image)

a) Symmetric Lamb mode $S_0$ and b) anti-symmetric Lamb mode $A_0$ \[27\]

For SHM, Lamb wave methods have been investigated extensively, as they are highly sensitive and effective in detecting damage in thin structure \[20, 30, 31\]. PWAS are especially efficient, as little energy is required to transmit waves large distances in materials, in
particular, materials which have a high attenuation ratio such as carbon fibre composites [20]. As has been reported, the sensing radius for PWAS can be as much as 0.4m for composites and up to 2m for metals [19], although this is highly dependent on the thickness of the structure, bonding adhesive and sensor size.

![Diagram of Propagating Lamb Waves](image)

Figure 2-4: Damage detection techniques using PWAS [26]
- a) Pitch-catch
- b) Pulse-echo
- c) Thickness mode
- d) Impact/AE Detection

Several methods that utilising propagating Lamb waves for damage detection can be used as seen in Figure 2-4 [26], which in some cases can detect the size, location and severity of damage. The Pitch-catch technique, as shown in Figure 2-4 a), employs two sensors, a transmitter and a receiver, to detect possible damage in the structures. With a pristine structure, the transmitted wave will be unaffected and have a consistent signal when it reaches the receiver. After introducing damage, the elastic wave will be altered as it passes through this region and results in the signal modified at the receiver. Apart from detecting if damage has occurred, this technique can also be used in a phase array (PWAS network) where multiple receivers are used. Utilising this method, an image of the structure can be created that is able to indicate the specific size and location of the damage. Figure 2-4 b) is
an example of the Pulse-echo technique. In this case, only a single PWAS is required which acts as both a transmitter and receiver. The transmitter creates a wave in the structure and then records any waves that are reflected back. These reflections can be caused by the wave interacting with the structures boundary or damage when is present. Under thickness mode, Figure 2-4 c), the elastic waves are created in the thickness direction rather than the in-plane direction. This is achieved by exciting the PWAS at much higher frequencies; generally in the megahertz range; where else for in-plane Lamb waves, frequencies in the hundreds of KHz are used. This technique is good for detecting damage in the thickness direction such as delamination and corrosion, however for damage to be detected it requires the sensor to be directly above the damage. Finally, an example of the impact/acoustic emission (AE) method is presented in Figure 2-4 d). For this case rather than being an active technique where a PWAS create a wave, it remains in passive mode acting as a receiver. When an event such as impact occurs or a crack grows, the resultant wave they create in the structure can be detected by the receiver. The advantage of this method is that damage can be detected when it occurs without the need to supply power.

One issue with using many of these methods is that they can require extensive data analysis, which can be a time consuming process. As such, in recent times the EM impedance method has become a popular method, which is discussed in the next section.

2.4.2. Electromechanical impedance method

The electromechanical (EM) impedance method is another damage detection method using PWAS and complements wave prorogation techniques. This method has progressed significantly in recent times and has been shown to be an effective way of detecting many types of incipient damage in complex structures [19, 32-34]. In addition, EM impedance is an effective method for checking the integrity of both the PWAS and adhesive interface, helping to ensure structural damage is correctly identified [18, 19].
Theory

This EM method relies upon the principle of electromechanical coupling between the piezoelectric sensor and the structure it is attached to. Liang et al. [35] was one of the first to propose this technique, which showed the electrical admittance (inverse of impedance) of a piezoelectric material can directly relate to the mechanical impedance of the structure. A schematic illustration developed by Liang [35] for a one degree of freedom spring-mass-damper (SMD) system driven by a PWAS can be seen in Figure 2-5.

Traditionally measuring the impedance of a structure was performed using a transducer, which applies a normal force to a structure and then measured the resultant velocity of the waves generated. The EM method where else, uses a bonded PWAS to generate a local strain parallel to the structure’s surface. This in turn, results in stationary elastic waves being created which are presented back to the PWAS as the drive-point impedance. An analytical expression representing the structure’s mechanical impedance is shown in EQ. 6 [19]. Due to the electro-mechanical coupling, the mechanical impedance is then directly represented in the PWAS’s electrical impedance.

![Figure 2-5 - 1-D model used to represent a PZT-driven SMD system](image)

Based on this model developed by Liang, EQ. 7 was generated, which represents the admittance of a PWAS attached to a structure. This also is a direct ratio of the output current and input voltage of the PWAS. The full derivation of this equation can be found in Liang et al. and Giurgiutiu [26,35].
where,

\[ Y = \frac{I}{V} = i\omega \left( \frac{\varepsilon_{33}^T - \frac{Z_S(\omega)}{Z_S(\omega) + Z_a(\omega)} d_{3x}^2 P_x}{Z_S(\omega) + Z_a(\omega)} \right) = Z^{-1} \]

Rather than measuring the PWAS admittance in most SHM cases, its inverse, impedance, is used, as seen in EQ. 8. The impedance is comprised of two components, the resistance, \( R(Z) \), which is the real part of impedance, and the reactance \( X(Z) \), the imaginary part of impedance. The real part of the impedance reflects the PZT’s vibration spectrum, which has been found to be more reactive to damage (or changes in the structure’s integrity) and is less affected by boundary conditions.\[^{19}\] The imaginary part of impedance where else can be used to verify the integrity of the sensor and the adhesive layer. The reactance can however be sensitive to temperature variations, which is a result of changes in the dielectric constant, so caution needs to be taken when analysing results.

\[ \frac{1}{Y(\omega)} = Z(\omega) = \frac{V}{I} = R(Z) + jX(Z) \]  

**Detecting Damage Using EM Impedance Method**

As previously mentioned, when integrated with a structure, a PWAS’s impedance reflects both its electrical impedance and the mechanical impedance of the structure. When damage then occurs, the resultant change in the stiffness and dampening will cause the impedance of the sensor to change. The EM impedance method is applied by scanning a predetermined frequency range, often somewhere between 1 kHz - 2 MHz, and measuring both the real and imaginary impedance. This frequency range is generally used as it has been found to be more sensitive to incipient and small damage in a structure, as the...
wavelength in the structure needs to be shorter than the damage for it to be detected \[19\]. By comparing the impedance spectra at various intervals during a structure’s life, a judgement on whether damage has then occurred can be made. Assuming that the PWAS has not been damaged during its life and its properties have not changed, any changes in the impedance graph could then be attributed to damage in the structure. Similarly, assuming no damage has occurred to the structure then a change in impedance would indicate degradation in the PWAS.

Figure 2-6- Comparison of electromechanical impedance before and after damage
  a) Real impedance b) Imaginary admittance

Examples of the impedance spectra for a bonded PWAS can be seen in Figure 2-6, which shows the effects of both structural damage and damage to a sensor. Figure 2-6 a) shows the real impedance spectra for a PWAS before and after damage has occurred, which as seen can significantly alter the signal and create new resonant peaks. Figure 2-6 b) is an example of the imaginary admittance for a bonded PWAS. As suggested by Park et al. \[36\], the gradient of the curve is a good indicator of the sensors integrity and bond quality. With an increased gradient the PWAS signal begins to closely match that of a free sensor, suggesting a degradation of the adhesive layer and sensor debonding. On the other hand, a reduction in gradient can be attributed to a fracture of the sensor or degradation in its material properties\[36\].

While comparing the impedance spectra provides a simple way of assessing damage in a structure, it still remains somewhat of a qualitative approach which can make it difficult to determine the extent of damage/degradation. As a result, damage metrics are commonly
used as a simple way to compare and summarise data sets, providing a more quantitative assessment $^{19,37}$.

One of the most commonly used methods is the "root-mean-square deviation" (RSMD), which is based on a frequency-by-frequency comparison of the sensors impedance $^{17,38,39}$:

$$RSMD = \sqrt{\frac{\sum_{i=1}^{n}[Re(Z_{i,1}) - Re(Z_{i,2})]^2}{\sum_{i=1}^{n}[Re(Z_{i,1})]^2}}$$ \hspace{1cm} EQ. 9

Where, $Z_{i,1}$ is the baseline impedance, $Z_{i,2}$ is the impedance being compared and $i$ the frequency interval. The larger the RSMD value is, the greater the difference between the two signals, thus suggesting a greater severity of damage.

One of the main problems with using this method however is that it doesn’t account for horizontal and vertical shifts in the signal, which can be attributed to several factors including changes in temperature. Some PWAS parameters, such as the dielectric and strain constant are highly dependent on temperature $^{25}$. To account for this, several other damage metrics / algorithms have been developed to compensate this effect. Krishamurthy $^{40}$ developed a software-based correction technique, which was able to eliminate the temperature effects on a PWAS while not eliminating the effects of structural damage. This method although requires the temperature coefficient of the PWAS to be acquired prior to testing.

Park et al. $^{41}$ has also investigated the effect temperature changes can have with a modified version of the RSMD metric which was able to compensate shifts in impedance. Although this didn't account for drops in peak amplitudes, it was shown to significantly improve the damage metric and allowed for easier detection of damage. While, Raju $^{37}$ used a method referred to as the "cross correlation" metric, which produced similar results.

**Impedance measuring equipment**

The fundamental equipment when performing impedance testing is an Impedance Analyser. The most commonly used analysers include the HP-4192A and its successor the HP-4194A, which can operate at 5Hz-13MHz and 100Hz-40 MHz respectively. A variety of measurements can be taken with these devices, including complex admittance $|Y|$, complex
impedance $|Z|$, phase angle $\theta$, and the real and imaginary parts for both $R-X$ & $G-B$. The HP-4194A also has a display screen which allows the user to view the graphical result. As both machines are several decades old they don't have direct data storage to modern equipment, as such a GPIB data bus is required to connect them to a computer for post-processing of results.

A significant study on the HP-4192A was undertaken by Raju [37], which looked at the effect of a variety of factors can have of a PWAS impedance, including the wire length and the applied input voltage. For the wire length tests, wires ranging from 1 metre to 30 metres were tested, with results showing that only a small vertical shift occurred with increasing wire length. The input voltage tests were conducted to determine the effect it has on the detection of damage and involved four voltage levels ranging between 1.0 volts to 0.01 volts. These results showed that the noise level in the impedance increased as the voltage level was reduced; which was at an acceptable level up to 0.1, any lower and the noise would significantly alter the impedance spectra.

Figure 2-7- Comparison between impedance analysers
a) Analog Devices Inc. AD5933 $^{[42]}$ b) HP 4192A

One of the main drawbacks of using both machines, however is their cost, size and weight, particularly the HP-4194A. For laboratory work this is less of an issue, however if an EM impedance system were to be integrated into a structure, for example an aircraft, weight and size play a critical role. Some prototype and commercial impedance analysers have been developed which has been shown to produce high-quality results, while being small and light weight. Xu and Giurgiutiu $^{[43]}$ developed their own impedance analyser which
required a function generator to create the signal. The impedance spectra for PWAS was found to match up very well with the HP 4194A, only some small discrepancies were noted which may have been caused by a calibrated resistor or the terminal configuration. Analog Devices Inc. also produces two single chip impedance measurement devices, AD5933 and the AD5934. Park et al. [42] and Mascarenas [44] used the AD5933 version in the research in developing wireless impedance systems, which was significantly cheaper than a traditional impedance analyser. The impedance results from an MFC patch when using AD5933 were found to closely match a HP 4194A, however its main drawback is that it could only scan between a range of 10–100 kHz.
2.5. PWAS Integration

Unlike traditional ultrasonic NDT methods, which use a transfer medium (gel, water) to transmit waves from sensor to structure, PWAS are physically attached to a structure and as a result allows them to be more efficient in sending and receiving waves [17]. When it comes to integrating sensors with a structure, PWAS can be either bonded to the surface or for the case of composite materials they can be embedded in the material. In this section advantages and disadvantages of both techniques will be discussed, along with factors which need to be considered when selecting each integrating method.

2.5.1. Surface bonded

The conventional method for attaching PWAS to a structure is to adhesively bond them to the substrate surface. This technique can be used with various materials and is commonly implemented as it generally requires only minimal modifications to the manufacturing process. Also, it shouldn't have any effects on the structure’s mechanical properties.

For a bonded PWAS the adhesive layer plays an important role, as it is responsible for transferring the strain from the sensor to the structure and vice versa [45]. Given its importance, numerous studies have looked into the influence of the adhesive layer has on a PWAS performance [45-47]. Several factors have been identified as part of the bonding process which can help to ensure a high-quality bond and to achieve maximum strain transfer. One of which is the surface preparation, as sanding and cleaning can remove contaminants such as dirt and oil which could result in the PWAS not fully bonding to the substrate surface.

Selecting an appropriate type of adhesive is also critical, as failure to do so could cause premature debonding of the sensor and lead to an added costs for re-bonding. Factors such as the operating conditions of the structure being monitored (temperature, moisture, ect), adhesive stiffness and required operating lifetime need to be considered before selecting the adhesive used. Having said this however, the option to re-bond the PWAS is available unlike embedded methods, where it is not possible to replace them.

The most common adhesive utilised for SHM are Cyanoacrylate adhesives and epoxies, which are commonly used for bonding strain gauges [34, 48, 49]. Cyanoacrylate adhesives, such as M-Bond 200, are suitable and convenient for short-term monitoring where
environmental factors don’t play a significant role \[^{34, 50}\]. The main advantage of using Cyanoacrylate adhesives is that they cure at room temperature, generally within a few minutes and only require finger pressure to ensure a good bond. For long-term health monitoring periods, epoxies such as M-bond AE-10 and 610 are more appropriate, which are more durable when it comes to operating temperatures and exposure to wet/moist conditions \[^{34}\]. One drawback however, is that they have significantly longer cure time, greater than 6 hours. To achieve the maximum strength, post-curing may be required which can be difficult depending on the size and type of structure the sensor is being attached to.

Once bonded there are a number of additional factors which need to be considered, such as verification of bond quality and the thickness of the adhesive. Determining if a sensor was fully bonded can be a difficult process and aside from measuring its EM impedance, techniques using laser vibrometers can also be implemented \[^{46}\]. Controlling the thickness of the adhesive layer is also a challenge during manufacturing and an investigation by Quing et al. \[^{51}\] looked at how this can affect the EM impedance of the PWAS. The results showed that as the thickness increased so did the amplitude of resonant peaks and also caused a shift to lower frequencies.

2.5.2. Embedded

The unique advantage of using composite materials over metals is that PWAS can be bonded to the surface and embedded between the composite plies. In some cases, this may be more efficient in transferring Lamb waves into a structure and increase the damage sensing range. Embedding PWAS may also help improve their durability by protecting them from being exposed to impact and liquids. Although having many advantages, several considerations need to be made when embedding sensors into composites.

Firstly the method for manufacturing the composite, whether using prepregs or woven fabrics, the curing temperature and pressure required should be considered as they may cause cracks and/or depolarise the sensor. Another consideration is the effect embedding the sensor has on the mechanical properties of the composite. Ideally from a design point, the sensors shouldn’t have any effect on the stiffness or strength of the composite structure. However, this can be dependent on the sensor size, type of composite material, stacking sequence and the method for embedding the sensor.
Several investigations have looked into different methods for embedding sensors and their effect on the strength and stiffness of the composites \[^{52-55}\]. These methods range from relatively simple designs, which can be easily used with current manufacturing methods, to more complex methods which would be time-consuming and costly to manufacture. A diagram showing three common methods can be seen in Figure 2-8 and a list of their advantages and disadvantage listed in Table 3.

![Figure 2-8- Embedding methods](image)

**Figure 2-8- Embedding methods**

a) Insertion b) Cut-out c) Interlaced

<table>
<thead>
<tr>
<th>Embedding method</th>
<th>Advantages</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion</td>
<td>• Easy to manufacture</td>
<td>• Can create large resin rich region</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• uneven on top surface</td>
</tr>
<tr>
<td>Cut-Out</td>
<td>• Smooth top surface</td>
<td>• Cutting plies may reduce strength</td>
</tr>
<tr>
<td>Interlaced</td>
<td>• Smooth top surface</td>
<td>• Requires significant manufacturing time</td>
</tr>
<tr>
<td></td>
<td>• Reduced resin rich zone</td>
<td>• cut plies may reduce strength</td>
</tr>
</tbody>
</table>

From those studies, it would appear that embedding a PZT in a composite has a varied reaction to the mechanical properties of the composite. While the Young's modulus in most cases remained unaffected, the ultimate strength is dependent on the lay-up method. When it comes to interlacing, it would appear to only delay the onset of damage and not increase the strength when compared to the cut-out method. The ratio of width of PZT vs. specimen
width would also have an effect on mechanical properties, however this was not considered in the study.

Other issue which needs to be considered when embedding sensors in composite structures includes the material used, as carbon fibres are conductive and may short-circuit the sensor. As such, an electrical insulation material such as Kapton or Teflon is often required. This however may weaken the interfacial strength between the sensor and composite. There are currently a few commercial products available which have PWAS integrated with a dielectric film and use circuit printing to connect the sensors, see Figure 2-9. The advantage of printed circuits is that it allows for the sensors to be precisely located and can be used in a network to monitor large areas [56].

Finally, how the lead wires exit the material need to be considered. Given in most cases the edges of the material need to be trimmed, any embedded wires would also be cut rendering the sensor inoperable. Ghasemi-Nejhad et al. [57] came up with several possible options and compared them, which included embedded, cut-out holes and moulded in holes. Based on their rating system, embedded was the most favourable, but noted it is very much depended on the application.
2.6. Durability of PWAS

As already presented, a significant amount of research has been undertaken proving the effectiveness of PWAS for identifying damage in structures. However, if they are relied upon for detecting damage for an extended period of time, then concerns about their durability arise. Exposure to certain environment may alter their performance, so during the data analysis stage factors such as degradation may need to be taken into account to prevent misdiagnosis of damage, inaccurate results and false alarms.

In this section, a review of the work already undertaken with regards to PWAS durability will be discussed, which included both environmental and mechanical effects.

2.6.1. Environmental effects

PWAS will be required to monitor various types of structures under different environmental conditions, so understanding how this can affect their performance needs to be considered and fully understood. Structures can be subjected to a variety of environmental conditions during their operation, including temperature, moisture and exposure to chemicals. These conditions may not significantly affect the structure, however may damage or alter the sensors and its performance.

Temperature

The temperature on an aircraft can vary significantly during operation, depending on ambient weather, altitude and component location, for example near an engine. Certain electrical properties of PWAS can vary with increasing temperature and more importantly once the Curie temperature is reached the sensors loses it piezoelectric effect.

Studies into the effects of high temperatures, cryogenic and cyclic temperature have on APC-850 PWAS has been conducted by Lin and Giurgiutiu \[^{34}\] \[^{58}\]. Both free sensors and sensors bonded to an aluminium substrate were tested using a number of adhesive types, including M-Bond 200, M-Bond 610 and AE-10. For the high-temperature testing, the free and bonded sensors were placed in an oven for 30 min interval where the temperature was ramped up to the desired level, after which the PWAS were then cooled and had their impedance measured. For the free sensors, the results showed that little change in the impedance occurred up to 260°C. With further increase in temperature, a significant change
was then observed with the loss in piezoelectric properties, indicating it had reached its Curie temperature. For bonded sensor, it was observed that up to 94 °C no significant change occurred. However after this point, a noticeable drop in the performance was observed and by 204 °C the resonate peaks had diminished to a point where the sensor could be considered as failing. Given that the bonded sensors degraded much sooner at lower temperature compared to the free sensors, it could suggest that the mismatch in thermal expansion between the sensor, adhesive and aluminium resulted in damage.

The Cryogenic testing was conducted by placing the samples in liquid nitrogen (-196 °C) for 10 minutes before removing them and measuring their impedance. Both the free and AE-15 bonded specimens survived 10 submissions and maintained their peak EM impedance value. The M-bond 200 PWAS where else failed to last one submersion before failing, which was attributed to the adhesive only having an operating zone from -184 to +93 °C which caused it to fail.

Finally, the effect of temperature cycling on the performance of PWAS was investigated. Both free and bonded sensors with M-bond 20 were placed in an oven and cycled between 38-85 °C. In the early stages of testing both specimens showed a setting-in period with a small drop in impedance before eventually levelling off. The free PWAS were tested up to 1,700 cycles without any significant change in their performance. The bonded specimens where else lasted 1,400 cycles without any changes. After this, a small drop in impedance occurred between 1,500 and 1600 cycle, with a significant drop finally noticed after 1,700 cycles. This significant drop was attributed to the failure of the adhesive interface which was verified using C-scan equipment; Figure 2-10 shows an example of a poorly bonded sensor and a good bond.
Moisture and exposure to outdoor conditions

Moisture is another factor which can influence Lamb wave propagation. Depending on the application, the SHM system may be fully immersed in water or subjected to wet and humid environments. Possible consequences to the PWAS and adhesive may include, short-circuit of the sensor caused by moisture penetrating into the material, softening of the adhesive layer and de-bonding.

The type of substrate material used may also be significantly impacted by moisture. Unlike metallic, the matrix material in polymer composites absorbs moisture through the process of diffusion. Depending on the type of matrix, thermoset polymers such as epoxies can absorb moisture between 2-4% by weight and thermoplastic resins up to 1%\(^4\). This can result in a softening of the matrix and a reduction in the glass transition temperature. Consequently, this causes a degradation of mechanical properties of the composite, particularly those matrix dominated at elevated temperatures.

The classical method for predicting moisture absorption is Fickian behaviour, which applies to most epoxies. This behaviour assumes that moisture is absorbed at a logarithmic rate before reaching an equilibrium moisture content, where it is fully saturated and will no longer increase in mass. The maximum amount of moisture that can be absorbed is controlled by the humidity level while the rate of absorption is affected by the temperature. A graph representing the role humidity and temperature levels can be seen in Figure 2-11. This processes in often fully reversible by drying the composite and thus removing the moisture.

**Figure 2-10- C-scan image of bonded PWAS \(^{34}\)**
a) Poorly bonded sensor b) Good bond

![C-scan image of bonded PWAS](image_url)
from the matrix. For those matrix materials which don’t follow Fickian behaviour, the effect of moisture can vary, within some extreme cases chemical or physical breakdown can occur resulting in a significant drop in mechanical properties.

![Figure 2-11- Fickian diffusion](image)

**Figure 2-11- Fickian diffusion**  
a) Influence of humidity level   b) Influence of temperature

The effect of long-term exposure to different environmental conditions was investigated by Lin \[^{34}\] where free and surface bonded PWAS to aluminium substrates were exposed to outdoor weather conditions, rain humidity and elevated temperatures. The study examined many factors including adhesive types and the addition of protective coatings. After 120 weeks, four out of the eight free sensors were survived, with polyurethane and silicone coating found to be the most effective in protecting the sensors. For the bonded specimens only two sensors functioned correctly, with adhesive failure being the primary cause.

Schubert and Herrmann \[^{59}\] investigated the influence of hot/wet conditions on PWAS bonded to a carbon/epoxy composite. This study looked at the changes in the resonant frequencies and dampening of PWAS when they subjected to 70°C and 85% relative humidity in an environmental chamber. The results showed that the \(A_0\)–mode for the PWAS shifted towards higher frequencies as the exposure time increased. In addition, it was also seen that the dampening factor increased, which was likely to have been a result of the increase in mass and a change in the mechanical properties of the resin matrix. One area which was not investigated was the failure mechanisms of the adhesive layer and whether debonding or degradation had occurred.
Finally, the effects of long-term exposure of common aviation fluids were also investigated by Lin et al. [34]. This included distilled water, saline, kerosene and a variety of hydraulic fluids. Free PZT's were submerged in these fluids for up to 128 weeks and had their EM impedance measured at weekly intervals. Apart from the specimen submerged in saline, all of the other sensors were survived the testing. The saline was found to corrode the soldered connection which occurred after 15 weeks and resulted in the lead wire to disconnect.

2.6.2. Mechanical effect

Apart from environmental effects, PWAS are also likely to be subjected to mechanical loads, which could include static loading, fatigue and impact. Such loading could result in numerous types of damage including micro cracking, large cracks and degradation in the adhesive layer.

Static and fatigue loading

Research by Doane and Giurgiutiu [48] looked at the effect of both large strains and fatigue loading on a PWAS, which was bonded to 1 mm thick aluminium using M-bond 200. For the large strain testing, the EM impedance was recorded at intervals up to a strain of 7,200με. Results showed that between 3,000 – 4,000 με the EM impedance overall shape remained unchanged, with the peak amplitude reducing by 60% which almost recovered fully after unloading. After this point, a significant change occurred to the impedance and was not recovered after unloading. The final failure occurred at above 7,200 με which was caused by a crack in the PZT.

For the fatigue loading, a 1mm diameter hole was drilled into the aluminium to act as a stress concentration and help to ensure the specimen’s failure would not happen where the PWAS was bonded. Five specimens were tested under different mean tensile load, varying from 577- 1,157 N. All PWAS survived the testing with the aluminium always failing first. After an initial settling in period (from between 50k-100k cycles) the EM impedance remained constant up until failure. For the specimen which was cycled between 107 N- 1067 N it took approximately 12.2 million cycles for failure, indicating a high fatigue life for the PZT and adhesive.
The effect of large strains and fatigue loading on the performance of PWAS has also been investigated by Kuhn et al.\cite{49} Pairs of the sensors were used in a pitch-catch systems, which were bonded to aluminium using an M-bond and epoxy adhesive. Although having different properties, both adhesives performed the same under both loading conditions. Under static loading and up to 3,000 με, the output voltage exhibited only a small reduction. On the other hand for fatigue loading, 510K cycles at 800 με had no effect on the output voltage. For the case of 510k cycles at 1,700 με a 15% reduction in voltage occurs in the first 100k cycles with it then levelling off. Finally cycling PWAS at 2,600 με resulted in an 18% reduction after 390k cycle with a large standard deviation.

Paget \cite{60} also looked at static and fatigue loading of PWAS, which were embedded in a carbon/epoxy composite laminate. The PWAS used in the study were 10mm X 10mm and were simply inserted into the cross-ply composite. For the static case, the impedance only reduced by 12% at an applied stress of 560 MPa. For the fatigue tests, 400k cycles at ±0.15% failure strain were tested with only a slight reduction in the Lamb wave response of the PWAS. For higher levels (±0.20% and ±0.30%) of the failure strain a significant reduction was observed between 50k -100k cycles. This was attributed to matrix cracking and debonding between adhesive and PWAS, which was more noticeable for the 0.30% case.

Finally, Muscat \cite{61} looked at bonded PWAS under 4-point fatigue bending. The PWAS used were SONOX P502 Diam. 8.7 X 0.5 mm WFB and were manufactured by Cermatec. These were bonded to a carbon/epoxy laminate, with a layup of [45, -45, 90, 0]. Each specimen had two PWAS so that the pitch-catch method could be used. For the 4-point bending the surface with the PWAS was placed under tension and tested at three strain levels, 4K με, 6,000 με and 7,000 με. All PWAS failed before 100k cycles, with cracks developing where the wires had been soldered to the sensors. A possible reason for this could have been due to the high temperature of the soldering, which may have damaged the sensors and caused them to fail after a lower number of cycles than expected.

From these investigations, it would appear that under static loading PWAS are able to survive strain levels between 3,000-4,000 με without any significant drop in their performance. While under cyclic fatigue, a variety of load / number of cycle combinations have been tested. In general, it would appear PWAS have quite a good fatigue life, however with a mixture of load and strain control used it is difficult to draw any definitive conclusion.
**Impact Loading**

In the open literature, a limited number of publications have been found in which investigate the effect of impact loading on the functionality of a PWAS. As identified by Kessler \[21\] and Chambers \[22\], before an SHM system could be certified, impact testing on PWAS would be necessary for distinguishing between damage sensor and structural damage. Most research conducted so far has only looked at the detection of impact damage in a structure \[62, 63\]. However in an aircrafts lifetime it is also highly possible a tool drop, bird strike or hail could damage a PWAS.

Research has been conducted at RMIT University by Hayei \[64\]. For their testing, 230 X 40 mm carbon/epoxy prepregs were used with a layup of \([0/\pm 45/90]_s\). APC-850 PWAS with a dimension of 6.35-0.25 mm were then bonded to the specimens using a conductive glue, with wires connected to both the top of the PWAS and composite. The impacts were applied with a flat impactor which acted on the opposite side to the PWAS and was either applied directly above the PWAS or 30 mm away. For the direct impact case, the capacitance of the PWAS appeared to increase as the number of impacts increased at a low impact level. As suggested in Park \[36\] this can be contributed to the degradation of the bonding layer. For the case of the impact at 30 mm away from the PWAS the capacitance remained relatively constant until failure.
2.7. Numerical Modelling of Piezoelectric Materials

In addition to experimental testing, numerical modelling also plays an important role in achieving a greater understanding of the performance of piezoelectric sensors under different loading conditions. Over the past few decades, numerical modelling methods have progressed significantly, with advancement in both Finite Element (FE) packages and computational capabilities. While previously only simple analyses could only be performed; now more complex systems can easily be studied and take hours, not days as they used to. While numerical models can be used to investigate the influence of a piezoelectric sensor’s shape and material properties, they can also provide an insight into how structures and sensors interact with each other. In addition, they can be used in helping to distinguish between structural damage and sensor degradation/damage.

Numerous studies using the Impedance method have been undertaken in recent times, which have looked at piezoelectric materials and PWAS integrated with a variety of materials. This includes aluminium [65-67], concrete [68, 69] and fibreglass [70]. Lalande [71] was one of the first to looked at the dynamic behaviour of a piezoelectric ring using shell elements in ANSYS. A strong correlation was found with an impedance based analytical model.

Bhalla [68, 69] and Lim [65] developed 1D and 2D models of aluminium and concrete structures with a simplified representation of PWAS as a force and moment, and were able to derive the sensor’s impedance from the structural characteristics. Makkonen et al. [72] then developed their own FE code which was able to incorporate both the mechanical and electrical components for modelling a piezoelectric device. By conducting a harmonic analysis, they were able to study the electrical response of various electrode shapes. They also compared the results for a variety of geometric shapes using 2D and 3D models and found a full 3D model achieved the most accurate results.

Once coupled field elements were introduced into the FE packages such as ANSYS, Liu and Giurgiutiu [67] were able to study the electrical impedance of square and circular PWAS. Results were obtained directly from the sensor and closely matched the experimental results, as shown in Figure 2-12. The study also compared the impedance of a 1D steel beam using an FE structural simulation, FE model using coupled field elements and an analytical
model. Of the methods investigated, the coupled field model was found to produce the most accurate results.

![Figure 2-12: Comparison of real impedance between experimental and FEA][67]

Gresil et al. [70] continued this work and investigated a PWAS, bonded to a GFRP specimen, using a similar method with the coupled field elements. Once a 2D model had been developed, they investigated the effects of dampening, adhesive layer degradation, sensor damage and delamination in the composite. Interestingly, for the adhesive degradation model, the slope of the imaginary admittance curve decreased rather than increasing as reported in Park [36], which may suggest a 2D model was not the most appropriate option. Finally, a 3D model was generated, which showed relatively good agreement with the experimental results at low frequencies.
2.8. Conclusions

This chapter has presented a review of publications relating to PWAS and their use in SHM systems. The review has included the theory behind PWAS, methods for detecting damage in structures, durability studies and numerical simulations.

Implementation of PWAS is a promising SHM technique due to their ability to detect various types of damage over relatively large regions. Of the methods for detecting damage, the EM impedance method was identified as the simplest for measuring the sensors performance and detecting damage, as only one sensor is required and minimal analysis is needed to distinguish between structural and sensor damage.

Many aspects of PWAS durability were identified as part of this review and those areas which have been investigated were discussed. Degradation of PWAS under static and fatigue testing was identified as one critical area, and while several studies have already looked into their effects on PWAS, due to variations in testing procedures and data collection, it is difficult to draw any major conclusions.

Another area identified as warranting further investigation is the effect of impact events, due to the lack of studies into this area. Given the brittle nature of PWAS this is considered as a critical aspect of their durability. Low-velocity impact events may not cause damage to the host structure but could break the sensors or degrade the adhesive interface, leading to misdiagnose of damage.

A majority of studies so far have also been focused on PWAS bonded to metallic structures. Composite materials are becoming commonly used in aircraft structures due to their enhanced material properties compared to those of metals such as aluminium. Besides, composite laminates have the advantage in that not only can PWAS be bonded to their surface they can also be embedded between plies. As studies have shown, it would appear embedding PWAS has little to no effect on the composite materials properties and embedding them could help to improve their durability. However, the extension of PWAS degradation in embedded systems has not been thoroughly investigated.

When working with composites, the environmental effects such as hot/wet conditions could have a large impact on their performance. To the best of author’s knowledge, only one
study has directly investigated the behaviour of PWAS bonded to composites subjected to humidity. Further investigations into the role of sensors, the adhesive layer and substrate material should be undertaken for both bonded and embedded sensors.

Numerical models of PWAS can also help to provide a greater understanding into their performance and how they interact with hosting structures. PWAS simulations have progressed significantly in recent time and so far 3D models of free PWAS have been found to yield impedance results that closely match the experimental findings. When it comes to integrating PWAS with structures, most studies have only investigated 2D models, which is likely due to the high computational time associated with more complicated models. However thanks to advances in software packages and computing power, this investigation hopes to be able to provide further insight by generating a 3D model.

This review has identified several gaps in literature and the aims of this thesis, which were listed in section 2.2, are to address some of these critical areas of uncertainty and build upon the current investigations.
3. Manufacturing and Damage Identification

3.1. Introduction

In this section, the manufacturing methodology and the methods used for identifying damage shall be discussed. To begin with, the materials used and methods for bonding and embedding the sensors are discussed, this includes the PWAS, composite materials and bonding adhesive. This is then followed by the methods for identifying degradation and monitoring the sensor's performance during the experimental testing. Finally the results from a statistical analysis of PWAS performance before and after being integrated with the host composite is presented and discussed.

3.2. Manufacturing Test Specimens

3.2.1. Materials

Piezoelectric sensor package

When it comes to piezoelectric sensors, there are a variety of types to choose from and deciding on a particular type is highly depending on the application. For this investigation APC-850 (Navy II) PWAS were selected, which are manufactured by APC International Ltd. [25]. This type of sensors are commonly used for SHM and have already been utilised for durability studies [17, 34, 49]. Some of the main reasons for this selection are related to their excellent electrical and mechanical properties, along with a relatively high curie temperature when compared to other piezoelectric materials. This is particularly important given that some of the PWAS would be embedded in a carbon fibre composite, where they will be subjected to high temperatures in an autoclave. All PWAS used were circular disc-shaped with a diameter of 6.35 mm (1/4 inch) and had a thickness of 0.254mm. This size was chosen after consulting with industry and since they have been used in several SHM studies [17, 34, 49]. A summary of the material properties can be found in Table 3-1, with the full data sheet available in Appendix 1.
Table 3-1- PWAS material properties

<table>
<thead>
<tr>
<th>APC Material 850 (Navy II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative dielectric constant</td>
</tr>
<tr>
<td>Curie temperature</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Young’s Modulus</td>
</tr>
<tr>
<td>Y11</td>
</tr>
<tr>
<td>Y33</td>
</tr>
<tr>
<td>Tensile strength</td>
</tr>
<tr>
<td>Poisons ratio</td>
</tr>
</tbody>
</table>

For this investigation, two different electrode pattern were chosen, solid electrodes and WFB (Wrap-around electrode). An image of both types can be seen in Figure 3-1.

Figure 3-1- Types of PWAS electrode patterns

For the specimens where the PWAS were embedded in the carbon fibre composite, the solid electrode type was chosen, which has its silver electrodes on each side of the sensor. Temco 28 AWG (diameter 0.36mm) magnet wires were soldered to the PWAS, which has an insulation temperature rating of 200 °C [73], which is 10% above the curing temperature of the composite. In selecting this wire several others sizes were considered, however, this particular size was chosen as it was found to be less prone to breakage during manufacturing and had an insignificant impact on the material properties of the composite when they were embedded. To prevent carbon fibres from short-circuiting the PWAS, Kapton tape was used as an insulator, with each layer having a thickness of 30 µm. An illustration of the PWAS package can be seen in Figure 3-2.
For the specimens where the PWAS would be bonded to the host composite, WFB (Wrap-around electrode) type was used. This electrode type has an insulation strip which enables the bottom electrode to wrap around the edge of the sensor and sits on the top surface of the PWAS. This allows both wires to be soldered on the same surface and thus a flat surface for bonding to the composite. The thicknesses of the wires were not a major concern for the bonded sensors, so 22 AWG Teflon insulated wires (diam. 0.64 mm) were used.

**Carbon Fibre Composite**

As carbon-fibre-reinforced polymer (CFRP) composites are commonly used for aircraft structures, AS4-3501-6 CFRP prepreg tape was selected for all testing, which consists of AS4 3k carbon fibres in a Hexcel 3501-6 epoxy matrix. This material is extensively used in primary aircraft structures, in particular high-temperature regions. A summary of its material properties can be found in Table 3-2.

<table>
<thead>
<tr>
<th>AS4-3501-6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibres</td>
<td>AS4 Carbon 3 K</td>
</tr>
<tr>
<td>Fibre Volume fraction</td>
<td>62%</td>
</tr>
<tr>
<td>Ply thickness after cure</td>
<td>0.27 mm</td>
</tr>
<tr>
<td>Density</td>
<td>1580 Kg/m³</td>
</tr>
<tr>
<td>Cure cycle</td>
<td>2 h at 177°C and 100 psi</td>
</tr>
<tr>
<td>Young modulus (E₁₁)</td>
<td>126 GPa</td>
</tr>
</tbody>
</table>

The layup configuration chosen for all testing was [0,±45,90]₅₁, which is well suited to a variety of testing conditions, in particular impact. The steps for manufacturing the CFRP specimens are listed below.
1. Cut the CFRP prepreg into 300 x 300 mm panels with the desired ply angles.
2. Layup down the first four layers in the configuration listed.
3. Place panel in the debulking machine to remove any air from the laminate, preventing voids between the plies and in the resin matrix.
4. Place down the remaining 4 layers and again debulk.
5. Vacuum bagging – Using an aluminium tool, the laminate was vacuum bagged as indicated in Figure 3-3.
6. The composite was then placed in the autoclave and cured at 180°C and 100 psi for 2 hours. The ramp rates used was approximate 2°C/min.
7. Each panel was then cut using a diamond toothed saw, producing specimens which were 35 X 28 X 2.2 mm.

![Diagram of vacuum bagging composite laminate](image)

**Figure 3-3- Vacuum bagging composite laminate**

*Bonding Adhesives*

For bonding the PWAS to the composite Loctite 406 was chosen, which is a Cyanoacrylate adhesive. The main reasons for its selection were its short curing time and its low cost compared to many other adhesives. Loctite is somewhat susceptible to liquids, which is why it was only used for mechanical testing in a controlled environment. For studies where environmental factors would be considered, an epoxy such as M-Bond AE-10 would be appropriate.

**3.2.2. Bonded PWAS specimens**

For surface bonded specimens, once the CRFP panels were cut to the desired size, the PWAS were bonded using a similar method as used for bonding strain gauges. A
summary of the step-by-step process is listed below and an image of the equipment used can be seen in Figure 3-4.

1. Surface preparation – Using 600 grade sandpaper and M-Prep Conditioner-A, the bonding surface of the composite was cleaned so to remove any dirt and oils. This process was repeated until the surface became dull and smooth. Gauze was then used to wipe the surface dry.

2. Mark out sensor location – The location of the sensor was marked out using a 4H lead pencil. The M-Prep A and cotton buds were then used to further clean the surface and remove any excess lead remaining on the surface.

3. Neutralise surface – Using M-Prep Neutraliser 5A and cotton buds, the surface was then cleaned to remove the conditioning agent. Gauze was then used to wipe the surface dry.

4. Attaching PWAS using tape – Using Mylar tape, the PWAS was then placed onto the composite in the location marked out.

5. Apply Catalyst - The tape was then pulled back to expose the sensor and a light coating of M-bond catalyst was then applied.

6. Apply adhesive – Two drops of the adhesive were then placed in the junction between the tape and the composite. The tape is then pulled back slowly onto the composite ensuring a thin layer of adhesive is created.

7. Apply pressure - A small amount of pressure was then applied to the sensor using a finger, to help ensure it properly bonds to the surface. After 2-3 min the pressure was taken off and the tape then slowly removed.

Figure 3-4- Equipment used for bonding sensors

In order to measure the thickness of the adhesive layer, a few specimens were cut in half, polished and then examined using an optical microscope. This was a challenging process, as
often when cutting the sensor in half, would result in damage to the sensor or cause debonding, which can lead to false measurements. A microscopic image of one of the bonded sensors can be seen in Figure 3-5. On average, the thickness of the adhesive layer was 10 μm; however this was found to vary significantly particularly at the edges of the sensor. This variability can be contributed to a number of factors including, the amount of adhesive deposited, the pressure applied and the smoothness of both the PWAS and CFRP bonding surface. It is expected a more consistent thickness could be achieved in large-scale manufacturing when more precise equipment is available.

![Figure 3-5- Bonded PWAS](image)

**3.2.3. Embedded PWAS specimens**

As discussed in the literature review chapter, several factors need to be considered when embedding the PWAS into the CFRP. After reviewing the possible techniques, it was decided the insertion method would be employed, with the PWAS package embedded into mid-plane of the composite. This is the simplest technique, making it easier to manufacture a large number of specimens, and prior testing found this technique to have no significant impact on the strength and stiffness of the CFRP. A picture illustrating how the PWAS package was embedded can be seen in Figure 3-6.

![Figure 3-6- Embedded specimen](image)
The method for manufacturing the CFRP panels was the same as previously discussed, with an additional step incorporated. After debulking the first 4 CFRP plies, a template was then placed on top on the panel with the required location on the PWAS, a copy of which can be seen in Appendix 2. Each PWAS package was then carefully positioned and a small strip of Kapton tape was used to keep them in place. Once all 5 sensors were in place, the template was then carefully removed and the remaining 4 composite plies were then laid down and debulked.

During manufacturing two main problems were encountered, the wires breaking off at the end of the composite, and the failure of a significant number of the sensor during curing. The main reason for the wires breaking was believed to be a result of the resin from the composite seeping out during curing and this caused the wires becoming brittle. To prevent this, small pieces of Kapton tape were placed on the edges where the wires exited the composite, as seen in Figure 3-6. This helped to prevent the resin from attaching its self to the wires and resulted in fewer breakages.

Specimens where the PWAS was found to have failed were sectioned and studied using an optical microscope. As can be seen in Figure 3-7 a), the PWAS's were subjected to a bending load, causing them to crack. To visualise this better, sample specimens were made with Teflon sheets placed on either side of the sensor, so that after curing the panel could be opened up and the PWAS inspected. An image of a cracked PWAS can be seen in Figure 3-7 b).
Several attempts were made to resolve this issue, which included varying the curing pressure from 100 psi to 45 psi, however, this was unsuccessful. As can be seen in the figure, the size of the solder was relatively large and a lot of skill was required to produce consistent results. As such, attaching the wires was outsourced to APC, which was able to reduce the solder size by more than 50%. In addition, two extra layers of Kapton tape were used, with a section cut out around the solder, so as to produce a flatter surface for the sensor to rest on. After making these changes, a significant improvement in the sensor's survivability after curing was observed, with the survival rate going from 25% to 95%. An image of a typical successfully embedded PWAS is shown in Figure 3-8, along with a top view of a PWAS before embedding.

Figure 3-8 a) shows the resin rich zone adjacent to the sensor, which had a length of 0.7mm and at an angle of 10°. Having this shallow angle should help to reduce the waviness of the carbon fibre and minimise any change in the stiffness of composite laminate as a result of embedding the sensor.
Figure 3-8- Embedded PWAS
a) Sectioned view  b) Top view
3.3. Damage Identification

3.3.1. Data acquisition

To measure the PWAS performance and detect possible degradation/damage, the EM impedance and capacitance of the PWAS was measured using a HP-4192A LF Impedance Analyser. As this instrument does not have a graphic display or data acquisition system, a National Instruments (NI) General Purpose Interface Bus (GPIB) acquisition bus was utilised and connected to a laptop computer for controlling the instrument's functions. A LabView virtual instrument was then created with an NI driver \(^{[76]}\), which was able to remotely control all the instrument's functions and record all data. The main user interface of the VI allowed for the control of frequency range, step size and measurement mode. Other functions, such as voltage or bias, could be changed in the block diagram if required. A diagram of this setup can be seen in Figure 3-9.

![Figure 3-9 - Setup for impedance measurements](image)

Once the wires from the PWAS were connected to the impedance analyser's test fixture, the LabView run button was used to activate the VI. The first step in the sequence was to measure the capacitance of the sensor, which was measured at 1 kHz. Once completed, the machine was switched to the impedance measurement mode for measuring both the real and imaginary impedance simultaneously. After sweeping through the frequency range, both sets of data were then plotted graphically, this could then be easily exported to Excel for further analysis. For all measurements, the impedance was measured with a 1-volt input and a frequency sweep of either 1-100 kHz at 1kHz intervals or 100 kHz - 2 MHz at 5 kHz intervals, which should be sufficient for detecting both small and incipient damage.
3.3.2. PWAS performance

During manufacturing and prior to testing, free and bonded/embedded PWAS had their electrical response measured to determine the consistency of their performance. In this section, an example of their performance is presented, along with a comparison of their response before and after being attached to the CFRP. This is then followed by a statistical analysis, which compares the performance of all 100 of the WFB and 35 of the Solid electrode PWAS.

**WFB electrode before and after bonding**

An example of a WFB response before and after being bonded to the CFRP can be found in Figure 3-10. The real impedance, as seen in Figure 3-10 a), was measured between 100 kHz and 2 MHz, which captures the first 4 resonant peaks of the PWAS, with the 1st being at 345 kHz. As can be seen from this figure, the signal for the free sensor was found to be quite noisy, when compared to a solid electrode PWAS (refer to the next section), and is likely to be caused by the irregular shape of the electrode. Once bonded, this noise diminished, which was the result of restraining the sensor and increasing its dampening. Bonding the PWAS also caused a noticeable drop in the amplitude of each peak and a shift to higher frequencies, with the 1st mode shifting to 520 kHz. The imaginary admittance, derived from the inverse of its impedance, was measured between 1-100 kHz. As can be seen in Figure 3-10 b) bonding the PWAS caused a reduction in the gradient of the curve, which is consistent with finding from previous studies [36].

![Figure 3-10- WFB PWAS response before and after embedding](image)

a) Real Impedance  b) Imaginary Admittance
A statistical comparison of the PWAS performance was also performed and can be seen in Figure 3-11. This includes the real impedance and capacitance values, which were compared to determine the reliability of the sensor’s performance and the manufacturing method. Of those measurements compared, the maximum impedance for the free PWAS, Figure 3-11 a), was found to be the most inconsistent case and varied by up to 50%. The capacitance, Figure 3-11 c), was found to drop from 1.76 nF to 1.44 nF after bonding. With no signs of damage in the sensor, it would suggest the capacitance could be a good indicator of determining any changes in bond quality during testing.

![Figure 3-11- Statistical analysis of WFB PWAS before and after embedding (box plots)](image)

- a) Real Impedance
- b) 1St Anti-Resonance Frequency
- c) Capacitance

**Solid Electrode before and after embedding**

A typical impedance response for a solid-electrode PWAS before and after being embedded in the CFRP can be seen in Figure 3-12. The real impedance signal for the free sensor, Figure 3-12 a), was noticeably less noisy compared to that of the WFB and while having very similar resonant frequencies, its amplitude was on average nearly two times greater than that of the embedded one. Interestingly after being embedded in the CFRP composite, the resonant frequencies for the Solid-electrode PWAS were almost identical, while the amplitude did not drop as much when compared to surface bonded sensors. The gradient of the imaginary admittance, seen in Figure 3-12 b), was almost identical for the free and embedded PWAS, in contrast to the previous case. This would suggest that the gradient of
the imaginary impedance may not be effective in identifying damage at the sensor and CFRP interface.

![Figure 3-12- Solid PWAS response before and after embedding](image)

**Figure 3-12- Solid PWAS response before and after embedding**

a) Real Impedance  b) Imaginary Admittance

The Statistical analysis for the solid-electrod PWAS can be seen in Figure 3-13. The measurement of most interest was the capacitance, which was unchanged after embedding. This result is consistent with the imaginary admittance, as both are highly dependent on the dielectric properties of the sensor.

![Figure 3-13 - Statistical analysis of solid PWAS before and after embedding (box plots)](image)

**Figure 3-13 - Statistical analysis of solid PWAS before and after embedding (box plots)**

a) Real Impedance  b) 1st Anti-Resonance Frequency  c) Capacitance
3.4. Conclusion

This chapter has described the materials selected and manufacturing methods for both the bonded and embedded PWAS. For those bonded sensors, the technique adopted was based predominantly on methods used for bonding strain gauges. When embedding the PWAS in the composite some issues were encountered which included, the sensors cracking and the wires breaking off after manufacturing. Eventually after a number of trials, a reliable manufacturing technique was achieved with an acceptable failure rate.

Furthermore the methods for assessing the durability of PWAS were discussed. This included measuring the capacitance and EM impedance of the sensors, which will be compared before and after each test. In addition to the electrical measurements, the combination of optical microscope and SEM imaging were used to provide an insight into the reasons behind any change in performance.

Finally, a statistical analysis was then undertaken which compared the electrical performance of the PWAS before and after being integrated with the composite specimens. This showed the consistencies in sensor performance after manufacturing, which provides confidence in the chosen manufacturing methodologies. This information will also prove to be useful when identify possible damage during experimental testing.
4. Influence of Static and Fatigue Loading on PWAS

4.1. Introduction

During their operations, PWAS are likely to be subjected to numerous loading conditions, including both static and fatigue loads. Understanding how these loading conditions affect the performance of PWAS is vital in determining the parameters they will be most effective in for an SHM system.

As was identified in the literature review, numerous studies have investigated the durability of bonded PWAS under both static and fatigue conditions \[^{48, 49, 60, 61}\]. These however have predominantly only looked at tensile loads, with the presumption that being a ceramic material PWAS would perform better under compression loading. Also with a varied range of load/strain levels tested and performance measurements taken to assess the sensors durability, it is difficult to come to any clear conclusion.

For this investigation, four-point bending was chosen as the testing method, as it gives the unique ability to subject the bonded PWAS to both tensile and compressive surface strains at the same time. Not only will this allow for a direct comparison, but it also eliminates the need to test each loading case separately, saving a considerable amount of time and effort. In addition to bonded sensors, PWAS embedded in a carbon/fibre composite laminate were also included in the test matrix. Being embedded in the mid-plane, the PWAS will be subjected to lower stresses and are expected to be able to withstand higher applied surface strain levels.

4.2. Testing Procedure

The methodology for both the static and fatigue testing was based on ASTM-D6272 \[^{77}\], which required minor adjustments to account for variations in the testing setup and procedure. An Instron Electro Pulse E3000 testing machine was used for all tests, which was capable of producing loads up to ±3,000 N during dynamic loading and can operate at frequencies over 100 Hz \[^{78}\].

An illustration of the test setup can be seen in Figure 4-1. As shown, a loading to support span of 1:2 was used, with the loading span of 80 mm and a support span of 160 mm. The loading span to thickness ratio was significantly greater than that is recommended in the
testing procedure but was chosen to ensure the PWAS, which was placed midway between the loading noses, would be subjected to a relatively constant strain and out of plane displacement. To prevent the specimen from moving from side-to-side or back and forwards during the fatigue testing, support brackets were also used which were covered in Teflon to minimise any friction with the specimen.

Due to limitations with the test setup, an LVDT sensor used to measure deflection and to calculate surface strain, could not be mounted between the support fixtures. As such, CFRP specimens equipped with strain gauges were statically loaded. These strain gauges \[^{79}\], with at gauge length of 10 mm were bonded to the composite specimens using the same method as described for the PWAS \[^{75}\]. These specimens were then loaded in the four-point bending rig so that the relationship between surface strain and cross-head displacement could be established. This information would then be used to determine the required cross-head displacement for a given strain level for the static and fatigue testing. In addition to plain CFRP specimens, strain gauges were also bonded to specimens with embedded PWAS. This was done to determine if embedding the sensors had any significant effect on the bending stiffness of the CFRP specimens.

![Figure 4-1- Four-point bending setup](image-url)
After establishing the relationship between cross-head displacement and strain level, static tests were conducted. Using displacement control with a rate of 1mm/s, the specimens were loaded from 2,000 µƐ up to 8,000 µƐ, at 1,000 µƐ intervals. At each strain level, specimens were held under loading for 5 minutes and then unloaded, where the capacitance and impedance of PWAS was measured. The specimens were then loaded up again to the next strain level. A graph illustrating the loading sequence can be seen in Figure 4-2.

![Figure 4-2- Loading sequence for static testing](image)

After determining the effects of static loading on the performance of PWAS, the fatigue testing was conducted under displacement control to produce a sinusoidal waveform with a constant amplitude. The maximum applied strain levels used in this study was between 2,000 µƐ – 6,000 µƐ. For each test, a ratio of maximum strain to minimum strain (R-ratio) of 0.2 was used, which was chosen to ensure the testing machine could properly achieve the required displacement. At surface strain levels between 2,000 - 3,000 µƐ a frequency of 12 Hz, for strain levels between 4,000 - 5,000 µƐ a frequency of 10 Hz, and for a strain level of 6,000 µƐ a frequency of 8 Hz was used. Each specimen was fatigued up to 260,000 cycles, which is a conservative estimation of the number of cycles an aircraft may experience over 10 years [80]. The PWAS durability was monitored during the test by recording the sensor's output voltage using an oscilloscope. At predetermined intervals the tests were stopped, with the impedance and capacitance of PWAS then measured. A summary of the test matrix can be seen in Table 4-1, and an image of the testing equipment and setup is given in Figure 4-3.
### Table 4-1 - Test matrix

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>PWAS integrations</th>
<th>Maximum Surface strain (µƐ)</th>
<th>levels tested</th>
<th>Repeats</th>
<th>Total Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>Bonded-Tension/Compression</td>
<td>2,000 - 8,000</td>
<td>-</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Embedded</td>
<td>2,000 - 8,000</td>
<td>-</td>
<td>5</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Bonded-Tension/Compression</td>
<td>2,000 - 6,000</td>
<td>5</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Embedded</td>
<td>3,000 - 6,000</td>
<td>4</td>
<td>3</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27</td>
</tr>
</tbody>
</table>

---

**Figure 4-3- Fatigue testing equipment and setup**

Including, oscilloscope, impedance analyser and computer, Instron E300
4.3. Results and Discussion

4.3.1. Surface strain and stiffness measurement

The preliminary tests were conducted to establish a relationship between cross-head displacement and surface strain and to identify the possible effects of embedding the PWAS had on the bending stiffness of CFRP specimens. As shown in Figure 4-4 a), the composite specimens without bonded PWAS exhibited a reasonably linear relationship for out-of-plane displacement and surface strain. The slight nonlinearity is likely due to the specimen's slipping on the supports, due to the larger deflection at high strain levels. The results for all three tests matched with a high level of consistency. For the CFRP specimens with embedded PWAS the strain levels were however found to be less consistent, with two of the five specimens having a lower gradient, Figure 4-4 b). As can be seen, the embedding of PWAS had no significant effect on the stiffness of the laminate with both values around 60,000 N/m.

![Figure 4-4- Static testing results](image)

a) Cross head displacement vs. surface strain   b) Bending Stiffness

Based on the results from these tests, a calibration curve for the average displacement vs. surface strain was obtained. This curve was then used to determine the displacement range for the static and fatigue tests (see Table 4-2).
### Table 4-2 - Surface strain and cross-head displacement for static and fatigue testing

<table>
<thead>
<tr>
<th>Maximum strain level (με)</th>
<th>Static Testing</th>
<th></th>
<th>Fatigue Testing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Displacement (mm)</td>
<td>Mean Disp. (mm)</td>
<td>Amplitude (mm)</td>
<td></td>
</tr>
<tr>
<td>2,000</td>
<td>4.13</td>
<td>2.50</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td>3,000</td>
<td>6.42</td>
<td>3.82</td>
<td>2.60</td>
<td></td>
</tr>
<tr>
<td>4,000</td>
<td>8.84</td>
<td>5.24</td>
<td>3.60</td>
<td></td>
</tr>
<tr>
<td>5,000</td>
<td>11.34</td>
<td>6.70</td>
<td>4.63</td>
<td></td>
</tr>
<tr>
<td>6,000</td>
<td>14.05</td>
<td>8.24</td>
<td>5.81</td>
<td></td>
</tr>
<tr>
<td>7,000</td>
<td>16.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8,000</td>
<td>19.96</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 4.3.2. Static testing

In this section the results from the static testing are discussed where the specimens were loaded under four-point bending from a surface strain level of 0-8,000 με. The normalised capacitance for the PWAS versus the applied strain level is illustrated in Figure 4-5. This includes the results for PWAS, either bonded to the compressive surface (C), tensile surface (T) and those embedded (E) in a composite laminate.

![Figure 4-5- Strain level vs. normalised capacitance for PWAS](image)

As can be seen from Figure 4-5, the normalised capacitance for the PWAS subjected to compression showed almost a bilinear behaviour. While the increment rate was small up to 3,000 με, the normalised capacitance increased at a greater rate when the applied strain was higher than 3,000 με. Eventually, at 8,000 με the capacitance of PWAS closely matched that of a free sensor. Based on the previous work [36], the increase in capacitance would indicate that sensor debonding is occurring, although a visual inspection during testing...
showed no signs of damage to the specimen. The SEM images were taken after applying the maximum strain level and those results shall be discussed later in this chapter.

For the PWAS bonded on the tensile surface, a 6% increase in the normalised capacitance was noticed after only 2,000 με. Once the strain level was further increased, the capacitance then remained constant suggesting any PWAS debonding had ceased. The final plot “Static-E” shows the variation of the normalised capacitance by increasing the applied strain for the embedded PWAS. Considering the sensor was embedded in the mid-plane where the strain level is considerably lower than the surface strain, very little change in its performance was observed.

The impedance of PWAS for a selected few strain levels is illustrated in the following figures, which includes both the real impedance and imaginary admittance. The impedance of a PWAS subjected to a compression strain of 5,000 με and 8,000 με is shown in Figure 4-6, specimen C-2. As was found with the capacitance results, for strain levels below 5,000 με there was a very little shift in the real impedance curve, Figure 4-6 a). Beyond this point, however, a significant shift in all four frequency modes occurred, and at 8,000 με twin peaks could be seen. The imaginary impedance, Figure 4-6 b), shows that as the strain level was increased so did the gradient of the curve and at 8,000με the slope closely matched the results of a free sensor. These observations agree with the capacitance results previously presented and suggest that sensor debonding was occurring.

Figure 4-7 shows the SEM images of the PWAS subjected to a compression strain of 8,000 με and clearly shows adhesive failure at the PWAS - adhesive interface. A crack in the PWAS was also observed which may have caused the distorted observed at 8,000 με.
Figure 4-6- Impedance for bonded PWAS subjected to compressive strain
a) Real impedance b) Imaginary Admittance

Figure 4-7- SEM images of bonded PWAS subjected to 8,000 με (compression)
a) PWAS debonding b) Crack in PWAS

Figure 4-8- Impedance for bonded PWAS subjected to tensile strain
a) Real impedance b) Imaginary Admittance
The effect of static loading on the performance of a PWAS subjected to tensile strain is illustrated in Figure 4-8, (T-1). As with the capacitance results, after an initial settling in period, very little change in the impedance and admittance was observed. For the real impedance (Figure 4-8 a), a small reduction in peaks was observed, while a shift to the left was also seen at higher frequencies. Since the imaginary admittance, Figure 4-8 b), did not change, it is suggesting the sensor still had a good bond quality up to 8,000 με. One possible reason for the initial change in performance could be due to excess glue on the top and sided of the PWAS, which became detached after applying a low strain level.

The real impedance and imaginary admittance for a PWAS embedded in the CFRP is shown in Figure 4-9 (E-2). For this case, unlike the capacitance measurements, the real impedance, Figure 4-9 a), exhibited a reduction in its peak value from 300 ohms to 225 ohms, which occurred between 5,000 – 8,000 με. At the same time, the slope of the imaginary admittance, Figure 4-9 b), did not change with the increase in applied strain. The SEM images of the embedded specimens can be seen in Figure 4-10. The sensor showed no signs of damage as a result of the static loading, which would suggest the reduction in the real impedance may have been caused by a degradation in the PWAS piezoelectric properties. Upon closer inspection delaminations between Kapton tape layers and at the resin interface were found. Given the imaginary admittance did not change as a result of these delaminations; it would suggest this technique is less effective for embedded PWAS in detecting interfacial damage.
Figure 4-9 - Impedance for PWAS embedded subjected to tensile strain
   a) Real impedance b) Imaginary Admittance

Figure 4-10 - SEM images embedded PWAS subjected to static loading

Delamination at Kapton-Resin interface
4.3.3. Fatigue testing

In this section, the results of the fatigue testing are presented and as with the static case the PWAS were bonded, either on the compression or tension side or embedded in CFRP laminates. The maximum surface strain levels tested in this study were between 2,000 – 6,000 µε, with Table 4-2 listing the corresponding displacements associated with these strain levels.

Bonded PWAS under compressive

A summarised version of the results for the PWAS subjected to compression strain can be found in Table 4-3. Due to the variability in bonding conditions and sensor performance, it was somewhat difficult to directly compare results for a particular strain level. As such, a selection of the results will be presented which depict the trends observed during testing.

Table 4-3: Effect of cyclic loading on the performance of PWAS subjected to compression

<table>
<thead>
<tr>
<th>Strain Level (µε)</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>2k-1</td>
<td>2k-2</td>
<td>2k-3</td>
</tr>
<tr>
<td></td>
<td>No Change</td>
<td>No Change</td>
<td>-</td>
</tr>
<tr>
<td>3,000</td>
<td>3k-1</td>
<td>3k-2</td>
<td>3k-3</td>
</tr>
<tr>
<td></td>
<td>0-40k cycles debonding, Stable</td>
<td>0-40k cycles debonding, 60k fail, depolarised (?)</td>
<td>0-80k cycles debonding, Stable</td>
</tr>
<tr>
<td>4,000</td>
<td>4k-1</td>
<td>4k-2</td>
<td>4k-3</td>
</tr>
<tr>
<td></td>
<td>0-60k cycles debonding, Stable</td>
<td>0-20k cycles debonding, Stable</td>
<td>0-40k cycles debonding, Stable</td>
</tr>
<tr>
<td>5,000</td>
<td>5k-1</td>
<td>5k-2</td>
<td>5k-3</td>
</tr>
<tr>
<td></td>
<td>Stable after 10k cycles</td>
<td>120K fully debonded</td>
<td>60K fully debonded</td>
</tr>
<tr>
<td>6,000</td>
<td>6k-1</td>
<td>6k-2</td>
<td>6k-3</td>
</tr>
<tr>
<td></td>
<td>Stable after 40k cycles</td>
<td>60k fully debonded</td>
<td>40k fully debonded</td>
</tr>
</tbody>
</table>

Figure 4-11 a) shows the peak output voltage of bonded PWAS vs. the number of cycles for various compressive strain levels. The specimens subjected to 2,000 µε compression strain (2k-1) had a relatively steady output voltage with a peak voltage of around 8 volts. The output voltage versus time for these PWAS had a consistent sinusoidal shape (Figure 4-11 b)), which matched that of the applied frequency the test fixture.
Once the compressive strain level increased, the output voltage was found to reduce significantly for those PWAS subjected to 3,000 (3k-1) and 4,000 με (4k-3), as shown in Figure 4-11 a). Considering the fact that increasing the strain levels should have increased the output voltage, the reduction of the voltage in these cases suggests some degree of degradation in either the piezoelectric materials properties or the adhesive layer. The only exception to this observation was specimen 3k-2, which stopped functioning after 60k cycles. No visible signs of damage could be seen upon inspection of this specimen, with one possibility being the PWAS was depolarised by a magnet used to attach the loading noses to the fixture.

Finally, for the high fatigue strain levels of 5,000 and 6,000 με, the output voltage of the PWAS dropped with the increasing number of cycles. However in a majority of cases, the entire PWAS debonded from the specimen. Upon visual inspection, cohesive failure was observed in these specimens.
Figure 4-11- PWAS output voltage under compression
a) Comparison of peak output voltage with various strain levels
b) Output voltage for 2k-1 c) Output voltage for 4k-1
As with the static tests, the capacitance of the PWAS was measured at specific intervals while the specimen was subjected to fatigue. The normalised capacitance of PWAS for different strain levels is shown in Figure 4-12. Aside from the 2,000 με case (2k-1), the capacitance for all of the other PWAS increased between 0-60k cycles, which would indicate some degree of debonding between PWAS and the hosting composite. For the specimens subjected to 5,000 and 6,000 με, once the PWAS had fully detached after 140k cycles the capacitance matched that of a free sensor. Therefore, it can be concluded that the sensor was not degrading as a result of the fatigue testing and only cohesive failure was occurring.

The impedance curves for the PWAS subjected to different compression strain levels can also be seen in Figure 4-13 to Figure 4-15. As with the output voltage and capacitance, the impedance and admittance for the 2,000 με case remained consistent up to the 260k cycles. At the next strain level, 3,000 με, as illustrated in Figure 4-14, a significant change after only 10k cycles can be identified. For the real impedance, Figure 4-14 a), the resonant frequency shifted to the left and its magnitude increased by 500%. The slope of the imaginary admittance increased initially and after 100K cycles remained constant, with a slope almost that of a free sensor. Lastly, when the strain level was increased to 5,000 με and above, Figure 4-15, immediate changes occurred only after 10k cycles. As mentioned previously, many of the sensors fully detached during the fatigue testing, and the corresponding impedance results were comparable to those before bonding, suggesting again no damage had occurred to the PWAS while being subjected to fatigue.

![Figure 4-12- Normalized capacitance for PWAS under compression](image-url)
Figure 4-13- Impedance for PWAS subjected to fatigue at 2,000 με (compression)  
a) Real impedance b) Imaginary admittance

Figure 4-14- Impedance for PWAS subjected to fatigue at 3,000 με (compression)  
a) Real impedance b) Imaginary admittance

Figure 4-15- Impedance for PWAS subjected to fatigue at 5,000 με (compression)  
a) Real impedance b) Imaginary admittance
Figure 4-16 - SEM images of bonded PWAS subjected to 4,000 με (compression)

The SEM images of bonded PWAS subjected to a cyclic compressive strain level of 2,000 με showed no signs of damage to the PWAS or adhesive layer. This was reflected in their electrical response which remained constant over 260k cycles. When the strain level was then increased, signs of debonding of the PWAS were evident as can be seen in Figure 4-16, (4k-1). The micrograph in this figure shows a specimen, subjected to a compressive strain of 4,000 με, and experienced extensive signs of cohesive failure at the PWAS-adhesive interface.
**Bonded PWAS under tension**

A summarised version of the results for the PWAS subjected to tension is presented in Table 4-4. Unlike those sensors subjected to compression, none of the sensors detached but as will be discussed, some variations in the performance were observed.

**Table 4-4: Effect of cyclic loading on the performance of PWAS subjected to tension**

<table>
<thead>
<tr>
<th>Strain Level (µƐ)</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>2k-1</td>
<td>2k-2</td>
<td>2k-3</td>
</tr>
<tr>
<td></td>
<td>No Change</td>
<td>No Change</td>
<td>-</td>
</tr>
<tr>
<td>3,000</td>
<td>3k-1</td>
<td>3k-2</td>
<td>3k-3</td>
</tr>
<tr>
<td></td>
<td>After 10k stabilised and little change</td>
<td>After 10k stabilised and little change</td>
<td>After 10k stabilised and little change</td>
</tr>
<tr>
<td>4,000</td>
<td>4k-1</td>
<td>4k-2</td>
<td>4k-3</td>
</tr>
<tr>
<td></td>
<td>After 10k stabilised and little change</td>
<td>After 10k stabilised and little change</td>
<td>After 10k stabilised and little change</td>
</tr>
<tr>
<td>5,000</td>
<td>5k-1</td>
<td>5k-2</td>
<td>5k-3</td>
</tr>
<tr>
<td></td>
<td>After settling in, changed after 200k</td>
<td>No major change</td>
<td>After settling in, changed after 80k</td>
</tr>
<tr>
<td>6,000</td>
<td>6k-1</td>
<td>6k-2</td>
<td>6k-3</td>
</tr>
<tr>
<td></td>
<td>After 10k stabilised and little change</td>
<td>No major change</td>
<td>After 10k stabilised and little change</td>
</tr>
</tbody>
</table>

As with the compression case, the output voltage for the PWAS subjected to tension strain was measured during the cyclic loading and is depicted in Figure 4-17 a). The output voltage of the PWAS initially dropped quite dramatically in the first 10k cycles, which for the 3k-2 case was a drop of 400%. The output voltage was then fairly consistent up to 250k cycles. As expected, increasing the tensile strain level produced a higher voltage which ranged from 1.5V for the 2,000 µƐ case and up to roughly 3.5 v for the 6,000 µƐ case.

An example of the output voltage versus time for the 4k-2 specimens subjected to a strain level of 4,000 µƐ is shown in Figure 4-17 b). After just 1k cycles, an apparent double peak was noticed in initially a sinusoidal behaviour. Applying further cyclic loading resulted in more distortion and lower amplitude of the output voltage.
Figure 4-17 - PWAS output voltage under tension

a) Comparison of peak output voltage with various strain levels
b) Output voltage for 4k-2

Figure 4-18 shows the normalised capacitance for the sensors subjected to different levels of tensile strain. The results showed that the capacitance was fairly steady during testing for those cases between 2,000-4,000 με, after an initial settling in period. For the specimen subjected to a maximum tensile strain of 5,000 με (5k-1), a noticeable increase of approximately 4% occurred after 120k cycles, suggesting that debonding of the PWAS may have occurred. For the last strain level tested (6k-1), an increase of 7% in the capacitance after just 10k cycles was observed for the remaining number of cycles. The SEM images showing the extent of damage shall be presented later on in this chapter, however, based on these capacitance results 4,000 με would appear to be the upper strain limit without significant debonding occurring.

Figure 4-18 - Normalised capacitance for PWAS under tension
Finally, examples of the impedance curves for the sensors under tension can be found in Figure 4-19 to 24. The real impedance results for the 4,000 με case can be found in Figure 4-19 a) which showed only a small shift in the resonant peak frequencies during the test while the slope of the imaginary admittance, Figure 4-20 b), was relatively stable after an initial increased. At a higher strain level of 6,000 με, Figure 4-20, the real impedance not only shifted but the maximum peak was increased significantly from 150 - 300 ohms. Again the imaginary admittance was relatively stable after an initial settling period. These results support the previous conclusion of the PWAS debonding.

![Figure 4-19- Impedance for PWAS subjected to fatigue at 4,000 με (tension)](image)
a) Real impedance b) Imaginary admittance

![Figure 4-20- Impedance for PWAS subjected to fatigue at 6,000 με (tension)](image)
a) Real impedance b) Imaginary admittance

An SEM image analysis of the fracture surface of specimens showed no signs of cracking on the PWAS or interfacial debonding at strain levels up to 4,000 με. By increasing the applied strain to 6,000 με, visible signs of damage were observed, as shown in Figure 4-21. As noted
in Table 4-4, two damage mechanisms were identified for this load case. In Figure 4-21 a), as with the compressive case, cohesive failure at the adhesive-PWAS interface and a crack between the silver electrode and the piezoelectric material was noticed. From the three specimens tested at this strain level, the PWAS on specimen 6k-2 had minimal change in its performance during the cyclic loading. This behaviour is reflected in the SEM images of this specimen Figure 4-21 b), where no signs of bonding degradation in the adhesive layer can be identified, however, a small vertical crack in the PWAS was evident. Given that the sensor's performance was not affected by the number of cycles, the crack may have occurred during sectioning of the specimen. Possible reasons for why this specimen did not experience debonding may include better surface preparation during the manufacturing or excess adhesive at the edges of the PWAS that prevented the debonding initiation. This however, would require further investigation, which was not undertaken as part of this study.
Figure 4-21 - SEM images of bonded PWAS subjected to 6,000 με (tension)
a) PWAS debonding (6k-1)  b) Crack in PWAS (6k-2)
**Embedded PWAS**

A summary of the effect of fatigue loading on the behaviour of embedded PWAS can be seen in Table 4-5. Generally speaking, there was little to no change in the performance of the embedded sensors. It was only at an applied surface strain level of 6,000 με, where the 1st peak of the real impedance increased, which would indicate damage at the PZT-CFRP interface.

**Table 4-5- Effect of fatigue loading on the performance of embedded PWAS**

<table>
<thead>
<tr>
<th>Applied Surface Strain level (µƐ)</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,000</td>
<td>3k-1</td>
<td>3k-2</td>
<td>3k-3</td>
</tr>
<tr>
<td></td>
<td>No Change</td>
<td>No Change</td>
<td>No Change</td>
</tr>
<tr>
<td>4,000</td>
<td>4k-1</td>
<td>4k-2</td>
<td>4k-3</td>
</tr>
<tr>
<td></td>
<td>No Change</td>
<td>Gradual shift in 1st peak</td>
<td>-</td>
</tr>
<tr>
<td>5,000</td>
<td>5k-1</td>
<td>5k-2</td>
<td>5k-3</td>
</tr>
<tr>
<td></td>
<td>Gradual shift in 1st peak</td>
<td>Gradual shift in 1st peak</td>
<td>Gradual shift in 1st peak</td>
</tr>
<tr>
<td>6,000</td>
<td>6k-1</td>
<td>6k-2</td>
<td>6k-3</td>
</tr>
<tr>
<td></td>
<td>Significant increase in 1st peak</td>
<td>Gradual shift in 1st peak</td>
<td>Significant increase in 1st peak</td>
</tr>
</tbody>
</table>

The output voltage for a selection of the PWAS is presented in Figure 4-22, where for most cases after the initial settling period the voltage was fairly constant. As expected, the output voltage was considerably lower than that of the bonded cases, given the embedded PWAS was in the mid-plane of the specimen and would be subjected to lower strain levels. The waveform for specimen 6k-1 can be seen in Figure 4-22 b), which showed that after only 1k cycles the voltage was no longer a sinusoidal shape. After applying 10k cycles, the peak voltage was found to have reduced by around 50%, indicating either sensor degradation or damage at the PWAS interface.
**Figure 4-22- Output voltage for embedded PWAS**

a) Output voltage at various strain levels  
b) Output voltage for 6k-1

**Figure 4-23- Normalised capacitance embedded PWAS**

**Figure 4-24 - Impedance for PWAS subjected to fatigue at 6,000 με (tension)**

a) Real impedance  
b) Imaginary admittance
The capacitance and impedance for the embedded sensors are presented in Figure 4-23 and Figure 4-24. As with the static testing, the capacitance and imaginary impedance for the PWAS did not change as a result of the fatigue loading. The only fatigue level that caused a significant change in the real impedance was the 6,000 με level. As seen in Figure 4-24 a), the magnitude of the 1st peak increased by around 110 ohms, which is a shift towards the response of a free PWAS. The SEM images of the 6k-1 specimens, illustrated in Figure 4-25, showed significant delamination between Kapton layers and at the PWAS and resin-rich region interface. This is likely the reason why a reduction in output voltage and an increase in the real impedance was observed.

![Figure 4-25- SEM image of embedded PWAS at a fatigue level of 6,000 με](image-url)
4.4. Conclusion

The focus of this chapter was on the effect of static and fatigue loading on the degradation of bonded and embedded PWAS. The chosen method for investigation was four-point bending since it allows simultaneous study of the surface-bonded PWAS subjected to compressive and tensile strain.

For the static testing, those PWAS subjected to compression strain were found to perform the poorest, with a significant change in the performance after being loaded above 4,000 με. The SEM image analysis showed both sensor debonding and existence of cracks in the PWAS were the cause of this change. Those PWAS exposed to tensile strain where else performed much better and after an initial settling in period, remained stable up to 8,000 με. Finally, as expected the embedded PWAS, which was subjected to lower strain levels in the mid-plane, performed well up to a high surface strain level of 8,000 με. While the capacitance was found to remain constant, there was a small reduction in the 1st anti-resonant peak, which based on the SEM images may have been a result of minor delamination between Kapton layers.

As with the static testing, the PWAS subjected to compressive fatigue loading performed the poorest and the sensor debonding was found to occur at a strain level as low as 3,000 με. The PWAS tested under tensile fatigue loading were able to survive up to full 260k cycles at 4,000 με without any significant changes. Once again, the sensor debonding and cracks at the silver electrode – piezoelectric material interface was observed in specimens subjected to high level of surface strain. For those specimens with PWAS embedded in the mid-plane of CFRP laminates only the strain level of 6,000 με caused a change in the real impedance, while the capacitance and imaginary admittance remained unchanged.

Based on these results, the capacitance and slope of the imaginary admittance are good indicators of the sensor bond quality, which was verified with the SEM images. These techniques, however, were not effective in detecting delamination between Kapton layers and the PWAS for those embedded specimens. The only noticeable change occurred to the real impedance, which is predominantly used for detecting damage in the structure. This then creates a challenge of how one can distinguish between the two modes of damage for embedded PWAS. Another common theme observed during the study was debonding of the
PWAS, which was particularly an issue for those sensors subjected to compressive strain. The adhesive layer thickness and surface preparation are two factors which would have had some influence, however, there are limitations controlling these parameters. The type of adhesive used would have also played a significant role in the sensor's debonding, however this was not included in the scope of this investigation.
5. Effects of Impact Events on PWAS

5.1. Introduction

Another area of interest when it comes to PWAS durability is the effect of impact loading on their integrity and performance. So far, most investigations have been focused on the identification of damage in the structures caused by impacts using PWAS, and no significant investigations have been undertaken to assess the durability of the sensors themselves. In some ways, understanding how the sensor performs when subjected to impact is almost as equally important as detecting the structural damage. False alarms and misdiagnosis of structural damage could lead to additional maintenance costs and have adverse effects on their reputation.

The aim of this particular investigation is to study the effects of impact loading on the durability of PWAS bonded to and embedded in a carbon/fibre composite laminate. Only low energy impact levels will be considered, which can be caused by events such as hail, tyre debris or small birds. Such events can cause BVID underneath the surface of the material and in some ways can be considered more critical when it comes to composites. Any impact do cause visible damage to a structure would more than likely be detected during a normal inspection, and not require a costly method such as SHM or NDT for it to be detected. Where else, BVID can significantly reduce structures strength and lead to failure without warning.

5.2. Test Procedure

The methodology followed during testing was adopted from ASTM D7136/D7136M, which is used to measure the damage resistance of composites subjected to impact events. The only major deviation in procedure was the support fixture and span, which was modified to accommodate for the specimen size. In an attempt to have consistent boundary condition as used for the static and fatigue testing, the same size specimens, 280 X 35 X 2.14 mm, and support span, 160 mm, were used.

The test rig was a double-column guide type, shown in Figure 5-1. The impactor system consisted of a spherical impactor head, with a diameter of 25.4 mm, a 100 kN force transducer and a crosshead structure, which contained the majority of the mass in the
system and had a set of bearing connecting it to the guide rails. The specimen clamping mechanism can also be seen in Figure 5-1, which involved two metal pins which were sandwiched together using screws. To ensure consistent boundary conditions, each screw was tightened to 5 N.m using a torque wrench before each test. The impact energy was controlled by altering the height of the impactor with respect to the specimen and was released using an electromagnetic system. This setup had no automatic catcher system to prevent rebound and multiple impacts from occurring. As such during testing, a wooden block was manually placed in-between the specimen and impactor head after each impact event.

The applied Impact energy was calculated based on the kinetic energy of the impactor at the time of impact, $E_k$

$$E_k = 0.5 \times M \times V^2$$

EQ. 10
where $M$, the mass of the impactor system was 1.25 kg. The velocity of the impactor at impact was calculated using a high-speed camera, which recorded at 5,200 frames per second and was used to measure the time it took the impactor to travel 10 mm. An example of a high-speed camera image can be seen in Figure 5-2.

In this study, five different impact energy levels were tested, which ranged from 4J to 12 J. These impact energy levels were selected as they covered a variety of levels while producing no visible damage to the composite specimens. Before testing, the energy levels were determined based on a given drop height, with each height recorded three times to ensure consistency in velocity results. A summary of the drop heights and specific impact energies tested can be seen in Table 5-1.

<table>
<thead>
<tr>
<th>Drop Height (m)</th>
<th>Average Impact Velocity (m/s)</th>
<th>Kinetic Energy ± Std. (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>2.51</td>
<td>3.96 ± 0.01</td>
</tr>
<tr>
<td>0.44</td>
<td>2.75</td>
<td>4.74 ± 0.14</td>
</tr>
<tr>
<td>0.6</td>
<td>3.39</td>
<td>7.03 ± 0.28</td>
</tr>
<tr>
<td>0.88</td>
<td>3.99</td>
<td>9.96 ± 0.34</td>
</tr>
<tr>
<td>1.16</td>
<td>4.36</td>
<td>11.93 ± 0.13</td>
</tr>
</tbody>
</table>
For Simplicity, when referring to these energy levels they will be referred to as, 4, 5, 7, 10 and 12 J. At energy levels above 12 J, surface damage and fibre breakage was evident in the composite host, while at 16 J significant damage in the form of delaminations were observed, as shown in Figure 5-3.

![Figure 5-3- CFRP specimen after subjected to 16 joule impact](image)

During events such as a hail storm, it is highly probable that multiple impacts could occur in close proximity to one another and PWAS would be expected to survive after being subjecting to these impact loadings. As such during this investigation each specimen would be subjected to a maximum of 9 impacts or until the PWAS was found to fail. Between each event, an inspection was undertaken to check for any visible signs of damage.

The final part of this study investigated the effects of impact location on the degradation of surface bonded and/or embedded PWAS. Impacts were applied 30mm (~ 5x the PWAS diameters) away from the sensor. For this case, in addition to having the PWAS located on the back surface and embedded, they were also bonded to the top surface which was not tested previously due to the sensor being a ceramic and a direct impact as low as 3 joule would have cause it to crack.

As with the fatigue testing, the capacitance and impedance of the sensors were measured before and after each impact event. The force imparted on the specimen was also measured to determine if embedding the sensors caused a reduction in bending stiffness of the host composite. Also comparing the force-time data after each impact is a viable technique to detect any possible damage caused by multiple impacts. Finally, the output voltage from the sensors at the time of impact was recorded using an oscilloscope, to study the PWAS performance degradation after repeated impacts. A list of the full test matrix for the impact testing can be found in Table 5-2.

Table 5-2- Test matrix impact testing
5.3. Results and discussion

5.3.1. Impact Force

While not a primary objective in this durability study, the force versus time history was recorded during the impact test. This data was used to detect possible structural damage in the CFRP specimens and to evaluate the effects of embedding the PWAS had on the specimen flexural stiffness. The force versus time history curves for the selected cases are shown in Figure 5-4, along with a summary of the maximum force and impulse which can be found in Figure 5-5. It should be noted that a 2,400 Hz low bypass filter was used on the raw data to reduce noise in the recorded signal. The possible noise sources were likely to be a combination of resonance in the impactor, force transducer and/or the specimen. Caution was taken when applying this filter to ensure any peaks or troughs caused by damage to the composite laminates were not removed from the signal. An example of a force versus time curve comparing the raw data to that of the filtered one can be seen in Figure 5-4 a).

The force-time history for the 4 J impact can be found in Figure 5-4 b). The performance of the bonded and embedded specimens was quite similar, with a maximum force of approximately 480 N and an impact time of 17 ms. However when the applied impact energy was then increased to 5 J, Figure 5-4 c), a clear discrepancy between the two specimens was identified. The bonded specimen experienced a maximum force of 615 N and an impact time of 16 ms, whereas for the embedded specimens the corresponding parameters were 480 N and 21 ms. A similar variation was also seen for the specimens subjected to 7 J impacts. With a higher impact force and shorter time for the bonded specimens, it would suggest that embedding the PWAS in the CFRP composites caused a
reduction in the specimen's flexural stiffness, which would seem to contradict the results seen of the four-point bending testing. One possible reason for this could be that the impact events, which is similar to three-point bending, causes a maximum stress at the point of contact and this was more sensitive to the local stiffness changes in the CFRP composite caused by the PWAS. Where else the four-point bending distributes the stresses over a larger region, which means it was less sensitive to the local changes in stiffness.

The result for the 10 J impact can be seen in Figure 5-4 d), and as with the previous energy levels, the maximum force and impact time varied between the bonded and embedded specimens. However additionally, the force-time results for the bonded specimen also show a significant variation in the shape of the curve, which was no longer parabolic. Several peaks and troughs are present which would indicate that damage had occurred to the specimens. After a visual inspection, apart from a few small splits/cracks on the surface, the specimen appeared to be undamaged, suggesting matrix cracking and perhaps delamination had also occurred. The force-time curve for the embedded specimen was much the same as the 7 J case, indicating no damage. The reason for this is again likely to be a result of variations in stiffness which meant the embedded specimen was able to absorb more energy without inducing damage.
A summary of the maximum force versus the applied energy levels for all specimens can be seen in Figure 5-5 a). As was previously discussed, after the 4 J case, a distinct difference between the bonded and embedded specimens was seen, which was between 12-28 %. For both specimen types as the applied energy level increased so did the maximum force, except for the 10 J bonded case where damage was seen. The impulse, the area underneath the force versus time curve, for each energy level can be found in Figure 5-5 b). As expected while the maximum force varied for the two specimen types as the energy level increased, the impulse applied was very much the same. The only noticeable difference again is the 10 J impacts, which is a result of the structural damage.
Figure 5-5- Effect of the impact energy on the 
(a) Maximum force (b) Impulse imparted
5.3.2. Degradation of PWAS subjected to direct impact

Surface bonded

In this section, the results of those PWAS bonded to the back face of the CFRP specimens and subjected to direct impact events are presented. As previously mentioned, up to 9 impacts were applied to each specimen or until a significant reduction in the performance of the sensor was observed. The first set of results is the normalised capacitance and can be seen in Figure 5-6. Due to the unpredictable nature of the impacts and variability in adhesive thickness all of the results are presented and in most cases two of the three samples tested at each impact level displayed a similar response.

![Figure 5-6- Normalised capacitance of bonded PWAS after impacts](image)

a) 4 Joule Impact  b) 5 Joule Impact  c) 7 Joule Impact  d) 10 Joule Impact
The results for the 4 J impact can be seen in Figure 5-6 a). In general, the PWAS were unaffected by the first impact event, then with repeated impacts an increase of up to 6% in the capacitance was observed, which would suggest some sensor debonding. Figure 5-6 b) shows the results for the 5 J impacts and as with the previous case, the PWAS capacitance showed little change after the first impact. While some signs of sensor debonding can be seen with the rise in capacitance, more importantly, a reduction in capacitance for two of the sensors was observed which occurred between the 3rd and 5th impacts. After visually inspecting the sensors no signs of damage were evident on the surface, with the most likely cause being a degradation of the PWAS electrical properties / damage to the sensor.

An example of the PWAS output voltage during a 5 J impact can be seen in Figure 5-7. The output voltage from the sensor peaks at more than 200 volts, which is significantly greater than the maximum recommended operating voltage of 5-7 volts/mm for the sensor, as listed in the PWAS material properties found in Appendix 1. This high voltage could be responsible for the degradation in the dielectric properties as a result of portions of the sensor de-poling.

![Figure 5-7- PWAS output voltage- 5 joule impact](image)

The results for the 7 J impacts can be found in Figure 5-6 c), which are similar to the 5 J case with signs of sensor debonding occurring after only one impact and a significant drop after the 3rd impact. For the final impact level 10 J (Figure 5-6 c), after only a single impact two of the three PWAS had a significant reduction in capacitance, roughly 80%. A visual inspection of the sensors revealed a longitudinal crack which was along the length of the PWAS, see Figure 5-8.
In addition to measuring the capacitance of the PWAS, the real impedance and imaginary admittance was also used to assess the sensor’s durability. The impedance results for a 4 J impact are shown in Figure 5-9. As seen, the real impedance and imaginary admittance were fairly consistent after being subjected to 9 impacts, with only small shift seen as a result of the first impact. This change is likely to have been caused by excess adhesive on the PWAS from the manufacturing process which separated after the first impact.

The next impact energy level tested was 5 J and the results from one of the PWAS can be found in Figure 5-10. As with the previous case the real impedance, Figure 5-10 a), had an initial shift after the first impact event. Up until the 3rd impact only a minimal change in performance was observed, however by the 5th impact we can see a dramatic transformation in the signal. The imaginary admittance, Figure 5-10 b), shows that as results of the 5th impact, the gradient of the curve dropped significantly suggesting sensor damage. The SEM images for one for the specimens can be seen in Figure 5-11, which shows two clear significant cracks (left image). The image on the right also shows cracking at the bottom electrode/piezoelectric material interface as well as sensor debonding.
Figure 5-9 - Impedance of bonded PWAS subjected to 4 joule impacts
   a) Real impedance b) Imaginary admittance

Figure 5-10 - Impedance of bonded PWAS subjected to 5 joule impacts
   a) Real impedance b) Imaginary admittance
The results for a specimen subjected to 7 J can be found in Figure 5-12. After the first impact, the real impedance, Figure 5-12 a), had its first resonant peak shift to the left and an increase in its magnitude, which is representative of sensor debonding. The curve for the imaginary admittance, Figure 5-12 b), also had its first peak increase in magnitude which would again indicate PWAS debonding. Further debonding occurred after the second impact, with the peaks for both curves increasing. Finally, the 3rd impact would appear to have caused damage to the PWAS, with the real impedance distorted and the slope of the imaginary admittance significantly diminished.

The final energy level tested for the bonded PWAS was 10 J and the results for which can be found in Figure 5-13. After just one impact both the real impedance and the imaginary admittance showed significant variations. The reduced slope of the imaginary admittance, Figure 5-13 b), clearly indicates damage to the PWAS. Given the significant change after only just one impact, further impacts were not applied. The SEM images from the fracture surface can be found in Figure 5-14. These images show major cracking to the PWAS, with both cracks in the piezoelectric material and at the interface with the electrode.
Figure 5-12- Impedance of bonded PWAS subjected to 7 joule impacts
  a) Real impedance b) Imaginary admittance

Figure 5-13- Impedance of bonded PWAS subjected to 10 joule impacts
  a) Real impedance b) Imaginary admittance
Figure 5-14- Bonded PWAS subjected to 10 joule impact
The degradation of embedded PWAS under impact loading is presented in this section. As with the bonded case, the specimens were subjected to impact energy levels of 4, 5, 7 and 10 J.

The normalised capacitance of PWAS after each impact event and under various impact energy levels can be found in Figure 5-15. In general, for most of the cases, the capacitance remained consistent throughout all of the impact energy levels and multiple impacts seemed to have an insignificant impact. The 4 J impact case, Figure 5-15 a), was surprisingly one of the cases which did show some variation in the normalised capacitance, in particular, specimen B3 which had a significant change after the first impact. This may however have been a defective/damaged sensor given that this was not observed in any of the other specimens tested at this energy level or the 5 J case. The results for the 5 and 7 J cases can be found in Figure 5-15 b) and c), which showed a gradual increase in capacitance as a result of increased number of impact, however, is not significant enough to draw any major conclusion. Finally, the 10 J case is shown in Figure 5-15 d) and these results also provide little insight into the PWAS quality. The only result of interest was from specimen B12 which stopped functioning after the 7th impact. The SEM images of this specimen will be presented later in this chapter.
With the capacitance providing little insight into the sensor quality or damage in the composite, the next set of results presented are the real impedance and imaginary admittance of the PWAS.

The results for the 4 J case are illustrated in Figure 5-16. The real impedance, Figure 5-16 a), show that the first impact caused a 20% reduction in the amplitude of the 1st resonant peak, while the remaining resonant peaks were unaffected. With repeated impact applied, a dramatic change in the signal was seen, with a significant reduction in the resonant peaks. The Imaginary admittance, Figure 5-16 b), shows applying impacts caused a reduction in peaks and a shift in frequency, while the gradient remained consistent. Based on these results, after applying the first impact a significant decrease in performance was seen which is likely to be a result of damage to the PWAS. The SEM images of the embedded PWAS after testing can be found in Figure 5-17, which shows numerous modes of damage. The most significant damage is the larger fracture in the sensor, Figure 5-17 left image. This is likely to have occurred between the 7th and 9th impact which corresponds to the
capacitance drop, but given the PWAS had fully cracked, it is interesting to observe that the sensor was still functioning. The image on the right shows both delaminations at the Kapton interfaces, which likely occurred after the first impact some minor cracking in the PWAS.

Figure 5-16- Impedance of embedded PWAS subjected to 4 J impacts
a) Real impedance b) Imaginary admittance

The results for the next impact energy level, 5 J, can be found in Figure 5-18. The real impedance result showed a similar trend as the previous case, in that the first impact resulted in a 15% reduction in the 1st resonant peak. After the 2nd impact, however, which caused a further 20% reduction, the PWAS impedance performance was fairly consistent. It was not until the 9th impact that the 1st peak became much sharper and a noticeable shift in the 2nd resonant frequency was identified. The imaginary admittance, shown in Figure 5-18 b), followed a similar trend as the real impedance with the impacts resulting in a reduction
in amplitudes and shift in peaks, in particular, the 2\(^{nd}\) and 3\(^{rd}\). The 9\(^{th}\) impact caused the most notable change with a vertical shift in the signal.

![Figure 5-18: Impedance of embedded PWAS subjected to 5 J impacts](image)

The real impedance variations were somewhat unexpected as the first 3 impact had no effect on the PWAS performance. When further impacts were applied, the amplitude of the 1\(^{st}\) resonant peak did decrease, by up to 20\% after the 9\(^{th}\) impact, however, the shape of the curve still remained consistent. The imaginary admittance is depicted in Figure 5-19 b), which also shows the performance of the sensor was generally constant, with the only minor variation being a slight shift in the 2\(^{nd}\) resonant peak after 9 impacts. The SEM images of this specimen can be found in Figure 5-20. As shown in the image on the left, delamination at the Kapton interfaces and resin-rich region can clearly be identified. The image on the right also shows a small crack which was propagating through the thickness direction. Unlike the 4 J case, this crack had not grown enough to fully fracture the PWAS, which is why the change in real impedance was less prominent than that of the fractured sensor. Possible reasons for less reduction of the real impedance, observed for this 7J case, could be due to misalignment of the impactor with the embedded sensor and/or the experimental variability since only three specimens were tested.
The final set of impedance results is for the 10 J case and can be found in Figure 5-21. The real impedance shows that the 1\textsuperscript{st} impact caused a 20\% reduction in the amplitude for the 1\textsuperscript{st} resonant peak. After applying the 2\textsuperscript{nd} impact a further significant drop in the peak impedance was observed, while the 2\textsuperscript{nd} and 3\textsuperscript{rd} resonant peaks became significantly distorted. Eventually by the 5\textsuperscript{th} impact the PWAS had stopped functioning. The imaginary admittance results in Figure 5-21 b) show a similar trend with the 3\textsuperscript{rd} and 5\textsuperscript{th} curves shifted vertically. The SEM images are illustrated in Figure 5-22, which show significant cracking and fractures in the sensor that would explain the dramatic reduction in the PWAS performance.
Figure 5-21- Impedance of embedded PWAS subjected to 10 J impacts
a) Real impedance b) Imaginary admittance

Figure 5-22- Embedded PWAS subjected to 10 J impacts (B9)
5.3.3. Effect of impact location on degradation of PWAS

This section discusses the results for those specimens subjected to impact events 30 mm away from the PWAS. Given the lower likelihood of a direct impact, this case is expected to be more representative of the type of impact loading which could occur to a PWAS while in-service. The test matrix for this case can be found in Table 5-2, with PWAS bonded to the back face, front face and embedded in the CFRP specimen, while the energy levels were tailored based on the previous testing. A summary of the results can be found in Table 5-3.

<table>
<thead>
<tr>
<th>Impact Location &amp; Energy (J)</th>
<th>Specimen 1, 2, 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Face</td>
<td></td>
</tr>
<tr>
<td>- 10</td>
<td>Little change after 1st impact then stable</td>
</tr>
<tr>
<td>- 12</td>
<td>Little change after 1st impact then stable</td>
</tr>
<tr>
<td>Front Face</td>
<td></td>
</tr>
<tr>
<td>- 5</td>
<td>Moderate change after 1st impact, significant after 5th</td>
</tr>
<tr>
<td>- 7</td>
<td>Significant change after 1st impact</td>
</tr>
<tr>
<td>- 10</td>
<td>Significant change after 1st impact</td>
</tr>
<tr>
<td>Embedded</td>
<td></td>
</tr>
<tr>
<td>- 12</td>
<td>no change after 5 impacts</td>
</tr>
</tbody>
</table>

Those specimens where the PWAS was bonded to the back face performed significantly better than previously, where the impacts had been applied directly in line with the sensor. After the initial change followed the 1st impact, as observed with all previously bonded cases, the PWAS performance remained consistent for both the 10 and 12 J cases. An example of the results for the 12 J case can be found in Figure 5-23, which includes the capacitance, real impedance and imaginary admittance. After conducting a visual inspection and acquiring SEM images, no signs of damage to the PWAS or the adhesive layer were observed.
Figure 5-23- PWAS bonded to back face subjected to 12 J impact 30mm away
a) Capacitance b) Real Impedance c) Imaginary Admittance

The next cases tested were those specimens where the PWAS was bonded to the front face. The results for an impact energy of 5 J can be found in Figure 5-24. The capacitance of PWAS was increased by increasing the number of impacts which suggests sensor debonding was occurring. This was backed up by the real impedance results, Figure 5-24 b), which showed after only the 1st impact, the resonant peaks shifted to the right and their magnitude increased. With further impacts, the magnitude of the first peak continued to increase and by the 5th impact this was over 300% greater than its original value. The SEM images of a specimen can be found in Figure 5-25, and this clearly shows cohesive failure at the CFRP-adhesive interface. A small crack was also found at the edge of the sensor, however, may have been caused by sectioning of the specimen rather than the impact loading.

When the impact energy was then increased to 7 and then 10 J, the PWAS performance was found to significantly change after only the first impact event. The results based on the
capacitance and impedance suggested again debonding of the sensor. Being bonded to the front face of the specimen, the impact events caused a compressive strain on the adhesive. As was found during the fatigue testing, relatively low strain levels could cause sensor debonding which is most likely what occurred in these cases.

Figure 5-24- PWAS bonded to front face subjected to 5 J impacts at 30mm
a) Capacitance b) Real Impedance c) Imaginary Admittance
The final set of tests was on embedded PWAS specimen subjected to 12 J impact loading at 30 mm away from the centre of PWAS. This was the only impact level tested due to the fact higher impact energy levels creating visible damage to the composite. The results for one of the specimens can be found in Figure 5-26. After 5 impacts neither the capacitance nor the real impedance or imaginary admittance changed which suggesting the PWAS and CFRP specimen were undamaged. This was validated by SEM micrographs, which showed no signs of damage.
Figure 5-26- Embedded PWAS subjected to 12 J impacts at 30mm
a) Capacitance b) Real Impedance c) Imaginary Admittance
5.4. Conclusion

This chapter of the thesis has been focused on the durability of PWAS when subjected to impact events. While being able to detect impact damage in structures is important, PWAS should also be durable enough so that low impact levels do not damage the sensor and produce a false reading.

The force vs time curves during the impacts was examined to determine the effects of embedding the PWAS on the host CFRP properties. The results showed that at a low impact level of 4 J there were no noticeable differences in the force curves for a plane CFRP specimen compared to one with a PWAS embedded. However, when the impact energy was increased to 5 and 7 J, the specimens with the embedded PWAS had a lower maximum force experienced and a longer impact time, which indicated a reduction in flexural stiffness. At 10 J the shape of the force vs. time curve for the specimens without the PWAS embedded was no longer a parabolic and had several peaks and troughs, suggesting damage had occurred. The specimen with the embedded sensor where else showed no signs of damage and its force vs. time curve was parabolic.

The specimens with PWAS bonded to the back surface and subjected to direct impact were tested next, with the sensors capacitance, real impedance and imaginary admittance measured before and after applying impacts. Results showed that at impacts up to 7 J the PWAS could survive a single impact without significant change in its performance. At 10 J the PWAS was found to have significant cracking. Apart from applying a single impact, multiple impacts were also applied to each specimen and the only case where no signs of degradation were seen was the 4 J case. The 5 and 7 J cases where else showing signs of sensor debonding and cracking between the 2\textsuperscript{nd} and 5\textsuperscript{th} impact event.

Direct impacts were also applied to specimens where the PWAS were embedded inside the CFRP laminate specimens. All of the sensors were able to survive a signal impact up to 10 J with minimal change in the performance. When it came to multiple impacts, surprisingly the 4 and 5 J cases showed a change in performance which can be attributed to delamination between the Kapton insulation layers and the resin interface, as well as some cracking to the sensor. However, the 7 J cases showed very little change in performance and SEM images only showed minimal delamination and a small crack. Given that applying a higher
impact level seemingly caused less damage, these results may be explained by the unpredictable nature associated with experimental testing and the brittle nature of the PWAS.

The final part of this chapter examined the effects of applying impact 30 mm away from the sensors, which was performed on specimens with the PWAS embedded, as well as bonded to both the front and back surface. For those specimens with embedded PWAS and bonded to the back face, after an initial change followed by first impact, the sensors were able to survive multiple impacts up to 12 J. Those PWAS bonded to the front face where else were only able to survive a single impact at 5 J and were found to have a significant change in performance after the 5th impact. The SEM images revealed significant sensor debonding had occurred which can be attributed the adhesive performing poorly under compressive strains.

In summary, this testing has shown the criticality of the adhesive layer when it comes to the sensors performance of bonded PWAS and the degradation caused by impacts. A more robust adhesive which is less prone to cohesive failure may results in the PWAS being able to survive higher impact levels. Embedding the PWAS in CFRP specimens was found to be an effective method for protecting them from impact events. These results are only based on a small sample size of 3 repeats and given the unpredictable nature associated with experimental testing; a greater number of testing would be required to achieve more conclusive results.
6. Numerical Modelling of PWAS

6.1. Introduction

In addition to the experimental investigation, a numerical analysis was also undertaken. The aim of which was to validate the experimental findings and gain a further insight into the effect of certain types of damage can have on the impedance spectrum for a PWAS. As it was discussed in the literature review, numerical modelling has progressed significantly in recent time and results have been found to closely match experimental data. While these studies have investigated both free sensors and sensors bonded to numerous materials, they have predominantly been 2D models and not 3D.

For this investigation, ANSYS Mechanical APDL 14.5 was utilised, which is well suited for conducting multiphysics analyses. The study consisted of three parts: firstly a free PWAS model was developed, which was used as a starting point to compare the accuracy of results and gain a fundamental understanding of the influence of certain material properties. Next, a bonded model was generated, which involved the PWAS attached to a carbon fibre composite specimen. Finally, a study into the effects damage/degradation causes to the PWAS impedance spectrum was carried out. In each section, the methodology and results are presented, which is then followed by a conclusion of the findings.

6.2. Free PWAS model

The first stage of this numerical investigation was to develop a free PWAS model, which would provide a fundamental understanding of the multi-physics in ANSYS and an insight into the effects of certain properties may have on the impedance spectrum. The results obtained from this model would then be compared to experimental results for a free PWAS to both validate the model and help to ensure accurate data to validate the model and help to develop more complex models.

As a starting point, studies conducted by the University of South Carolina were used for generating the model \cite{70,81}, as results using this technique were found to closely match the experimental results. This process involved conducting a harmonic analysis using coupled field elements, which link the mechanical and electrical DOF (degrees of freedom) together. A voltage is then applied to the piezoelectric material, which in turn generates a surface
charge for a particular frequency. From this, the impedance of the PWAS can then be found, using EQ.11.

\[ |Z| = \frac{V_{in}}{I_{out}} = \frac{V}{j\omega \Sigma Q_i} = Re(Z) + i Im(Z) \]

EQ.11

where, \(|Z|\) is the complex impedance, \(V_{in}\) is the input voltage, \(\omega\) is the angular velocity \((2\pi f)\), \(\Sigma Q_i\) is the summed complex nodal charge and \(j\) is \(\sqrt{-1}\).

For this study two element types were investigated, SOLID 5 and SOLID 226 both of which are both coupled-field brick elements and have 8-nodes and 20-nodes, respectively. Being a piezoelectric analysis, the voltage DOF was also added to the three displacements DOF. Apart from having a greater number of nodes per element, SOLID 226 elements also allow for the addition of dielectric loss as the materials properties, which may have some influence on results. The APC-850 material properties used for the PWAS model are from Gresil [70] and can be found in Table 6-1.

**Table 6-1- APC-850 material properties**

<table>
<thead>
<tr>
<th>PWAS Material Properties – APC-850</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stiffness Matrix</strong></td>
</tr>
<tr>
<td>([C_p] = \begin{bmatrix} 97 &amp; 49 &amp; 49 &amp; 0 &amp; 0 &amp; 0 \ 49 &amp; 97 &amp; 44 &amp; 0 &amp; 0 &amp; 0 \ 49 &amp; 44 &amp; 84 &amp; 0 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 24 &amp; 0 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 &amp; 22 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 0 &amp; 0 &amp; 22 \end{bmatrix} ) GPa</td>
</tr>
<tr>
<td><strong>Piezoelectric Stress Matrix</strong></td>
</tr>
<tr>
<td>([e_p] = \begin{bmatrix} 0 &amp; 0 &amp; 0 &amp; 0 &amp; 12.84 &amp; 0 \ 0 &amp; 0 &amp; 0 &amp; 12.84 &amp; 0 &amp; 0 \ -8.02 &amp; -8.02 &amp; 18.3 &amp; 0 &amp; 0 &amp; 0 \end{bmatrix} C/m^2 )</td>
</tr>
<tr>
<td><strong>Dielectric Matrix</strong></td>
</tr>
<tr>
<td>([\varepsilon_p] = \begin{bmatrix} 947 &amp; 0 &amp; 0 \ 0 &amp; 947 &amp; 0 \ 0 &amp; 0 &amp; 605 \end{bmatrix} \times 10^{-8} F/m )</td>
</tr>
<tr>
<td><strong>Density</strong></td>
</tr>
<tr>
<td>(\rho_{PWAS} = 7600 \text{ kg/m}^3)</td>
</tr>
<tr>
<td><strong>Dielectric Dissipation Factor (Dielectric Loss (%))</strong></td>
</tr>
<tr>
<td>(\tan \delta = 1.40)</td>
</tr>
</tbody>
</table>
PWAS used for the experimental studies were disc-shaped, with a diameter of 6.35 mm (1/4 inch) and thickness of 0.254 mm. Each sensor has a silver electrode on its top and bottom surface with a thickness of approximately 17 μm, as seen in Figure 6-1. To simplify the modelling process the electrodes weren't included, as such a sensor thickness of 0.22 mm was used. Being a disc shape, double symmetry could also be utilised for modelling which helped to significantly reduce the computational time. As a starting point, the mesh used for modelling was comprised of Quad elements with a global element size of 0.25 mm and one element in the thickness direction. A summary of the meshed sensor can be found in Table 6-2 with an image in Figure 6-1.

**Table 6-2 - Summary of free PWAS models**

<table>
<thead>
<tr>
<th>Element type</th>
<th>Radius</th>
<th>Thickness</th>
<th>Element Length</th>
<th>Nu# of elements</th>
<th>Nu# of Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLID5</td>
<td>3.175 mm</td>
<td>0.22 mm</td>
<td>0.25 mm</td>
<td>294</td>
<td>646</td>
</tr>
<tr>
<td>SOLID226</td>
<td>3.175 mm</td>
<td>0.22 mm</td>
<td>0.25 mm</td>
<td>294</td>
<td>2201</td>
</tr>
</tbody>
</table>

![Figure 6-1 - Images of PWAS](image)

a) Silver electrode on top surface b) 3D Mesh of Quarter PWAS

To simulate the electrodes and simplify the solution process, the nodes on the top and the bottom surface of the PWAS had their voltage DOF coupled to master nodes. A voltage was then applied to both the master nodes on each side, which was 1 volt and 0 volt, respectively. Finally, structural dampening of 1% was added and the required frequency range was selected.
The results for the baseline FE model can be seen in Figure 6-2, which includes both types of elements and are compared to a set of experimental results. The real impedance and imaginary admittance curves produced by the two FE solutions are quite similar, aside from a few small variations. As it can be seen in Figure 6-2 a), the resonant peaks from simulations with the Solid5 type element were found to be shifted towards the right, when compared to that of the SOLID226 elements, and was more noticeable at higher frequencies. A mesh sensitivity study, which can be seen in Figure 6-3, showed that by reducing the SOLID5 element size from 0.25 to 0.05 mm the 4th resonant peak will align with that of the SOLID226 case, while further reductions in the element size had little effect on frequencies and their corresponding amplitudes. It was also noticed that the troughs between peaks were higher in simulations conducted using the SOLID226 elements when compared to those with the SOLID 5 element. A further investigation found that the addition of the dielectric loss contributed to this phenomenon.

![Figure 6-2: Comparison of Baseline FEA with experimental results](image)

**Figure 6-2- Comparison of Baseline FEA with experimental results**

a) Real Impedance, Re(Z)  
b) Imaginary Admittance, Im(Y)
When comparing the numerical results to the experimental curves in Figure 6-2, relatively good agreement was achieved, particularly when using the SOLID226 elements. However, again the period between resonant peaks was found to be over predicted and was clearly noticeable for the 4th peak. Having eliminated the mesh size as an issue, several other possible reasons for these discrepancies were considered, including simplifications in the modelling, and variations in geometry or the material properties. A parametric study was conducted to gain a greater understanding of those properties and determine their influence on the results. The outcome of this parametric study for a selected few cases can be seen in Figure 6-4, while the full set of results can be found in Appendix 4.
Of the parameters considered in this study, dampening, density and sensor radius were found to have the greatest influence, with the latter two contributing to changes in the period between resonant peaks. Given the sensors dimensions have an extremely small manufacturing tolerance, it is believed that the density could be the main reason for the deviation of numerical and experimental results. The wires and solder, which were present in the experimental testing, were neglected in this numerical analysis and they would have contributed somewhat to the overall mass of the system. As such an adjusted model using SOLID226 elements with an increased density of 10% was developed. Figure 6-5 shows the results for the adjusted model and as it can be seen, a good agreement between experimental and FE model was achieved.
For the experimental study, in addition to PWAS with a solid electrode shape, a WFB (Wrap-around electrode) pattern was also examined. The main reason for which was so that the wires could be soldered on to the same top surface and thus allowing the opposing side to have a flat surface for bonding to the composite. An image of the two PWAS types can be seen in Figure 3-1.

The experimental results for WFB type of sensors have also been included in Figure 6-5 for comparison. It should be noted that both solid and WFB made from APC-850 and had the same dimensions. While the WFB and solid pattern have similar resonant frequencies there were some noticeable differences. For the real impedance graph, Figure 6-5 a), the peaks for the WFB were found to be lower and base levels are higher than that of solid cases. The imaginary admittance, Figure 6-5 b), also had reduced peaks and its gradient was also found to be lower for WFB sensors. Further, a significant amount of noise was seen in the signal which is likely to have been caused by the irregular shape of the top electrode.

Several attempts at modelling this type of electrode pattern were made. This included altering the coupled nodes on the top surface and reducing the dialectic properties, which were found to be 10% lower on the WFB compared to the solid type. However, none of these attempts yielded any meaningful results. As such, for the purposes of the numerical study, the solid electrode type shall be used and variations between the two types will be taken on board when comparing experimental and numerical results in the future.
6.3. Bonded Specimen

After the free PWAS model had been generated and was able to closely match the experimental results for the solid PWAS, the next part of the analysis was to study the performance of a PWAS bonded to a carbon/epoxy composite laminate.

As with the previous case, a 3D model was generated and double symmetry utilised to reduce the computational time. The carbon/epoxy composite laminate used in this study was AS4-3501-6, as used in the experimental testing, with its geometry 280 x 35 x 2.2 mm. The composite had a layup of [0, ±45, 90], as seen in Figure 6-6, with each ply modelled individually and had a thickness of 0.27 mm. Solid185 Hex elements were used for meshing the composite with 2 elements in the through-thickness direction of each ply and the elements size ranging from 0.25 mm in the region nearest the PWAS to 1.0 mm for the rest of the specimen. The full laminar properties for the AS4-3501-6 composite are listed in Table 6-3.

![Figure 6-6- Summary Carbon/Epoxy Material Properties](image)

During manufacturing, the PWAS were bonded to the composites surface using a cyanoacrylate adhesive, Loctite 406. For modelling purposes the adhesive layer was modelled as a quarter cylinder shape which had the same radius as the PWAS, 3.175 mm. For this study the excess adhesive on the side of the PWAS was ignored, which may have added to the sensor dampening.
Table 6-3- Carbon/epoxy material properties

<table>
<thead>
<tr>
<th>Carbon/Epoxy Material Properties – AS4-3501-6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Young’s Modulus</strong></td>
</tr>
<tr>
<td>$E_{11}$</td>
</tr>
<tr>
<td>$E_{22}$</td>
</tr>
<tr>
<td>$E_{33}$</td>
</tr>
<tr>
<td><strong>Poisson’s Ratio</strong></td>
</tr>
<tr>
<td>$\nu_{12}$</td>
</tr>
<tr>
<td>$\nu_{23}$</td>
</tr>
<tr>
<td>$\nu_{13}$</td>
</tr>
<tr>
<td><strong>Shear Modulus</strong></td>
</tr>
<tr>
<td>$G_{12}$</td>
</tr>
<tr>
<td>$G_{23}$</td>
</tr>
<tr>
<td>$G_{13}$</td>
</tr>
<tr>
<td><strong>Density</strong></td>
</tr>
<tr>
<td>$\rho$</td>
</tr>
</tbody>
</table>

The thickness of the adhesive was obtained experimentally using an optical microscope and was found to be on average 10 $\mu$m as seen in Figure 6-7. The adhesive thickness did vary significantly, in particular at the edges. As such, part of this investigation will also look into the effect of adhesive thickness that may have on the PWAS performance. The material properties used for the Loctite were generic values for a cyanoacrylate adhesive and are listed in Table 6-4 $^{[70,82]}$.

Table 6-4- Adhesive material properties

<table>
<thead>
<tr>
<th>Adhesive Material Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Young’s Modulus</strong></td>
</tr>
<tr>
<td>$E$</td>
</tr>
<tr>
<td><strong>Poisson’s Ratio</strong></td>
</tr>
<tr>
<td>$\nu$</td>
</tr>
<tr>
<td><strong>Density</strong></td>
</tr>
<tr>
<td>$\rho$</td>
</tr>
</tbody>
</table>
For the PWAS, as with the free model, SOLID 226 elements were used along with the same mesh. To connect the PWAS, adhesive layer and composites together the 'Contact Wizard' in ANSYS was utilised, which generated contact and target elements on adjoining surfaces. For both cases, a "bonded always" multipoint constraint (MPC) contact algorithm was employed, which uses constraint equations to tie the displacements between adjacent surfaces [83]. A summary of the meshed model can be found in Table 6-5 and Figure 6-8.

Table 6-5- Summary of bonded model

<table>
<thead>
<tr>
<th>Component</th>
<th>Thickness</th>
<th>Element type</th>
<th>Element Length</th>
<th>Nu# of elements</th>
<th>Nu# of Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWAS</td>
<td>0.254 mm</td>
<td>SOLID 226</td>
<td>0.25 mm</td>
<td>294</td>
<td>2201</td>
</tr>
<tr>
<td>Adhesive</td>
<td>0.010 mm</td>
<td>SOLID 185</td>
<td>0.1 mm</td>
<td>3328</td>
<td>5193</td>
</tr>
<tr>
<td>CFRP</td>
<td>2.170 mm</td>
<td>SOLID 185</td>
<td>0.25 – 1.0 mm</td>
<td>42560</td>
<td>48195</td>
</tr>
</tbody>
</table>

Figure 6-7- Image of bonded PWAS

For this bonded case in addition to including structural dampening, Rayleigh damping was also included, which has a mass and stiffness component as listed in EQ. 12.

\[ [C] = \alpha_M[M] + \beta_K[K] \]  

EQ. 12

Figure 6-8- Mesh of PWAS bonded to composite
where, \([C]\) is the structure damping matrix, \(\alpha_M\) the mass proportional damping, \([M]\) the structure mass matrix, \(\beta_k\) the stiffness proportional damping and \([K]\) the structure stiffness matrix.

The mass proportional damping factor \(\alpha_M\) is used to introduce dampening forces caused by the absolute velocity of the model, which simulates the model moving through a viscous medium \(^{[84]}\). The stiffness proportional damping factor \(\beta_k\), introduces dampening which is proportional to the strain rate, which can be considered as dampening proportional to the material stiffness. Effects of the components of Rayleigh damping on the total dampening of the system can be seen in Figure 6-9. The \(\beta_k\) follows a linear relationship with frequency, where \(\alpha_M\) negatively decays. Gressel \(^{[70]}\) showed that for PWAS at a higher frequency the \(\alpha_M\) has no influence on the impedance, as such it wasn’t included in this model. As a starting point for this study, a value of \(\beta_k=1\times10^{-9}\) was used, which could be later adjusted to achieve better agreement with the experimental results. The specimen’s nodal displacement at 100 kHz and the impedance results for the bonded PWAS are presented in Figure 6-10 and Figure 6-11, respectively.

![Figure 6-9- Rayleigh damping](image-url)
Figure 6-10- Example of specimen nodal displacement at 100 kHz

Figure 6-11- Comparison of bonded PWAS
a) Real Impedance b) Imaginary Admittance

The FE results for the real impedance curve, are in good agreement with the experimental data, as seen in Figure 6-11 a). The only major discrepancy was the unexpected peak just before the second resonant frequency. Another observation noted was that at higher frequencies the dampening had a greater influence on the resonant peaks, in particular at 1.8 MHz. If a higher frequency was to be used then further refinement in dampening values would be required to obtain better agreement. The imaginary admittance curves can be seen in Figure 6-11 b), with the main discrepancy between the FEA and the experimental result being the gradient. This observation was also noticed for the free PWAS case and is likely due to the experimental setup in using the WFB type sensors.

As mentioned previously, the thickness of the adhesive when bonding the PWAS to the composite was found to vary somewhat across the bonded area and from specimens to
specimen. As such a comparative study into the adhesive thicknesses was undertaken and the results for which can be seen in Figure 6-12.

![Comparison of adhesive thickness](image.png)

Figure 6-12- Comparison of adhesive thickness

As observed, by increasing the thickness of the adhesive the peak impedance increased. This can be attributed to shear lag effects between the composite surface and the PWAS. For the adhesive thickness of 0 and 5 µm cases similar results were found, with reduced peaks and both thicknesses producing two smaller peaks at 900 kHz rather than just the one. This may have been a mesh size issue; however using a smaller element size wasn't practical due to the already long simulation time. In conclusion, it was decided that the 10 µm case produced the most accurate result and would be used for the remaining studies.
6.4. Damage Simulated Models

The final part of the numerical investigation was to determine the effect certain types of damage can have on a PWAS impedance spectrum. Given the EM impedance reflects both the impedance of the sensor and the impedance of the structure, being able to distinguish between sensor damage and structural damage will be extremely beneficial in preventing false alarms and ensuring damage is correctly identified. Three types of damage were chosen for this study, which included a poor bonded/degraded adhesive layer, delamination in composite and a crack in the PWAS.

6.4.1. Degradation in adhesive layer

The adhesive layer plays an important role in transferring mechanical deformation from the PWAS to the host structure and vice versa. If the sensors were to be poorly bonded during manufacturing or the adhesive layer degraded while in service then its ability to excite a structure and detect damage can be reduced significantly.

For this study, both circumstances were considered. Case A: a poorly bonded PWAS, where debonding began at the centre of the sensor and propagates outwards to its edge, and Case B where the debonding of the PWAS initiates at the edges of the sensor and moves towards its centre.

Using the same quarter model, as described in the previous section, debonding was achieved by changing the contact surface between the CFRP and adhesive layer from fully bonded to a “Standard Contact”, which allows separation and sliding of the surfaces but prevents penetration between the two. The severity of the debonding was controlled by changing the size of the contact region between the adhesive layer and the composite using partitions. A diagram illustrating the two degraded adhesive layer cases can be seen in Figure 6-13.
Figure 6-13- Example of degraded adhesive layer
a) Case A - Poorly bonded  b) Case B - Debonding of PWAS

Figure 6-14- Case A- poorly bonded PWAS
a) Real Impedance spectrum (100k-2MHz)  b) Imaginary Admittance (100k-2MHz)
 c) Change in 1st Anti-resonance peak  d) Imaginary Admittance (0-100kHz)
The results for the PWAS Case A – "poorly bonded" are illustrated in Figure 6-14, with a) and b) being the real impedance and imaginary admittance, respectively, for a frequency range of 100 k- 2 MHz. For both cases, as the area deboned increases, the peaks shift to the left and begin to closely match the response of a free PWAS. A plot of the 1st resonant mode for the real impedance can be seen in Figure 6-14 c), which shows the change in both maximum impedance value and its associated frequency. It is worthy to note that, up to 40% debonding there was very little change in the maximum impedance. However after increasing to a debonding area of 60% a more noticeable change occurred and finally at 100%, fully debond, a significant change in impedance can be seen. Previous studies[36], have shown that the gradient of the Im(Y) at lower frequencies can be a good indicator of the quality of the bond and results for this is shown in Figure 6-14 d). As the “area debonded” increased only a small change in admittance was observed. Although even for the 80% case, this change was insignificant when compared to the fully debonded case. This could be explained by the fact the outer radius of the PWAS was still attached, which is where the maximum strain is imparted on the CFRP specimen.

![Figure 6-15- Case B- debonding of PWAS](image)

a) Change in 1st Anti-resonance peak b) Imaginary Admittance (0-100kHz)

The results for Case B- “debonding of PWAS” can be seen in Figure 6-15. Regarding the Real impedance and Imaginary admittance for the frequency range of 100 kHz – 2 MHz, a similar trend was observed as with the previous case: an increase in the debonding area causing the response to shift towards that of a free PWAS. It is interesting to note that this occurred at much quicker rate when compared to the poorly bonded case, as seen in Figure 6-15 a).
At 20% debond there was little change in the maximum impedance; however for higher deboned cases it increased more sharply when compared to the poorly bonded cases. At the same time however, the anti-resonant frequency was the same for both cases. The imaginary admittance, Figure 6-15 b), at lower frequencies was also found to be more reactive to debonding, with a clear change in the slope at 60% debonded area.

In summary, these results show that debonding of a PWAS from outer circumference has a greater impact on its performance when compared to being poorly bonded (unbonded area towards the centre of PWAS). Even when 40% of the adhesive has debonded, a poorly bonded sensor would appear to still functioning without any major effects. This suggests the bonding process may be less critical when compared to selecting an appropriate adhesive for the operating environment of the PWAS.
6.4.2. Delamination in composite

The next part of the analysis considers the effects of delamination in the host composite structure that can have on the PWAS performance. Two cases were considered: a single delamination between the 45° and 90° ply of the composite which could be representative of a manufacturing defect in the material; and the other case involves multiple delaminations in the composite laminate which propagate through the thickness, which could be representative of impact damage. For both cases, 6 levels of damage were considered, with the delamination size increasing by 2.1 mm (1/3rd of the radius of the PWAS) at each level. As it was with the previous case, the delamination was created by changing the surface contacts to that of a "standard contact". An illustration of the each case can be seen in Figure 6-16 and Figure 6-17

![Figure 6-16- Case A- centre delamination model](image)

![Figure 6-17- Case B- propagating delamination model](image)
The results for the central delamination, Case A, can be seen in Figure 6-18. For the real impedance, Figure 6-18 a), only a few selected damage levels are shown. The results indicated that up to the 3rd damage level there was very little change in the PWAS response. Once the delamination size reached 8.4 mm, level 4, the first resonant frequency was found to have multiple peaks and its magnitude increased by approximately 60%.

One problem with only using the real impedance is that it can be difficult sometimes to detect changes in the signal. As such, the RMSD for the real impedance at all damage levels was calculated using EQ.9, previously listed in the literature review, and the results are presented in Figure 6-18 b. This clearly shows that the delamination levels of 4-6 had the most effect on the PWAS impedance and the 100 kHz - 1 MHz was the most sensitive frequency range. Only a small change was seen in the 1 - 2 MHz range, which is like to be a

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**Figure 6-18- Case A- centre delamination**

a) Real Impedance  b) RMSD for Real Impedance  c) Imaginary Admittance
result of a high level of dampening. The imaginary admittance for the PWAS, Figure 6-18 c), where else did not change as a result of the damage.

The results for Case B- “propagating delamination” can be seen in Figure 6-19. Up until the 4th damage level, there was very little change in the real impedance response of PWAS. When the level of damage was further increased a more dramatic change was noted, especially at the 6th damage level where the delamination had propagated through the entire thickness of the specimen. As it can be seen from Figure 6-19 a), the resonant peaks have shifted to the left and the second resonant peak, which had been around 950 kHz, was replaced by several smaller peaks.

The RSMD results for Case B are presented in Figure 6-19 b). This shows that after the introduction of the first delamination, the damage index for the 100 - 1,000 kHz range was fairly consistent up to the 3rd delamination. The introduction of the 4th and 5th delamination showed a further increase in the damage index, which came as a surprise given there
appeared to be little change in their real impedance spectrum. This jump in the RMSD is likely a result of a small shift in their first resonant peak, which can be a limitation when using the RMSD method. While as expected the 6th damage level had the highest damage index.

Finally, the imaginary admittance for damage cases can be seen in Figure 6-19 c). As with the previous delamination, the slope was fairly consistent which aligns with the sensor having a good bond to the composite specimen. The only exception to this was the 6th damage level, where an increase in the slope was observed. One possible reason for this behaviour could have been the fact that only one composite ply was directly connecting the PWAS to the structure. As a result of this, the boundary conditions would have significantly changed, which is why we also saw a dramatic change in the real impedance at this damage level.

6.4.3. Crack in PWAS

The final part of this numerical analysis was to investigate the effect of possible cracks on a PWAS that might have on its performance. As was found during the impact testing, some of the sensors developed cracks which resulted in their significant degradation in performance. The main issue with this is how one can distinguish between a crack in the sensor or structural damage without a visual inspection. As has been observed experimentally, a crack will cause a significant reduction in the slope of the imaginary admittance curve for the PWAS. The objective of this part of the numerical study was to simulate a crack on a sensor and to investigate its effects on the performance.

To simulate a crack in the PWAS a number of methods were attempted. One such method included creating a longitudinal patrician in the centre of the sensor, which would generate a finite crack where the two opposing surfaces could slide relative to each other. This method however was unsuccessful as both un-cracked and cracked model were found to have the same impedance results. When comparing the displacement results for both cases it was found that since the crack ran directly towards the centre of the sensor, the expansion and contraction caused by the voltage was unaffected, which resulted in having same impedance results for an un-cracked and cracked models.
Keeping the model simple, a technique whereby removing a wedge section of the sensor was thus adopted, as can be seen in Figure 6-20, given that when a crack occurs, the surrounding area would also likely lose some if not all of its piezoelectric properties.

![Figure 6-20- Example of PWAS with 30° crack](image)

For the investigation, 3 cases were considered: no crack, a 15° and 30° section cut-out. As there was no longer symmetry in the model, a full specimen was required for the simulations, which effectively increased the computation time fourfold due to the additional elements. Aside from these changes, the same specimen parameters as the previous quarter models were applied. An image of a nodal displacement plot of the specimen at 100 kHz can be seen in Figure 6-21, along with the impedance results in Figure 6-22.

![Figure 6-21 - Example of nodal displacement for full model at 100 kHz](image)
The real impedance for the 3 cases can be seen in Figure 6-22 a). The first observation noticed is the magnitude of the peaks for the no-crack case that are clearly larger than those of the previous quarter models, Figure 6-11. For the first peak, the real impedance from full PWAS model was 250 ohms, compared to 200 ohms for the quarter models. This discrepancy is likely due to the dampening factors, which had been tailored for the quarter model and not for a full model. Given that the purpose of this study was to compare the effect of a cracked sensor on its impedance and not achieving a result that matches experimental data, these dampening values were deemed satisfactory and were used for the remainder of the study. When the cracks were introduced, a noticeable difference in the real impedance can be seen. The resonant peaks were no longer distinct and the signals were noisy up to 1 MHz.

The imaginary admittance plots for the PWAS can also be seen in Figure 6-22 b). These results showed that introducing the crack caused a small reduction in the slope of the curves. This observation aligns with previous studies [36] and those from the impact testing. While there was a reduction in the slope, however, this reduction was lower than expected. A possible reason for this could be due to the fact that while the analysis considered the physical effect of the crack, it does not account for any reduction in electrical properties which may have also occurred. Events such as impacts were found to generate a significantly large output voltage, well above the manufacturers recommended levels. These large voltages could have then led to partial depoling of the sensor. Never the less this study

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**Figure 6-22 Cracked PWAS**

a) Real Impedance b) Imaginary Admittance
has still shown that a crack to the sensor does cause a reduction in the imaginary admittance slope.

### 6.5. Conclusion

The results from this numerical investigation have shown that 3D simulations are a highly effective method for determining the electrical impedance of PWAS bonded to a carbon/epoxy composite. The first part of this study involved developing a free sensor model, which for a solid-electrode PWAS was found to strongly align with experimental results. While attempts made at modelling the WFB-electrode shaped sensors were unsuccessful. When it came to the bonded case, good agreement was achieved even though an attempt at modelling the WFB electrode were unsuccessful.

After developing the bonded case, 3 modes of artificial damage were introduced into the model, to gain a greater insight into their influence on the PWAS impedance and help in interpreting the experimental findings. This included investigating the role of the adhesive layer, by looking at the effects of a poorly bonded sensor and sensor debonding. Of the two cases, sensor debonding was found to have the greater influence with an increase in both the real impedance peaks and the slope of the imaginary admittance. These results are in line with those seen in the fatigue testing when sensors debonded occurred and is also consistent with literature.

The impact of delamination in the composite was investigated next with two cases considered, a centre delamination and a through thickness propagating delamination. Of most interest was the slope of the imaginary admittance, which was found do not change as a result of introducing the damage. Finally, the effects of a crack in the sensor’s degradation were investigated. When compared to the observations in the impact testing when a crack occurred, the change in the PWAS signal was not as pronouns as expected, with only a small reduction in the admittance slope. This reduction is in line with the theory, however further investigations are required so as to achieve a more accurate result.
7. Conclusions and Recommendations for Future Work

This Master of Engineering thesis has contributed to the current body of knowledge about Structural Health Monitoring (SHM) systems, focusing on the durability of Piezoelectric Wafer Active Sensors (PWAS). Gaining a greater understanding of the behaviour of PWAS under different loading conditions will help to facilitate their introduction into mainstream usage.

As it was identified in the literature review, the SHM systems based on PWAS would appear to be one of the most promising technologies, due to their ability to detect various types of damage over a large region. Some concerns however still remain about the durability and long-term survivability of these sensors. The main focus of this investigation was to assess the durability of PWAS, which are bonded to or embedded in composite structures. Firstly, the fundamental theory behind the operation and damage detection of PWAS was discussed. A comprehensive literature review resulted in identifying research gaps related to the durability of PWAS, in particular under bending fatigue and impact loading, and a lack of a numerical methodology in this regard. Experimental investigation into the effects of fatigue loading and impact events on the performance of PWAS was conducted after establishing a manufacturing method for surface-bonded and embedded sensors. Finally, a numerical methodology was developed and validated using experimental observations. The numerical model was utilised to study the effects of various types of damage on the impedance of PWAS.

A summary of the main findings along with recommendations for future work can be found in the next section.

7.1. Main Findings

The main findings ascertained from this investigation include:

- PWAS can be embedded in composite laminates without any significant variation in conventional manufacturing procedures. However, attaching electrodes and soldering wires to the PWAS was challenging since some sensors (depending on the solder size) were found to bend or break due to their brittle nature. Modifying the method for encapsulating the PWAS using a Kapton tape resulted in a consistent embedding method. When larger scale
manufacturing is undertaken, it is expected more sophisticated techniques such as circuit printing could be used, which would further reduce the integration issues.

- Embedding PWAS in the CFRP laminates was found to cause a local reduction in the flexural stiffness of the specimens. This was evident in the impact testing which showed that at high impact energy levels, the maximum force applied to the specimen was lower for those specimens with embedded PWAS. As a result of this stiffness reduction, the onset of visible damage to the specimens was delayed. For the static four-point bending tests conclusive results were found, which is likely due to the load being applied over a greater region where local effects are less prominent.

- Under both static and fatigue four-point bending tests, it was found that those PWAS bonded to the compressive surface of the host laminate were prone to debonding at much lower strain levels than those subjected to tensile strain. As expected, embedded sensors were able to survive higher bending conditions, as they were subjected to lower strain levels close to the mid-ply, i.e. neutral axis. When damage did develop in the embedded specimens, it was delamination at the interface between the Kapton tape and the CFRP resin which occurred first, with the PWAS remaining undamaged.

- Due to the brittle nature of PWAS, any low impact events which directly strike the sensor is likely to cause a significant damage. When the sensors were bonded to the back surface of the host composite laminate, they were able to survive a single event at most impact energy levels used in this investigation. However, after subjecting to multiple impacts the PWAS were found to be cracked and debonded. While embedding PWAS protected them from a single impact event at all energy levels, again multiple impacts caused significant damage to the sensor. The study also showed that when impacts were applied 30 mm away from the sensor, visible damage to the structure is likely to happen well before the PWAS is affected.

- A numerical methodology was developed and the investigation found that both free and bonded PWAS can be modelled with a high level of accuracy when compared to experimental results. The numerical study also investigated the effects of numerous modes of damage, including delamination in the host composite, cracks to the PWAS and debonding of the sensor. The numerical analysis produced similar trends to that of experimental observations using the electro-mechanical impedance of PWAS. It also
observed that debonding from the edges of the sensor has more influence on the PWAS behaviour compared to that propagating from the centre of the sensors.

7.2. Recommendations for Future Work

While this investigation has looked into several aspects of PWAS durability and performance, both experimentally and numerically, there are a number of areas which haven't been investigated and warrant further work. This includes:

- Investigating the effect of adhesive: This study has only considered one adhesive type and cohesive failure was a common theme, especially under compressive strain. Using an adhesive such as an epoxy could increase the SHM systems ability to withstand higher strain levels.

- Research on the effects of hot/wet environments on PWAS: Understanding how a PWAS performance changes under hot/wet conditions will be essential in preventing misdiagnosis of damage when integrating them with composite materials, given their ability to absorb moisture over time.

- Numerical models can provide valuable insight into PWAS performance, and a simulation where the PWAS is embedded in the CFRP specimen is a possible area to build upon this investigation.
8. References


35. Liang, C., F.P. Sun, and C.A. Rogers, *Coupled electro-mechanical analysis of adaptive material systems - determination of the actuator power*


43. Xu, B. and V. Giurgiutiu, A low-cost and field portable electromechanical (E/M) impedance analyzer for active structural health monitoring, 2005, University of South Carolina Dept of Mechanical Engineering: Columbia.


48. Doane, J. and V. Giurgiutiu. An initial investigation of the large strain and fatigue loading behaviour of piezoelectric wafer active sensors. in Smart


73. TEMCo, *Copper Magnet Wire - Data Sheet*, 2013, TEMCo - Tower Electric Motor Company.


76. NI. *Agilent Technologies HP4192A Analyzer*. Instrument Driver Network 2013 18/7/2013]; Available from:


80. Kuhn, J.D., Changes in structural health monitoring system capability due to aircraft environmental factors, 2009, DTIC Document.


83. ANSYS 14.5 Users Manule, 2012, Ansys Inc.: Canonsburg, PA.

9. Appendices

Appendix 1- APC Material Properties

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The values listed above pertain to test specimens. They are for reference purposes only and cannot be applied unconditionally to other shapes and dimensions. In practice, piezoelectric materials show varying values depending on their thickness, actual shape, surface finish, shaping process and post-processing.

Note: measurements made 24 hours after polarization.

Maximum voltage: 5.7 VAC /mil for 850, 851, Type VI VDC ~2X.
9-VAC /mil for 840, 841, 842, 844, 840, 881 VDC ~2X.
*At 2 kHz, low field.
**Maximum operating temperature = Curie point/2.

Standard Tolerances
- Capacitance: ±5%
- Dissipation: ±20%
(Tighter tolerances available on request)

Updated: 9/27/2011
# Physical and Piezoelectric Properties of APC Materials

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9-11 VAC/mil for 840, 841, 842, 844, 880, 881 VDC ~2X.
*At 1 kHz, low field.
**Maximum operating temperature = Curie point/2.

Standard Tolerances
- Capacitance: ±20%
- $d_{33}$ Value: ±20%
- Frequency: ±5% (to ±0.5% on request)

Tight tolerances available on request

Updated 9/27/2011
Appendix 3 - Static Impedance Results

Static 1-C

Static 2-C

Static 3-C

Appendices | Chapter 8
Appendix 4 - Parametric Study of Free PWAS