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Performance Evaluation of Thin Acoustic Emission Sensors in a
Laminated Composite for Structural Health Monitoring

School of Aerospace, Transport and Manufacturing
PhD in Manufacturing

PhD
Academic Year: 2020 - 2023

Supervisor: Dr David Ayre
Associate Supervisor: Dr Alex Skordas
Oct 2023



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Abstract

Acoustic emission (AE) is a viable technique for structural health monitoring. Structures can be monitored by placing the AE sensors on the surface. However, with polymer-reinforced composites, it is possible to embed the acoustic emission sensor within the structure. The embedding process is postulated to increase the sensor's sensitivity and thus detect subtle structural changes. However, researchers have differed on whether the sensitivity increases or not. To investigate the sensitivity of the sensors, the acoustic emission source used can be either artificial or natural.

Artificial acoustic emission sources such as the pencil lead breaking and transducer methods were investigated for their precision and accuracy. To increase the versatility of the transducer method, repositionable double-sided and thin double-sided tapes were assessed as removable and repositionable couplants. The PLB and transducer methods were found to have different frequency responses on both the metal and the composite. The results also indicate that the transducer must be coupled permanently or at least not repositioned for best performance.

The artificial acoustic emission sources, PLB and transducer methods were used to investigate the sensitivity of the fully embedded AE sensor. A test was set up with pre-determined AE initiation locations (surface and sub-surface) and pre-determined receiving sensor's location (surface and sub-surface) to ensure any sensitivity increase was evident. The results indicated that the sensitivity of the sensors was influenced by the frequency of the artificial acoustic emission source.

The sensitivity was then analysed using natural acoustic emission sources by inducing failure using mechanical loading. Two mechanical testing methods are used: three-point bend and double cantilever beam (DCB) mode I. Three AE sensors were tested. The results suggested that the sensitivity is more related to the crack's frequency than the crack initiation point.

Keywords:

PZT, PVDF, Embedding, Integration, AE, SHM

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List of Abbreviations

A_0	Anti-Symmetric Lamb Wave
AE	Acoustic Emission
AIC	Akaike Information Criteria
C_L	Longitudinal wave velocity
ASL	Amplitude Source Location
CFRPs	Carbon Fibre Reinforced Polymers
DC	Direct Current
DCB	Double Cantilever Beam
DMA	N-dimethylacetamide
DMF	Dimethylformamide
EMI	Electromagnetic Interference
FBG	Fibre Bragg Grating
FE	Fully Embedded
FOAES	Fibre Optic Acoustic Emission Sensors
FRP	Fibre Reinforced Polymer
HDT	Hit Definition Time
HLT	Hit Lockout Time
IF	Initial Frequency
LS	Large Sensor
LTA	Long-Time Average
NDT	Non Destructive Testing
PDT	Peak Definition Time
PLB	Pencil Lead Breaking
PVDF	Polyvinylidene Fluoride
PZT	Lead Zirconate Titanate
Ract	Actuator with Repositionable double-sided couplant
RF	Reverberation Frequency
RFI	Radio Frequency Interference
S_0	Symmetric Lamb wave
SE	Surface Embedded
SHM	Structural Health Monitoring
SS	Small Sensor

STA	Short-Time Average
Tact	Actuator with Thin double-sided couplant
TOA	Time of Arrival
UTS	Ultimate Tensile Strength
WS	Without Sensor

Introduction

Structural health monitoring (SHM) is essential for identifying failures and ensuring structural integrity, thus its safety. SHM offers the benefit of autonomous structural assessment, eliminating the requirement for on-site inspectors, which sets it apart from non-destructive testing (NDT). Acoustic emission is a promising passive technique capable of SHM, enabling the detection of failures without requiring external simulations.

The use of acoustic emission in composites has been explored for many industries, including automotive[1], energy (wind turbine blades)[2], aerospace[3], liquid rocket motor casing[4] and hydrogen tank[5]. The advantage of using AE in composite structures is the ability to detect the failure location and the type of failure. Even though the anisotropic properties pose a challenge in detecting the source location, multiple studies were undertaken to suggest solutions[6–8]. The capability to discern failure modes in glass fibre composites is attributed to the characteristics of the AE signal associated with these failures. The identification is reported to rely on specific AE features[9] or signal frequency[10–16].

The use of surface mounted AE sensors is a viable option. However, embedding the sensor in a composite is postulated to offer multiple advantages such as higher sensitivity, protection from environmental factors such as foreign objects and eliminating the need for a couplant. While conventional acoustic emission sensors are too large for embedding, alternatives like lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) can be embedded due to their thin profile.

The increased sensitivity, a major advantage postulated from embedding the AE sensors, remained inconclusive among researchers. Multiple studies have explored the increased sensitivity from embedding various AE sensors, yielding mixed sensitivity outcomes, including no enhancement[17], slight enhancement[18] and definite enhancement[19].

This work provides a robust experimental plan providing robust results. To measure the sensitivity of the fully embedded sensor compared to the surface embedded sensor, artificial and natural acoustic emission sources are used.

The first package (section and paper 1) includes a review on acoustic emission encompassing multiple aspects of acoustic emission, including AE sensors, artificial AE sources, couplants and research concerning fully embedding AE sensors.

The second package (section and paper 2) tested the precision and accuracy of the artificial acoustic emission sources: pencil lead breaking (PLB) and transducer methods.

The third package (section and paper 3) included using the same artificial AE sources to assess the sensitivity of the embedded sensor. The PLB method is limited to surface application, whereas the transducer method allows for embedding. Multiple transducers were employed to assess the embedded sensor's sensitivity, with some positioned on the surface and others embedded. In conjunction with the PLB, the surface-embedded transducer served as an artificial surface AE source, contrasting with the embedded transducer, which functioned as a subsurface artificial AE source. Hence, the sensitivity of the surface embedded AE sensor was evaluated compared to the fully embedded sensor based on surface and subsurface artificial AE sources.

The fourth package (section and paper 4) assessed the embedded sensor's sensitivity based on natural AE sources. Two mechanical testing methods were utilised to assess the embedded sensor's sensitivity based on the crack's location (surface or subsurface). The damage induced by the mechanical testing resulted in the production of natural AE hits. The three-point bend test was used to induce AE signals from the surface compared to the double cantilever beam (DCB mode I), which induced AE signals from within the sample.

Informative terminology frequently employed within this work encompasses the concept of an 'actuator,' which denotes the transducer (PZT) responsible for signal transmission. A 'receiver' designates the acoustic emission sensor

responsible for receiving the AE signal. The term surface embedded refers to the actuator or receiver attached to the surface using permanent coupling (resin). Whereas, the fully embedded refers to the actuator or receiver fully embedded within the composite. The term 'sensor', when isolated, is predominantly referred to the 'receiver'.

Table 0-1. The state of papers included in the thesis at the time of submitting

Paper Number: Summary	Objective number	Status
Paper 1: Literature review	1	Published in Sensors - MDPI
Paper 2: Artificial AE sources	2	To be determined
Paper 3: Comparison of Surface and fully embedded AE sensor using artificial AE hits	3	Published in Composite Science & Technology - Elsevier
Paper 4: Comparison of Surface and fully embedded AE sensor using natural AE hits	4	Accepted in Applied Acoustics - Elsevier

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Aim and Objectives

Aim: Examining AE sensor position for detecting failure events in glass fibre-reinforced composite (structural health monitoring).

Objectives:

1. Conducting a literature review to understand AE and analyse existing research on the topic.
2. Investigate and identify a removable and reproducible artificial acoustic emission source suitable for testing AE sensors and effectively measuring the material's attenuation.
3. Investigate the sensitivity of the embedded sensor using artificial AE sources, considering the relative position of the crack in relation to the sensor placement.
4. Implement mechanical testing giving rise to natural AE failure sources (surface and subsurface) to verify the sensor's sensitivity using multiple AE sensors (PZT, silver PVDF and gold PVDF).

1 [Paper 1] A Review on Acoustic Emission Testing for Structural Health Monitoring of Polymer Based Composites

1.1 Abstract

Acoustic emission (AE) has received increased interest as a structural health monitoring (SHM) technique for various materials, including laminated polymer composites. Piezoelectric sensors, including PZT (piezoelectric ceramic) and PVDF (piezoelectric polymer), can monitor AE in materials. The thickness of the piezoelectric sensors (as low as 28 μm —PVDF) allows embedding the sensors within the laminated composite, creating a smart material. Incorporating piezoelectric sensors within composites has several benefits but presents numerous difficulties and challenges. This paper provides an overview of acoustic emission testing, concluding with a discussion on embedding piezoelectric AE sensors within fibre-polymer composites. Various aspects are covered, including the underlying AE principles in fibre-based composites, factors that influence the reliability and accuracy of AE measurements, methods to artificially induce acoustic emission, and the correlation between AE events and damage in polymer composites.

1.2 Introduction

Monitoring the structure's condition, i.e., health, is essential to ensuring failure is never reached in the structure's lifespan. SHM can be defined as the ability to observe changes during the structure's lifespan using a sensor. Three central components are typically needed to create an effective structural health monitoring system: a sensor network, incorporated hardware, and software[1]. The use of non-destructive testing (NDT) methods to evaluate damage inside structures has been well-developed. However, using NDT requires the presence of an inspector or for the structure to be dismantled. SHM will improve the structure's safety dramatically due to continuous monitoring compared to the interval inspection by NDT. The shift has changed in the last 30 years to embed the sensor inside the structure, which will overcome NDT challenges[2], creating

a smart material. Embedding the sensor within the structure will provide more accurate results due to how close the sensor is to the substructure[3].

A smart composite is a composite that has been modified either actively or passively. According to Fairweather[4], an active smart material is a material that can change its geometric or material properties under the influence of electric, thermal, or magnetic fields, thus having a built-in ability to transduce energy. Examples of active materials include shape memory alloys (SMA), piezoelectric materials, electrorheological (ER) fluids, and magnetostrictive materials. In contrast, a passive smart material is a material that lacks the ability to transduce energy. For example, an optical sensor can sense the signal but not actuate it.

Rogers[5] defined smart materials as materials that can alter their physical properties in a particular manner when subjected to a particular stimulus. The physical change could be related to shape, viscosity, damping, or stiffness. Examples of stimuli include magnetic and electric fields, pressure, and temperature.

Different levels of damage assessment can be distinguished when assessing a structure: a qualitative indication of damage presence, damage location, damage size, and an estimation of the structure's safety at this level of damage[6].

According to Cawley et al.[7], there are three reasons why the industry is slowly adopting SHM. Firstly, not enough attention is given to the business case, i.e., although the technology is available, the economic benefits might still be unclear. Secondly, the technology must be proven on an actual structure under realistic service conditions. Thirdly, it must be demonstrated that the technology needs to be robust, as it needs to provide understandable information and prove robust against different structures and load cases.

Piezoelectric sensors are one of the vast number of sensors that can be used for SHM. Piezoelectric materials can induce an electric charge when mechanically deformed (direct piezoelectric effect) and mechanically deform when an electric charge is applied (inverse piezoelectric effect). The effect occurs because of the non-symmetrical crystal lattice of the material. Despite the non-symmetrical

lattice, the crystal is still electrically neutral. As shown in Figure 1-1, atoms move when compressed or tensioned, altering the crystal and causing imbalance due to the position of the positive and negative atoms. The movement of the atoms will create two regions: positively charged dominant and negatively charged dominant[8]. The inverse piezoelectric material is based on applying a voltage to the piezoelectric, causing the crystal to realign its internal dipole structure, which will cause contraction and lengthening. This phenomenon causes electrical energy to be converted into mechanical energy.

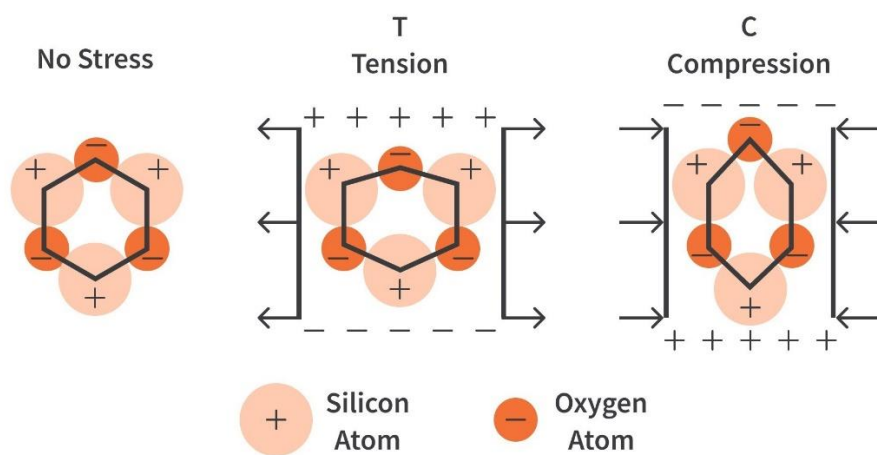


Figure 1-1. The piezoelectric effect in Quartz, reproduced with permission from[9].

Four categories of piezoelectric materials can be identified: ceramics, single crystals, composites, and polymers. Composite piezoelectrics can be a combination of a single crystal or a piezoelectric material in a polymer matrix[10].

Piezoelectric materials can be used as receiving sensors and actuators due to their ability to induce a voltage when mechanically deformed and vice versa; i.e., they can be used for both active and passive sensing modes. Active sensing depends on the ability to send a signal from the sensor and measure the sent signal using either the same or a different sensor. In comparison, passive sensing depends on the ability to receive a signal without prior activation. Active acoustic monitoring can also be accomplished using irradiation-transient grating spectroscopy[11]. Active sensing commonly depends on a baseline measurement taken from undamaged structures to be later compared when in

service[12]. Two active sensing methods can be used: electromechanical impedance and wave propagation[13]. Passive sensing, on the other hand, includes acoustic emission and stress wave propagation (impact sensing). However, the signal arising from the piezoelectric can change depending on the environment, including noise and temperature[14]. Hence, compensating for these effects is crucial.

1.3 Acoustic Emission

Acoustic emission is a naturally occurring phenomenon due to the sudden release of energy within the structure, resulting in a transient elastic wave[15]. Acoustic emission is considered a non-destructive testing (NDT) technique for 'listening' to the material. However, recent progress in SHM has increased interest in converting it into an SHM technique. AE works based on listening to the sounds produced by the structure when stressed or internally damaged, for example, when delamination or crack propagation occurs. AE equipment can detect sound frequencies ranging from 30 kHz to 1 MHz, with lower frequency ranges available if required.

The acoustic emission output signal is usually confined to three types[16]: bursts, continuous, and mixed. Burst signals are transient signals that occur due to damage inside the material, including delamination and fibre breakage. In comparison, the continuous signal results from overlapping bursts where each burst cannot be individually identified. Mixed-signal, typically encountered in service, is where individual bursts and a continuous signal are present.

The type of failure occurring in a composite, whether delamination or fibre pull-out, can represent the current deterioration stage. Each type of failure has unique characteristics such as frequency, amplitude, rise time, and duration due to the distinct process that occurs at failure. That includes the crack tip's motion, the crack surface area generated, and the crack propagation speed[17], as will be explained later.

The acoustic emission technique allows the user not only to identify the failure type but also to locate the source of the crack generated. The time of arrival (TOA)

difference can be used to determine the crack's location. However, multiple sensors are required, and composites are mostly anisotropic, adding further complication, as later explained. Hence, one AE sensor is enough to detect damage but not enough to pinpoint the location of the damage.

The threshold technique used by the acoustic emission system helps eliminate noise and allows for better readings. However, this technique will not always present the actual number of hits, as multiple transient signals can overlap, creating a strong burst (without dropping below the threshold) registered as one hit[16]. A better technique has been developed by Unnpórrsson[16], which detects the hit start and end based on the trough and peaks of the signals.

It is also preferable to use energy rather than the number of counts to analyse the magnitude of a source event. The energy is more sensitive to amplitude and duration and less sensitive to voltage threshold and operating frequency[18].

Manufacturing composites does not always require high temperatures compared to metals, as low-temperature resins could be utilised. The thickness of the composite can also be controlled, enabling sensors to be embedded due to the manufacturing process. However, the size of a conventional acoustic emission sensor is too large to be embedded as seen in Figure 1-2. Regular piezoelectric sensors such as lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) can be embedded in the structure due to their small size (gold-coated PVDF is available at 28 μm thickness[19]). Regular sensors are adequate but not covered by a shielding material, which is used to improve the signal-to-noise ratio of a piezoelectric sensor. AE sensors are typically placed on the surface of the specimen to be tested using a couplant, eliminating the acoustic impedance mismatch arising from the air. However, embedding the sensor will eliminate the need for a couplant.

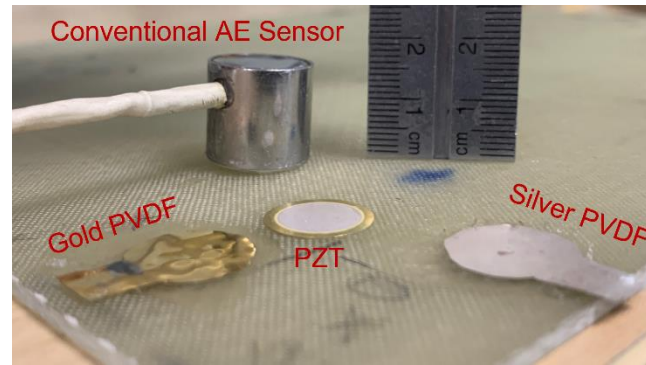


Figure 1-2. Comparison of the types of sensors applicable for AE testing.

1.3.1 AE Parametric Features

The parameters[20] used for AE analysis are listed and defined below:

AE event: The frequency domain or time domain of the acoustic emission signal emitted due to the elastic wave generation. The total AE wave during AE testing.

AE hit: An AE signal that crosses the threshold defined by the user from one channel, multiple AE hits can be generated due to multiple AE events or channels.

Maximum amplitude: The highest amplitude (voltage present;[21]) of an AE hit measured in decibels (dB) or voltage.

Rise time: The period from when the pulse first crosses the threshold and reaching the maximum amplitude.

Counts: The number of pulses of an AE hit greater than the threshold defined.

Energy: The area under the detection envelope within the AE hit duration.

Duration: The period between when the pulse first crosses the threshold until the last pulse threshold crossing

Peak frequency: The maximum frequency detected in an AE wave spectrum.

Centre frequency: The centre of gravity in an AE wave spectrum.

Average frequency:

Equation

$$AF = \frac{Counts}{Duration} \quad (1-1)$$

Initial frequency (IF): the AE spectrum's initial condition. *IF* can be calculated by dividing the counts by the rise time.

$$IF = \frac{Counts}{Rise\ time} \quad (1-2)$$

RA Value: It can be calculated by dividing rise time by maximum amplitude. It represents the type of crack (unit: ms/V)

$$RA\ value = \frac{Rise\ time}{Maximum\ amplitude} \quad (1-3)$$

Reverberation frequency (RF):

$$RF = \frac{AE\ counts - counts\ to\ peak}{Duration - rise\ time} \quad (1-4)$$

Parameters used to determine the AE hits, shown in Figure 1-3[16], are

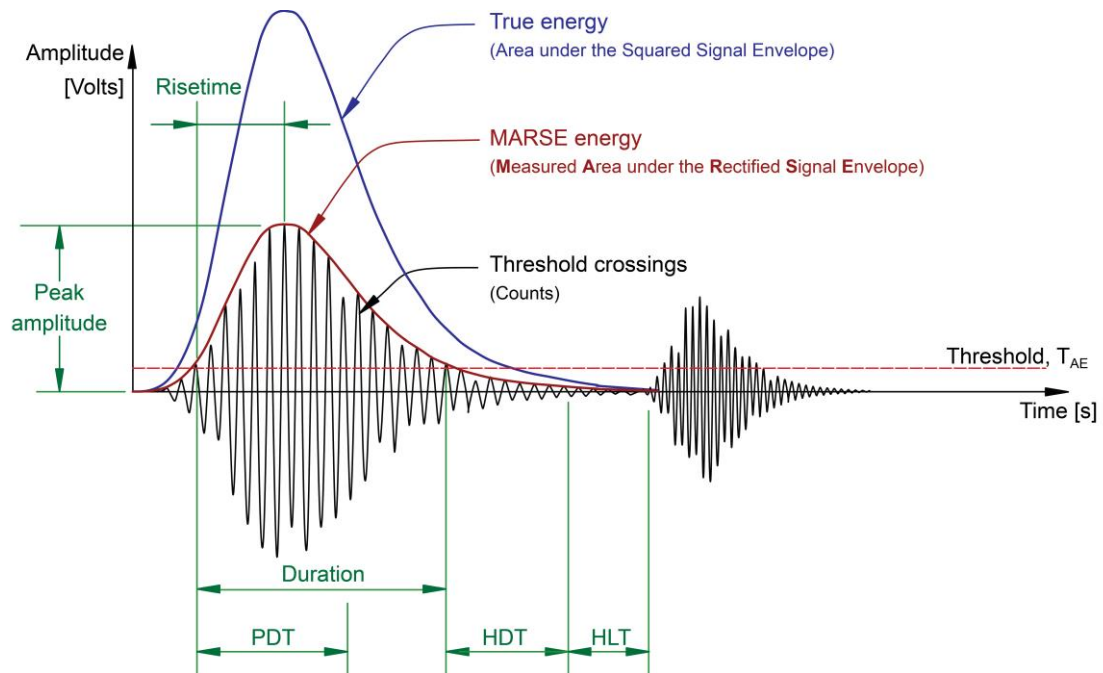


Figure 1-3. AE hit common parametric features extracted from hits, reproduced from[16].

Peak definition time (PDT): The amount of time allowed to identify the peak amplitude after the hit is registered (signal above threshold). Setting the PDT value too low or too high could cause false peak amplitude identification.

Hit definition time (HDT): The time specified after the signal becomes lower than the threshold to consider that a hit has ended. i.e., if the signal does not recross the threshold, the hit is considered to have ended. Setting the HDT value too low could prevent the whole hit from being captured and possibly treat one hit as multiple hits. Yet, if set too high, it may capture the next hit and treat two real hits as one hit.

Hit lockout time (HLT): The time that must elapse after a hit has ended before registering a new hit. If the HLT value is too high, a new hit can be missed, and if set too low, the system may capture late-arriving components or reflections as a hit.

1.3.2 AE Sources

The acoustic emission technique has been explored for implementation in composite structures by many industries, including aerospace[22], energy (wind turbine blades)[23], liquid hydrogen tanks[24], rocket motor casings[25], and automotive[26]. The approach is beneficial for the industry; however, the anisotropy within the composite poses a challenge with detecting failure events as the wave speed could differ based on the fibre direction, as will be discussed later.

1.3.2.1 Composite Mechanical Loading

Different damage mechanisms can be analysed using the AE signals from fibre-matrix composites. AE signals emitted from fibre matrix composites can be divided into matrix cracking, fibre-matrix debonding, fibre breaking, and delamination[27][28]. Each damage mechanism has a unique acoustic (waveform) characterization[29]:

- Matrix cracking can be distinguished by low amplitude, low energy, and a slow rise time.

- Fibre-matrix debonding has a higher amplitude, higher energy, and shorter rise time.
- Fibre breakage has a quicker rise time, a short duration, a higher amplitude, and a higher energy.
- Delamination has a slow rise time, a much longer duration, and higher energy.

Knowing the failure type's characteristics will enable the user to establish the danger level. That is, if the characteristics match those of fibre cracking, which is the structure's load bearing, then the user can identify a critical danger level.

The average frequency response arising from the mechanisms is shown in Table 1-1. The frequency response registered by different authors is different due to the different fibre directions used, plies lay-up differences, final thickness, and AE machine used during the experiment. However, a general trend shows that the frequency response of matrix cracking < Fibre-matrix cracking < Fibre Fracture.

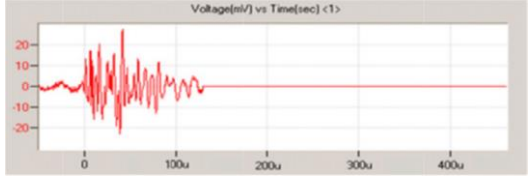
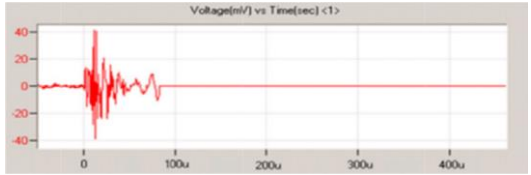
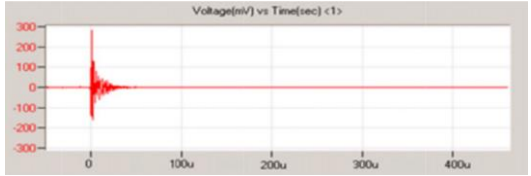
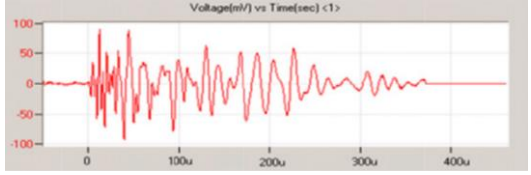
Table 1-1. Failure frequency response of glass fibre/epoxy matrix composites.

Reference	Thickness (mm)	Frequency Response (kHz)			
		Matrix Cracking	Fibre-Matrix Cracking	Delamination	Fibre Fracture
[30]	2.78	90–110	-	130–200	250–280
[31]	4	62.5–125	125–187.5	-	187.5–250
[32]	5	100–190	200–320	-	380–430
[33]	4.8	60–180	190–250	-	350–500
[34]	4.8	11–93	82–210	-	160–281

The magnitude-frequency graphs of the failure events have been identified by Asokan et al.[30].

The response of the damage mechanisms is also different when comparing the voltage-time graphs, as seen in Table 1-2.

Table 1-2. An overview of the responses acquired due to different damage mechanisms, reproduced from[29].

Damage mechanism	Form of signal
Matrix cracking (A class)	
Fibre-matrix debonding (B class)	
Fibres breaking (C class)	
Delamination (D class)	

In composites, acoustic emission is produced as expected when the material is under load. However, the acoustic emission may continue under certain conditions even at a constant load, as seen in Figure 1-4[35]. The deformation can be delayed for several reasons. For example, in a fibre-reinforced polymer (FRP), the delay is due to the visco-elastic nature of glass fibres. Additionally, the structure's stress history is particularly important since stress-induced deformation generates acoustic emission[36]. Certain materials take time to respond to load due to their intrinsic properties, such as the viscoelastic response in resin. Other materials produce AE almost instantaneously; upon holding the load, the emission stabilises. Other materials, such as structures with hydrogen-

induced cracking, may never stabilise upon holding the load, causing continuous AE until failure[36].

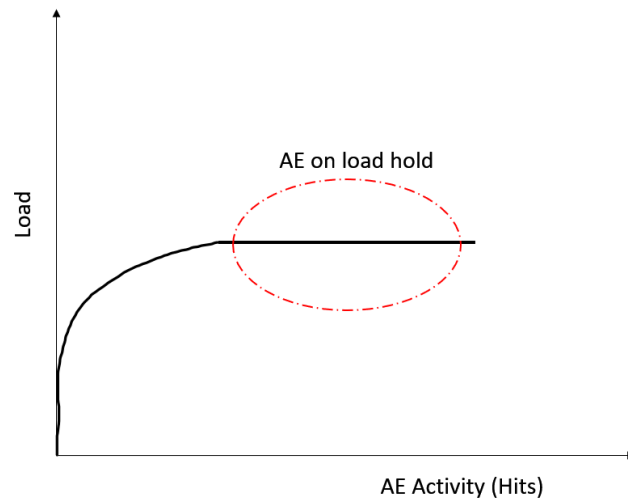


Figure 1-4. The acoustic emission with a constant load of an FRP, concept from[35].

The damage mechanisms, however, differ for sandwich-core composites[29]. Four types of signals can arise from sandwich core composites: resin cracking, fibres breaking, interfacial debonding between skin and core, and core damage.

- Core damage is characterised by a short rise time, a short time, and low amplitude and energy.
- Resin cracking is characterised by a slower rise time and higher energy and amplitude.
- Interfacial debonding waveforms have a slow rise time, a long duration, and a higher amplitude and energy.
- Fibre-breaking signals have a quick rise time, an extremely short time, and a very high amplitude and energy.

The characteristics of the AE waveforms can be correlated to a specific damage mechanism when applying simple loads. However, applying the AE technique to large structures can pose extra challenges due to the simultaneous activities occurring, leading to overlap or even signal misinterpretation. To demonstrate, a

study performed on a full-scale aircraft fuselage composite panel showed that the high rate of failure within the composite is an added difficulty for detecting the damage source location[37].

Acoustic emission arises when the material is mechanically loaded (LC1, Figure 1-5). However, if the material is unloaded and loaded back up again, then no AE is recorded (horizontal line), which is known as the Kaiser effect[38]. The absence of AE is linked to damage already exerted from the first cycle, and no further damage occurs during the second loading. Upon loading the material (LC2, LC3 and LC4), new AE is detected due to damage occurring at higher loads than previously. Loading the material to higher loads produces significant damage compared to the low-level loads. Hence, upon unloading (end of LC4) and loading (LC5), the emission is exerted at a load lower than the maximum load exerted from previous cycles; the effect is known as the Felicity ratio (Equation (1-5)). The emission arising at previously reached loads is due to the cracks and their corresponding stress concentration areas that exhibit a local increase in stress with lower loads[17].

$$FR = \frac{\text{Load at which emission begins again}}{\text{previous maximum load}} \quad (1-5)$$

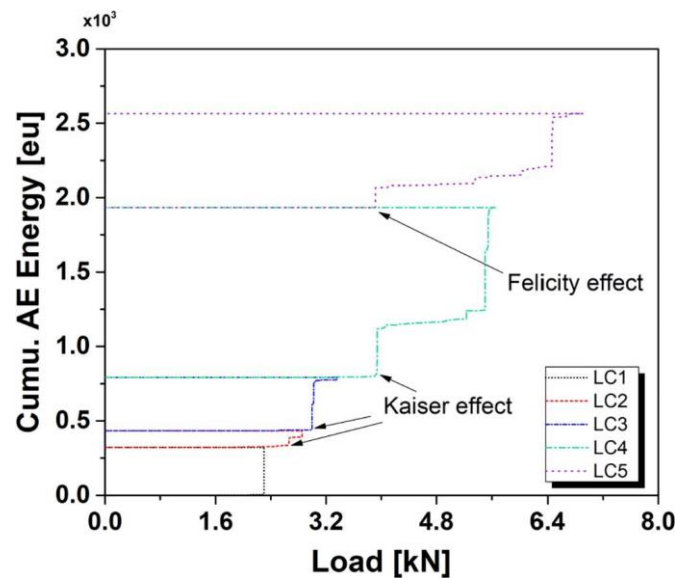


Figure 1-5. A graph showing the Kaiser effect, Felicity effect, reproduced from[39].

The Kaiser effect takes place when the Felicity ratio is 1.0 or greater. That is when the load at which emission begins is equal to or greater than the previous maximum load[36]. Acquiring an FR of less than 1.0 can indicate that the structure has significant defects.

1.3.2.2 Physical Contact

Frictional noise that occurs due to mechanical contact between surfaces, such as the slip-stick mechanism, could result in rubbing or fretting, giving rise to the AE signal. Additionally, foreign objects impacting the structure, such as sand or rain, could produce a signal[40].

1.3.2.3 Noise

Noises arising from within the structure and the outside environment could give rise to false alarms or even cover integral signals, yet some are distinguishable and hence could be easily disregarded. External acoustic noise, besides structural vibration, does not heavily impact the acquisition system[20]. However, external rubbing and electrical noise can result in a continuous AE signal[16]. Internal rubbing between crack surfaces during damaged components' loading and unloading phases produces an AE event as the crack opens and closes[40,41]. The noise in AE detection can be dealt with in multiple ways[36]. Firstly, narrowing the frequency upper and lower limits will eliminate signals arising outside the limits. Secondly, the noise could be eliminated from the source; if not, it could be eliminated by placing items such as damping materials in critical areas. Some electrical noise can be dealt with by proper grounding, shielding, or using differential sensors. If the noise cannot be dealt with directly, the AE software could be used to set a floating or fixed threshold that will ensure AE signals below a particular dB will not be detected.

Electromagnetic interference (EMI) and radio frequency interference (RFI) are produced from multiple sources, such as welding machines, fluorescent lighting, electric motor switches, and radio transmitters[40]. Pulse generators have also been identified as a source of EMI. Although it is challenging to eliminate EMI, it is typically associated with waveforms distinguishable from actual AE sources[17].

1.3.3 Artificial AE Sources

Multiple methods can be used to artificially induce an acoustic emission signal in samples, including pencil lead breaking, gas jet blasting, and transducer methods[42]. The methods induce an identical and reproducible signal, which enables the user to ensure the stability of the sensor, test attenuation, imitate a crack, or analyse different wave types.

1.3.3.1 Pencil Lead Breaking

The pencil lead breaking method, also known as HSU-Nielsen Source, is a method where a mechanical pencil is placed at an angle with the aid of a 'shoe' to be broken to generate an AE signal, as seen in Figure 1-6. The shoe is used to ensure consistency in the breaking angle with respect to the lead length (3 mm). Breaking the pencil lead will release the accumulated stress, causing the surface to displace microscopically, leading to the AE signal[43]. The test is widely used due to its availability, ease of use, portability, and avoidance of extra equipment. As the pencil must be broken at a certain angle, damage to the shoe's 'guide tube' can lead to inaccurate results. The method does not allow for frequency control, which could be required in some instances. Acoustic emission testing aims to quantify the characteristics of emitted signals, such as amplitude, duration, and frequency content. However, pencil lead breaking may not provide sufficient control over these parameters, making it difficult to measure and analyse the data accurately.



Figure 1-6. The pencil lead-breaking method.

1.3.3.2 Gas Jet

The Gas jet method is less used than the pencil lead-breaking method due to the setup and equipment required for the test. However, the test is performed by permanently attaching a nozzle at one end and an AE sensor at the receiving end. A gas, which could be helium or dry air, is released at a recommended pressure of 150 to 200 kPa, inducing an AE signal. The test could be set up to induce a longitudinal wave, as shown in Figure 1-7A or a transverse wave, as shown in Figure 1-7B. Its requirement for high pressure poses a safety concern if it is not attached adequately compared to the other actuator methods.

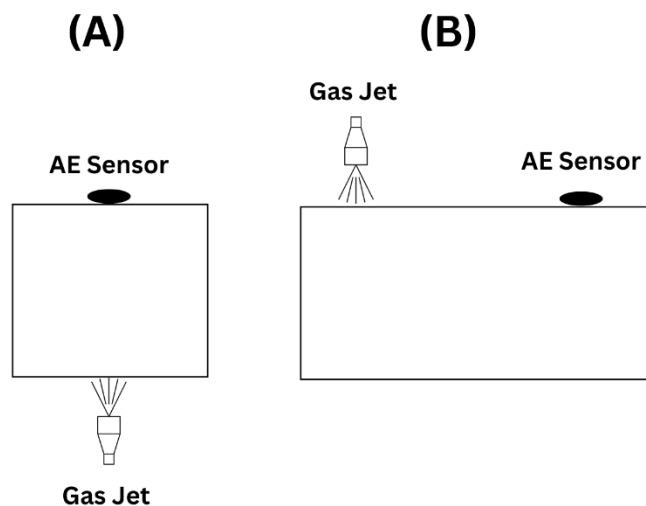


Figure 1-7. A Simplified drawing showing the gas jet method setup producing (A) longitudinal wave and (B) transverse wave, concept from[42].

1.3.3.3 Transducer

An electrically driven transducer can generate an acoustic emission signal using either a white noise generator, sweep generator, or pulse generator[42]. Depending on the wave required, the transducer can be placed facing the sensor or on the same surface. When a white noise generator is used to power an ultrasonic transducer, an acoustic wave without coherent wave trains of many wavelengths at one frequency is created. In comparison, a sweep generator produces a signal with varying frequencies depending on the user's input. For example, starting at 1 kHz and ending at 100 kHz for 10 s. A pulse generator,

however, produces a pulse with a known rise and fall time, pulse width, and frequency. Although the transducer method requires extra equipment to operate, it can produce accurate results when permanently attached. The transducer method allows for frequency control compared to the other methods. However, the requirement for permanently attaching the sensor and the inability to remove and replace it pose a significant disadvantage.

1.3.4 AE Details in Composites

The acoustic emission source wave characteristics are linked to the dynamics of the crack[41]. That is, the crack growth speed of the source is linked to the material's properties in addition to the loading parameters, which as a result, produces a specific frequency bandwidth. In addition, the failure mode and orientation of the AE source will create a distinctive radiation pattern. The position of the AE source within the composite could also influence the radiation pattern. Although different opinions were found regarding the intensity of the signal, Figure 1-8 shows an overview of the acoustic emission details according to the author's opinion.

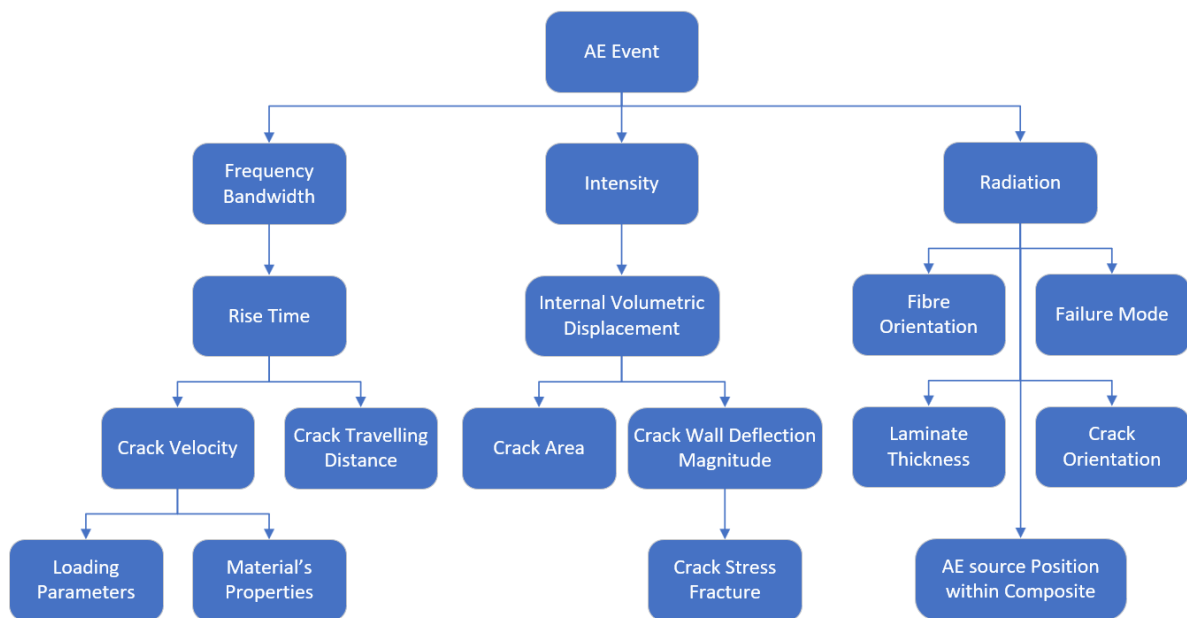


Figure 1-8. An overview of the acoustic emission details.

1.3.4.1 Bandwidth Response

Acoustic emission sources occurring inside a material will produce a distinctive frequency bandwidth due to the dynamics of the source mechanism. The frequency bandwidth of the crack is directly related to the rise time of the crack[41]. As shown Figure 1-9, the rise time is the period required for the crack to reach its maximum displacement. However, once the crack has stopped (reached its final displacement), the displacement of the crack will not come to equilibrium due to its inertia, adding a contribution to the AE signal, as seen in the green line in Figure 1-9.

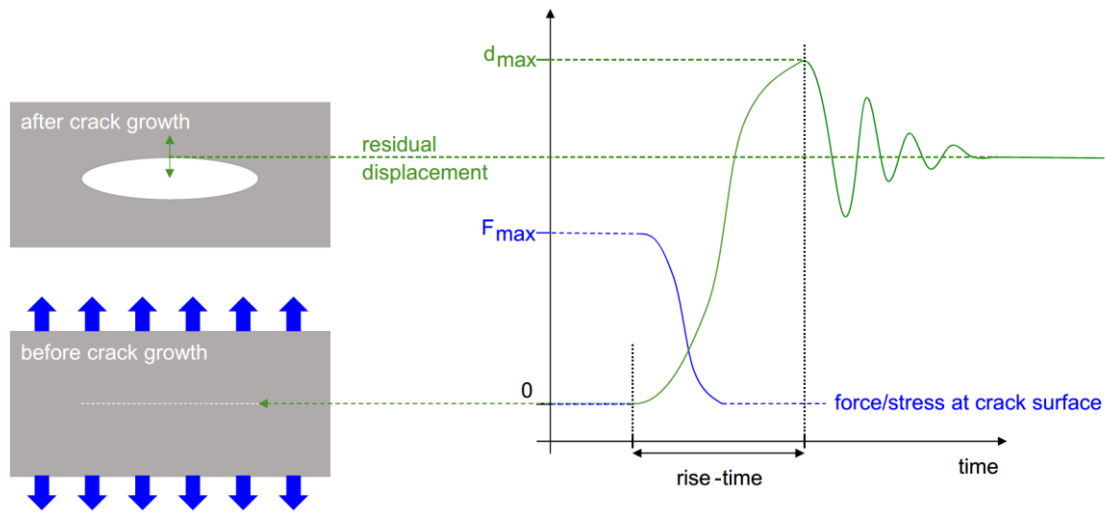


Figure 1-9. Crack growth with respect to the rise time, reproduced from[41].

Rise time depends on the propagating crack's speed and the distance the crack will travel[41]. A fibre fracture will occur at a small distance of one fibre diameter and a high crack speed, producing a shorter rise time and hence high frequency bandwidth. However, matrix cracking occurs at a lower speed since the sound velocity in polymers is low[41] due to their lower Young's modulus and higher density as per the general sound velocity in solids, Equation (1-6).

$$v = \sqrt{\frac{E}{\rho}} \quad (1-6)$$

where v is the sound velocity in solids and E is the Young's modulus of the material and ρ is the density.

1.3.4.2 The Intensity of the AE Signal

According to Hellier[40], the amplitude and energy released from the acoustic emission source depend on the source event's speed and size. A theory states that the AE amplitude is proportional to the crack's velocity, and the AE energy released is proportional to the area of the new surface created. For example, a discrete, sudden crack will release high energy and produce a higher energy signal, whereas a creeping, slow crack will release less energy over the same distance.

According to Hamstad[41], according to the generalised theory of acoustic emission[44,45], the intensity of the AE source is linked to the internal volumetric displacement (ΔV) of the source. ΔV is linked to the crack's area and the crack wall's deflection magnitude, as seen in Figure 1-10[41]. The crack's wall deflection is related to the accumulated stress prior to the fracture. Materials with higher fracture stress will result in larger wall deflection, producing a more intense signal (higher AE amplitude). Rise time will also affect the signal's intensity; a longer rise time will result in a more intense signal compared to a low rise time while keeping the fracture stress constant[41]. In contrast, Hellier's theory[40] states that a discrete and sudden crack (indicating a low rise time) will produce a higher amplitude signal when compared to a creeping and slow crack (indicating a high rise time).

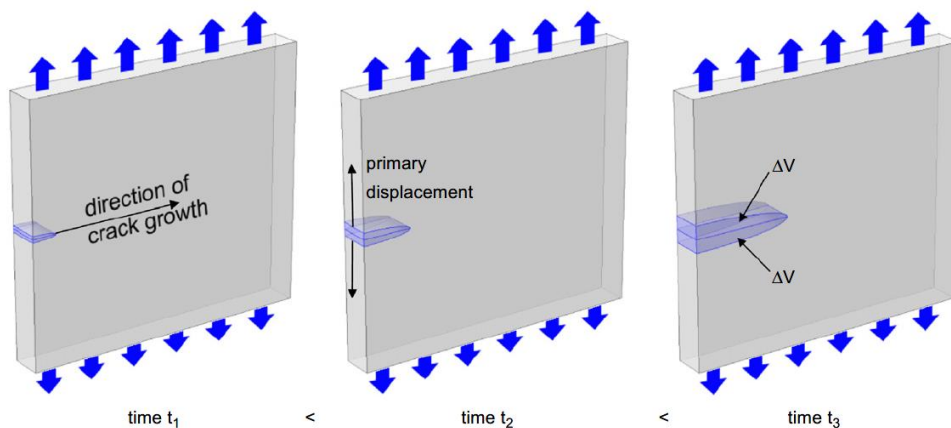


Figure 1-10. The process of forming the internal volumetric displacement, reproduced from[41].

The rise time will affect the signal's frequency bandwidth, potentially causing the signal's main intensity to be shifted to a frequency beyond detectable. A glass fibre in a polymer-reinforced composite has a higher fracture stress when compared to the resin. However, the displacement volume is much lower when compared to fibre/matrix cracking, which could extend throughout the composite, compensating for the strength and potentially matching the amplitude[41].

1.3.4.3 Radiation through the Material

The acoustic radiation pattern in composites is different from that of isotropic materials due to the thickness of the structure and the anisotropy associated with composites. For example, the AE event in metals is expected to spread evenly around the source, but that is not the case for composites, as seen in Figure 1-11. The fibre directionality in composites and the sound velocity difference between components affect the signal's propagating path. Additionally, failures at the fibre/matrix interface or within the matrix material occur at arbitrary angles with complex superimposed stress states, meaning no unique radiation pattern can be identified[41].

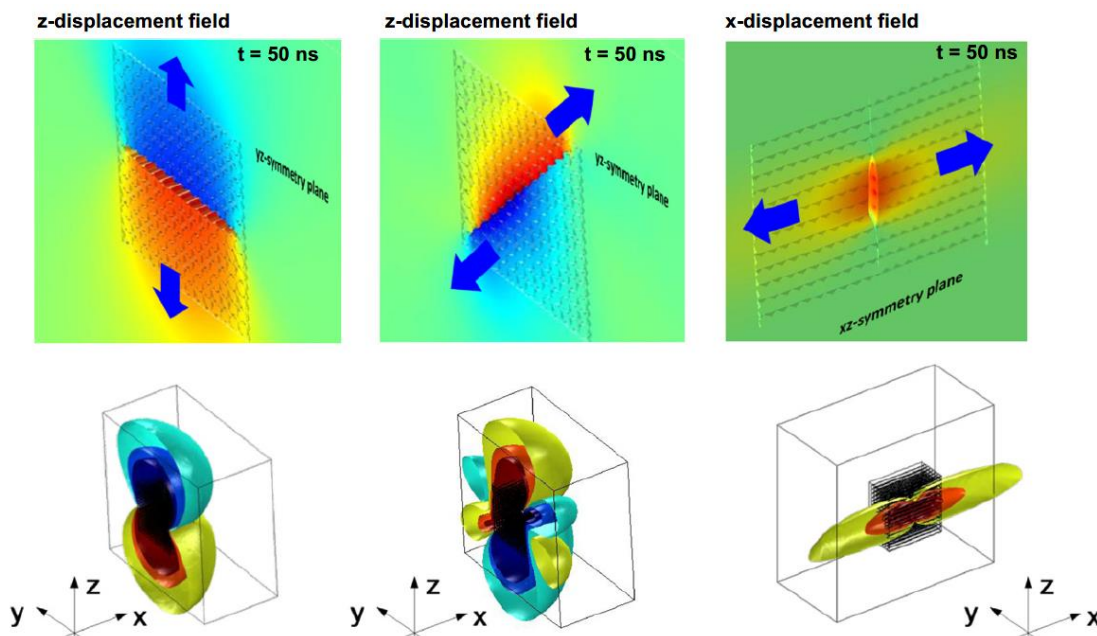


Figure 1-11. AE radiation patterns of (left) mode I interfiber failure mode, (centre) mode II interfiber failure, (right) mode I fibre failure, with the z -axis being the thickness of the laminate, reproduced from[41].

The orientation of the AE source could also affect the shape of the waveform[17], as shown in Figure 1-12. That is, a vertical crack would produce different waveform characteristics when compared to a horizontal crack. The reason is that the vertical crack produces a mostly dominant symmetric wave compared to the horizontal crack, which produces an anti-symmetric wave due to the transient motion. Further details of the wave types are mentioned in 1.3.5.2.

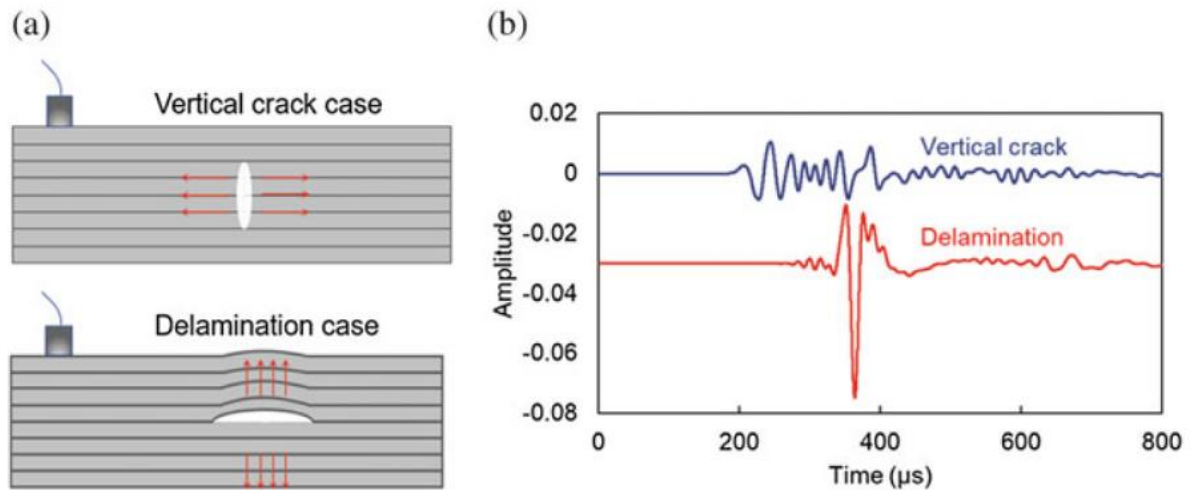


Figure 1-12. (a) Illustration of the crack orientation difference (b) signals originating from different crack orientations, reproduced from[17].

1.3.5 The Signal-Shaping Chain

Four links have been identified to directly affect the shape and size of the measured signal: propagation of the sound wave, source, sensor and signal-conditioning electronics[35]. The signal shape between the source and the sensor is significantly different. That is, the shape of the signal reaching the sensor will not be identical to the signal at the source.

1.3.5.1 Propagation of the Wave

The wave propagation inside a structure can be complex due to the surface geometry, which could reflect or deflect the wave. In addition, solid structures support compressional and shear forces, introducing numerous wave modes that can be simultaneously triggered. The two most important aspects of wave propagation are wave velocity and attenuation[35]. The wave velocity is essential

to locating the source location compared to the attenuation, which determines the distances between sensors. It is also worth noting that information regarding the source mechanism is concentrated at the start of the waveform compared to the latter part, which is more influenced by geometry and could contain reflections[17].

1.3.5.2 Wave Modes[35]

The waves emitted at the source location are bulk waves with two components, longitudinal and shear. Bulk waves are nondispersive, i.e., all waves have a constant velocity. Bulk waves attenuate quickly and can only be useful in very small specimens.

Other wave modes, such as Lamb waves and Rayleigh waves, are produced at the surface from a partial wave energy conversion. If the wall thickness is lower than one wavelength, Lamb waves are produced, but if the wall thickness is higher than one wavelength, Rayleigh waves are produced. Lamb waves are dispersive, meaning their velocity depends on the material thickness and frequency.

Lamb's theory identifies two wave modes: flexural, also known as anti-symmetric (a_0 or A_0), and extensional, also known as symmetric (s_0 or S_0), as shown in Figure 1-13. Other wave modes from the same family exist, but their amplitude is insignificant and hence can be disregarded. The two wave modes travel at different speeds. In a 0.17 cm thick steel plate at 100 kHz, the extensional wave travels at 4.7 km/s, whereas the flexural wave travels at 3.3 km/s. Hence, the extensional wave will reach the sensor before the flexural does. However, the flexural wave has a higher amplitude than the extensional wave, as seen in Figure 1-14.

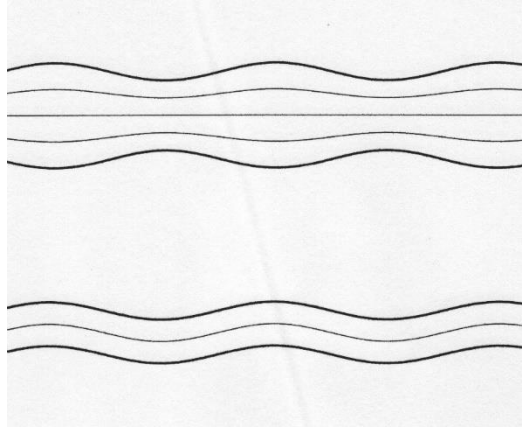


Figure 1-13. Lamb wave modes in plates, (top) Extensional (S_0) and (bottom) Flexural (A_0), reproduced from[46].

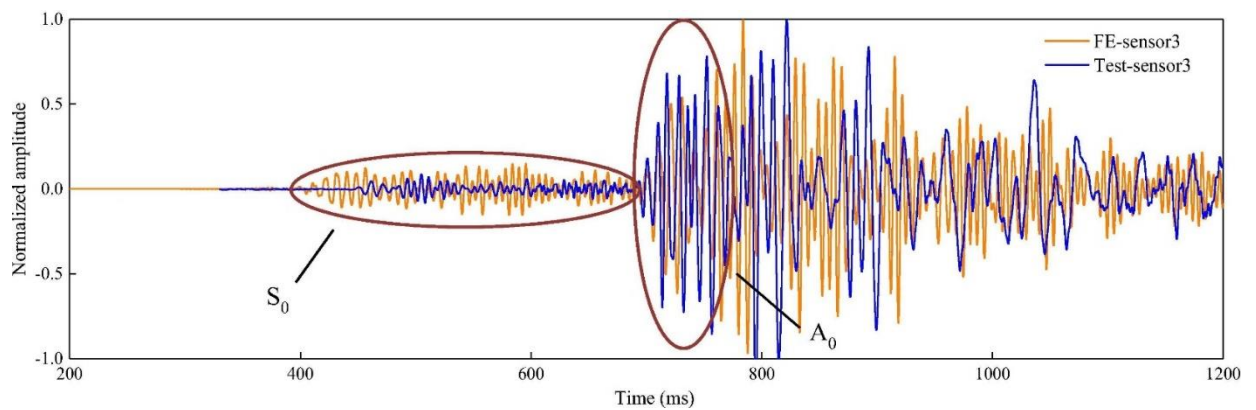


Figure 1-14. A representation of the AE waveform received by the sensor, reproduced from[47].

Flexural mode (a_0) is where the plate's body deforms with the wave moving in the same direction. The motion is primarily transverse with very little longitudinal motion. The force applied needs to be perpendicular to the plate or parallel but offset from the centre to produce this wave mode.

Extensional mode (s_0), or symmetric mode, is where the plate is alternately compressing and stretching in the wave direction. To produce this wave mode, the force applied has to be parallel to the plate or released by a rapid release of in-plane tension.

In thin plates, edge lead break preferentially produces the symmetric (S_0) mode, whereas surface lead break preferentially produces the anti-symmetric (A_0) wave[48].

The symmetric and anti-symmetric modes have also been identified to exist at different frequencies when excited. Different wave modes exist at different frequency ranges when producing guided waves, as seen in Figure 1-15. The structure's thickness is also essential to consider. If the fundamental modes (A_0 and S_0) exist below 1 MHz-mm, then for a 10 mm-thick structure, the fundamental modes will propagate at below 100 kHz frequencies. In addition, note that the amplitude of the signal is also influenced by the excited frequency, as seen in Figure 1-15c[49]. Pant et al.[50] tested carbon fibre prepreg with a total thickness of 0.17 mm while placing PZT sensors and receivers at the surface. They found that the A_0 wave is dominant at frequencies less than 100 kHz compared to the S_0 wave, which was dominant from 200 kHz to 500 kHz, while both wave modes coexisted at frequencies between 100 kHz and 200 kHz.

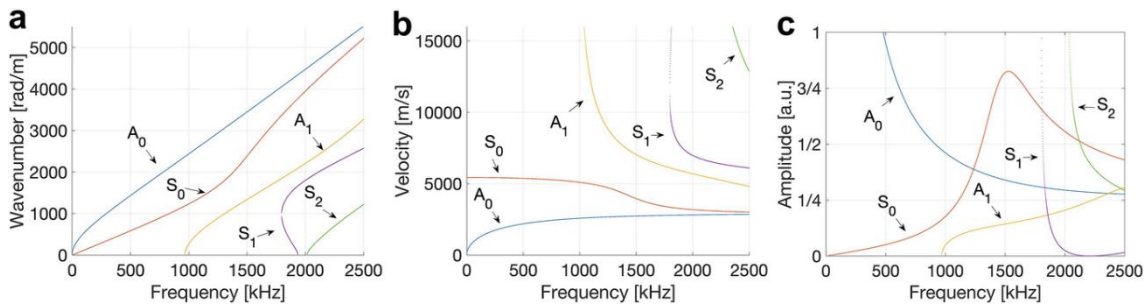


Figure 1-15. 2 mm thick aluminium plate dispersion curves (a) wavenumber-frequency (b) velocity-frequency and (c) amplitude-frequency, reproduced from[49].

According to the mathematical theory of “eigenfunctions”, wave modes travel independently and do not interfere with each other; i.e., multiple wave modes can travel simultaneously in the same material. At a given point, the motion can be defined as the sum of the motion of all the wave modes[35].

1.3.5.3 Attenuation[35]

Attenuation in structures is defined as the loss of amplitude as the wave travels through. The attenuation curve is particularly essential for optimising sensor placement and allowing full structure coverage. Attenuation is caused by multiple factors: geometric spreading, absorption, and reflection (scattering). The influence of each factor is directly related to the distance between the sensor and the source event. If the distance between the sensor and the source event is close (a few cm), geometric spreading is the most influential. However, if the distance is large, absorption and reflection are the most influential.

The geometric spreading effect can be explained as the sound wave attempting to travel in all 360° directions from the source event throughout the structure. The maximum change in wave motion and the static stress field is near the source event. Hence, the highest loss of energy occurs at the source event. In theory, the stress wave will propagate spherically and attenuate in a large-dimensional structure. In realistic structures, the structure's dimensions will force the wave to propagate in a defined space, lowering the attenuation from the beam spreading. For example, a rod's attenuation from geometric spreading is less than that of a concrete block.

The absorption of the wave by the structure itself causes attenuation. Polymer-based composites are more prone to attenuation due to their viscoelastic nature, which causes thermoelastic dissipation. The material through which the wave passes absorbs and converts elastic and kinetic energies into heat. At higher frequencies, the absorption of the wave is higher due to the shorter wavelength. One of the differences between the geometric spreading and the absorption mechanisms is that absorption is constant in the structure, whereas spreading is higher at the source. For example, if the structure absorbs 5 dB per cm, it will continue to absorb 5 dB per cm. In comparison, the decibel loss in geometric spreading is not linear.

Wave reflection that occurs at geometrical discontinuities and structural boundaries causes attenuation. Some wave energy is reflected when the wave encounters a discontinuity. Additionally, discontinuities can give rise to mode

conversion. This effect is particularly essential for structures with complex geometry, which could have changes in connections, direction, stiffeners, and other boundaries between the source event and the sensor.

1.3.6 Couplant

The piezoelectric transducer signal can be affected by the medium between the structure and the transducer. Three main factors influence the signal: the transducer's pressure against the material, the material's surface, and the couplant[51]. The pressure applied to the AE sensor is crucial to achieving a good coupling condition. The pressure applied on a dry contact needs to be 0.7 MPa according to ASTM E650M–12[52]. It was concluded that, generally, as mounting pressure increases, sensitivity increases.

A couplant material is needed between the surface-mounted sensor and the sample to obtain good signal strength and avoid signal reflection. A dry contact is highly undesirable, as the signal will weaken due to the air between the sensor and the specimen. The interface must be air-free as air has an acoustic impedance approximately five orders of magnitude smaller than the two touching surfaces[53]. To reduce the reflection of the AE, the couplant material's acoustic impedance must be close to that of the tested material. A study was done by Theobald[53] to compare the couplants used and their influence on the signal. Multiple couplants were compared on a hemispherical aluminium block: silicon grease, ultrasound gel, propylene glycol, and glycerin. A dry contact was also tested. The couplant effect was recorded for both longitudinal and shear waves[53].

According to ASTM E650M–12[52], it is best to ensure that the couplant is as thin as possible and that there should be no voids or air gaps in the couplant. Additionally, taper or unevenness in the couplant can reduce sensitivity. Furthermore, it is not recommended to use double-sided tape as a bonding agent.

1.3.7 Piezoelectric-Based Acoustic Emission Sensors

1.3.7.1 Piezoceramic Discs (PZT)

PZT, or lead zirconate titanate $\text{Pb}[\text{Zr}_x\text{Ti}_{1-x}]\text{O}_3$, is a ceramic piezoelectric material. PZT has a perovskite crystal structure, where a small tetravalent metal ion (zirconium or titanium) is embedded in a lattice of large divalent metal ions (lead) in each unit[54], as shown in Figure 1-16. The crystal has a dipole moment if the structure is either tetragonal or rhombohedral. The PZT is made using multilayer technology where temperatures can reach 1100 °C; refer to[55] for more information.

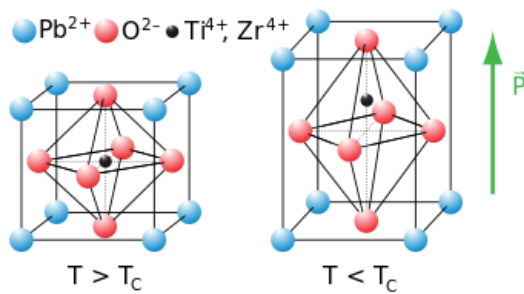


Figure 1-16. A schematic diagram showing a perovskite crystal structure where the PZT crystallites are (left) isotropic (centrosymmetric cubic) above curie temperature (right) anisotropic (tetragonal symmetry) below curie temperature, reproduced from[56].

1.3.7.2 Polyvinylidene Fluoride (PVDF) Sensor

Piezoelectric polymers can be divided into three categories: bulk polymers, voided charged polymers, and polymer composites[57]. One of the most widely used bulk polymers is Polyvinylidene fluoride (PVDF) because of its high chemical and mechanical stability, fast electromechanical response, low acoustic impedance, and flexibility. The piezoelectric effect in bulk polymers is mainly dependent on the molecular structure. Ferroelectricity largely depends on the material's crystallinity, with amorphous polymers also having ferroelectricity due to the molecular dipoles in the amorphous region. A semi-crystalline material has an ordered structure (randomly oriented crystals) within an amorphous bulk. To enhance the piezoelectricity within the amorphous region, the material can be stretched to align the amorphous strands along the plane, which facilitates

uniform rotation of crystallites when applying the electric field. The material must be poled just below the Curie temperature using a strong DC electric field to align the domains. The domains near the electric field would expand, causing a slight increase in length, usually in the micrometre range. Once the electric field is removed, the domains are locked into a near-alignment configuration, as seen in Figure 1-17.

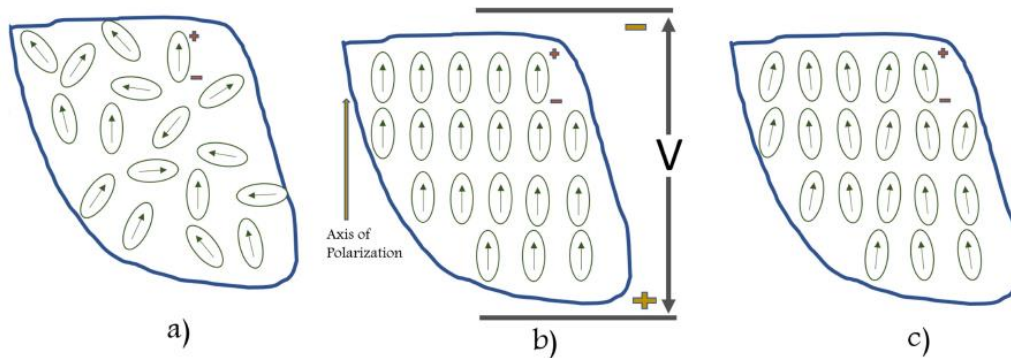


Figure 1-17. The polarisation process (a) domains are randomly distributed before polarising (b) Applying a large electric field across the structure to align the domains (c) after removing the electric field, the remnant polarisation persists, reproduced from[57].

PVDF has multiple semi-crystalline phases that are α , β , γ , δ and ϵ where α and β are dominant[58,59]. The α -phase is the most stable, and upon cooling from the melt, it develops a trans-gauche-trans-gauche semi-helical conformation. PVDF with a dominant α -phase has zero net dipole moment due to the crystalline regions aligning such that dipole moments cancel each other. However, β -phase is the most suitable for piezoelectric applications as it is polar and electroactive. The β -phase has a non-zero dipole moment due to the trans-conformation, meaning Fluorine and Hydrogen atoms exist on the opposite side of the main backbone chain, as seen in Figure 1-18. Thermal annealing, high-voltage treatment, and mechanical orientation can all be used to achieve the required crystalline phase transformation. For more information refer to[60,61] .

One of the methods adopted to create PVDF is solvent casting, where PVDF is dissolved in solvents like Dimethylformamide (DMF) or N-dimethylacetamide

(DMA). The mixture is poured into a mould to create the shape and size desired, which can then be heated to remove the solvent. Spin coating can be used to achieve thin PVDF films.

The direction of stretching will change the behaviour of the PVDF (uniaxial or biaxial stretching). Stretching the material will result in an orthotropic material in the piezoelectric sense. However, the material is considered isotropic with low strains[62].

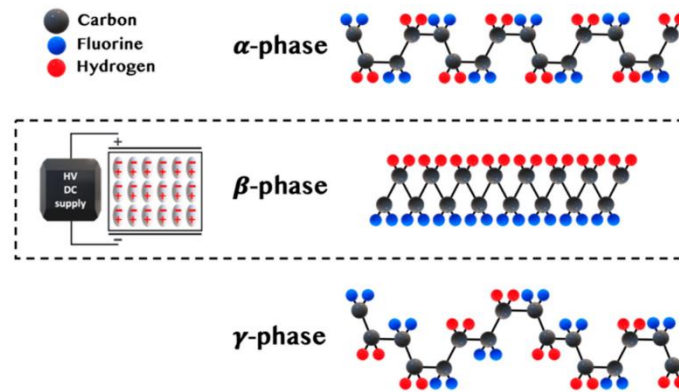


Figure 1-18. PVDF α -phase at the top, β -phase at the center and γ -phase at the bottom, where black atoms are Carbon, blue are Fluorine, and red are Hydrogen, reproduced from[63].

PVDF piezopolymers can be used for actuating and sensing applications. PVDF, as a sensor, is thought to be superior to piezoceramic because it is flexible (promoting easy formability), lightweight, and tough[64]. PVDF film size can be as low as 28 μm in thickness[19]. However, if PVDF is used as an actuator, it will produce a lower force than piezoceramic due to its lower modulus. PVDF property comparison with piezoceramic is presented in Table 1-3[64], which shows the difference in the piezo activity (d_{31}) and Young's modulus between the PZT and PVDF films. Another advantage of PVDF is its ability to be cut to the required size and shape[65].

Table 1-3. Property difference between multiple piezo materials, reproduced from[64].

Property	Units	PVD F film	PZT (PbZrTiO ₃)	BaTiO ₃
Density	kg/m ³	1780	7500	5700
Relative permittivity	ϵ/ϵ_0	12	1200	1700
d_{31}	10 ⁻¹² C/N	23	110	78
g_{31}	10 ⁻³ Vm/N	216	10	5
k_{31}	at 1 kHz	0.12	0.30	0.21
Young's modulus	GPa	~3	~60	~110
Acoustic impedance	10 ⁶ kg/m ² -sec	2.7	30	30

Multiple PVDF sheets are available on the market, one of which is a PVDF poled, gold coated on both surfaces, sold by Precision Acoustics[19]. An alternative is a piezo film sensor made up of rectangular piezo film elements with silver ink screen-printed electrodes. The maximum operating temperature of both sensors is 70 °C, further details in Table 1-4.

Table 1-4. A comparison between the gold and silver PVDF.

	Gold PVDF[19]	Silver PVDF[66]
<i>Thickness</i>	28, 52 and 110 μm	28, 52 and 110 μm (+12 μm for the protective film)
<i>Maximum operating temperature</i>	70 $^{\circ}\text{C}$	70 $^{\circ}\text{C}$
<i>Piezo strain constant (d_{31})</i>	22 pC/N	23 pC/N
<i>Piezo strain constant (d_{32})</i>	3 pC/N	N/A
<i>Piezo strain constant (d_{33})</i>	-30 pC/N	-33 pC/N

PVDF piezoelectricity is characterised by coefficients between the electrical and mechanical values[67]. The coefficients of the piezoelectric materials are formed based on the direction due to the anisotropic nature of the materials. The index of the value is X_{ij} , where i represents the direction of the electrical value measurement and j represents the direction of mechanical input. The numbers are based on the axis of the material (numbered from 1 to 3). As shown in Figure 1-19, numbers 1, 2, and 3 represent the machine direction, perpendicular (transverse direction), and through-thickness, respectively. For example, X_{31} represents the electrical value on the 3rd plane and the mechanical input in the 1st plane. Most of the coefficients will start with i as 3 because the electrical electrodes are usually placed on top of the material.

Units of the piezoelectric coefficient to be considered[67], shown in Figure 1-19:

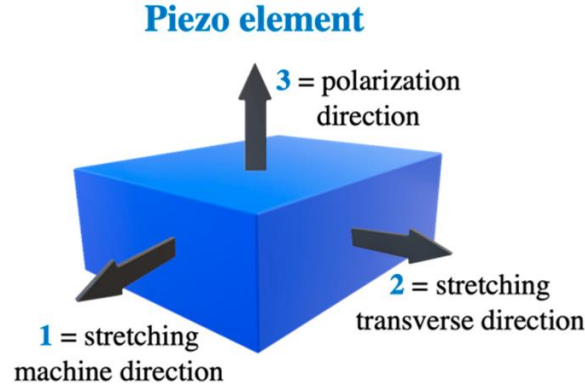


Figure 1-19. Piezoelectric material axis direction, reproduced from[63].

d_{3j} (units: C/N) represents the film's piezo activity. It corresponds to the electrical charge yielded from 1 m^2 when a 1 Pa stress is applied in the j direction. In addition, the mechanical strain when an electric field of 1 V/m is applied is denoted by (dL_j/L_j) .

g_{3j} (units: Vm/N) represents the electrical field supplied when a stress of 1 Pa is applied in the j direction.

g and d coefficients can be related using $g_{3j} = d_{3j}/\epsilon$

ρ (units: C/m²K) indicates the electrical charge density induced when the temperature increases by $1 \text{ }^\circ\text{K}$.

Where C is coulomb, N is Newton, Pa is pascal, V is voltage, m is meter and K is Kelvin.

1.3.8 Fibre Optic Acoustic Emission Sensors (FOAES)

Optical fibres for AE sensing include various designs such as Mach-Zehnder interferometers, Michaelson interferometers, Fabry-Perot interferometers, fused-tapered couplers, and fibre gratings (FBGs)[68]. The dominant advantage of optical fibres over PVDF is their higher operating temperature. For example, the operational temperature for FBG AE sensing is reported to be between $25 \text{ }^\circ\text{C}$ and $200 \text{ }^\circ\text{C}$ [69]. Additionally, the performance of fibre-optic sensors is unaffected by electromagnetic interference[68].

1.3.8.1 Fused Tapered Couplers

The technique is based on placing two optical fibres into parallel contact and then merging both using polishing, fibre fusion, or etching. When an AE event is triggered, stress waves interact with the fibres, which causes a change in the effective strain field, changing the two fibres' coupling ratio's output[68].

1.3.8.2 Intensity-Modulated Fibre Optic Sensors

Intensity modulation is a method that uses a photodetector to measure the light intensity travelling through the optical fibre or reflected at the input. The lightwave intensity passing through the optical fibre can be altered by micro-bending the fibre, affecting the coupling between the fibres and the surrounding medium, or even breaking the fibre[70]. A study investigated damage monitoring in carbon-fibre reinforced polymers (CFRPs) using intensity-modulated fibre optic sensors[71]. The optical fibres will displace (micro-bend) due to the AE event. The detected AE event can then be analysed for possible matrix cracking, delamination, and fibre fracture.

1.3.8.3 Fibre Bragg Grating

Fibre Bragg grating (FBG) is an optical fibre with gratings in specific locations. The grating reflects a particular frequency depending on the spacing between the gratings. FBG can be used for strain measurement; when a structure is deforming, the spacing between the gratings will change, which will change the reflected frequency when compared to the undeformed state.

An essential aspect of detecting a crack or delamination in a composite is the overall structure's strain change. The crack occurrence will only cause local strain (noticed at the crack tip), which is too low to be detected on the global strain field. In addition, if the fibre optic sensor, whether a line or point-distributed sensor, is not placed where the damage has occurred, the damage will not be detected[14].

Fibre Bragg grating can also be used for acoustic emission sensing by detecting the vibrations produced by the acoustic event[72]. However, the fibres can only detect vibrations along the fibre length, not perpendicular to the fibres. However,

this can be enhanced using a cylindrical design where the fibres are wrapped around the cylinder.

1.3.9 Wave Velocity inside the Material

1.3.9.1 Experimental Calculation of Wave Velocity

Measuring the wave speed propagating inside the material is crucial for identifying the source location of a crack. Two sensors are required to calculate the wave velocity separated by a known distance (d). The sensors and the artificial AE wave must be aligned in a straight line[73]. The time of arrival for both sensors is registered and subtracted to find the time of arrival. The wave speed can then be calculated using the following formula:

$$Velocity = \frac{\text{Distance between sensor spacing } (d)}{\text{Time to arrival}} \quad (1-7)$$

If the material is anisotropic, the wave velocity should be calculated in all directions.

1.3.9.2 Theoretical Wave Velocity Inside the Material[74]

The plate wave theory calculates the wave velocity inside a material. While it is difficult to distinguish between the flexural and extensional wave modes, specific techniques, as previously mentioned, can preferentially induce either. To measure the longitudinal wave velocity (C_L) in an isotropic plate, the following equation is used:

$$C_L = \sqrt{\frac{E}{\rho(1 - \nu^2)}} \quad (1-8)$$

where E is Young's modulus, ρ is density, and ν is Poisson's ratio

Whereas to measure the longitudinal wave velocity in an orthotropic laminated composite plate, the formula used is:

$$C_L = \sqrt{\frac{E_{11}}{\rho(1 - \nu_{21}^2)}} \quad (1-9)$$

where E_{11} is the in-plane longitudinal elastic modulus in one direction, ρ is density and ν_{21} is the in-plane Poisson's ratio in one direction.

Nevertheless, placing rectangular arrays of sensors in an anisotropic composite, for example, can provide an approximate location of the crack within the defined area of the sensors. Several algorithms/methods have been developed to determine the amplitude source location (ASL) without taking into account the wave velocity, including, L-shaped sensor clusters[75–77], square-shaped sensor clusters[78], and Z-shaped sensor clusters[79], and the elliptic wavefront shape-based technique[80]. Special positioning of the sensors is necessary for the methods mentioned to operate effectively[80].

1.3.10 AE Source Location Identification Using Time of Arrival (TOA)[20]

Identifying the AE source location is a powerful tool that enables the user to identify the damage location. The simple method of calculating the source location is to know the time of arrival (TOA) and the wave velocity of each hit, therefore calculating the distance from the sensor. The ability to determine the location of the damage is based on the delay of the incoming signal, i.e., the further away the source from the sensor, the longer it takes to arrive. However, an elastic wave travelling inside the material heavily depends on the propagation path's properties and the propagation method to the AE sensor[20]. That is, different travelling effects, geometries (causing wave reflection), or intrinsic material heterogenous properties can cause imprecise wave velocity measurement. Hence, accurate wave velocity measurements are needed to provide the correct source location.

Measuring the signal delay for composites is challenging as the fibres could act as a preferential path for the elastic waveform. In other words, a signal travelling through a fibre may reach its destination sooner than a signal travelling on resin.

Different techniques have been developed to identify the source location of the AE event depending on the number of AE sensors placed, as detailed in Table 1-5.

Table 1-5. The source location technique to be used depending on the number of AE sensors[20].

<i>Number of AE Sensors Required</i>	<i>The Dimension of the Source Location</i>
<i>Two AE sensors</i>	<i>Single (one) degree of source location</i>
<i>Three AE sensor</i>	<i>Two-dimensional source location</i>
<i>Four or more AE sensors</i>	<i>Three-dimensional source location</i>

1.3.10.1 Linear Source Location Technique[20]

The linear source technique, also known as single (one) degree AE source location, is considered the most straightforward technique, requiring two AE sensors to determine the AE source location[20]. This technique is commonly used on pipes and bridges.

This technique depends on placing two AE sensors at a known and appropriate distance. The TOA from each sensor can be collected. The source location can be identified based on the difference in TOA between the two sensors. For example, if the difference in TOA between the two sensors is zero, then the source location is precisely centred between the two sensors. To further illustrate, the shorter the TOA, the closer the source location is to the sensor. Figure 1-20 shows a schematic of the technique, where s_1 and s_2 represent AE sensors. Furthermore, t_1 and t_2 represent the TOA to sensor 1 and the TOA to sensor 2, respectively. l , l_1 and l_2 represent the distance between the two sensors, axial distance to s_1 and axial distance to the $l/2$ (midpoint between the two sensors), respectively.

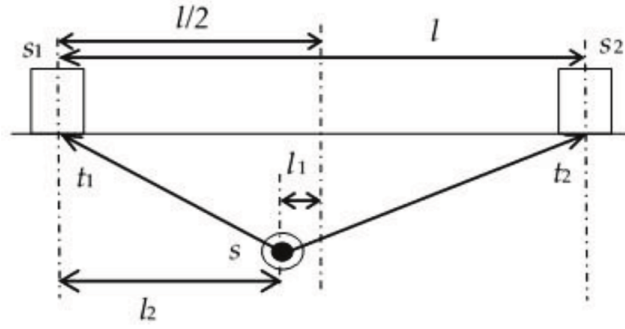


Figure 1-20. Linear source location schematic, reproduced from[20].

The source location can be calculated using the following mathematical relation, where Δt represents the difference in TOA between sensor 1 and sensor 2 ($t_1 - t_2$) and v represents the AE wave velocity[20].

$$l_1 = \frac{1}{2}(t_1 - t_2) \cdot v = \frac{1}{2}\Delta t \cdot v \quad (1-10)$$

$$l_2 = \frac{1}{2} l - l_1 = \frac{1}{2}(l - \Delta t \cdot v) \quad (1-11)$$

1.3.10.2 Two-Dimensional Source Location Technique[20][81]

This technique requires three or more sensors to identify the AE source location. The AE source will be surrounded by the three sensors, allowing the location to be more accurately measured[20]. Although three sensors are enough to identify the source location using the two-dimensional technique, a fourth sensor (often called a reference sensor) can improve the source location even further. The fourth sensor will allow a rectangular sensor array arrangement, producing six sensor pairs compared to three sensor pairs using three sensors. To achieve the two-dimensional AE source location, the TOA of each pair is calculated and correlated.

1.3.11 Determination of the Time of Arrival (Onset Picking)

It is crucial to correctly determine the time of arrival of an acoustic wave to allow accurate determination of the source event's location. To determine the time of arrival, the signal start must be identified. Multiple methods can be used to determine the TOA with varying complexity. The methods mentioned below were mainly used to detect seismic waves but can still be used for AE.

1.3.11.1 Amplitude Threshold Picker

The simplest method to determine the TOA is to choose an amplitude threshold picker. This method allows the user to predetermine an amplitude threshold; whenever the wave amplitude crosses the threshold, the time of arrival is registered[18]. However, this method is unsuitable for high-noise or low-amplitude signals.

1.3.11.2 Short-Time Average/Long-Time Average Ratio (STA/LTA)

This method compares the short-time average amplitude (leading) to the long-time average amplitude (trailing). If the STA value is greater than the LTA value, then the STA/LTA ratio is greater than 1. A channel is triggered if the ratio exceeds the preset STA/LTA ratio threshold[82]. The process is better illustrated in Figure 1-21, where no channels are triggered if the average STA and LTA are similar (A-B). A channel is triggered if the STA has a higher value than LTA (C). However, in the presence of noise, the average values between STA and LTA are similar; hence, no channel is triggered (D).

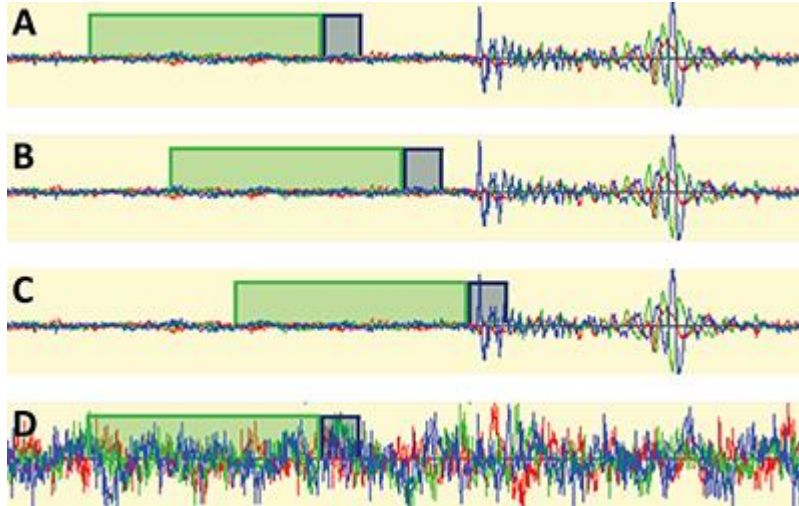


Figure 1-21. Green and grey boxes represent LTA and STA, respectively. (A–C) shows how the microseismic event is triggered (D) shows how false signals are not triggered, reproduced from[82].

1.3.11.3 Akaike Information Criteria (AIC)

The AIC technique is based on the idea that the periods before and after a waveform's arrival time are two separate stationary time series, each of which is

regarded as an autoregressive process[83]. Multiple developments have been carried out in the AIC techniques, with one of the most recent improvements being made by Zhou[83].

1.3.12 Embedding Sensors

Embedding acoustic emission sensors is not limited to polymer composites as it has been tested within concrete[84,85] and with hip stem construction[86]. However, this section focuses on the application of embedding PZT and PVDF sensors in composites for acoustic emission detection. Embedding PZT and PVDF sensors are not limited to AE detection; instead, they could be used to detect strain by measuring the capacitance[87].

When integrating PVDF or PZT sensors inside a composite, the maximum operating temperature of the sensors is disadvantageously low. The low operating temperature of the sensors will limit not only the manufacturing technique used but also the matrix choice. In addition, mixing epoxy with a hardener can cause an exothermic reaction that releases heat, potentially damaging the sensor.

A study was also carried out by De Rosa[65] to identify the effects of integrating a PVDF with silver ink screen printed electrodes in an E-glass fabric/epoxy composite. The PVDF sensor size was 41 mm (length) $\times$ 15 mm (width) $\times$ 70 μ m (thickness). The final specimen size was 200 mm (length) $\times$ 25 mm (width) $\times$ 1.8 mm (thickness). The study concluded from the tensile test that the modulus and the ultimate tensile strength of the samples with and without the sensor were within 6%. In addition, the flexural behaviour was similar, with a difference of 5% in modulus and 1% in bending strength between the samples. The number of AE events detected was slightly better with the embedded sensor when compared to the reference sample with surface-mounted sensors, as seen in Figure 1-22.

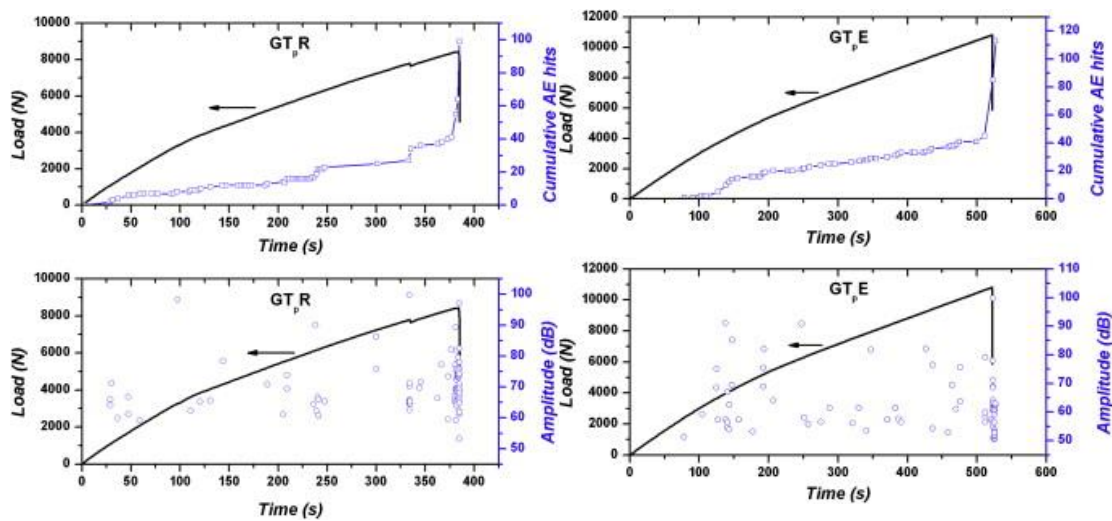


Figure 1-22. Cumulative hits and load (up) and amplitude distribution (bottom) for (left) sample with mounted sensor (Right) sample with an integrated sensor, reproduced from[61].

Masmoudi et al. conducted multiple studies investigating the influence of embedding sensors within composites[3,29,88–92]. The effect of placing a PZT sensor in an E-glass fibre composite was investigated[3]. Three different samples were prepared: a control sample with no sensors embedded (WS), a small sensor sample (SS), and a large sensor sample (LS) to be tested on a three-point bend test. The small sensor had a diameter of 5 mm and a thickness of 0.5 mm (SS), whereas the large sensor had a diameter of 10 mm and a thickness of 1 mm (LS). All the samples had a length of 150 mm, a width of 30 mm, and a thickness of 8 mm. The sensor was centred and placed 45 mm from the length edge. Compared to the controlled sample (WS), the failure load of the SS sample had a reduction of 8%, whereas the LS sample exhibited a decrease of 18%. On the other hand, the stiffness of the material remained the same, with a slight increase in the SS sample when compared to the controlled sample.

As seen in Figure 1-23, embedding the sensor inside the composite has the advantage of being more sensitive, and hence more hits can be ‘heard’, resulting in more accurate results. In addition, there is no need for protective cladding to protect the sensor from the outside, as the structure itself will protect it. Theoretically, it should provide a better signal-to-noise ratio as the material

surrounds it. However, it does have disadvantages, such as the inability to be integrated into existing structures, and if the sensor is damaged, false readings could arise.

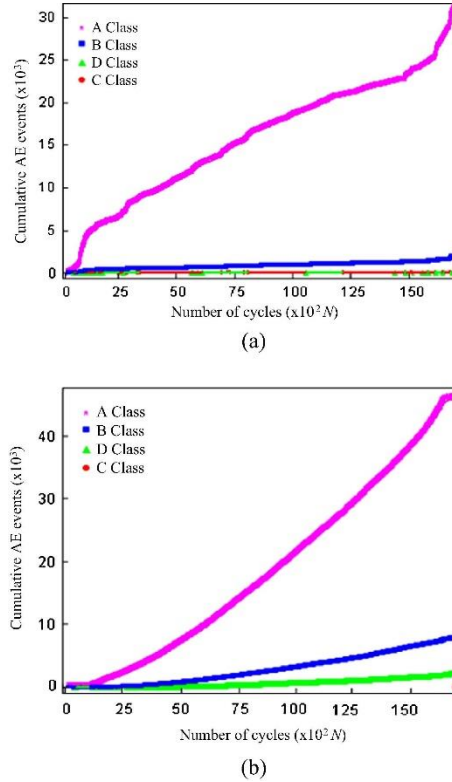


Figure 1-23. Cross ply laminate acoustic emission cumulative AE events difference between (a) specimen without integrating the sensor (b) specimen embedded with a small piezoelectric sensor[87]. A Class= matrix cracking, B Class= fibre-matrix debonding, D class= delamination and C= fibres breaking, reproduced from[91].

Another study[91] investigated embedding sensors in a cross-ply laminate [0₆/90₆]_s, prepared using the hand lay-up process. The thickness of the laminate was 8 mm, whereas the sensor thickness and diameter were 5 mm and 0.5 mm, respectively. It was concluded that embedding the sensor caused degradation to the mechanical properties and that the embedded sensor had higher sensitivity when compared to the surface-mounted sensor. A similar study on sandwiched composite[89] yielded similar results compared to the cross-ply laminate.

Syechal et al.[93] tested several sensor sizes with different fibre orientations in a natural fibre composite. The findings demonstrate that the inclusion of an insert

increases fibre deviation and makes matrix-rich zones a preferred choice for crack initiation. However, the effect of the inserts on the samples differed based on the mechanical test performed. For example, the tensile test showed a reduction in strength, whereas with the three-point bend test, the insert did not affect the results and even occasionally improved them. However, the tensile-tensile fatigue resistance was affected negatively. The insert's surroundings are affected by damage accumulating in the insert's surrounding area, but the insert does not modify the mode or damage kinetics.

Caneva et al.[94] have demonstrated that embedding the PVDF caused a slight mechanical strength reduction and the results demonstrate that the embedded sensors were not more sensitive. Another study performed by Jain et al.[95] showed that increasing the number of glass fibre layers encompassing the sensor increases the sensor's output voltage when testing using the lead break test. It also showed that the sensor with the lowest glass fibre layers yielded a higher voltage when performing an impact test until it fractured at 2 joules, but the sensor was still responding well.

Qing[13] investigated the ability to integrate a sensor network using piezoelectric sheets on a woven graphite/epoxy specimen. The thickness of the piezoelectric sheet is 0.15 mm. However, two different thicknesses of piezoelectric discs were used: 0.25 mm and 0.75 mm. It was found that the 0.75-mm disc got crushed once the mould was closed. Mechanical tests were conducted on a coupon specimen with a lay-up of $[0_4/90_4/0_4]$ an embedded piezoelectric sheet 0.15 mm in thickness and 0.25 mm piezoelectric discs. It was concluded that the sensor sheet defers delamination and does not noticeably affect the strength.

A recent study was done by Tuloup[87] to investigate the effects of embedding PZT and PVDF inside a glass fibre-reinforced polymer. Multiple tests were undertaken, such as monotonic tensile, load-unload, and cyclic loading. The embedded PZT and PVDF were used to compare the mechanical properties and investigate whether the embedding of the sensors causes a change in the acoustic emission response. When embedding PZT, the findings indicated a degradation in mechanical properties, with a 6% decrease in mechanical

resistance (UTS) and a 5% reduction in Young's modulus. However, the maximum longitudinal strain had increased by 11%, which caused a 26% reduction in Poisson's ratio. At around 0.3% strain (y-direction), the PZT registered a slope change in the capacitance; upon inspection, cracks were found in the sensor. The acoustic response from the pristine and embedded samples was similar, confirming that embedding the PVDF does not change the damage mechanism. PZT had a different acoustic response due to the cracking of the PZT itself. It was found that there is a linear relationship between the capacitance and strain in both PZT and PVDF. However, the electrical capacitance variation for PZT, when compared to PVDF at the same strain, was much higher at 30% compared to PVDF at 0.7%. PVDF can receive signals until a sample fails, whereas PZT used to crack at 0.3% and hence become useless. One of the main disadvantages of PZT is its inability to withstand strain due to its ceramic nature.

Ghezzi et al.[79] found that at least a four-layer laminate with a thickness of 1.05 mm is needed to integrate a 0.5 mm-thick PZT sensor. It was concluded that the thickness of the integrated device should be at least the same as the thickness of the laminates above and below it.

A large sensor cannot be embedded into thin composites because the sensor is a rigid inclusion that can indent the matrix and damage the fibres[96]. Theoretically, the decrease in mechanical properties can be reduced by increasing the composite's thickness and reducing the sensor's thickness.

3. Conclusions

The use of acoustic emission testing for structural health monitoring of polymer-based composite structures can be highly valuable in some instances while presenting significant challenges in others. The method can detect failure events and their locations without the need for activation. The crack location is challenging to determine in composites compared to metals due to their anisotropic nature, which leads to different wave speeds in different directions. Nevertheless, the effect of the anisotropy within the composite can be reduced using algorithms or special sensor placement. The current general trend towards

artificial intelligence and deep learning will further enhance the AE technique, and more use of AE within the industry may be seen.

Extensive research has proven the ability to embed acoustic emission sensors in composites with partial disagreement. It has been established that embedding the sensors will affect the material's mechanical properties depending on the sensor's size and the material's thickness. However, some research shows that embedding sensors improves their sensitivity, while others do not. The possible advantage of increased sensitivity can be more significant than the disadvantage of mechanical loss, depending on the application. The sensor can be placed in an uncritical location to reduce the effect of the mechanical properties drop.

The research conducted does not quantify the sensitivity of the sensors with respect to the location of the cracks. That is, whether a surface-mounted sensor is more sensitive to surface or sub-surface cracks or whether a fully embedded sensor is more sensitive to surface or sub-surface cracks. Previous work has focused on testing the acoustic emissions sensor's sensitivity using mechanical testing, such as the three-point bend and tensile tests, where cracks could arise from the surface or sub-surface.

Calibrating the sensors and testing their attenuation requires a reproducible artificial AE source. The pencil lead-breaking method has been extensively used due to its ease of use. However, compared to actuators, its reliability on uneven surfaces, such as a peel-ply-induced surface, requires further investigation.

The protection of the sensor from the outside environment is not adequately explored in the literature. Environmental factors such as rain, sand, hail and debris impacts can cause interference or provide false results. For example, does embedding the sensor in a sandy environment prevent false signals from foreign objects? Or is it better to surface mount the sensor on the opposite side of the incoming foreign object? Any improvement in signal-to-noise ratio arising from embedding a sensor into a material has yet to be assessed and published.

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2 [Paper 2] Assessment of Methods to Generate a Reproducible Acoustic Emission Signal on a Composite and a Metal

2.1 Abstract

A reliable artificial acoustic emission (AE) source ensures accurate sensor performance. Consistency in signal reproduction is particularly crucial especially when testing aged sensors or those that have been exposed to harsh environmental conditions. The Pencil-Lead Breaking (PLB) method is widely used but its accuracy and precision on a textured surface (caused by peel ply) composite requires further investigation. The transducer method is also used, yet its convenience would markedly rise with repositioning capabilities. This study delves into the reproducibility of artificial AE sources, specifically examining two sample materials: glass fibre-reinforced resin (composite) and aluminium. The effect of the PLB method due to the peaks and valleys caused by the composite's manufacturing process is analysed compared to the Aluminium's smooth surface. Surprisingly, the results revealed that the textured surface of the composite had minimal impact, if any, on the outcome when utilising the PLB method. To facilitate repositioning within the transducer method, two distinct types of double-sided tapes were explored, each varying in tackiness. While the lower-tack (Ract) double-sided tape outperformed the higher-tack variant (Tact), its precision diminished on the composite partly due to the reduced contact caused by the textured surface. The research aims to assess the reproducibility of artificial acoustic emission sources against different textured materials.

2.2 Introduction

Acoustic emission (AE) is a passive testing method that can be utilised for structural health monitoring (SHM). The method's ability to monitor a large area of the structure compared to other inspection methods[1], which require multiple local inspections, is highly advantageous. AE can distinguish between different failure modes in a fibre reinforced composite due to the characteristics of each failure event[2–9]. The type of failure occurring can represent the current

deterioration stage of the structure. For example, the occurrence of fibre pull-out represents the final failure stage, indicating a critical danger compared to matrix cracking.

Artificial acoustic emission sources serve various purposes, including generating or confirming a material's attenuation curve and assisting in damage source location studies where the AE source must be known. While the 'auto sensor test' method is employed to verify AE sensor repeatability using specialised equipment[10], artificial AE methods can also assess sensor response variation with time or ensure sensor integrity post-incident[11].

According to ASTM E976-10, three methods are recommended to produce a repeatable AE source: gas-jet test block, electrically driven ultrasonic transducer and pencil lead break (PLB)[11]. The gas jet test relies on pressurised gas impacting the surface, compared with the transducer method that necessitates exciting a transducer using instruments like a pulse generator. The pencil lead-breaking method stands out as the most straightforward, as it only requires a mechanical pencil with a 'shoe' to generate the signal.

Although the transducer and PLB methods were employed as artificial acoustic emission sources[12–14], the transducer method offers an advantage by producing a signal with a specific frequency despite needing more equipment than the PLB method. The specific frequency ability may prove useful with composites due to the frequencies associated with failure types. When employing the transducer method for testing, a notable benefit arises from its ability to reposition the transducer, a feature tested within this article on both a composite and a metal.

Although the pencil lead-breaking method's accuracy was tested against different breaking angles and lead hardnesses[15], laminated composites may have a textured surface due to the manufacturing process (peel ply), which was thought to affect the method's precision.

This paper investigates the repositioning ability of the transducer method, which, if proven, will increase its convenience and ease of use. It also assesses the effect of the PLB on the composite's textured surface.

2.3 Experimental procedure

2.3.1 Sensors

The acoustic emission sensor used is a wideband differential sensor from Physical Acoustic. It is attached to the plate using general-purpose clear silicone sealant. The transducer was attached to both plates using a thin double-sided tape from Ultratape (01035033CL), 70 μm thick and a repositionable double-sided tape (3M scotch removable double-sided), 80 μm thick. The pencil used was from the MISTRAS group, pre-fitted with a shoe.

The transducer (PZT) used is a piezoelectric element (7BB-15-6) from Farnell. The transducer's diameter and thickness were 15 mm and 0.22 mm, respectively.

Eight PZT actuators were prepared to test on both plates; half were attached with the thin double-sided tape referred to as 'Tact', and half were attached with the repositionable double-sided tape, referred to as 'Ract'. Also, 'Comp' and 'Alum' are placed before the couplant type, which refers to the composite and aluminium plates.

2.3.2 Material

Tests were conducted on aluminium and glass fibre-reinforced polymer plates. The aluminium plate dimensions were 665 mm x 520mm x 3.3 mm, and the glass fibre-reinforced polymer dimensions were 615 mm x 630 mm x 2.65 mm. The glass fibre composite was prepared using vacuum infusion, detailed in Table 2-1. Six woven glass fibre plies were stacked on a peel ply and covered with peel ply. A flow mesh was used to facilitate wetting.

Table 2-1: Glass fibre composite manufacturing details

Fibres	Glass woven roving 600 gsm plain weave
Epoxy Resin	RS-M135
Hardener	RS-MH137

2.3.3 Equipment

A PCI-2 based AE system (AEwin) was used to capture the AE data from the sensor. The sensor was connected to the preamplifier and set to 40 dB. The detection threshold was set to 45 dB.

The pulse generator was a TGP110 10MHz, from Thurlby Thandar Instruments (TTi). The generator was set to pulse with a period of 4 seconds, a pulse width of 5 μ s and an amplitude of 10 volts.

2.3.4 Testing Procedure

After permanently attaching the receiving sensor using silicone, the AE signal was produced at 5, 15 and 25 cm at 90° and 45° from the receiving sensor using the actuators and the PLB method. The testing was repeated three times at each distance to ensure precision. An average amplitude was then calculated alongside the standard deviation from each test. The testing sequence was as follows: 5 cm at 90°, 15 cm at 90°, 25 cm at 90°, 5 cm at 45°, 15 cm at 45° and 25 cm at 45°. After completing the initial test, the same testing sequence was repeated, referred to as 'rep' in the paper.

2.4 Results and Discussion

2.4.1 Practicality of the actuating methods

The ability to artificially induce a reproducible AE signal without altering the structure under investigation is highly advantageous. The pencil lead-breaking method is convenient as it only requires a pencil with a pre-fitted 'shoe', allowing

for a consistent AE signal without being permanently attached to the structure. However, the signal's frequency cannot be controlled.

The transducer method requires multiple pieces of equipment before a signal is acquired: a pulse generator, BNC connection, transducer with soldered wires and a couplant. The couplant must have consistent contact with the structure; permanent adhesive can be used. However, the use of permanent adhesive will not allow removal after testing. A significant advantage to be added to the transducer approach by using double-sided tape, which allows repositioning. Specialised equipment allows for precise control over the generated pulse frequency, a capability absent in regular pulse generators.

For this study, the precision of the methods is contingent on their capability to generate identical results during the test. This accuracy, however, is rooted in the ability to attain similar values when revisiting the test location. For instance, conducting five tests at the same time measures precision. However, revisiting the test location later and conducting five additional tests and comparing it to the previous results determines the accuracy.

Initially, the transducer method was thought to be much superior in precision when compared to the PLB, which was confirmed. However, the accuracy of the transducer when removed and repositioned on the substrate was uncertain.

The accuracy of the preamplifier is ± 0.2 dB, and the resolution of the AE equipment is less than 1 dB[10].

The aberration from the TGP110 pulse generator is less than 5%. Since 10V is the amplitude used, the aberration from the pulse generator is ± 0.5 V. A voltage of 10.5 Volts produces 100.42 dB, 10 Volts produces 100 dB and 9.5 Volts produces 99.55 dB, based on Equation (2-1)[10]. The error from the pulse generator can be disregarded if the AE system does not have an error, as a voltage of 9.5V and 10.5V will produce an amplitude of 100 dB as per the AE machine rounding to the nearest integer. However, the error cannot be disregarded due to the AE equipment and preamplifier accuracy compounding to increase or decrease the error.

$$dB = 20 \log \left(\frac{V_{max}}{1 \mu - volt} \right) - (Preamplifier \text{ Gain in dB}) \quad (2-1)$$

The change in pencil lead length, pencil 'shoe' and lead hardness can all contribute to the error produced by the pencil lead-breaking procedure. The lead hardness and pencil 'shoe' are fixed, but the lead length is a user variable.

2.4.2 Repeatability of methods on aluminium

Prior to testing, the edges of the plate to prevent AE reflection[9] were covered with tacky tape (vacuum sealant type). Testing the Tact transducers on the aluminium plate yielded precise but inaccurate results with AlumTact #1 and AlumTact #2, as seen in Figure 2-1. That is, when repeating the test on the same angle, different results were observed. That is, when repeating the test on the same angle, different results were observed. As seen in Table 2-2, at 90°, a maximum difference of 2.4 dB is noted compared to a 5 dB difference at 45° with AlumTact #1. With AlumTact #2, the maximum difference was 5 dB at 90° compared to 7.6 dB at 45°.

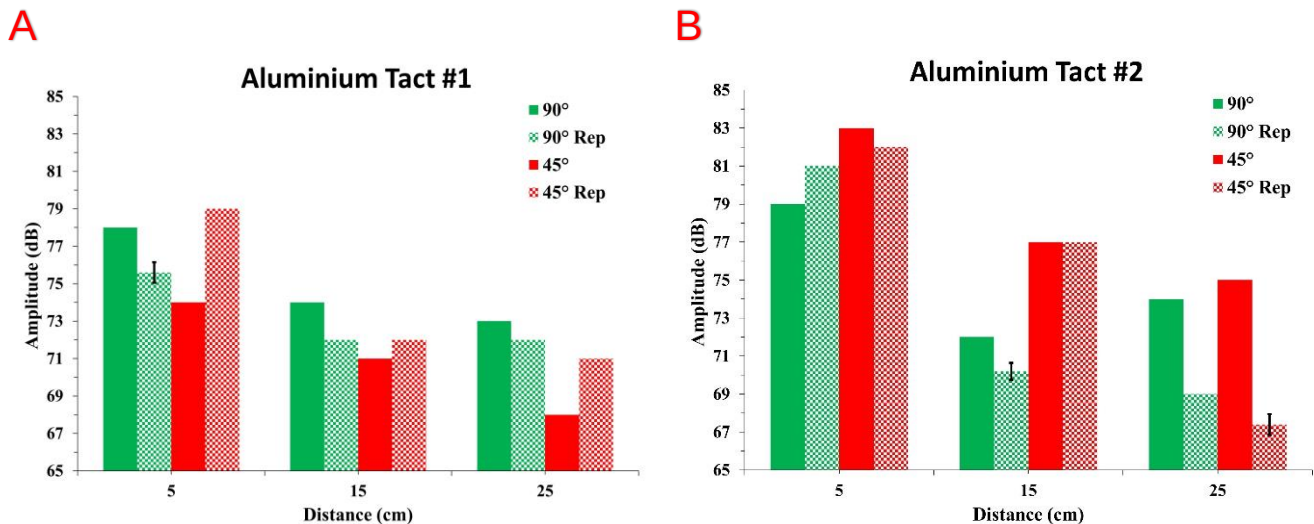


Figure 2-1. Attenuation curves generated utilising thin double-sided tape couplant actuator on aluminium using A) Tact #1 B) Tact #2

The attenuation of aluminium should have comparable results when testing at 90° and 45° due to the material's isotropic nature. Yet, some differences are seen

with AlumTact #1 and AlumTact #2. However, the unknown history of the plate could have affected its isotropy; hence the 90° and 45° results will be regarded separately. Also, the testing sequence could have affected the results. That is, the thin double-sided tape had strong adhesion on the plate's surface. Upon lifting the AlumTact, the transducer and double sided tape were damaged. Also, due to the strong adhesion, the transducer was prone to bending during lifting and reinstalling, further influencing the error. The values from the repeated test fluctuated rather than showing a steady rise or fall compared to the first test.

Comparing the first and repeated tests, AlumTact #1 exhibited a total attenuation difference of 1.4 dB and 2 dB at 90° and 45°, respectively. However, AlumTact #2 showed a 7 dB total attenuation difference at 90° and 6.6 dB at 45°.

As the couplant was causing a high percentage of the error, a repositionable double-sided tape was used to replace the thin double-sided tape. The repositionable double-sided tape had lower tackiness compared to the thin double sided tape which facilitated the lifting and placing of the actuators. However, it was noticed that the pressure applied to the actuator affected the amplitude of the output signal. Hence, upon reinstalling the actuators, the actuator was pressed firmly, ensuring similar contact with other tests.

Nevertheless, AlumRact #1 showed promising results even with the repeated test. Upon repeating the test at 90°, a maximum difference of 1.2 dB was seen at 90° when compared to 3 dB when repeating at 45°. The lower tackiness causes a lower adhesion between the plate and the actuator, which may cause the sensor to lift with time. To confirm the sensor lifting, a test was conducted where the AlumRact was placed for 3 minutes continuously actuating on the surface of the aluminium. The results show that the sensor amplitude decreased from 61 to 60 dB. The same phenomenon was seen with the composite material, as explained later.

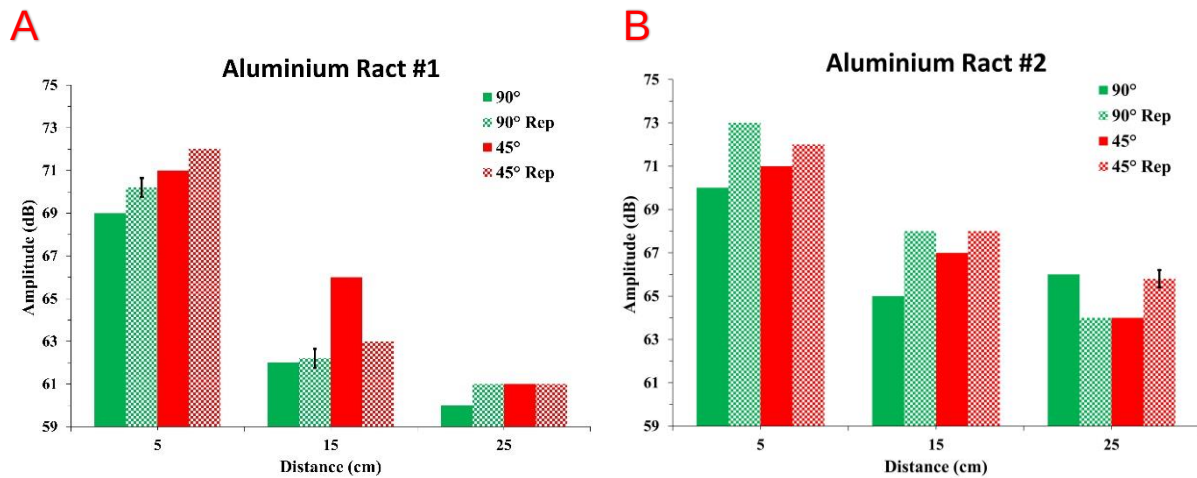


Figure 2-2. Amplitude registered when utilising repositionable double-sided tape couplant actuator on aluminium using A) Ract#1 B) Ract#2

AlumRact #1 showed a 1 dB overall attenuation difference between the first and repeated tests.

Repeating the test, AlumRact #2 showed a similar overall response to AlumRact #1 besides the first 90° test. AlumRact #2 showed a maximum difference of 3 dB between the first and repeated test at 90° compared to 1.8 dB at 45°. Also, AlumRact #2 total attenuation difference between the first and repeated tests was 5 dB at 90° compared to 0.8 dB at 45°.

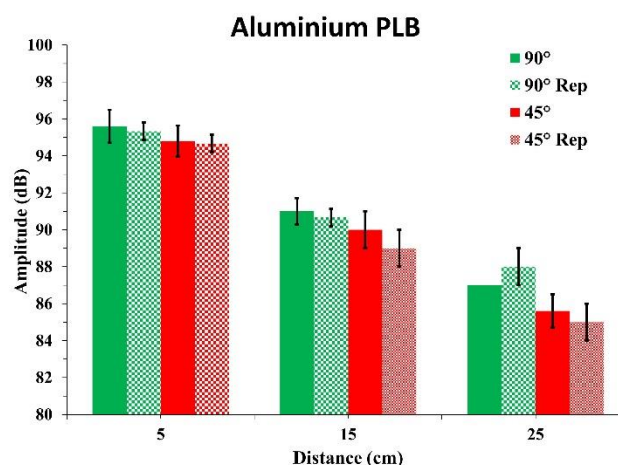


Figure 2-3. Amplitude registered when utilising the pencil lead breaking method on an aluminium plate

The pencil lead-breaking method showed high precision and accuracy on the aluminium plate. One pencil was used as the variation with the pencil is limited compared to the actuator method. The actuator's response to the same voltage could differ due to the manufacturing process compared to the pencil. The variations arising from the pencil method are the breaking angle and lead length. The 'shoe' of the pencil could deform over time, resulting in a change in the break angle and a different output force[15], leading to a varied amplitude. The operator can control the lead length to a good degree.

The PLB method had lower precision than the transducer method, which is visible from the error bars in Figure 2-3. However, the method's accuracy is high when taking the average of the individual hits. The maximum difference between the first and repeated tests at 90° and 45° was 1 dB. Also, the maximum difference in attenuation between the first and repeated tests was 1.1 dB. The lower accuracy could be due to the tolerance of the lead length and the change of lead surface angle after breaking. After breaking the pencil, the shape of the lead tip could change, causing a difference in the overall breaking angle.

Table 2-2. The attenuation of aluminium concerning five different actuating types.

Aluminium									
Actuating		5 cm Distance		15 cm Distance		25 cm Distance		Total attenuation (dB)	Error (dB)
Type	Angle (°)	Average amplitude (dB)	Error (dB)	Average amplitude (dB)	Error (dB)	Average amplitude (dB)	Error (dB)		
Tact #1	90	78 ± 0	2.4	74 ± 0	2	73 ± 0	1	5	1.4
	90 - rep	75.6 ± 0.5		72 ± 0		72 ± 0		3.6	
	45	74 ± 0	5	71 ± 0	1	68 ± 0	3	6	2
	45 - rep	79 ± 0		72 ± 0		71 ± 0		8	
Tact #2	90	79 ± 0	2	72 ± 0	2.2	74 ± 0	5	5	7
	90 - rep	81 ± 0		70.2 ± 0.4		69 ± 0		12	
	45	83 ± 0	1	77 ± 0	0	75 ± 0	7.6	8	6.6
	45 - rep	82 ± 0		77 ± 0		67.4 ± 0.5		14.6	
Ract #1	90	69 ± 0	1.2	62 ± 0	0.2	60 ± 0	1	9	0.2
	90 - rep	70.2 ± 0.4		62.2 ± 0.4		61 ± 0		9.2	
	45	71 ± 0	1	66 ± 0	3	61 ± 0	0	10	1
	45 - rep	72 ± 0		63 ± 0		61 ± 0		11	
Ract #2	90	70 ± 0	3	65 ± 0	3	66 ± 0	2	4	5
	90 - rep	73 ± 0		68 ± 0		64 ± 0		9	
	45	71 ± 0	1	67 ± 0	1	64 ± 0	1.8	7	0.8
	45 - rep	72 ± 0		68 ± 0		65.8 ± 0.4		6.2	

PLB	90	95.6 ± 0.9	0.1	91 ± 0.7	0.3	87 ± 0	1	8.6	1.3
	90 - rep	95.3 ± 0.5		90.7 ± 0.5		88 ± 1		7.3	
	45	94.8 ± 0.8	0.2	90 ± 1	1	85.6 ± 0.9	0.6	9.2	0.4
	45 - rep	94.6 ± 0.6		89 ± 1		85 ± 1		9.6	

2.4.3 Repeatability of methods on composite

The attenuation of the various angles in the glass fibre-reinforced polymer is predicted to vary due to the anisotropic properties. The woven fibres create preferential mechanical properties in the longitudinal and transverse directions. The fibres affect the propagation path of the wave; hence the sound spreads unevenly[9]. At 45°, the acoustic wave will travel through different mediums (fibre and resin), and scattering is more likely to occur. The viscoelastic nature of the polymer is more prone to attenuation, resulting in thermoelastic dissipation[16]. Hence, the attenuation at 45° was expected to be higher when compared to the 90°, i.e. attenuate more.

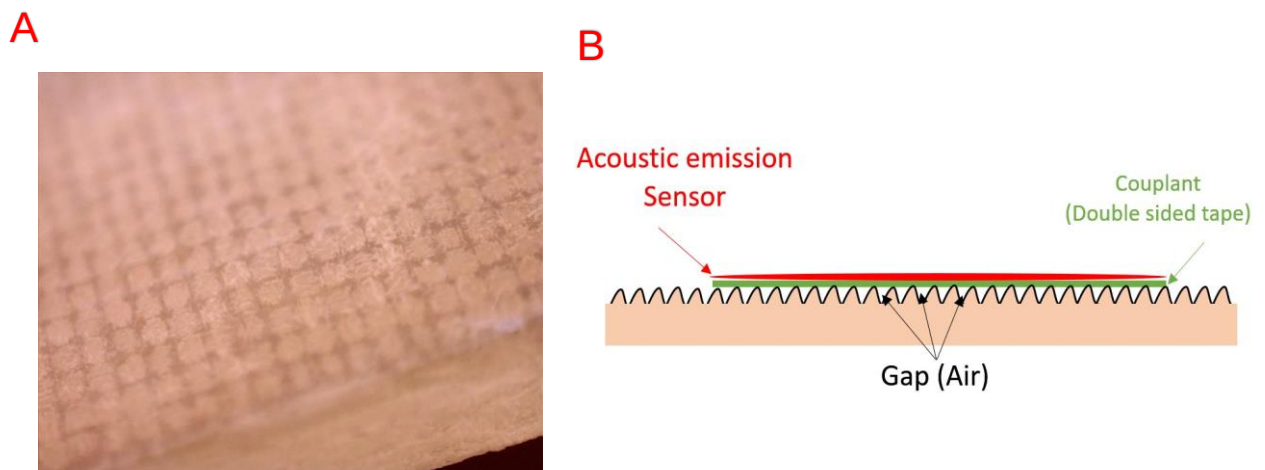


Figure 2-4. The effect of the peel ply on the surface of a glass fibre composite when attaching double sided tape A) microscopic image (dark regions are in contact) B) representation drawing

The actuator's performance on the composite was expected to differ due to the lower contact area between the plate's surface and the sensor. The contact area between the plate's surface and the actuator on the aluminium plate was 100% compared to 20% to 30% on the composite. The low contact area is due to the peel ply used during manufacturing, which produces low and high points, as seen in Figure 2-4. The low contact area on the composite's surface allows easier removal but lower adhesion.

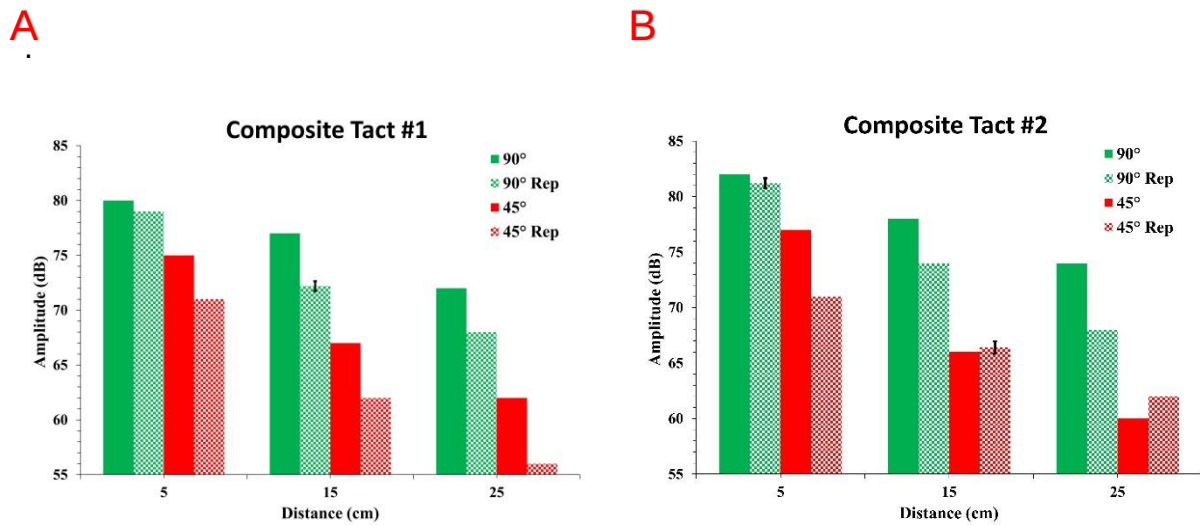


Figure 2-5. Amplitude registered when using the thin double-sided tape coupled A) Tact #1 B) Tact #2, on a woven glass fibre composite

The removal and placement of the thin double-sided tape actuator were more manageable on the composite compared to the aluminium due to the contact area. Still, the tape had resistance due to its high adhesion. The precision of the actuator on the composite using double-sided tape is high, but the accuracy is low, as seen in Figure 2-5. Repeating the test at 90° results in a maximum of 4.8 dB difference compared to a difference of 6 dB at 45° using CompTact #1, as seen in Figure 2-5A. The difference in total attenuation when repeating the test using CompTact#1 at 90° and 45° were 3 dB and 2 dB, respectively.

CompTact #2 showed similar behaviour to CompTact #1 at 90° with a maximum difference of 4.8 dB and 6 dB at 45°, as seen in Table 2-3. The total attenuation difference when repeating the test at 90° was 5.2 dB and 8 dB at 45°. The high difference in total attenuation shows that the tape's adhesion is causing a change

in amplitude even with the lower contact area caused by the peel-ply surface. The amplitude difference caused by the fibre orientation is apparent in both Figure 2-5A and Figure 2-5B.

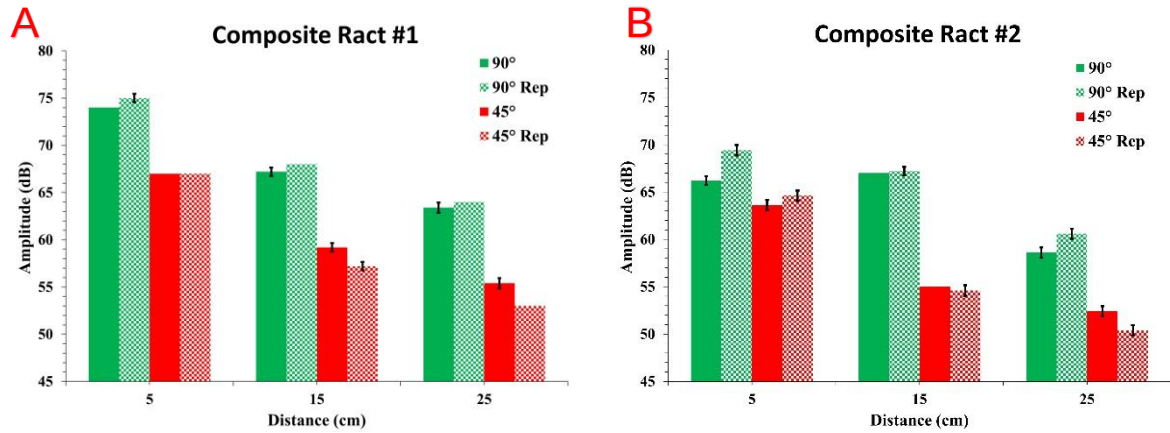


Figure 2-6. Amplitude registered when using the repositionable double-sided tape coupled A) Ract #1 B) Ract #2, on a woven glass fibre composite

The performance of the Ract sensors on the composite is better compared to the Tact sensors. The maximum difference in amplitude using CompRact #1, when repeating the test at 90° and 45° were 1 dB and 2.4 dB, respectively, as seen in Table 2-3. The total attenuation difference using CompRact #1 at 90° and 45° were 0.4 dB and 2.4 dB, respectively. However, a higher difference when repeating the test was noticed at 90° with CompRact#2, with a maximum difference of 3.2 dB.

The precision of the results decreased when utilising the repositionable tape due to its low adhesion. The low adhesion alongside the lower contact area on the composite caused a reduction in precision, as seen by the error bars in Figure 2-6. The repositionable double-sided tape was slightly lifting with time when actuating. The lifting process was confirmed by leaving the CompRact sensor to actuate for around 3 minutes, resulting in an amplitude drop of 3 dB (from 49 dB to 46 dB).

The pencil lead-breaking method has shown good accuracy and high precision on the composite, as seen in Figure 2-7. The maximum difference when repeating the test at 90° and 45° were 0.4 dB and 1.1 dB, respectively. After analysis, it

was discovered that the results obtained from the PLB at 90° (5cm) were invalid due to reaching the maximum amplitude with the current settings in the setup. Nevertheless, the results obtained from the remaining distances and angles collectively demonstrate a consistent and similar response.

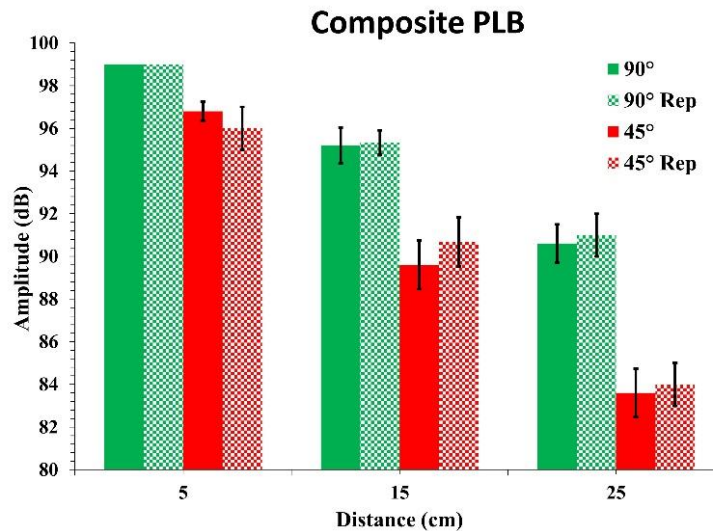


Figure 2-7. Amplitude registered when utilising the pencil lead breaking method on a woven glass fibre composite plate

The composite surface caused by the manufacturing process was thought to impact the signal's reproducibility when using the pencil lead-breaking method. Figure 2-8 shows the possible variation in the angle, which is caused by the surface peaks and valleys. The peaks and valleys result from the peel-ply surface and possibly the woven fibre shape. The valley can affect the pencil breakage in several ways. That is, creating higher contact between the pencil and the plate, causing a change in the breaking angle or changing the contact point from the tip. A combination of the probable factors is possible. When testing on the peak, it is also possible for the lead to slide towards the valley. However, upon testing without considering the lead position (whether on peak or valley), a negligible decrease in accuracy was seen on the composite compared to the aluminium. Two tests were deliberately performed on the peak and valley at different angles; results show that a difference of less than 1 dB is seen when taking the average.

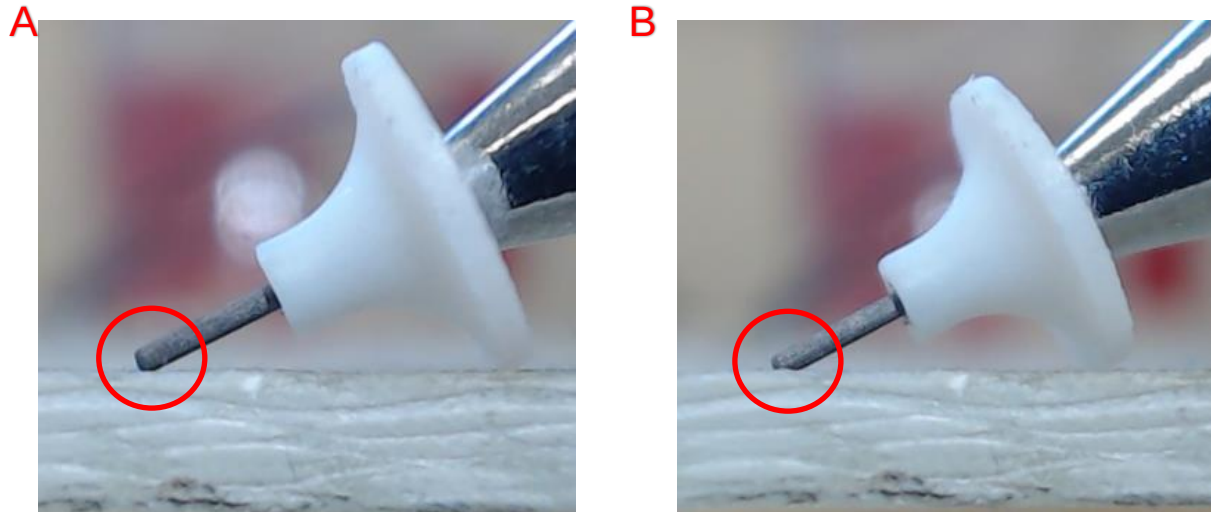


Figure 2-8. The change of angle when placing the pencil on different locations on the composite A) peak B) valley

The PLB method is more suitable to ensure that a sensor works as intended before and after placing in service due to the removability and the low error when repeating the test. The transducer method, however, requires permanent attachment for excellent results and therefore is unsuitable for validating the sensor's performance after exposure to an aggressive environment. That is, if the actuating sensor is permanently attached to the structure, it will undergo the same environment as the receiving sensor. Hence, a different transducer must be used if testing is required after placing the structure in service. Although employing high-tack double-sided tape for actuation is feasible, it should be used without repositioning for optimal results. The utilisation of a non-permanent couplant (such as double-sided tape) eliminates the necessity of modifying the structure through the application of epoxy.

Table 2-3. Glass fibre-reinforced polymer attenuation concerning five actuation types

Glass Fibre Reinforced Polymer									
Actuating		5 cm Distance		15 cm Distance		25 cm Distance		Total attenuation (dB)	Error (dB)
Type	Angle (°)	Average amplitude (dB)	Error (dB)	Average amplitude (dB)	Error (dB)	Average amplitude (dB)	Error (dB)		
Tact #1	90	80 ± 0	1	77 ± 0	4.8	72 ± 0	4	8	3
	90 - rep	79 ± 0		72.2 ± 0.4		68 ± 0		11	
	45	75 ± 0	4	67 ± 0	5	62 ± 0	6	13	2
	45 - rep	71 ± 0		62 ± 0		56 ± 0		15	
Tact #2	90	82 ± 0	0.8	78 ± 0	4	74 ± 0	6	8	5.2
	90 - rep	81.2 ± 0.4		74 ± 0		68 ± 0		13.2	
	45	77 ± 0	6	66 ± 0	0.4	60 ± 0	2	17	8
	45 - rep	71 ± 0		66.4 ± 0.5		62 ± 0		9	
Ract #1	90	74 ± 0	1	67.2 ± 0.4	0.8	63.4 ± 0.5	0.6	10.6	0.4
	90 - rep	75 ± 0		68		64 ± 0		11	
	45	67 ± 0	0	59.2 ± 0.4	2	55.4 ± 0.5	2.4	11.6	2.4
	45 - rep	67 ± 0		57.2 ± 0.4		53 ± 0		14	
Ract #2	90	66.2 ± 0.4	3.2	67 ± 0	0.2	58.6 ± 0.5	2	7.6	1.2
	90 - rep	69.4 ± 0.5		67.2 ± 0.4		60.6 ± 0.5		8.8	
	45	63.6 ± 0.5	1	55 ± 0	0.4	52.4 ± 0.5	2	11.2	3

	45 - rep	64.6 ± 0.5		54.6 ± 0.5		50.4 ± 0.5		14.2	
PLB	90	99 ± 0	0	95.2 ± 0.8	0.1	90.6 ± 0.9	0.4	8.4	0.4
	90 - rep	99 ± 0		95.3 ± 0.6		91 ± 1		8	
	45	96.8 ± 0.4	0.8	89.6 ± 1.1	1.1	83.6 ± 1.1	0.4	13.2	1.2
	45 - rep	96 ± 1		90.7 ± 1.2		84 ± 1		12	

2.4.4 Frequency Response

The frequency response of the actuator type, whether PLB or transducer, is critical as different frequency responses could trigger different wave types. Pant et al.[13] tested a carbon fibre composite and the results revealed that the antisymmetric wave was dominant at frequencies less than 100 kHz compared to the symmetric wave, which was dominant from 200 kHz to 500 kHz while both waves coexisted between 100 kHz and 200 kHz.

Glass fibre-reinforced polymer failure mechanisms, including matrix cracking, delamination, fibre/matrix cracking and fibre fracture, trigger different frequency responses[2–8]. The difference in frequency response by the failure mechanisms indicates that certain failure mechanisms can travel further compared to others as the attenuation of higher frequency is more significant due to the shorter wavelength, which increases absorption[16] compared to low frequency.

The frequency response of actuators was different compared to the pencil lead-breaking method, as seen in Figure 2-9. The actuator's frequency response on both double-sided tapes was similar. CompTact showed two apparent peaks at 31 kHz and 168 kHz compared to 31 kHz and 179 kHz using CompRact.

However, the PLB method on the composite only showed one prominent peak at 31 kHz.

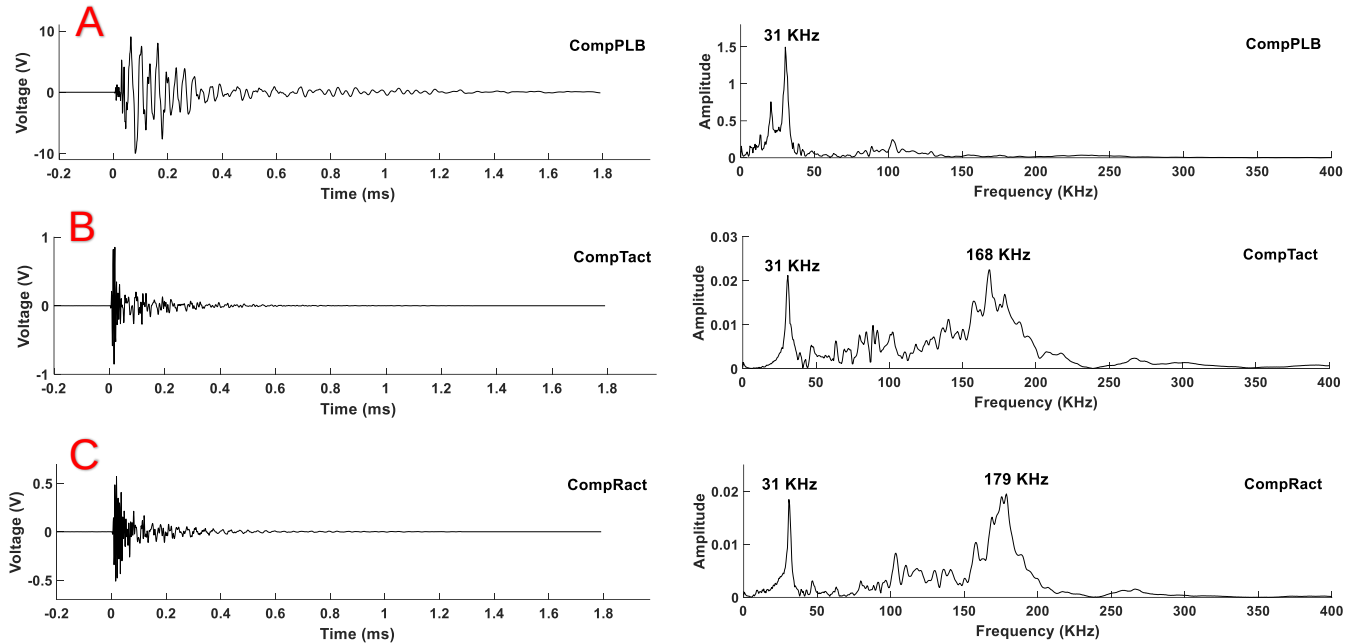


Figure 2-9. Reconstructed acoustic emission waveform on a composite at 90° and 5 cm away from the sensor showing time and frequency domain graphs using A) PLB B) thin double-sided tape coupled actuator C) repositionable double-sided tape coupled actuator.

The inability to control the frequency of the PLB method is a disadvantage compared to the actuator method. The actuator can be set to pulse at specific frequencies using special equipment[17]. Pulsing at known frequencies allows the user to measure the attenuation based on the expected failure mechanisms. For example, the frequency could be changed if the expected failure mechanism is a fibre/matrix cracking compared to matrix cracking[6]. It is worth noting that high frequency failure may not always represent fibre failure, as tested with carbon fibre reinforced polymer[18].

The frequency response of the transducers on the aluminium was similar, with minor differences, as seen in Figure 2-10. All actuator types had a dominant peak at around 100 kHz. However, the PLB method on the aluminium had an extra peak at lower frequencies (21 kHz). The transducers, on the other hand, had an extra peak at higher frequencies of 166 kHz and 179 kHz with AlumTact and AlumRact, respectively.

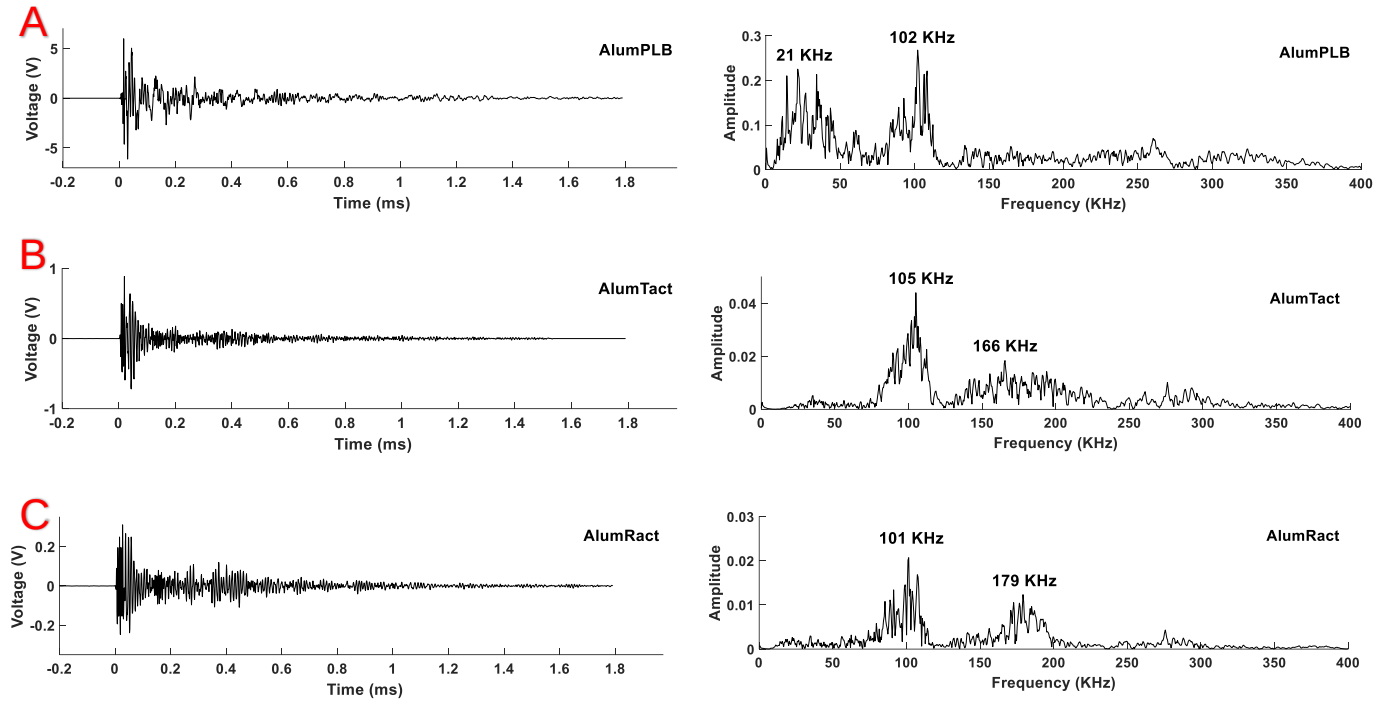


Figure 2-10. Reconstructed acoustic emission waveform on an Aluminium at 90° and 5 cm away from the sensor showing time and frequency domain graphs using A) PLB B) thin double-sided tape coupled actuator C) repositionable double-sided tape coupled actuator.

Although the frequency characteristics is significantly used with composites when testing AE, [19]research shows that a steel alloy could exhibit different frequency responses at different strain stages.

2.5 Conclusion

The reproducibility of the actuator methods ranking on the aluminium and fibre-reinforced polymer composite plates was Tact<Ract<Pencil Lead Breaking method. The higher tack double sided tape (Tact) reproducibility was affected when repositioning the transducer. However, the lower tack (Ract) improved the accuracy with some anomalies that can be considered within the acceptable error. The pencil lead-breaking method had the lowest precision but the highest accuracy compared to the other actuator methods.

The PLB method signal was assumed to be affected by the composite's surface due to the peaks and valleys, but the results demonstrate that the influence, if any, was minimal.

The pencil lead breaking method is recommended for verifying the performance of the receiving sensor compared to the actuator method, which is recommended for measuring signal attenuation behaviour for materials of interest.

The impact of the composite's fiber directionality became evident during attenuation testing at 90° in contrast to 45°. However, the attenuation observed in aluminum at both 90° and 45° did not display a clear difference.

The transducer method's frequency response, whether using the repositionable or thin double-sided tapes, was similar within each material. However, the pencil-lead breaking method's frequency response in each material had common peaks but was otherwise distinct from the actuator method.

The variation in frequency response between the PLB and actuator methods within the composite was apparent. As failure mechanisms in composites can display different frequency responses, the artificial AE sources may imprecisely represent certain failure mechanisms closer than other.

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3 [Paper 3] A Comparative Analysis of Acoustic Emission Sensor Embedding in Glass Fibre Composite

3.1 Abstract

The manufacturing process of composite structures permits fully embedding acoustic emission (AE) sensors. While the embedding process may pose challenges, its advantages, if proven, can offer benefits. The increased sensitivity resulting from embedding acoustic emission sensors in composites is still not definitively established. A test was set up with pre-determined AE initiation locations (surface and sub-surface) and pre-determined receiving sensor's location (surface and sub-surface) to ensure any sensitivity increase was evident. The receiving sensor's attenuation along (at 90°) and across the fibres (at 45°) was assessed using two test methods: pencil lead breaking (PLB) and actuator methods. The actuator method involved using two pulse generators, the TGP110 pulse generator and the Mistras FieldCal. A range of specific frequencies were utilised, 30, 60, 150 and 300 kHz, using the FieldCal. The results obtained from the test methods were not in agreement with each other. For example, comparing the sensitivity using surface cracks, the PLB method showed decreased sensitivity when embedding the receiving sensor compared to the actuator method, which demonstrated minimal changes in sensitivity. The research aims to clarify the sensitivity increase obtained when embedding an AE sensor while taking into account the crack's position and frequency.

3.2 Introduction

The use of acoustic emission in composites has been explored for many industries, including automotive[1], energy (wind turbine blades)[2], aerospace[3], liquid rocket motor casing[4] and hydrogen tank[5]. The method's valuable capability lies in detecting and identifying the crack location in a composite without external stimulation or excitation. Despite the challenges posed by the composite's anisotropic properties in locating the AE source, numerous studies have been undertaken to devise solutions[6–8]. In a

composite, the type of crack can be determined due to the unique waveform produced by each failure mode[9–15].

The ability to embed an acoustic emission sensor is particularly relevant for composites, given the manufacturing process involved. Piezoelectric sensors such as lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) can be embedded due to their low thickness. There are both benefits and challenges associated with the integration of AE sensors. Benefits include the theoretical high sensitivity, protection from environmental factors such as foreign objects and external noise, and eliminating the need for a couplant. However, several drawbacks are present, such as the mechanical properties loss associated with embedding, the manufacturing process's complexity, and the inability to incorporate on existing structures.

Several experiments have been conducted to investigate the utilisation of embedded acoustic emission sensors in various composites[9,10,16–23]. The mechanical properties deterioration due to embedding a foreign object is found to be dependent on multiple aspects, including the type of load exerted[24]. The enhanced sensitivity of the embedded acoustic emission sensor varies among researchers and is still open for investigation. This study considers the significance of the crack's frequency and initiation location, aspects that may be neglected but still hold importance.

This study aims to investigate the sensitivity of the embedded sensor, considering the relative position of the crack in relation to the sensor placement as well as the influence of frequency on the sensor's sensitivity.

3.3 Methodology

3.3.1 Sensors

A piezoelectric element (PZT) obtained from Farnell (7BB-15-6) was employed as the actuator. The actuator had a diameter of 15 mm and a thickness of 0.22 mm. The PZT receiving sensor, obtained from Farnell (MCFT-15T-4.0A1-121), had dimensions of 15 mm in diameter and 0.13 mm in thickness.

3.3.2 Plate Manufacturing

The testing plate employed was made of glass fibre-reinforced polymer. The testing plate was fabricated through resin vacuum infusion. Six woven glass fibre plies were stacked on a peel ply and covered with peel ply. A flow mesh was added to facilitate wetting. The sensors were positioned at the centre of the composite (between the third and fourth ply) when manufacturing the fully embedded actuators plate. The actuators were placed 10, 20 and 30 cm from the receiving sensor along and across the fibres, as shown in Figure 3-1B. A copper cable with backing adhesive was utilised to establish the electrical connections. A release film was positioned over the outgoing copper cables.

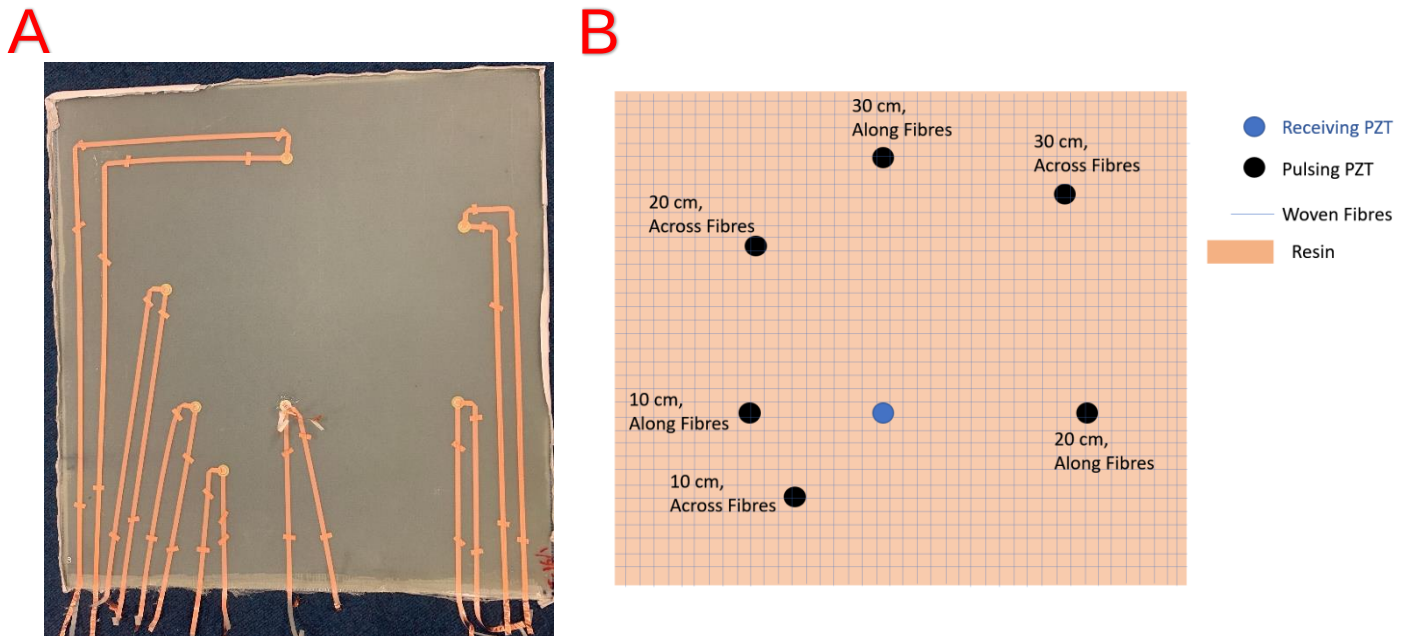


Figure 3-1. (A) The cured plate after manufacturing (B) sensor's configuration illustration.

Four plates were produced – two plates had surface embedded actuators alongside a surface embedded and a fully embedded receiver, as seen in Figure 3-2A. The other two plates integrated fully embedded actuators alongside surface embedded and fully embedded receivers, as seen in Figure 3-2B.

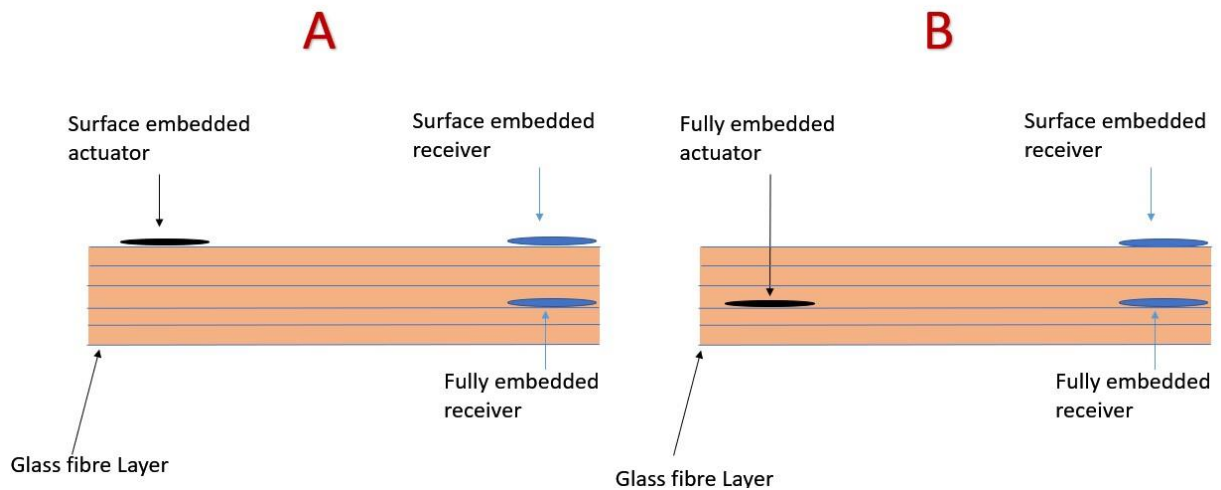


Figure 3-2. The test setup for (A) plates 1 and 2 (B) plates 3 and 4

The fully embedded receivers/actuators were positioned during manufacturing, whereas the surface receivers/actuators were positioned after curing, using the same epoxy. Ultimately, the plate measured 615 mm x 630 mm x 2.6 mm in its final dimensions. The materials used for the manufacturing are detailed in Table 3-1.

Table 3-1. Materials used for manufacturing the glass fibre plates

Epoxy Resin	RS-M135
Hardener	RS-MH137
Fibres	Glass woven roving 600 gsm plain weave

3.3.3 Equipment

A PCI-2 based AE system (AEwin) was utilised to capture the AE signal from the receiving sensor. The receiving sensor was connected to the AE system using a preamplifier set to a gain of 40 dB. The primary threshold used was 45 dB.

The pulse generator employed was a TGP110 10MHz model manufactured by Thurlby Thandar Instruments (TTi). It was configured to pulse with a pulse width of 5 μ s, a period of 4 seconds and an amplitude of 10 V.

The pencil used for the pencil lead breaking method was from MISTRAS, pre-fitted with a 'shoe'. The pencil lead used had a 0.5 mm diameter and 2H hardness.

The acoustic emission generator, FieldCal by Physical Acoustics, was utilised to generate a specific frequency signal. The amplitude was set to 90 dB, burst to AE, rate to 1 pps and range to 40 dB.

3.4 Results and discussion

Multiple researchers made a contributions to identify the effect of fully embedding the acoustic emissions sensor. Researchers have reported a variety of results when embedding the AE sensor, that is: no sensitivity change[20], slight improvement[17] and clear improvement[19]. The testing method used to identify the sensitivity improvement was mechanically testing specimens with and without embedded sensors. Various factors can be attributed to the different outcomes reported, including the sensors, material type, specimen thickness, manufacturing process and mechanical testing (crack location). The mechanical testing method is thought to have a significant effect as the different mechanical tests could give rise to cracks at random locations. Specific mechanical tests, such as the three-point bend test, produce initial surface failure, but cracks can occur from within as the test progresses. On the other hand, the tensile test produces failure at the weakest point, which its location could vary. Also, embedding the acoustic emission sensor within the high-stress regions may introduce failure around the inclusion (sensor), indicating a false increase in sensitivity.

The ability to distinguish the sensor response difference due to the location of a defect will allow the user to verify improvements, if any. The fully embedded actuators act as a defect from within the composite compared to the surface embedded actuator, representing a defect from the composite's surface.

The receiving sensors were placed on the same plate, i.e. the surface embedded receiver on top of the fully embedded receiver, as shown in Figure 3-2. The placement ensures that the test is accurate as both sensors receive the same event. Initially, concerns were raised regarding the potential impact of placing the surface embedded receiver on top of the fully embedded receiver. However, after conducting multiple tests before and after surface embedding, the variation in response primarily fell within the error margin of the testing machine and hence was disregarded. The fully embedded and surface embedded actuators were placed on separate plates to avoid potential complications when pulsing, as seen in Figure 3-2.

3.4.1 TGP pulse generator and PLB

The findings obtained from pulsing using the surface embedded actuator revealed that the fully embedded receiver had a higher amplitude than the surface embedded receiver, as seen in Figure 3-3A and Figure 3-3B. However, the increased sensitivity is inconclusive as the difference of 2 dB can be attributed to the error from the machine, i.e. ± 1 dB from each receiver. The difference in sensitivity was greater than 2 dB in certain conditions, such as at 20 and 30 cm in Figure 3-3B. However, it is inconclusive as plate 1, Figure 3-3A, produced different results. On the other hand, the fully embedded actuators showed comparable responses from both receivers, as shown in Figure 3-3C and Figure 3-3D. That is, the amplitude of the receivers was similar when pulsing using the fully embedded actuator and the surface embedded actuator, around 76 dB at 10 cm. A similar trend was recorded when testing across the fibres, as seen in Figure 3-4C and Figure 3-4D. A noticeable difference was observed when testing the attenuation along and across the fibres, which could stem from various factors, as elaborated later. No apparent difference can be observed when comparing the amplitude difference between pulsing from the surface or fully embedded actuator. Based on the actuator method results, it could have been concluded that the location of the crack does not significantly affect the sensitivity with respect to the receiver's location. This implies that the receiving sensor's sensitivity is not significantly affected by the crack's initiation location (surface or

from within). However, this was not the case upon utilising the second signal-generating method (PLB).

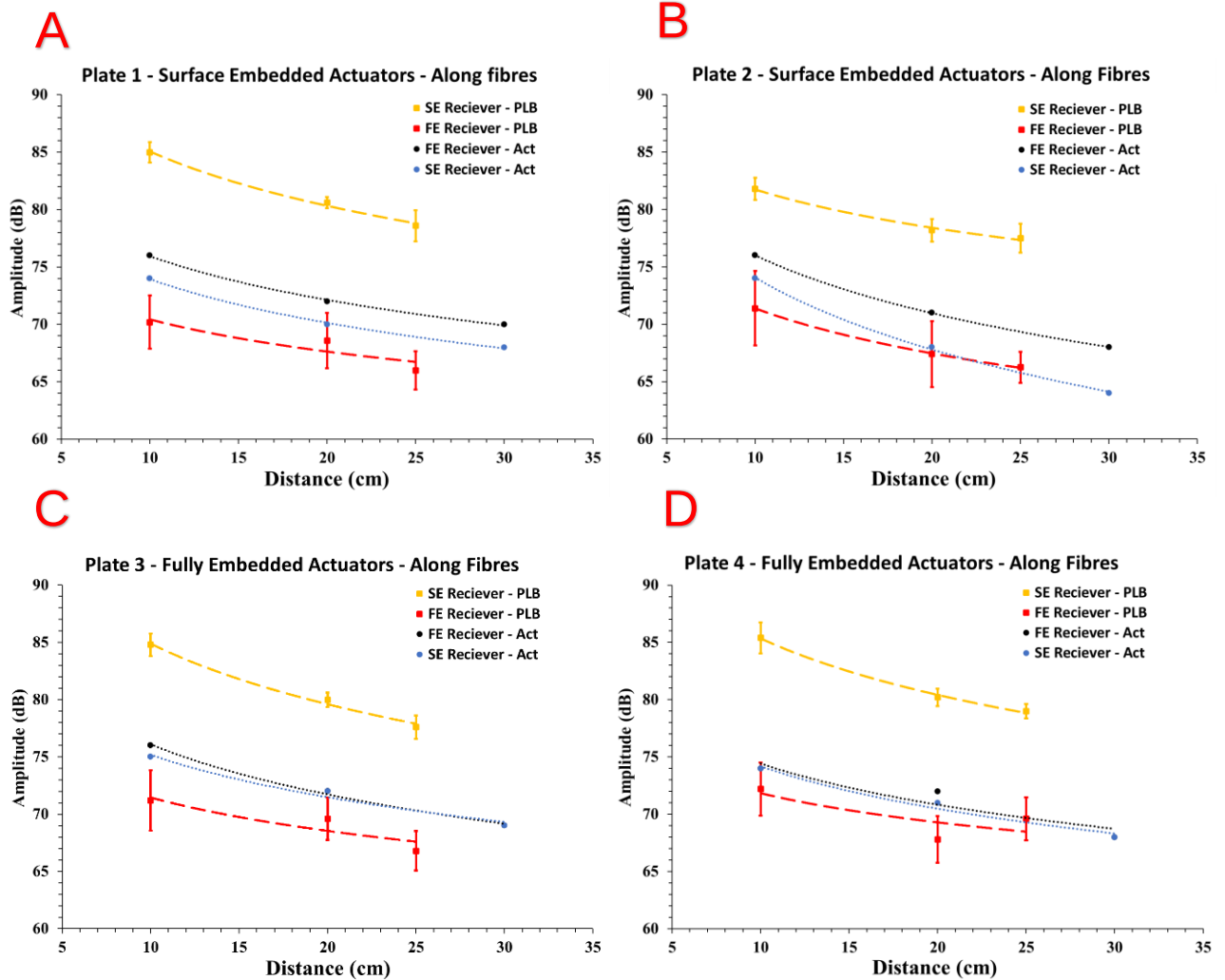


Figure 3-3. The attenuation of surface embedded (SE) and fully embedded (FE) PZT receivers along fibres utilising the PLB method (A and B) and surface embedded actuators - Act (C and D) and fully embedded actuators - Act.

The pencil lead-breaking method was used to generate an acoustic emission signal by breaking the pencil on the surface of the plate. Unlike the actuator method, a significant difference was evident between the surface embedded receiver and the fully embedded receiver when utilising the PLB for generating a test signal, as seen in Figure 3-3 and Figure 3-4. The results remained evident despite the receiver's data variability (error bars). The PLB was performed on

each plate individually, with a total of 5 tests conducted, and subsequently, an average of the results was recorded. The results show that the surface embedded receiver had a much higher amplitude than the fully embedded receiver, i.e. the fully embedded receiver's performance degraded. The results were consistent along and across fibres. A significant difference of approximately 10 to 15 dB was observed when comparing the responses of both receivers using the PLB method. The PLB test attenuation was limited to 25 cm compared to 30 cm with the actuator method due to the presence of the actuating sensor at 30 cm.

Even though the surface and embedded receivers responded to the same PLB hit, the variations (error bars) were different, as seen clearly in Figure 3-3B. When applying the PLB method, the variation associated with the fully embedded receiver was higher than the surface embedded receiver when testing along fibres (Figure 3-3) but lower when testing across fibres(Figure 3-4). The propagation path of the wave is affected by the fibres; as a result, the sound spreads unevenly[25]. The lower amplitude associated with testing across fibres compared to along fibres may be attributed mainly to the fibre alignment and different travelling mediums. That is, testing across the fibres would force the wave to travel across multiple fibre strands compared to a single fibre strand when along the fibres. Also, as the wave travels across the fibres, it will encounter two different mediums: resin and glass fibre. The polymer's (resin) viscoelastic nature results in thermoelastic dissipation, making it more susceptible to attenuation[26].

The pencil lead-breaking method shows that the number of plates tested is adequate to ensure the validity of the results. That is, the pencil lead-breaking method was performed on all the plates individually, and the results were similar. Hence, the effect of the sensor's intrinsic differences, if any, is minimal.

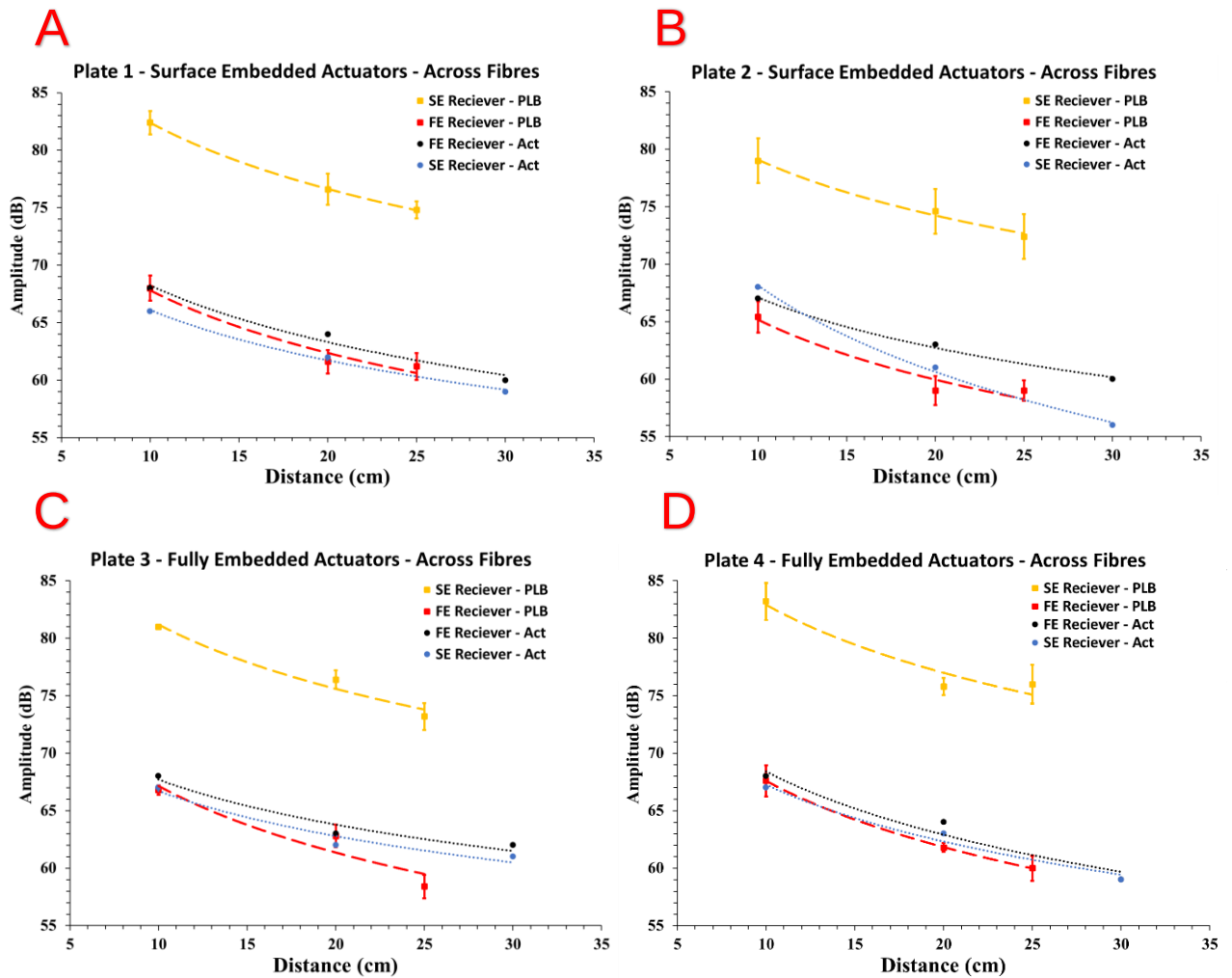


Figure 3-4. The attenuation of surface embedded (SE) and fully embedded (FE) PZT receivers across fibres utilising the PLB method (A and B) and surface embedded actuators - Act (C and D) and fully embedded actuators - Act.

The frequencies obtained from the PLB method and the PZT actuating method were significantly different, as evident in Figure 3-5, Figure 3-6 and Figure 3-7. The frequency response of the fully embedded and surface embedded receivers is similar when testing using the PLB method peaking at around 21 kHz, as seen in Figure 3-5. Even though both sensors received the same wave, the peak frequency did not always perfectly match. The frequencies acquired through the PLB method primarily fell within the range of 1 kHz to 50 kHz.

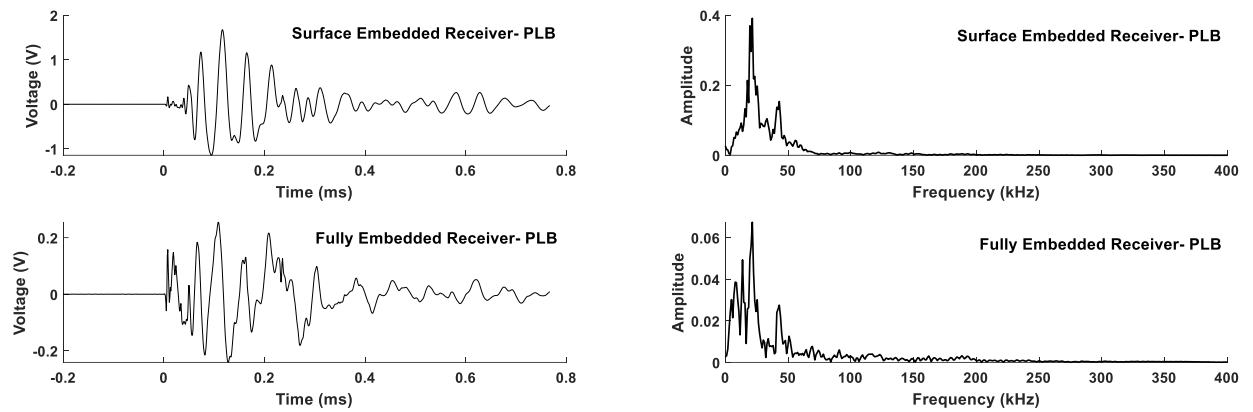


Figure 3-5. Comparison of time domain (left) and frequency domain (right) responses utilising the pencil lead breaking method (PLB) at 10 cm distance along fibres for (top) surface embedded receiver (bottom) fully embedded receiver.

On the other hand, when testing using the surface embedded actuators, the frequency response of the receivers was different, as evident in Figure 3-6. The fully embedded receiver's frequency response was broad (around 35 to 240 kHz) with a secondary peak between 240 and 325 kHz. On the other hand, the surface embedded receiver had an initial peak between 5 and 50 kHz. Beyond 50 kHz, it followed a similar trend as the fully embedded receiver. The initial peak between 5 and 50 kHz did not significantly affect the amplitude, i.e. both receivers' amplitude was similar.

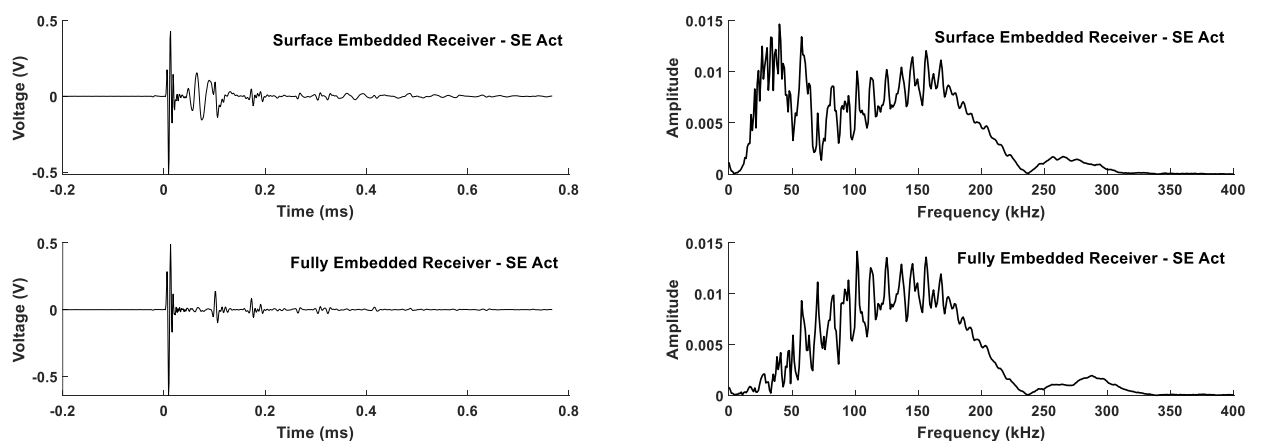


Figure 3-6. Comparison of time domain (left) and frequency domain (right) responses utilising the surface embedded (SE) actuator at 10 cm distance along fibres for (top) surface embedded receiver (bottom) fully embedded receiver.

The surface and the fully embedded receivers responded similarly when the signal was generated using the fully embedded actuator, as seen in Figure 3-7. Both recorded signals had a similar trend to the fully embedded receiver signal when the surface embedded actuator was utilised. Also, the time domain signals of both receivers were similar.

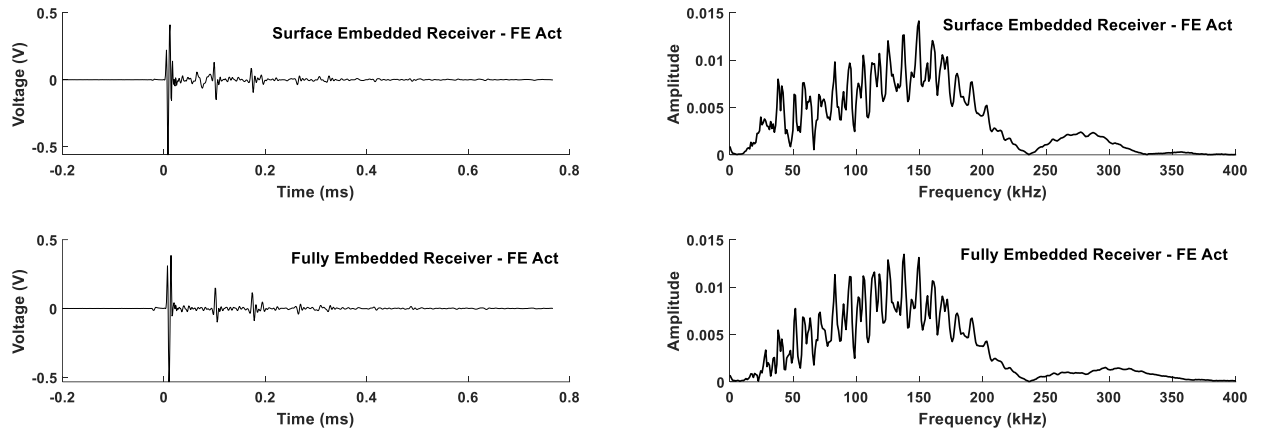


Figure 3-7. Comparison of time domain (left) and frequency domain (right) responses utilising the fully embedded (FE) actuator at 10 cm distance along fibres for (top) surface embedded receiver (bottom) fully embedded receiver.

The time domain signal using the surface actuating method differed significantly from the PLB method. The time domain signal of the actuating method showed secondary peaks with both receivers, as seen in Figure 3-6 and Figure 3-7. The possibility that the secondary hits and beyond are reflections from the plate edges is possible, even though measures were taken to prevent reflection. Measures include placing tacky tape on the plate edges as well as placing the sensors away from the edge, as seen in Figure 3-1. However, the secondary peaks are insignificant and can be disregarded due to their low amplitude compared to the main peak.

The predominant wave generated using the two methods is the anti-symmetric wave (A_0) based on the location of the signal-generating method's actuating and receiving sensors. That is, the force applied was perpendicular to the plate[26]. However, Pant's study showed that the dominant wave produced can be based

on the frequency generated, even when the force was perpendicular to the plate[27]. Consequently, this area requires further investigation.

Nevertheless, the difference in wave generation mechanism, area of contact and frequency response factors can account for the divergent results obtained from the different signal generation methods. The actuating method depends on an electrical signal transmitted to the PZT, which is converted to mechanical vibration, creating a wave that transmits through the material. In comparison, the PLB method relies on breaking a brittle material (pencil lead) to induce a stress wave at the material's surface. The contact area is much smaller when testing using the PLB compared to the TGP pulse generator. The frequencies acquired from both signal generation methods exhibited variation; nevertheless, their potential influence can be tested. The disadvantage of using the TGP pulse generator is the inability to control the wave's peak frequency precisely, prompting the use of an alternative device.

3.4.2 Pulsing targeted frequencies

The FieldCal device produced a pulse with a pre-set frequency peak which was used to validate the frequency effects on the receiving sensor sensitivity. The sensitivity of the receiving sensor, whether surface embedded or fully embedded, was tested against surface embedded and fully embedded actuators. Four frequencies were examined, namely 30 kHz, 60 kHz, 150 kHz, and 300 kHz.

Figure 3-8 shows the amplitude difference between the surface and fully embedded receiver when applying the pulse using the surface embedded actuator. The amplitude difference is calculated by subtracting the fully embedded receiver's amplitude from the surface embedded receiver's amplitude. If the amplitude difference is positive, the surface embedded receiver exhibited greater amplitude; conversely, if negative, the fully embedded receiver showed higher amplitude. Figure 3-8 shows an apparent trend when comparing the amplitude against the frequency; the lower the frequency, the higher the sensitivity of the surface embedded receiver. At 30 kHz, close to the PLB method signal frequency, the amplitude difference averaged around 12 dB along and across fibres. As the frequency increased, the amplitude difference decreased.

At 150 kHz, the closest frequency to the signal acquired from the TGP pulse generator, the amplitude difference was no longer noticeable. The amplitude difference acquired at 30 and 150 kHz roughly aligns with the results of the PLB and TGP pulsing methods, respectively. Thus, this validation highlights the frequency significance in influencing the sensor's sensitivity when embedding.

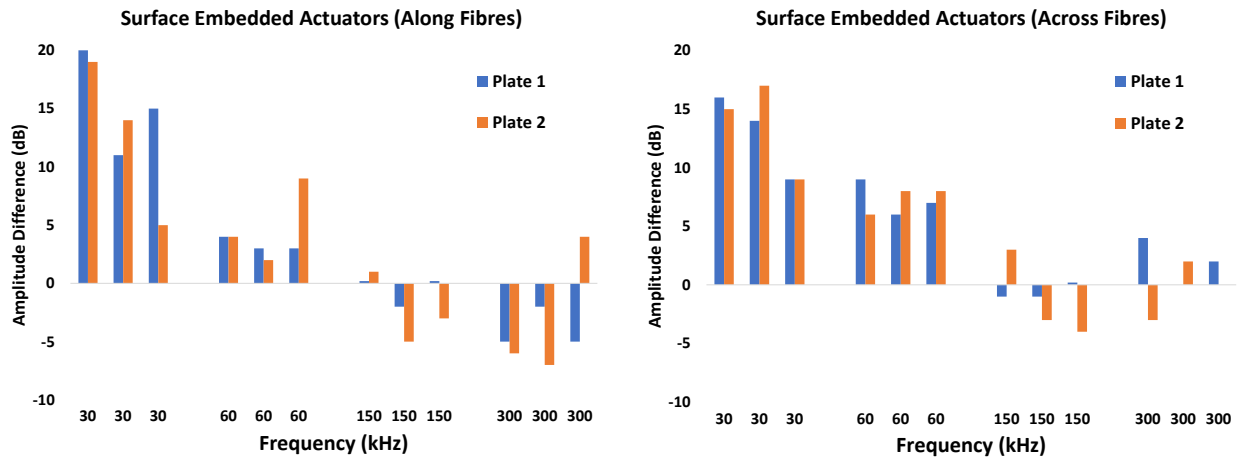


Figure 3-8. The amplitude difference between the surface and fully embedded receivers (SE - FE) based on the surface embedded actuator at four frequencies, (left) along fibres (right) across fibres.

The receivers' response along and across the fibres, induced by the surface embedded actuators, exhibited a comparable pattern. Although the fully embedded receiver had a higher sensitivity at 300 kHz along the fibres, as seen in Figure 3-8(left), the increase is not evident across the fibres, Figure 3-8(right). Initial results suggest the fully embedded receiver is more sensitive when the crack initiates along the fibres at 300 kHz. The difference in results along and across fibres suggests that the wave travelling path may also influence the sensor's sensitivity with respect to frequency.

The results from the surface embedded actuator suggest that the surface embedded receiver is more sensitive to surface cracks with low frequencies (30 and 60 kHz), both along and across fibres. However, with surface cracks with midrange frequency (150 kHz), the sensitivity of both receivers is similar along and across fibres. The fully embedded receiver is more sensitive than the surface embedded receiver when high frequency (300 kHz) is aligned along the fibres.

However, if the high-frequency surface crack is aligned across the fibres, both receivers sensitivity is similar.

The amplitude difference at 30 kHz dropped to around 6 dB using the fully embedded actuators along the fibres, as seen in Figure 3-9(left). Testing at 30 kHz using the fully embedded actuator is similar to testing using the pencil lead-breaking method but within the laminate. Beyond 30 kHz, the results indicate that the amplitude difference between both receivers is minimal (less than 2 dB), except for a few anomalies. On the other hand, when testing using the fully embedded actuators across the fibres, Figure 3-9(right), the receiver's amplitude difference is around 2 dB across all the frequencies tested, even 30 kHz. A 2 dB difference is considered insignificant due to the detection system's accuracy.

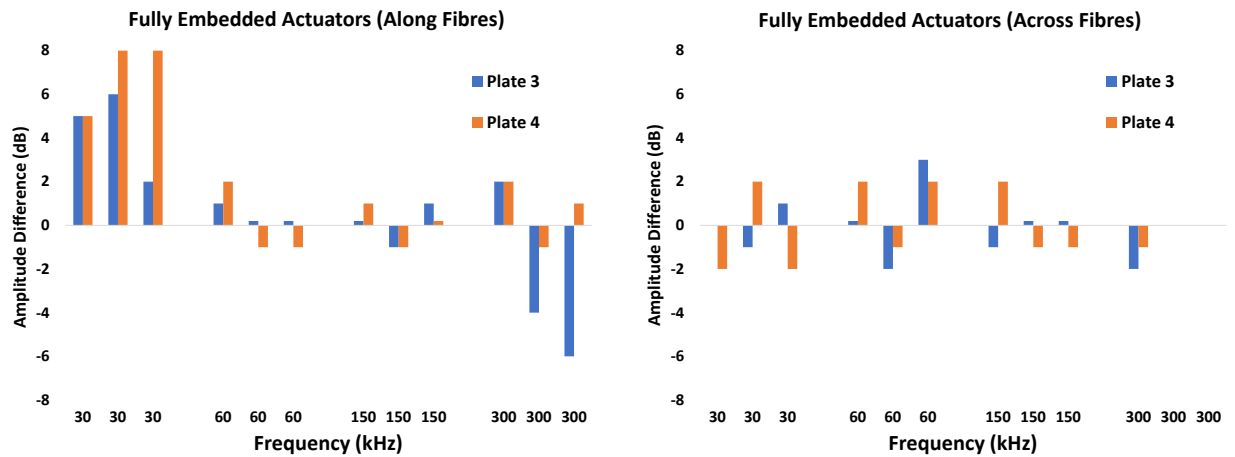


Figure 3-9. The amplitude difference between the surface and fully embedded receivers (SE - FE) based on the fully embedded actuators at four frequencies (left) along fibres (right) across fibres.

The results obtained from the fully embedded actuators reveal that the surface embedded receiver displays increased sensitivity solely to cracks originating from the composite's centre along the direction of the fibres, particularly at a frequency of 30 kHz. At all other frequencies (60, 150 and 300 kHz) along and across fibres, the sensitivity of both receivers is similar to cracks originating from the centre of the composite. Further investigation is needed to elucidate the cause behind the disparate outcomes observed during testing along and across the fibres.

3.4.3 The embedding process effect

Although the frequency sensitivity of the receiving PZT is not documented, the surface and fully embedded receiving PZT's were identical, implying that both exhibit matching frequency responses. For example, if the surface embedded PZT had a higher sensitivity response at 50 kHz, the fully embedded should have a higher sensitivity at 50 kHz. Additionally, the PZT sensor demonstrated sensitivity within the tested frequency range, as the AE machine software successfully received and displayed the frequency spectrum containing the peaks of each pulse. However, the frequency sensitivity of the receiving sensor may have shifted due to the embedding process (the pressure and surrounding material). The idea of frequency sensitivity transition due to the embedding process can be argued to have no effect using the PLB method data, which shows that a similar peak produced different amplitudes. However, when viewing the fully embedded actuating data, both receivers had a similar amplitude at a similar frequency response. Hence, the embedding process might have influenced the frequency sensitivity at specific frequencies.

The variation in results between the signal-generating methods is predominantly attributed to the frequency. However, it is essential to note that other factors, such as the sensor properties and material thickness can also contribute to this phenomenon. For example, if another receiving sensor is used, could the frequency transition occur at another frequency? Also, how does the change in material thickness affect the signal's amplitude with respect to the sensor's placement? If amplitude variation is exclusively dependent on frequency, it is not advisable to fully embed the acoustic emission sensor in composites because initial crack formation occurs at low frequencies. When a glass fibre composite fails, the initial failing mechanisms, depending on the situation, can be matrix cracking or fibre-matrix cracking which occur at a relatively low frequency, as seen in Table 3-2. Even though initial failure can occur at 300 kHz, more hits are likely at frequencies lower than 300 kHz. On the other hand, fibre fracture occurs at high frequencies, where the embedded sensor might have a higher sensitivity depending on the crack initiation point. However, detecting earlier failure events (at lower frequencies) where the fully embedded receiver is less sensitive or as

sensitive is preferable over high-frequency events that indicate critical structural conditions.

Table 3-2. The frequency acquired from glass fibre/epoxy matrix composite failure mechanisms, adapted from[28].

Reference	Thickness (mm)	Frequency Response (kHz)			
		Matrix Cracking	Fibre-Matrix Cracking	Delamination	Fibre Fracture
[11]	2.78	90–110	-	130–200	250–280
[12]	4	62.5–125	125–187.5	-	187.5–250
[13]	5	100–190	200–320	-	380–430
[14]	4.8	60–180	190–250	-	350–500
[15]	4.8	11–93	82–210	-	160–281

The drawbacks linked to the potential degradation of mechanical properties due to sensor embedding and manufacturing challenges overshadow the benefit of increased sensitivity at specific frequencies. The potential benefit of protecting sensors through embedding, which provides a shield from external conditions, can positively impact the viability of the embedding approach. However, further research is required in this aspect.

This study represents the initial phase of exploring sensor sensitivity based on location, which was accomplished using artificial acoustic emission sources. The artificial acoustic emission sources are valid and have been used elsewhere[6,27]. However, the next step is to demonstrate the behaviour using AE arising from actual failure.

3.5 Conclusion

The placement of the receiving sensors on the same test plate ensured that the results could be accurately compared, avoiding variability from the composite plate due to processing. The receiving sensor's sensitivity (registered amplitude) varied with the different signal-generating methods. The PLB method showed that the fully embedded receiver registered lower amplitude than the surface embedded receiver, proving lower sensitivity when embedding. On the other hand, PZT actuation utilising the TGP pulse generator showed that the receiving sensor's sensitivity variation was inconclusive and was, therefore, considered similar with both surface and fully embedded actuators. That is, the PLB method results showed that embedding AE sensors degrades their performance compared to the TGP pulse generator, which showed that performance is unchanged. The discrepancy in results among the testing methods was thought to stem from the acoustic signal frequency generated by each method. That is, the PLB frequency response peaked at a low frequency (around 21 kHz) compared to the TGP pulse generator, which mostly peaked at around 150 kHz.

The FieldCal was employed to verify the sensor's sensitivity concerning different frequencies. It was found that the receiving sensor's sensitivity varied when utilising different frequencies. In most cases, the surface embedded receiver had higher sensitivity at 30 kHz (near the PLB peak) compared to comparable behaviour at 150 kHz (near the TGP peak). Also, the location of the AE source (surface or fully embedded) affected the amplitude difference between the receiving sensors, depending on the frequency.

The fully embedded sensor can, at a specific condition, detect high frequency signals better than the surface embedded sensor. However, early failure mechanisms, such as matrix cracking, are usually lower frequency events where the fully embedded sensor was not proven to have any advantage over the surface mounted sensor.

Furthermore, the AE signal's amplitude was affected by the wave travelling path. That is, AE wave travelling across the fibres exhibited lower amplitude than along

the fibres, which was thought to be due to the different mediums and fibre orientation.

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4 [Paper 4] Performance Evaluation of Embedded Acoustic Emission Sensors in a Glass Fibre Composite under Mechanical Loading

4.1 Abstract

Fully embedding acoustic emission (AE) sensors in a composite is postulated to increase the sensor's sensitivity. The increased sensitivity will enable the sensor to detect subtle structural changes and lower the number of sensors required for monitoring. However, researchers have differed on whether the sensitivity increases or not. To robustly investigate the fully embedded AE sensor's sensitivity, the surface and fully embedded AE sensors are placed on the same specimen, away from the high-stress region and compared based on the same hit. Two mechanical testing methods are used: three-point bend and double cantilever beam (DCB) mode I. Three sensors are embedded: lead zirconate titanate (PZT), gold-plated polyvinylidene difluoride (PVDF), silver-ink PVDF. The DCB mode I method showed that the sensitivity of the surface embedded sensor was generally better or equal to the fully embedded sensor. However, the three-point bend method showed similar sensitivity with both surface and fully embedded sensors. The results indicate that the fully embedded sensor's sensitivity is based on the frequency of the AE event and, therefore, the failure type. The aim of the study is to analyse the sensitivity of the surface-embedded and fully embedded sensors concerning surface-originating and subsurface-originating cracks.

4.2 Introduction

The use of AE in composites has been explored to be used in many industries, such as automotive[1], aerospace[2] and energy[3]. One of the primary benefits lies in the capability to identify failure mechanisms attributed to different waveforms. For example, in glass fibre composite, the failure mechanism can be identified based on the wave frequency generated by the crack[4–10].

Embedding acoustic emission sensors is possible in composites due to the manufacturing process. Piezoelectric-based sensors such as lead zirconate

titanate (PZT) and polyvinylidene difluoride (PVDF) can be embedded due to their low thickness. Embedding the sensor is proposed to have multiple advantages, such as enhanced sensitivity, protection from the external environment and couplant elimination. The embedding process increases the complexity of the manufacturing process, thus increasing associated costs. However, the advantages, if proven, may outweigh the challenges.

The enhanced sensitivity, one of the main advantages of embedding AE sensors, has not been clearly established among researchers. Multiple studies were undertaken to establish the increased sensitivity when embedding different AE sensors[4,5,11–18]. Multiple studies have explored the increased sensitivity from embedding various AE sensors, yielding mixed sensitivity outcomes, including no enhancement[19], slight enhancement[16] and definite enhancement[14].

The crack-originating location will vary depending on the testing method adopted. Three-point bend testing will produce initial surface cracks compared to DCB mode I testing, which will produce cracks from within. The sensor may react differently to surface or subsurface-originating cracks. Also, the type of crack can influence the sensitivity of the embedded sensor. The aim of the study is to analyse the sensitivity of the surface-embedded and fully embedded sensors concerning surface-originating and subsurface-originating cracks.

4.3 Materials and methods

4.3.1 Sensors

The acoustic emission sensors utilised are silver ink PVDF, gold-plated PVDF and PZT. The silver ink PVDF sheet had a film thickness of 28 μm and a total thickness of 40 μm (protective layer) and was acquired through Mouser Electronics. The gold PVDF sheet had a total thickness of 28 μm and was acquired through Physical Acoustics. The PZT sensor, part number MCFT-15T-4.0A1-121 from Farnell, measured 15mm in diameter and 0.13mm in thickness. The silver ink and gold PVDF sensors were cut from the large sheet to match the PZT diameter (15mm). The connection terminals were established using conductive metallic tape.

4.3.2 Manufacturing

The specimens were produced using vacuum resin infusion, with the materials used for the infusion listed in Table 4-1. A total of 6 layers were used to create the plate, and the fully embedded sensors were placed between the third and fourth layers. The approximate dimension of the specimens manufactured has been listed in Table 4-2.

Table 4-1. The materials used for the vacuum infusion process

Fibres	Glass woven roving 600 gsm plain weave
Epoxy Resin	RS-M135
Hardener	RS-MH137

Three samples were manufactured for each sensor. The connection cables exiting the plate were sandwiched using release film. After curing, the surface embedded sensors were placed on top of the fully embedded sensor using the same epoxy. The sensors were placed approximately 35 mm from the edge of the specimen. A similar process was used to manufacture the double cantilever beam (DCB) mode I specimens. However, after curing, steel hinges were attached to the specimens, followed by the surface-mounted sensors.

Table 4-2. The approximate dimensions of the processed infusion specimens

Sample Type	Size - w x L x t (mm)
DCB Plate	500 x 200 x 2.6

DCB Specimen	25 x 200 x 2.6
Three-point Bend Plate	500 x 250 x 2.6
Three-point Bend Specimen	25 x 250 x 2.6

4.3.3 Equipment

An Instron testing machine was used for the three-point bend and DCB testing. The fixture used for each testing method differs, as shown in Figure 4-1(left) and Figure 4-1(right).

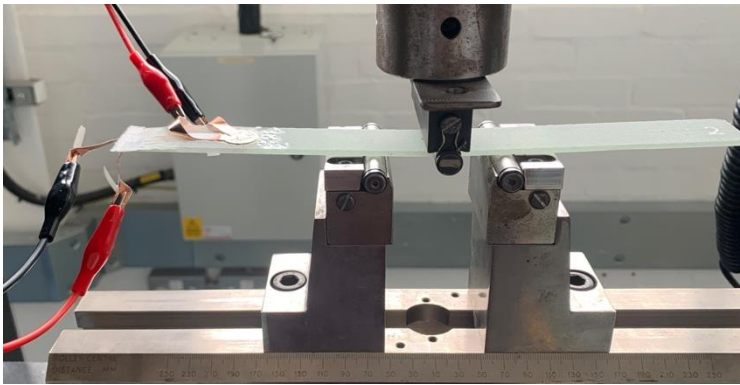


Figure 4-1. The test setup used for (left) three-point bend testing (right) DCB testing

A 5 kN cell was used for both methods. The width span of the three-point bend test specimen was 54 mm, and the testing speed was 1 mm/minute. The hinges on the DCB specimens were held using grippers, and the testing speed was set to 2 mm/minute.

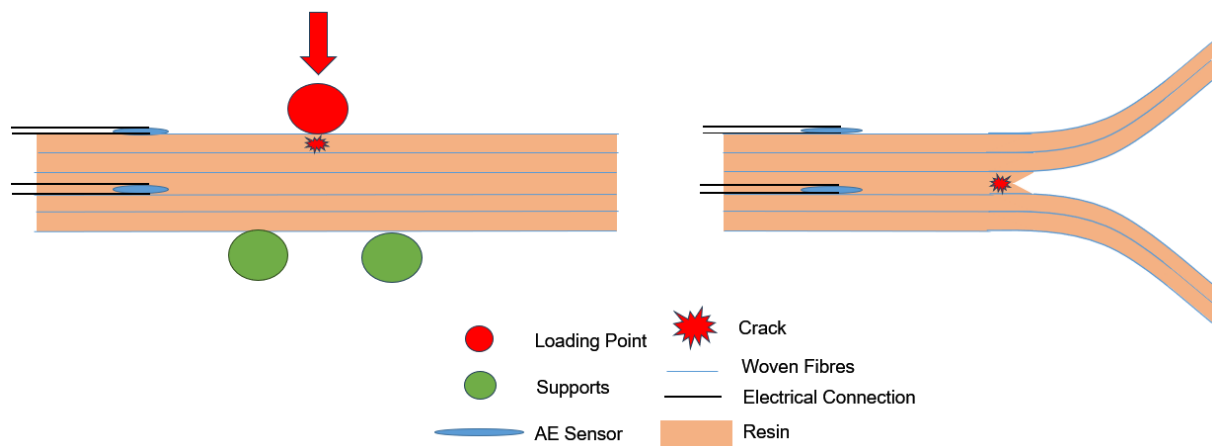


Figure 4-2. An approximate drawing of the testing setup used for (left) three-point bend (right) DCB Mode I

The software utilised for AE testing was PCI-2 based AE system (AEwin). The preamplifier was set to 20 dB whilst connected to a single-ended cable. The detection threshold was set to 55 dB.

4.3.4 Data processing

After acquiring the text file from the AE equipment, it was processed for use in Matlab. The primary stages, seen in Figure 4-3, were followed to extract information in Matlab.

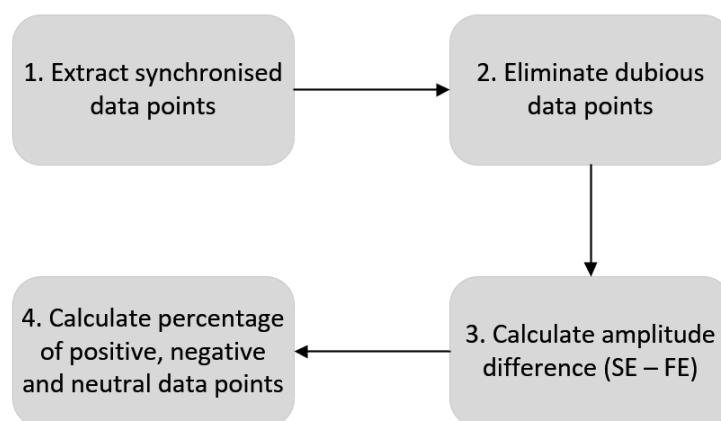


Figure 4-3. The primary steps followed in Matlab to ensure effective data comparison

1. The absolute difference in time between the arriving waves must be less than 1 μ s to ensure the same hit is being examined for both sensors. That is, the time difference between the waves reaching the surface embedded and fully embedded sensors must be less than 1 μ s.
2. Both data points are deleted if the surface-embedded (SE) or fully embedded (FE) receivers have a '0' energy.
3. The amplitude difference was calculated by subtracting the FE sensor's amplitude from the SE sensor's amplitude.
4. The positive points indicate higher sensitivity in the surface embedded sensor, negative points suggest higher sensitivity in the fully embedded sensor and neutral points suggest similar sensitivity. The percentage will illustrate the sensitivity distribution.

4.4 Results and discussion

The fully embedded and surface embedded sensors were placed on the same specimen away from the loading location when performing the mechanical testing, as seen in Figure 4-1. The sensor placement allowed robust comparison and prevented potentially false indications arising from stress accumulation around the sensors. The DCB test caused internal/subsurface cracking consistently throughout the test. However, for the three-point bend test, failure occurs initially on the compression side (surface), and then compression failure continues, layer by layer, moving below the surface and propagating towards the lower, tensile surface.

Rigorous filtering was implemented to ensure accurate results when assessing the sensor's sensitivity. The temporal gap between the waves reaching the sensors was kept to less than 1 μ s, ensuring the examination pertained to the same hit. Additionally, the results were screened to ensure good comparison.

Table 4-3. The average proportion of data eliminated during the processing phase

	DCB Mode I	Three-point Bend
Level 1: Gap arriving time (1 μ s)	89.3% - Eliminated	46% - Eliminated
Level 2: '0' energy	4.9% - Eliminated	37% - Eliminated
Amount of data utilised	5.8%	17%

The amount of data eliminated during processing varied between the tests, as seen in Table 4-3. The majority of the data are eliminated from the wave arriving gap may be due to the higher portion of low-amplitude events with DCB compared to the bending test. That is, the low amplitude causes the signal to be registered by one sensor and not the other (threshold settings), hence eliminated. Removing the '0' energy is related to the wave barely crossing the threshold, hence registering '0' energy content. The eliminated results may not necessarily be unuseful. Instead, they do not meet the criteria for producing highly confident results.

4.4.1 Statistical analysis of AE percentages

The number of hits acquired by the surface and fully embedded sensors varied. When testing using the DCB mode I method, the surface embedded sensor captured approximately three times the number of hits captured by the fully embedded sensor, as seen in Figure 4-4A. However, when subjected to the three-point bend test, the distribution of the hits appeared comparable, as depicted in Figure 4-4B. That is, the number of hits acquired by the surface and fully embedded sensors were approximately the same. The distribution of hits does not serve as the criterion for identifying the superior sensor. Instead, it merely illustrates the hit distribution between the surface and embedded sensors using different mechanical testing methods.

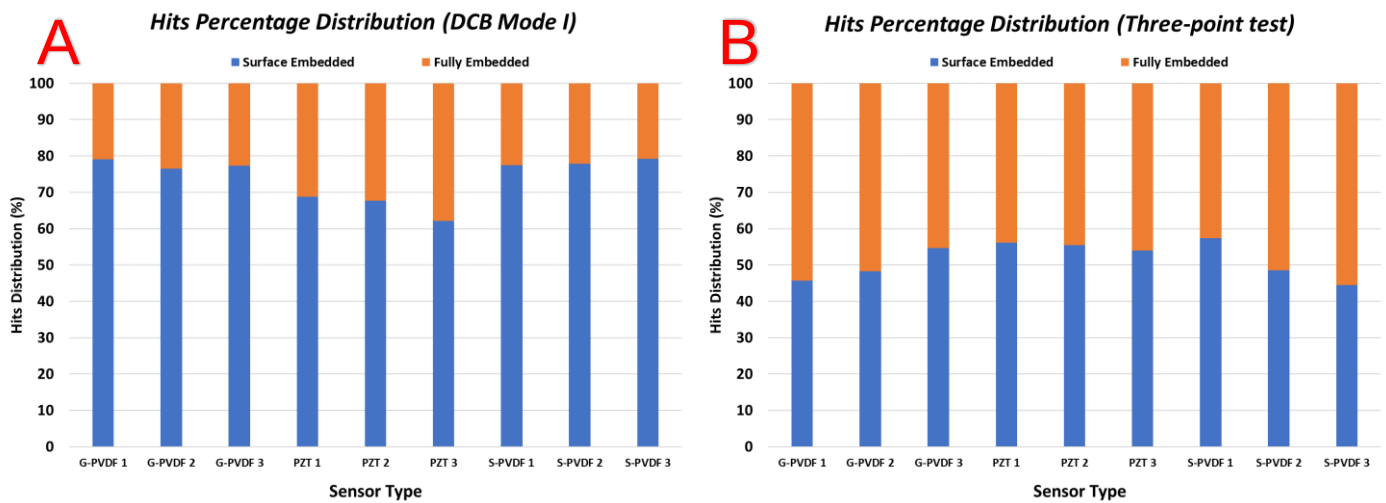


Figure 4-4. The hits percentage distribution between the surface and fully embedded sensors prior to data processing when subjected to (A) DCB mode I (B) Three-point test

During DCB testing, some audible cracks were observed to be captured solely by the surface-embedded sensor. However, loud audible cracks were picked up by both sensors. Although the number of hits can indicate the improved performance of the surface embedded sensor compared to the fully embedded sensor, it is insufficient for quantifying the sensitivity. To accurately assess the sensitivity, comparison of the amplitude captured from the same incoming hit is imperative.

Upon analysing the data and comparing each sensor's amplitude concerning the same hit, the surface embedded sensor exhibited greater amplitude than the fully embedded sensor when subjected to DCB testing, as seen in Figure 4-5A. On average, the surface embedded sensor registered a higher amplitude with 85% of the hits compared to the fully embedded sensor, registering a higher amplitude with 5% of the hits. The remaining 10% of the hits were recorded by both sensors at identical amplitudes. The sensitivity percentage distribution was similar across all the sensors.

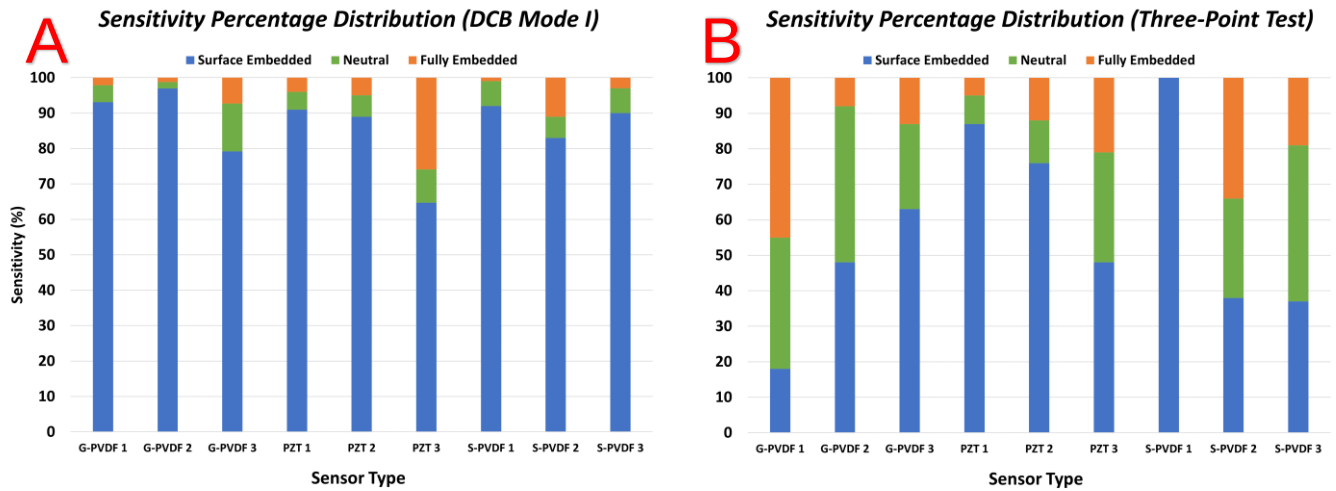


Figure 4-5. The sensitivity (amplitude difference) percentage distribution between the surface and fully embedded sensors post-data processing when subjected to (A) DCB mode I (B) Three-point test

The sensitivity analysis revealed a notable difference in the results obtained from the three-point bend test, as seen in Figure 4-5B. The results show that the number of neutral hits was significantly higher than the DCB method. On average, the surface embedded sensor received a higher amplitude with 59% of the hits, compared to 16% by the fully embedded sensor, while both sensors exhibited the same amplitude with 25% of the hits. The results variation was higher compared to the DCB method, which can be attributed to the acquiring time and type of load drops occurring using the three-point bend test. That is, the AE hits acquired using the DCB method spanned around 50 minutes compared to 2 minutes with the three-point bend test. The lower data acquisition time restricts the range of possible load drop events and, in turn, can increase the variability. This implies that the sensor's sensitivity is influenced by the specific type of failure, as will be discussed in the following section.

4.4.2 Correlation between mechanical loading and AE events

The sensitivity distribution of all the acoustic emission sensors examined using the DCB method is presented in Figure 4-6. A horizontal line was placed at the 0-amplitude difference to facilitate comparison; values higher suggest higher

sensitivity by the surface embedded sensor, while lower suggest higher sensitivity by the fully embedded sensor. Three specimens were tested per sensor, totalling nine tests. The curves in Figure 4-6 illustrate potential outcomes when conducting the DCB test using various sensors. The results display diversity yet collectively suggest a consistent pattern: the sensitivity of the surface-embedded sensor was mainly better or similar to the fully embedded sensor.

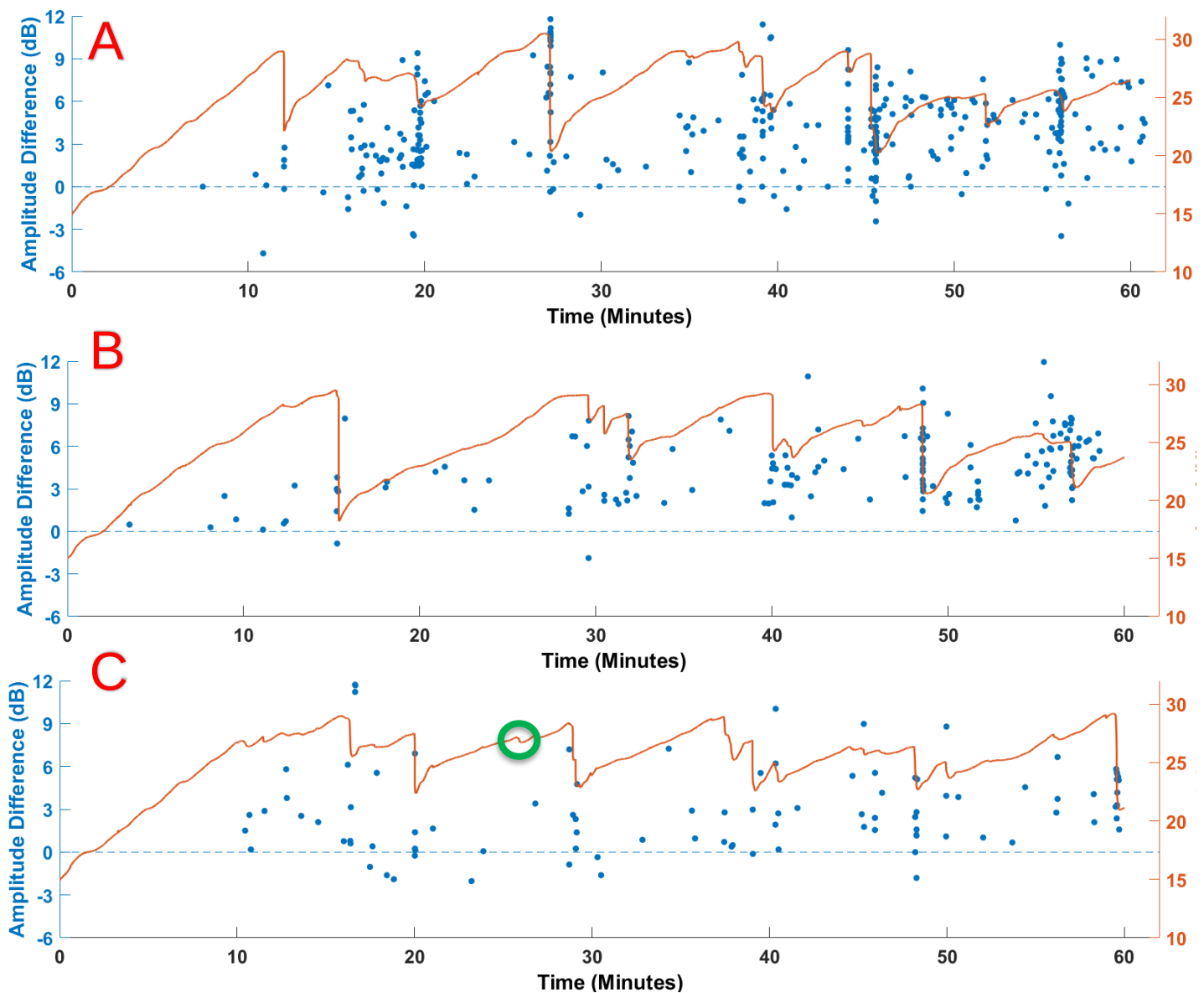


Figure 4-6. The amplitude difference between the surface and fully embedded sensors vs load when subjected to DCB mode I testing utilising different sensors (A) PZT (B) gold PVDF (C) Silver PVDF

The load curve exhibits several drops resulting from the crack propagating after stress accumulation. The load drops varied during the test, with some minor and others substantial. For example, as shown in Figure 4-6B, the load drop at 15 minutes was significantly higher than at 30 minutes. The acoustic emission hits intensity increases when a load drop occurs. However, not all the acoustic emission hits were aligned with a significant load drop, as miniature load drops were also present, as shown in the green circle in Figure 4-6C. The amplitude difference varied throughout the test, especially when an apparent load drop occurred. As depicted in Figure 4-6A, the amplitude difference spanned from -3 to 9 dB at the 20-minute mark during the test, whereas at the 12-minute mark, the amplitude difference ranged from 0 to 3 dB. The different number of drops increases the difficulty of comparing the sensor's performance due to the increased number of hits during the load drop. However, the sensor position sensitivity study is unaffected as the compared sensors (FE and SE) are placed on the same specimen, undergoing the same load drops.

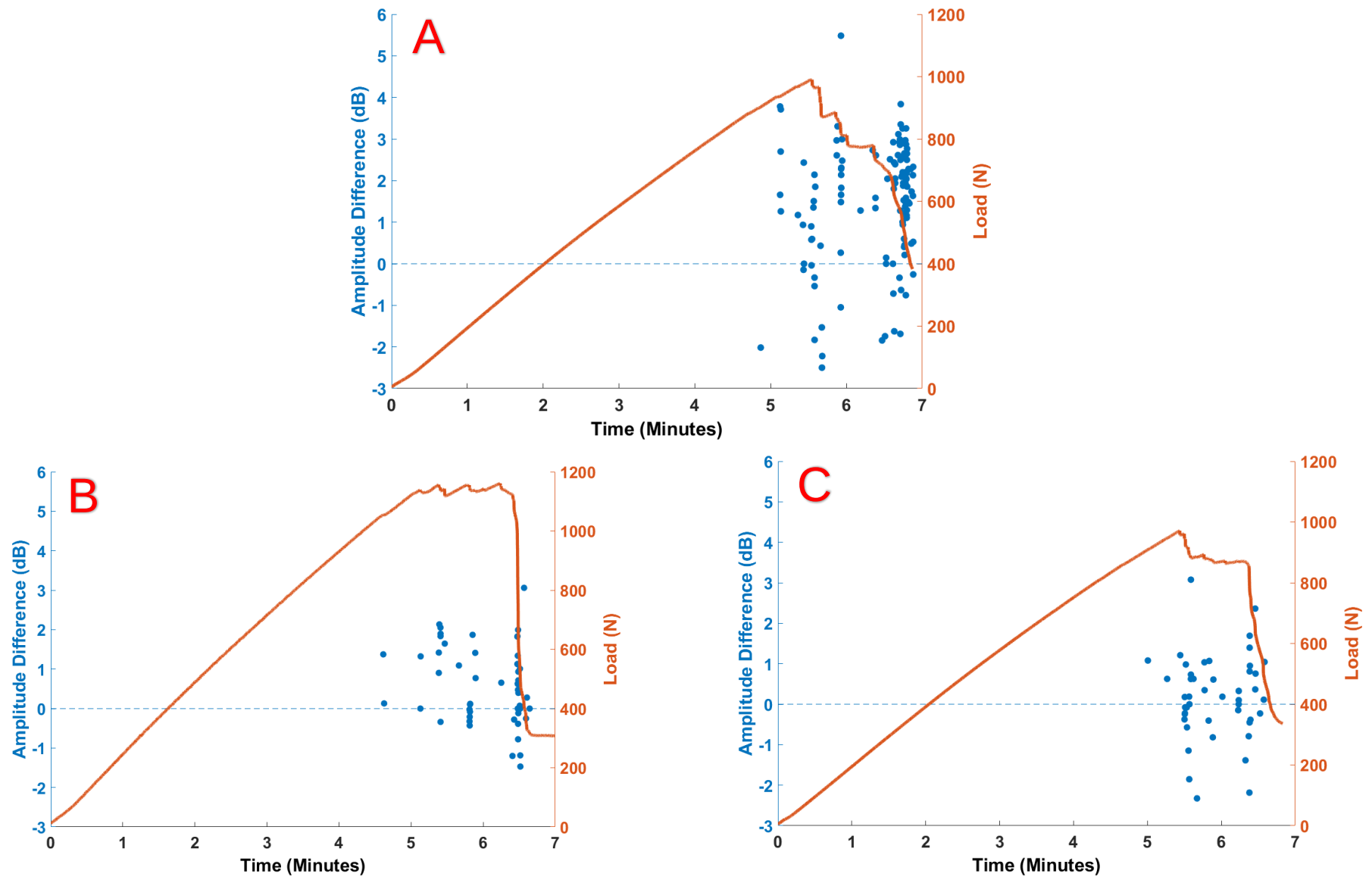


Figure 4-7. The amplitude difference between the surface and fully embedded sensors vs load when subjected to three-point bend testing utilising different sensors (A) PZT (B) gold PVDF (C) Silver PVDF

The results obtained from the three-point bend test were different in terms of the hits acquiring time and amplitude difference distribution compared to the DCB method. As shown in Figure 4-7, most of the AE activity is concentrated towards the end, where a load drop occurs. Furthermore, most of the hits were distributed within the range of 3 to -2 dB, and factoring in the ± 1 AE error margin, it can be concluded that the overall response of the three-point test is comparable. That is, the surface and fully embedded sensors had similar sensitivity.

The amplitude difference between the surface and fully embedded sensors when utilising the three-point test was lower than the DCB test. For example, comparing the PZT sensor (Figure 4-6A and Figure 4-7A), the DCB method yielded an amplitude range of 12 to -3 dB compared to 4 to -2 dB for the bend method.

Figure 4-6 and Figure 4-7 do not compare the performance of the sensors; they show the sensitivity distribution concerning the load curve. However, the results show a significant disparity in the number of hits between the PZT (Figure 4-6A) and PVDF (Figure 4-6B and Figure 4-6C) sensors, with the PZT sensor registering notably higher hit counts. The better performance of the PZT compared to the PVDF is due to the different properties, specifically the d_{31} (film's piezo activity). The PZT has a d_{31} value of 110 pC/N compared to 23 pC/N for PVDF[20]. The gold PVDF[21] and silver PVDF[22] sensors exhibit similar properties. However, the disparity may arise from the distinct positioning of the silver ink PVDF, attributed to the difficulty in establishing its polling direction. The electrical charge generated when mechanical stress aligns along the stretching direction is higher than when applied across the stretching direction[23,24]. However, the comparable number of hits registered using the 3-point bend test could be due to the high amplitude of the hits. Although bi-axial PVDF can be utilised, its properties are inferior to the uni-axial PVDF used in this research[23]. While additional research is needed to substantiate the hypothesis, its confirmation would suggest that employing PVDF for acoustic emission in large structures is not recommended. Nonetheless, the validity of the comparison remains intact due to consistent sensor orientation for both surface and fully embedded sensors.

A significant advantage of fully embedding the sensor of increased sensitivity was not apparent. That is, all the AE sensors exhibited a similar general trend of not favouring the fully embedded sensor. Most hits were not located on the negative side, suggesting better or equal performance when using the surface-embedded sensor. The observation suggests that the sensitivity is not related to the type of sensor, as three different sensors were examined. The instances where the fully embedded sensor outperformed were few, especially considering the ± 1 dB error margin of the AE machine. In situations where there was no evident load drop, the sensitivity of the fully embedded sensor typically did not exhibit superior performance.

As seen in Figure 4-6, under the best circumstances where the crack originated from within the sample and in line with the fully embedded sensor, the surface-embedded sensor had mostly better or equal performance. Also, as depicted in Figure 4-7A, upon reaching the final load drop, the crack's point of origin may not necessarily align with the surface. When comparing the amplitude difference distribution between the final load drop and the initial load drops, it becomes apparent that the amplitude difference is seemingly linked more to the crack's type than its initiation point.

The difference in the amplitude range between the mechanical testing methods suggests that the sensor's sensitivity is linked to the failure mechanism. Previous research shows that the composite's failure mechanisms can be linked to AE features[25] or signal frequency[4–10]. However, no clear correlation was observed when examining AE and frequency features such as rise time, counts, signal strength, peak frequency, centroid frequency and average frequency.

The AE signal received by the surface embedded sensor was decomposed into multiple frequency bands (0-65, 60-129 and 121-500 kHz), providing the energy percentage in each frequency band. The disparity in amplitude was observed to be linked to the quantity of low and high-frequency components within the signal, as depicted in Figure 4-8. Figure 4-8 shows the amplitude difference concerning the energy percentage present in 0-65 kHz compared to 60-129 kHz. The results shown in Figure 4-8 encompass three separate specimens conducted per

sensor. That is, the amplitude difference points were taken from three different specimens. The results show that the surface embedded sensor has higher sensitivity than the fully embedded sensor when the energy content of 60-129 kHz is below 5% and the energy content of 0-60 kHz is higher than 90%. The correlation is consistent across all the sensors and especially apparent when utilising the PZT, as seen in Figure 4-8A. These results match previous research, which suggests that the amplitude difference between surface and fully embedded sensors was linked to the signal's frequency[26].

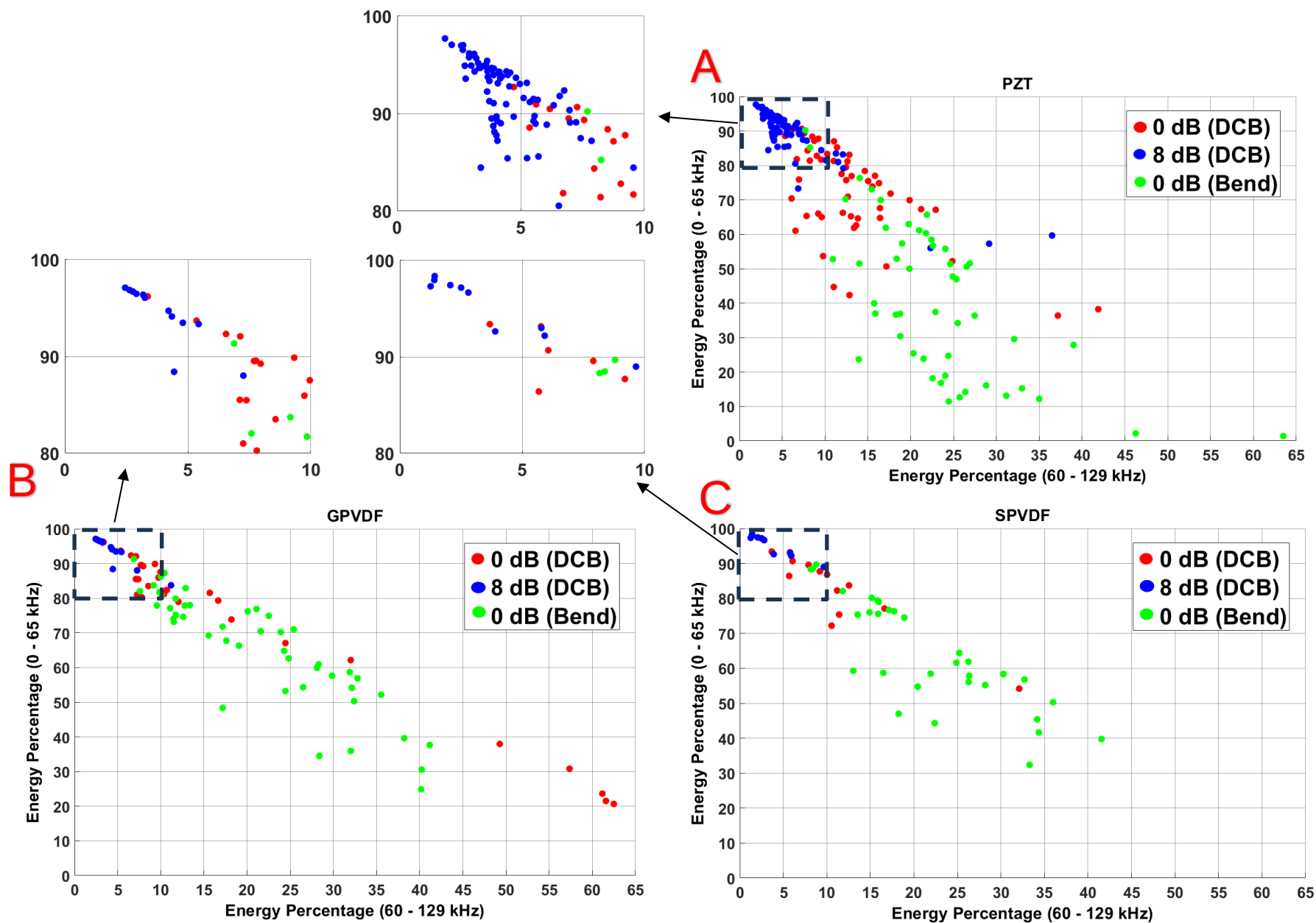


Figure 4-8. The distribution of the amplitude difference 8 dB – DCB, 0 dB – DCB and 0 dB – Bend when comparing low-frequency energy content (0-65kHz) and frequency content (60-129kHz) concerning (A) PZT sensor (B) gold PVDF sensor (C) silver PVDF sensor.

Hence, failure mechanisms with low high-frequency content will yield better performance by the surface embedded sensor. However, failure mechanisms with high high-frequency content will yield similar performance. As seen in Figure 4-8A, the frequency energy content when the amplitude difference was zero is different between the DCB and bend test, suggesting that different failure characteristics are occurring but yielding similar responses from both sensors.

The DCB mode I testing method is typically associated with delamination as the fibres are in one direction. However, the use of woven glass fibre introduces more failure mechanisms. The woven glass fibre creates resin-rich areas in undulation and interstitial areas[27]. The undulation area is the intersection of two yarns compared to the interstitial area, which is the intersection of four yarns[27]. Surface features such as bare fibres, matrix fractures, and matching fibre impressions were documented in the analysis of woven glass fibre under DCB mode I testing[27]. The undulation (red-dashed circle) and interstitial (solid red circle) areas are present on both sides of the sample, as seen in Figure 4-9A. Also, multiple failure mechanisms are observed in Figure 4-9A, including delamination (yellow circle) and fibre matrix cracking (green circle). Furthermore, Figure 4-9B demonstrates the presence of fibre fractures, which may account for the presence of high high-frequency hits present in Figure 4-8.

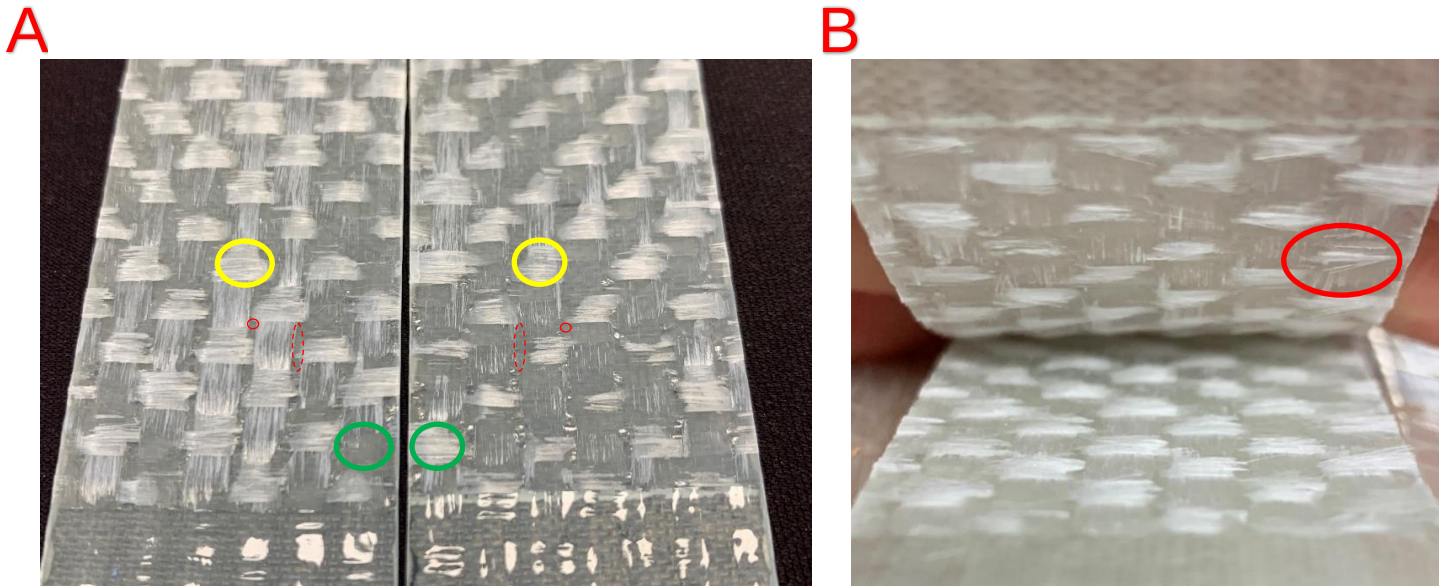


Figure 4-9. A specimen subjected to DCB mode I (A) side to side (B) vertically aligned

On the other hand, the three-point bend sample initial major failure occurred at the surface (compression side). Upon fracture, a cloud of dust was observed, indicating the presence of fibre fracture. It is feasible for various failure mechanisms to manifest upon loading, although the predominant mode is expected to be delamination, as seen in Figure 4-10.

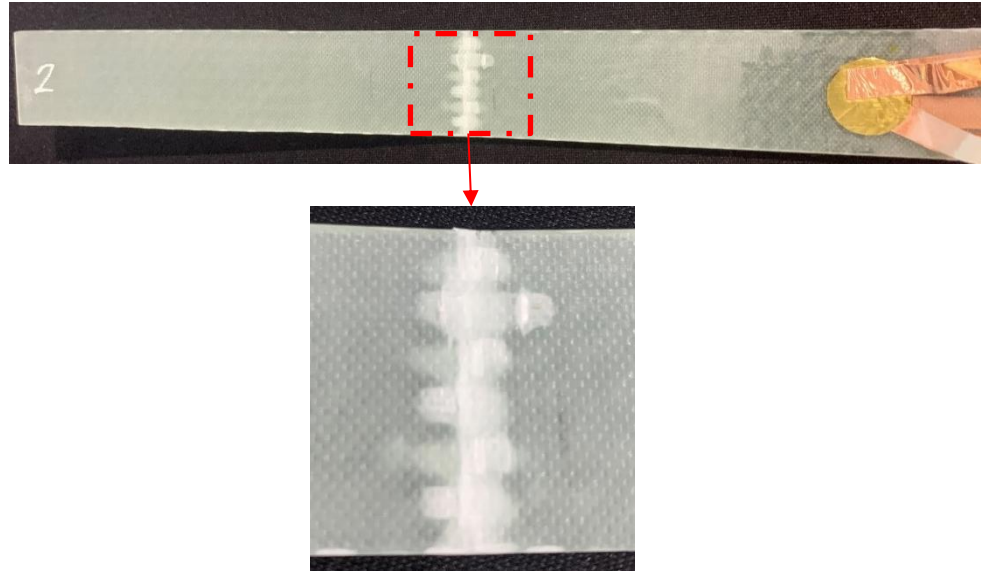


Figure 4-10. A specimen subjected to three-point bend test

The low-frequency components present in Figure 4-8 may be due to the presence of the matrix-rich areas (interstitial and undulation), giving rise to matrix cracking. Matrix cracking is reported to have the lowest frequency compared to the other failure mechanisms[4–10].

Although the three-point bend and DCB mode I methods can lead to the same failure mechanism, the failure mechanism's frequency can differ. The frequency bandwidth is dependent on the crack's rise time, which in turn, depends on the crack velocity and crack travelling distance[28]. The shorter the rise time, the broader the frequency bandwidth. For example, fibre fracture occurs at a short distance of one fibre diameter and high crack speed, producing a short rise time; thus, increased bandwidth towards the higher frequency is expected[28]. Additionally, the high-frequency response may not solely indicate fibre failure but could be attributed to matrix cracking, as demonstrated on a carbon fibre-reinforced laminate[29].

Although the frequency was identified to be linked to the sensor's sensitivity, it is unlikely to be the only factor. Other factors, such as the crack's orientation or stress surrounding the AE sensor, may affect the sensitivity. The stress surrounding the sensor from the high pressure induced during manufacturing

(resin vacuum infusion) may have affected the sensor's response. The surface-embedded sensor was not subjected to the same pressure as it was placed after manufacturing. However, the stress is unlikely to have caused permanent damage as, in some instances, the fully embedded sensor had equal or better sensitivity than the surface embedded sensor. Instead, the stress may have shifted the sensor's amplitude-frequency response, causing the change in amplitude.

This study presented significant challenges during analysis, especially when filtering factors that could influence the sensitivity difference. The 8 dB and 0 dB amplitude differences were considered to differentiate between the sensitivity of the surface and fully embedded sensors. The further apart the amplitude differences, the clearer the comparison. The 8 dB difference is part of the upper region of amplitude difference graph, as shown in Figure 4-6. Also, due to the error from the setup (± 1 dB), the 8 dB could be 7 dB or 9 dB compared to the 0 dB which could be -1 dB or 1 dB. As seen in Figure 8, the 8 dB and 0 dB results overlap, confirming that the frequency was not the only factor accounting for the higher sensitivity.

The differences in findings among researchers may potentially be ascribed to differences in sensors, manufacturing processes, layup configurations, glass fibre weight, specimen thicknesses, surface embedded sensor's couplant or a combination. The previously employed approach to confirm the enhanced sensitivity involved subjecting specimens with and without embedded sensors to mechanical testing, a method that could potentially produce false outcomes. However, a study conducted three-point bend while placing a dummy sensor in the neutral axis under the loading location and it showed that the AE hits acquired were similar to the reference specimen. Yet, when the dummy sensor is placed just above the last ply (tensile side), the number of hits was higher[30]. The surface embedded couplant used when comparing the sensitivity to the fully embedded sensor is essential to be considered. That is, some couplants will have better signal transfer as a result of matching the acoustic impedance.

4.4.3 Travelling wave type

The types of waves arising at the surface are bulk waves[31], part of the wave is converted to Lamb or Rayleigh waves at the surface, depending on the specimen's thickness. If the wall thickness is greater than one wavelength, then Rayleigh waves are produced, if less than one wavelength, Lamb waves are produced[31]. Based on the speed of sound in glass fibre composite 3300 m/s[16], the type of waves produced in this case are Lamb waves up to a frequency of 1.3 MHz. It remains uncertain how increasing wall thickness would affect the sensor's sensitivity.

The manufacturing process of composites enables the experimental investigation of potential variations in wave propagation on both the material's surface and within. Figure 4-11 shows an example of the frequency energy content distribution with both sensors. The sensor's frequency responses exhibited differences, even though both were excited using the same source. The

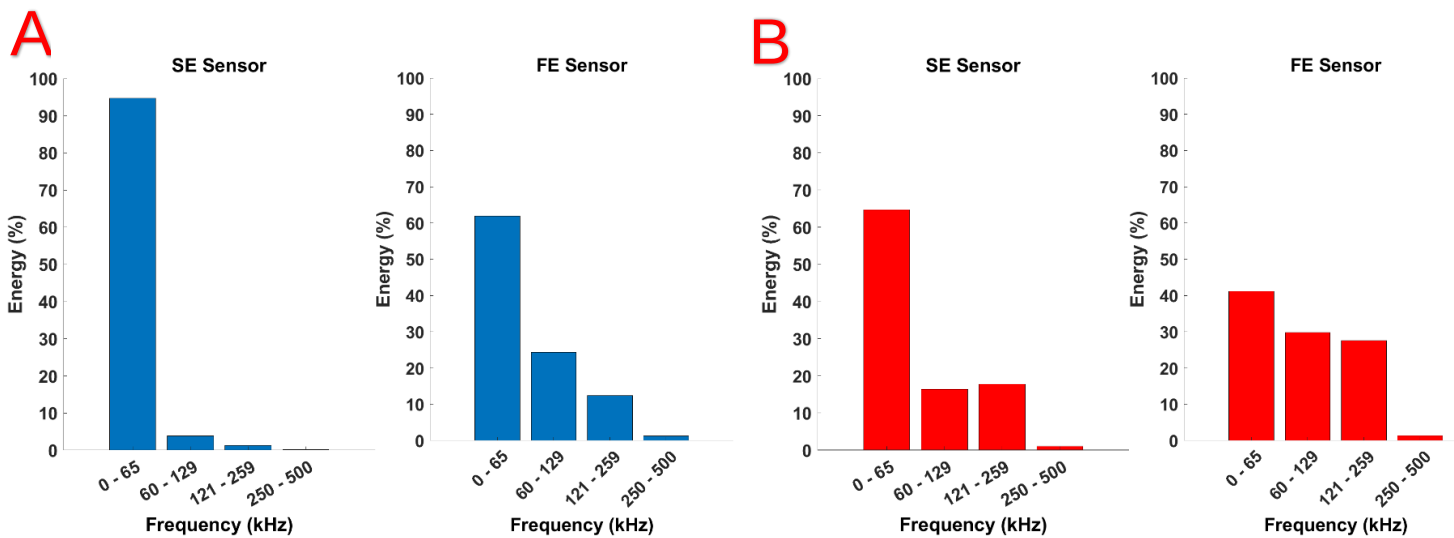


Figure 4-11. The frequency energy distribution between the surface embedded (SE) and fully embedded (FE) PZT sensors subjected to DCB mode I testing (A) 8 dB Amplitude difference (B) 0 dB Amplitude difference.

frequency difference suggests that the wave travelling on the surface may have different characteristics than from within. Even though the difference was present

with both DCB and three-point bend tests, the difference may be due to the embedded sensor being affected by the external environment.

The DCB method testing revealed that the fully embedded sensor received most of the correlated hits first. This suggests that the wave velocity differed on the surface and within the material. The wave velocity in a solid is related to the Young's modulus and the density of the material. Given the dual-material composition comprising resin and fibre, wave propagation velocity is anticipated to exhibit a notable disparity, with the wave traversing the fibre at a higher speed than the resin. The observed delay in wave arrival can be attributed to the conceivable resin concentration discrepancy between the surface and the interior, potentially influenced by the presence of the peel ply layer. Also, the resin placed to fix the surface embedded sensor could have an effect.

The frequency-amplitude difference relation and variance in wave velocity may also be attributed to the symmetric (S_0) and anti-symmetric (A_0) Lamb waves. A study showed that the dominant type of Lamb wave present depends on the frequency. That is, when testing carbon fibre, the A_0 is dominant at frequencies less than 100 kHz compared to the S_0 dominant at frequencies higher than 200 kHz, while both coexist between 100 and 200 kHz[32]. However, further investigation is required.

The study has confirmed that the sensor performance was influenced by frequency, but further investigation is required to understand the differences in the frequency energy content between surface embedded and fully embedded sensors, as well as to elucidate the underlying reasons for the observed frequency-amplitude difference relation effects.

4.5 Conclusion

After comparing the sensitivity based on the same hit, the fully embedded sensor mostly had similar or lower sensitivity compared to the surface embedded sensor. It was found that the frequency of the acoustic emission associated with the failure event influenced the sensitivity of the sensors rather than the crack initiation location. Upon decomposing the frequency energy content of the AE

signal into multiple bands (0-65, 60-129 and 121-500 kHz), the frequency energy content was found to be different between the surface and fully embedded sensors.

The surface embedded sensor exhibited significantly greater sensitivity compared to the fully embedded sensor when its frequency energy content, 0-60 kHz > 90% and 60-129 kHz <5%. However, when the 60-129 kHz energy band was greater than 5%, the surface and fully embedded sensors had mostly similar sensitivity. This indicates that failure modes with high low-frequency content may provide higher amplitude with the surface embedded sensor.

The PZT sensor had a significantly better performance compared to the PVDF sensor. However, the difference between the gold PVDF and silver PVDF requires further investigation.

Further investigation is required to determine why high low-frequency failure modes favour the surface embedded sensor. If the frequency effect remains evident with different reinforcements, thickness composites and manufacturing methods, it is not advisable to fully embed acoustic emission sensors in a polymer-reinforced composite due to the significant disadvantages associated.

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5 Overall Discussion

5.1 Novelty and Contribution

The author's investigations into the benefits of using thin film acoustic emission sensors and placement within a laminate structure for SHM have provided a significant contribution to learning, as discussed in this chapter.

The study evaluated the effectiveness of two artificial acoustic emission sources, namely PLB and the transducer methods, on a metal and a composite surface. The main concern was the lower precision caused by the textured surface of the composite when using the PLB. However, it was found that the effect, if any, was minimal. After utilising the artificial acoustic emission sources to analyse the sensitivity of the embedded sensors, it was found that the sensor's sensitivity was more linked to the frequency characteristic of the crack than the crack's initiation location (surface or subsurface). The use of mechanical testing methods to generate natural AE sources confirmed the frequency effect on the sensitivity. The sensitivity was found to be linked to the percentage of frequency present in the signal.

The two different approaches (artificial and real damage), alongside the use of different sensors affirmed the conclusion. The results indicate that surface embedding the AE sensor generally provides a better or similar response to the fully embedded sensor. Given the complexity associated with fully embedding AE sensors during manufacturing, thus increasing the cost, it is not recommended to fully embed an acoustic emission sensor for the materials and dimensions used. However, it is still unknown how an increase in plate thickness would impact the sensor's sensitivity.

The research encompassed multiple novelties:

- The most significant novelty was the methodology used for identifying the sensor's sensitivity. The woven fibres enabled a novel configuration that enabled actuation from various distances while maintaining the same angle within a single plate, ensuring an unobstructed actuation path to the receiving sensor (Figure 5-1).

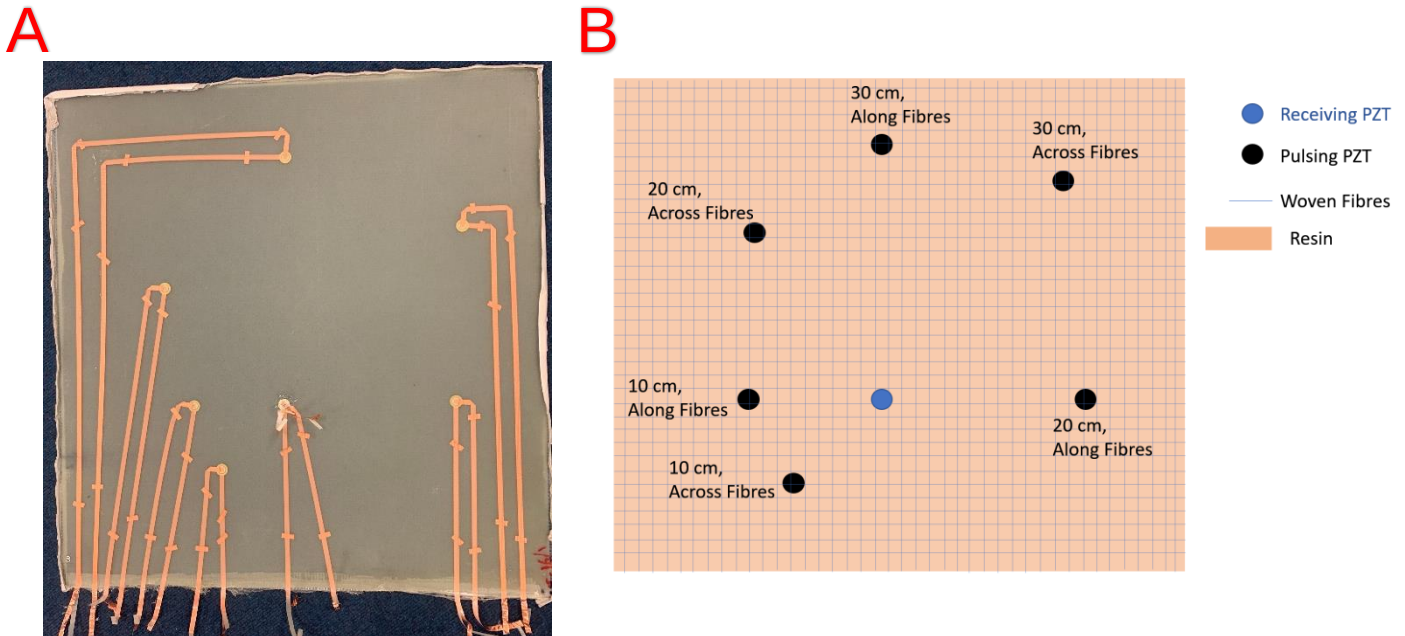


Figure 5-1. (A) The cured plate after manufacturing (B) sensor's configuration illustration.

- Testing using artificial acoustic emission sources presented a novelty when the actuators were fully embedded, simulating the effect of a subsurface crack.
- Another novelty was the ability to test the embedded sensor's sensitivity based on the same event. The employed methodology ensured the robustness of the results and mitigated potential drawbacks that may be associated with other approaches. The previous results did not compare the sensitivity based on the same event. Instead, it was compared based on the number of hits or the amplitude distribution, as the sensors were not necessarily placed on the same specimen.

Numerous contributions have been made, encompassing:

- Identified that surface embedding the AE sensor generally yields a response that is either better or similar to that of the fully embedded sensor.
- Established that the sensitivity of the AE sensors was more closely correlated with the crack's frequency than its initiation location.

- Identified that the wave characteristics captured by the surface and fully embedded sensors were not identical. The findings suggest that there may be different waves travelling on the surface and within. However, further investigation is required to confirm the presence of different waves travelling on the surface and within the composite.
- Explored the feasibility of using non-permanent couplants for actuation. It also identified the effect of the composite's surface (due to the presence of peel ply when manufacturing) when testing using the PLB method.
- Investigated the surface texture of the composite, previously concerned to influence the precision when testing using the PLB method, was confirmed to have little to no effect.
- Identified the frequency associated with each actuation method and highlighted the implications the frequency can have when testing a composite.
- Noted a potential issue with PVDF sensors when utilised for acoustic emission testing. If the issue is confirmed, it could become a notable drawback, potentially leading to the exclusion of uni-axial PVDF as a viable option for an acoustic emission sensor. Although bi-axial PVDF is available and may outcome the issue, its performance is lower than the uni-axial PVDF[1].

5.2 Further illustration

The results in chapter 3 [paper 3] and chapter 4 [paper 4] are presented differently. That is, chapter 3 assesses the embedded sensor's sensitivity based on the signal's peak frequency. However, chapter 4 compares the results based on the decomposition of the frequency signal. The pulse generator (FieldCal) in chapter 3 generated a single peak with the selected frequency. However, when assessing using natural acoustic emission sources, it was found that a frequency range may be present. It was found that when plotting 0-65 kHz and 60-129 kHz bands, meaningful results were obtained. The findings from both papers validate that the surface-embedded sensor yields a more favourable response in cases of very low-frequency failure.

However, a noteworthy aspect to explore further is the difference between the artificial and natural acoustic emissions occurring from within the sample. Figure 5-2(right) illustrates that, at 30 kHz, the surface-embedded sensor displayed a higher amplitude than the fully embedded sensor while remaining comparable at

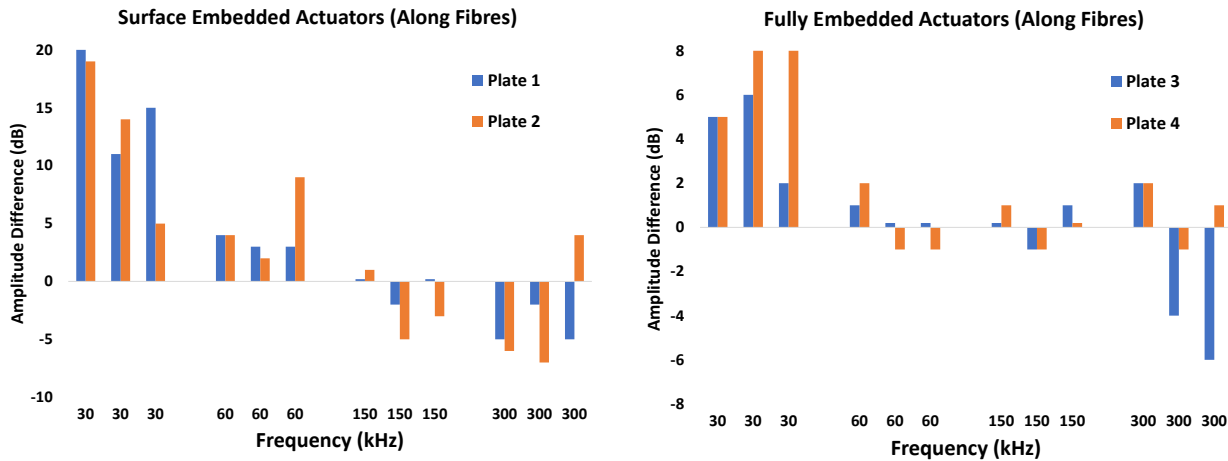


Figure 5-2. The amplitude difference between the surface and fully embedded receivers (SE - FE) along the fibres at four frequencies, (left) surface embedded actuator (right) fully embedded actuator. Taken from paper 3 [section 3.4.2]

other frequencies. Yet, when testing using the DCB mode I method, where cracks originate from within the sample, the results match the surface artificial crack, Figure 5-2(left), more than the subsurface artificial crack, Figure 5-2(right).

The difference between using a pulse generator and the naturally occurring cracks is substantial. That is, using the pulse generator (FieldCal), a single frequency is generated compared to the naturally occurring crack possessing a range of frequencies. However, as mentioned earlier, the sensitivity was more related to the crack frequency than its initiation point.

Identifying the exact cause of this difference is a challenging task. It could be argued that the embedding process of the actuator caused a reduction in performance to actuate due to the surrounding pressure. Theoretically, in the event of reduced performance, the receiving sensors would continue to receive the same signal, albeit with a diminished amplitude. Hence, the receiving amplitudes would reduce, but the amplitude difference between the sensors

would remain the same. However, further work is required to confirm whether a lower actuating amplitude will result in the same amplitude difference.

The reason for the difference may be due to the crack's surroundings, which when artificially induced, were entirely supported yet when naturally occurring, only partially supported, as seen in Figure 5-3. However, further investigation is required.

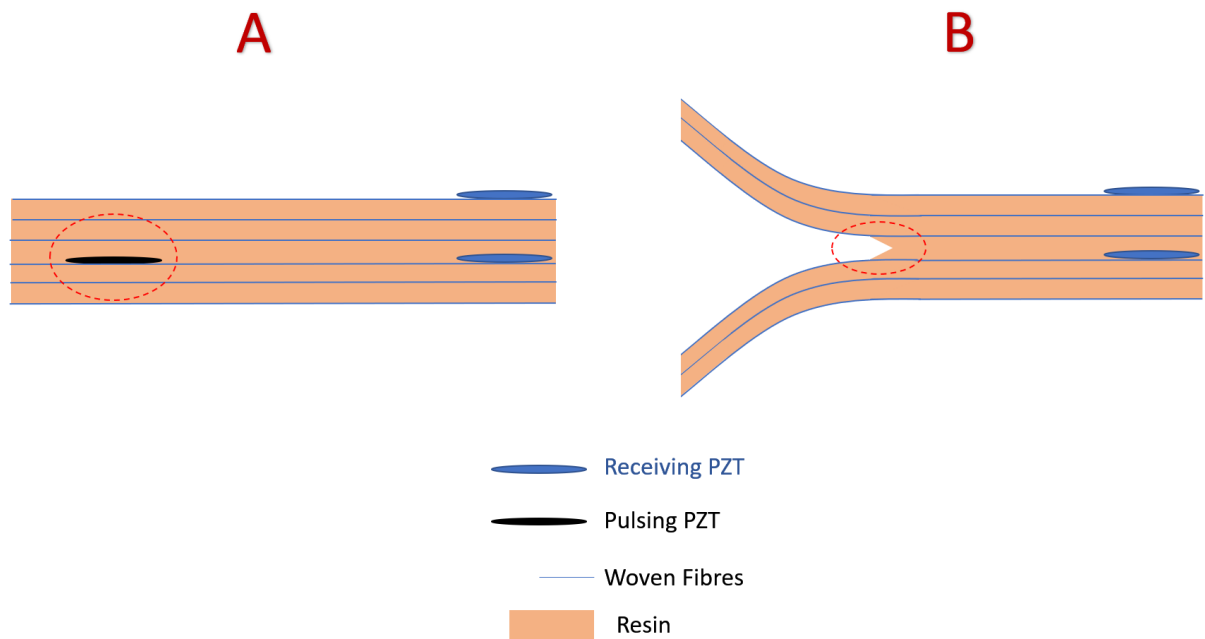


Figure 5-3. Approximate illustration of the surrounding medium that may affect the results (A) actuating PZT (B) DCB mode I.

The incorporation of glass fibre as a reinforcement will enable observation of the wetting process and the potential formation of bubbles during manufacturing. Nevertheless, the primary advantage of the resin lies in its low-temperature curing, a crucial factor given the sensor's inherently low operating temperatures.

5.3 Previous research

The differences in findings among researchers may potentially be ascribed to differences in sensors, manufacturing processes, layup configurations, glass fibre weight, specimen thicknesses, surface embedded sensor's couplant or a combination.

The research group led by Masmoudi reported an increased sensitivity when fully embedding the acoustic emission sensor. The group confirmed the increase in sensitivity by testing both laminate and sandwiched composites[3,4]. The group used a PZT as an acoustic emission sensor and fabricated the composites through hand-layup. The couplant used for the surface-mounted sensor was silicon grease. Three-point bend tests were employed to characterise the sensitivity of the fully embedded sensor whilst placing the sensors within the width span.

In comparison, research was done by De Rosa[5] using two silver ink PVDF sensors in an E-glass fibre composite. When testing using the three-point bend test, part of the sensor was within the width span. The couplant used for the surface-mounted sensor was double-sided tape. The results indicate that AE events captured by the embedded sensor were slightly better. Another research was conducted by Caneva, De Rosa et al.[6] using aramid fibre as the reinforcement. While the research did not provide a quantified assessment of whether the embedded sensor received greater sensitivity, a visual examination of the results did not indicate a higher sensitivity for the embedded sensor.

The placement of the sensor close to the loading position was thought to impact the AE activity. However, a study conducted a three-point bend test while placing a dummy sensor in the neutral axis under the loading location, and it showed that the AE hits acquired were similar to the reference specimen. However, when the dummy sensor was placed just above the last ply (tensile side), the number of hits was higher[2].

The surface embedded couplant used when comparing the sensitivity to the fully embedded sensor is essential to be considered. That is, some couplants will have better signal transfer as a result of matching the acoustic impedance. The acoustic impedance of the double-sided tape might yield superior results compared to silicon grease, given that the tape is a polymer and may potentially match the acoustic impedance of the matrix. Hence, it may be that the couplant was the reason for the inferior performance by the surface-mounted sensor for the work reported by Masmoudi.

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Conclusion

A robust experimental plan was required after establishing that researchers are reporting varying and contradictory behaviour of fully embedded acoustic emission sensors. Assessing artificial AE sources revealed that the reproducibility of the actuator methods ranking on the aluminium and fibre-reinforced polymer composite plates was Tact<Ract<Pencil Lead Breaking method (section 2.4.3). The frequency response between the PLB and actuator methods was different. Also, the effect of the composite's fibre directionality was apparent when testing the attenuation at 90° compared to 45° owing to the anisotropic nature of the composite. However, the attenuation of the aluminium at 90° and 45° was comparable. When testing using the transducer method, observations indicated that choosing a permanent couplant without repositioning was the most robust selection.

Artificial AE sources: PLB and actuator method were used to assess the sensitivity of the fully embedded receiver. The surface (permanently coupled) and fully embedded PZT actuators were placed at distances of 10, 20 and 30 cm both at 90° and 45° directions. The surface and fully embedded actuators represented a crack occurring at the surface and within the sample, respectively. The actuator method results show that the sensitivity of the fully embedded AE receiver was comparable to the surface embedded receiver. However, the PLB showed that the sensitivity of the fully embedded AE receiver was significantly lower than the surface embedded receiver. Upon testing utilising a device capable of pulsing a single frequency, the results showed that the sensitivity of the fully embedded AE receiver was affected by the frequency of the source. The fully embedded receiver had lower sensitivity at 30 kHz compared to comparable sensitivity at 150 kHz. Also, the location of the AE source (surface or fully embedded) affected the amplitude difference between the receiving sensors, depending on the frequency. Therefore, the frequency was considered to affect the fully embedded sensor's sensitivity.

After testing using artificial AE sources, AE sources arising from actual damage were introduced using mechanical testing. A three-point bend test and DCB mode

I were set up to introduce damage from the surface and within, respectively. The results revealed that the fully embedded sensor had mostly similar or lower sensitivity than the surface embedded sensor. It was found that the crack's frequency influenced the sensitivity of the sensors rather than the crack initiation point. The surface embedded sensor exhibited significantly greater sensitivity compared to the fully embedded sensor when its frequency energy content, 0-60 kHz > 90% and 60-129 kHz <5%. However, when the 60-129 kHz energy band was greater than 5%, the surface and fully embedded sensors had mostly similar sensitivity. This indicates that predominantly low-frequency failure modes provide higher amplitude with the surface embedded sensor. Although the study established a connection between the frequency and the embedded sensor's sensitivity, it is probable that additional factors exert an influence.

The PZT sensor had a significantly better performance compared to the PVDF sensor. However, the difference between the gold PVDF and silver PVDF requires further investigation.

Future Work

Determining the underlying cause of the frequency's influence on sensor sensitivity. That is, why does the surface embedded sensor outperform the fully embedded sensor when a predominantly low-frequency failure occurs? Is the phenomenon linked to the type of wave travelling on the surface and within the substrate, such as the S0 and A0 Lamb waves? How does the increase in frequency affect the type of wave excited? Looking at Figure 3-5 (page 95), the surface embedded sensor seem to have the S0 wave but not the fully embedded sensor, this might link why the frequency effect is occurring.

Assessing the impact of material thickness on the sensor sensitivity. That is, if the plate's thickness were to decrease, would the fully embedded sensor maintain its lower or equivalent sensitivity compared to the surface-embedded sensor? or would the surface embedded performance improve further?

The identification of whether the PVDF has a direction bias when testing using AE due to its internal properties.

Determine whether the fully embedded sensor is shielded from external environmental factors or exhibits reduced susceptibility to noise (such as EMI or impact) due to the embedding process.

Identify the reason why the sensitivity of the sensors was different when testing along and across the fibres.

Can the size of crack be identified from AE?

After noting that the capacitance method was used with PVDF, can the capacitance method be simultaneously deployed with the AE method using the same PZT?

Can the conventional acoustic emission sensor be used with measuring the capacitance alongside AE? Low strain might not output AE signal but can be detected by the change in capacitance. Hence, although there is one sensor, the strain and the sound are being monitored.

A conventional AE sensor was placed on a shaking battery housing (low Hz) but no emission was heard which means that AE may be suitable for wind turbines (surface embedded inside) for example. However, further examination is required.

Appendices

Appendix A Ethical approval letter



2 December 2020

Dear Mr Ghadarah ,

Reference: CURES/12481/2020

Title: Multifunctional Smart composite material for damage tolerance, structural health monitoring and self-healing

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/12481/2020 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

