

Performance evaluation of embedded acoustic emission sensors in a glass fibre composite under mechanical loading

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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.

1. 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.

2. Materials and methods

2.1. 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

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PZT sensor, part number MCFT-15T-4.0A1-121 from Farnell, measured 15 mm in diameter and 0.13 mm in thickness. The silver ink and gold PVDF sensors were cut from the large sheet to match the PZT diameter (15 mm). The connection terminals were established using conductive metallic tape.

2.2. Manufacturing

The specimens were produced using vacuum resin infusion, with the materials used for the infusion listed in Table 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 2.

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.

2.3. 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 Fig. 1(left) and Fig. 1(right). A representation of the testing samples with the sensors is shown in Fig. 2.

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.

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.

2.4. Data processing

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

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.

3. Results and discussion

The fully embedded and surface embedded sensors were placed on the same specimen away from the loading location when performing the

Table 1
The materials used for the vacuum infusion process.

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

Table 2

The approximate dimensions of the processed infusion specimens.

Sample Type	Size – w $\times$ L $\times$ t (mm)
DCB Plate	500 $\times$ 200 $\times$ 2.6
DCB Specimen	25 $\times$ 200 $\times$ 2.6
Three-point Bend Plate	500 $\times$ 250 $\times$ 2.6
Three-point Bend Specimen	25 $\times$ 250 $\times$ 2.6

mechanical testing, as seen in Fig. 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.

The amount of data eliminated during processing varied between the tests, as seen in Table 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 useless. Instead, they do not meet the criteria for producing highly confident results.

3.1. 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 Fig. 4A. However, when subjected to the three-point bend test, the distribution of the hits appeared comparable, as depicted in Fig. 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.

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 Fig. 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.

The sensitivity analysis revealed a notable difference in the results obtained from the three-point bend test, as seen in Fig. 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

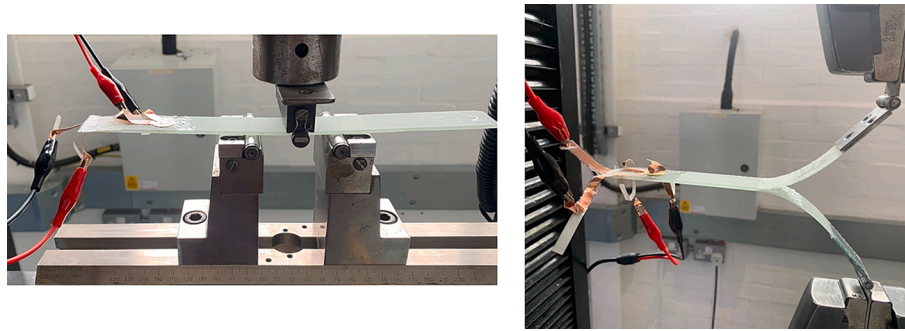


Fig. 1. The test setup used for (left) three-point bend testing (right) DCB testing.

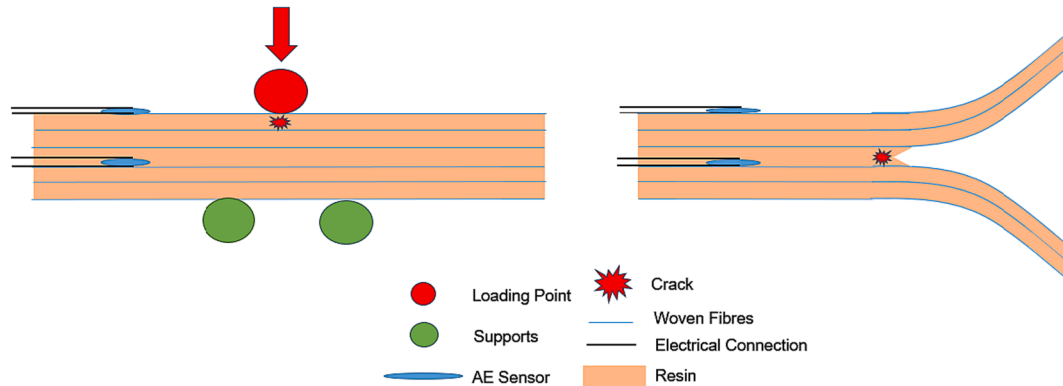


Fig. 2. An approximate drawing of the testing samples used for (left) three-point bend (right) DCB Mode I.

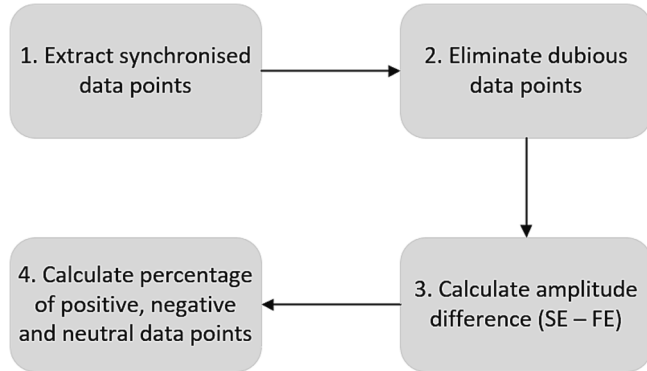


Fig. 3. The primary steps followed in Matlab to ensure effective data comparison.

Table 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 %

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 min compared to 2 min 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.

3.2. Correlation between mechanical loading and AE events

The sensitivity distribution of all the acoustic emission sensors examined using the DCB method is presented in Fig. 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 Fig. 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.

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 Fig. 6B, the load drop at 15 min was significantly higher than at 30 min. 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 Fig. 6C. The amplitude difference varied throughout the test, especially when an apparent load drop occurred. As depicted in Fig. 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.

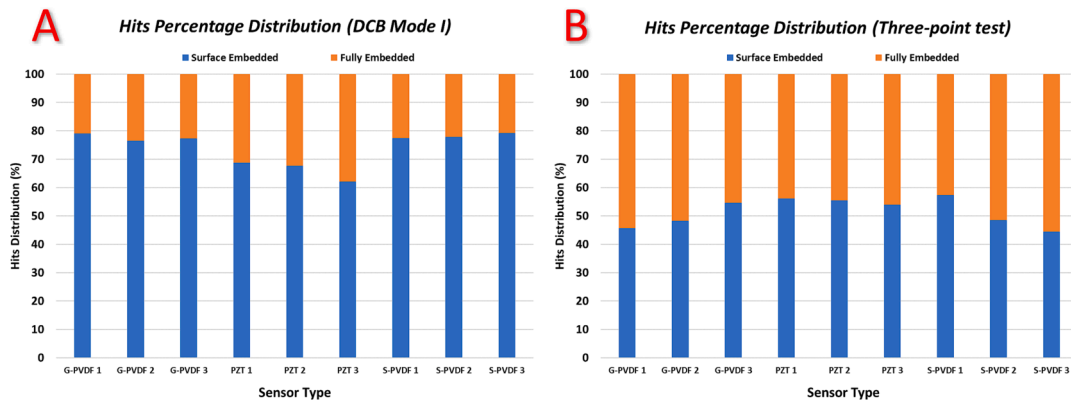


Fig. 4. The hits percentage distribution between the surface and fully embedded sensors prior to data processing when subjected to (A) DCB mode I (B) Three-point test.

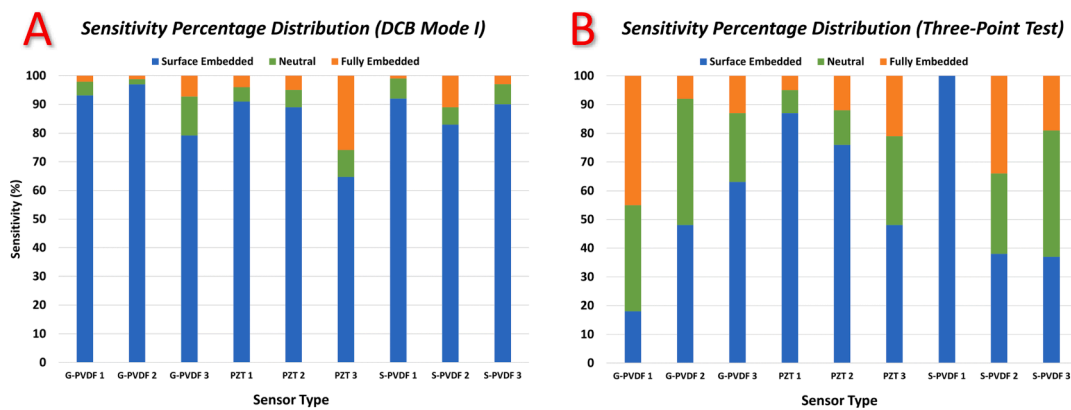


Fig. 5. The sensitivity (amplitude difference) percentage distribution between the surface and fully embedded sensors post-data processing when subjected to (A) DCB mode I (B) Three-point test.

The 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 Fig. 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 (Fig. 6A and Fig. 7A), the DCB method yielded an amplitude range of 12 to -3 dB compared to 4 to -2 dB for the bend method.

Fig. 6 and Fig. 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 (Fig. 6A) and PVDF (Fig. 6B and C) 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 Fig. 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 Fig. 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

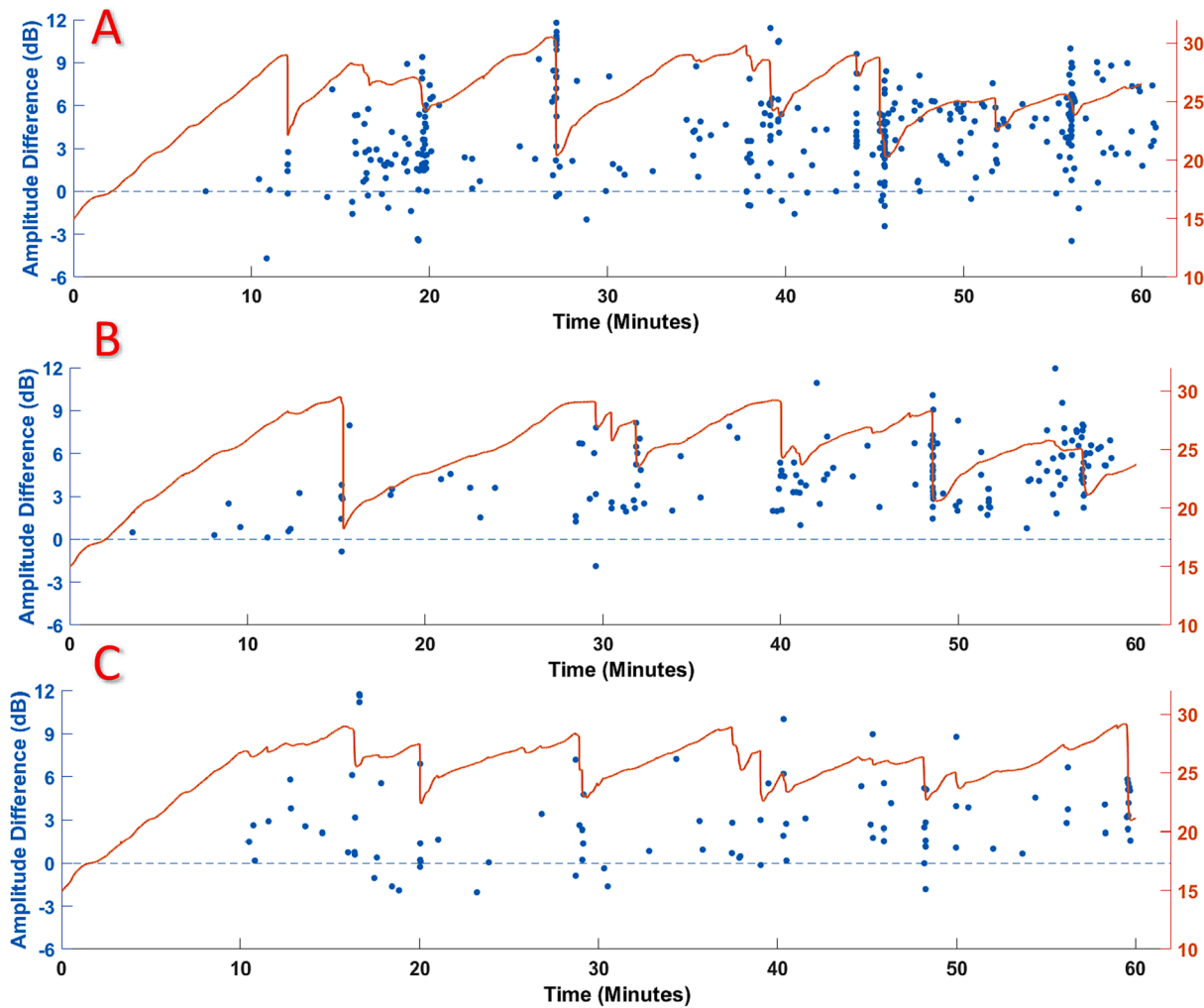


Fig. 6. The amplitude difference between the surface and fully embedded sensors vs load when subjected to DCB mode I testing utilising different sensors (A) PZT (B) gold PVDF (C) Silver PVDF.

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 Fig. 8. Fig. 8 shows the amplitude difference concerning the energy percentage present in 0–65 kHz compared to 60–129 kHz. The results shown in Fig. 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 Fig. 8A. These results match previous research, which suggested that the amplitude difference between surface and fully embedded sensors was linked to the signal's frequency [26].

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 Fig. 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 Fig. 9A. Also, multiple failure mechanisms are observed in Fig. 9A, including delamination (yellow circle) and fibre matrix cracking (green circle). Furthermore, Fig. 9B demonstrates the presence of fibre fractures, which may account for the presence of high high-frequency hits present in Fig. 8.

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 Fig. 10.

The low-frequency components present in Fig. 8 may be due to the presence of the matrix-rich areas (interstitial and undulation), giving

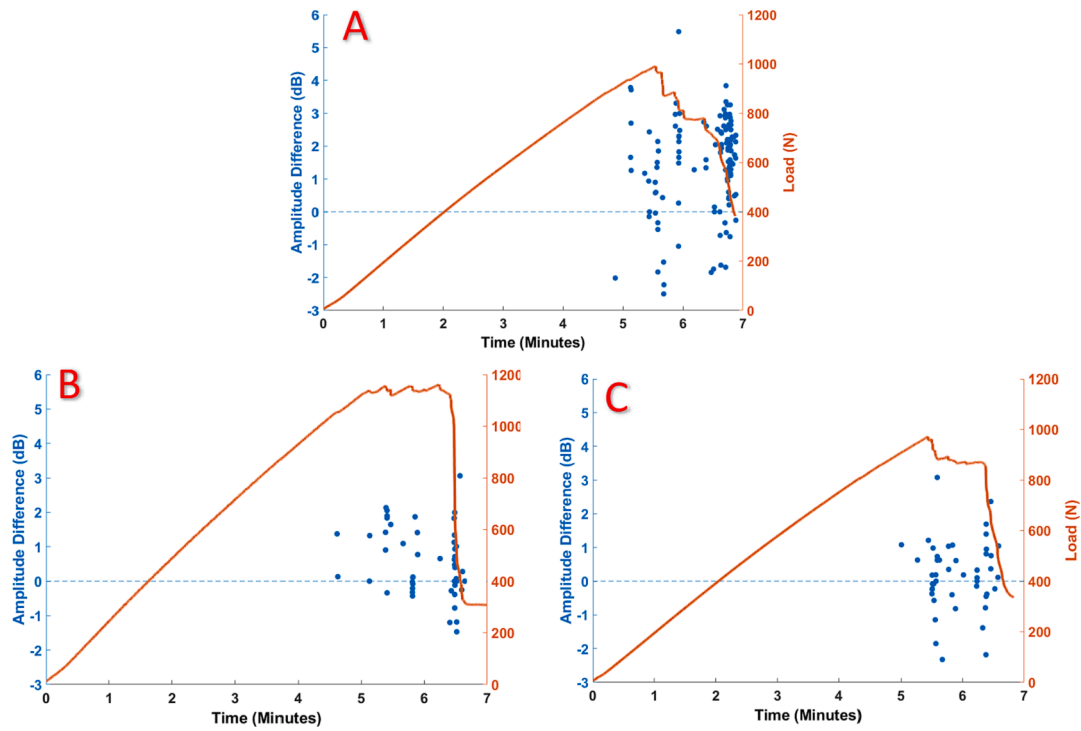


Fig. 7. The amplitude difference between the surface and fully embedded sensors vs load when subjected to three-point bend testing utilising different sensors (A) PZT (B) gold PVDF (C) Silver PVDF.

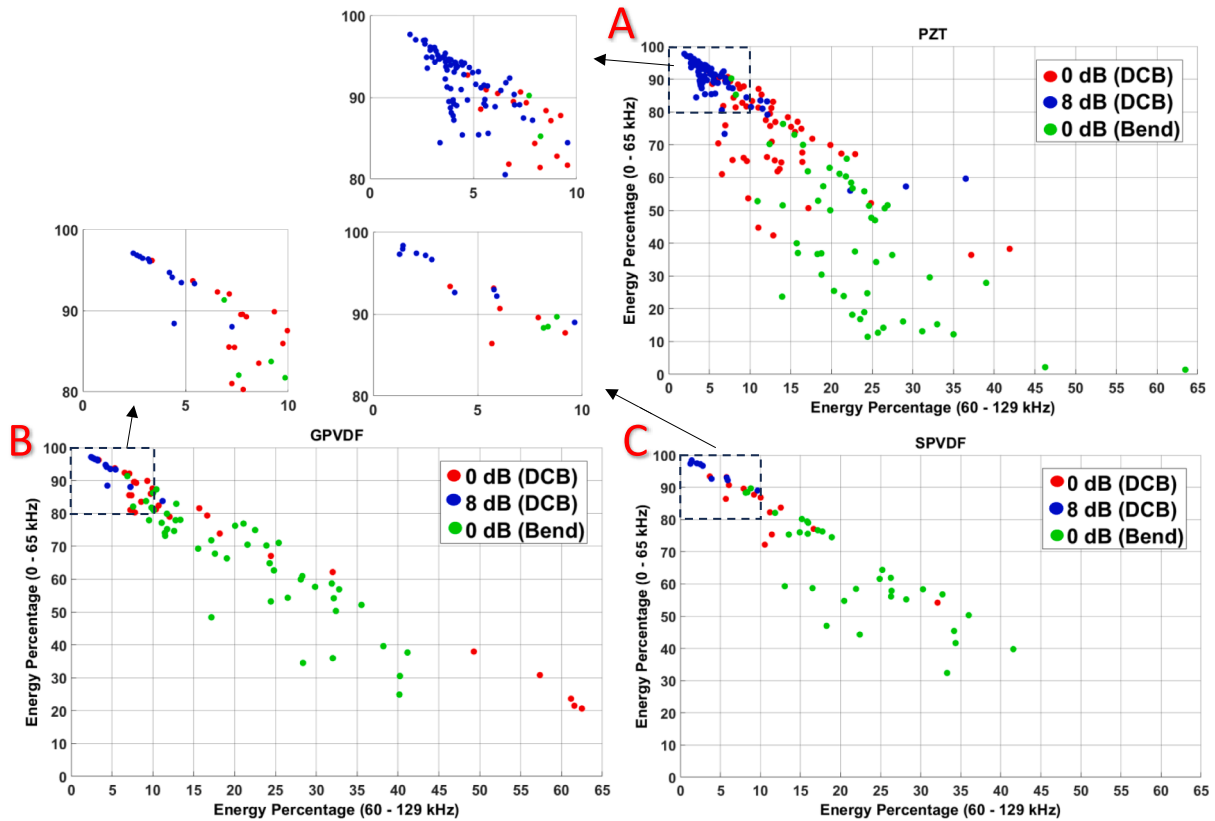


Fig. 8. The distribution of the amplitude difference 8 dB – DCB, 0 dB – DCB and 0 dB – Bend when comparing low-frequency energy content (0–65 kHz) and frequency content (60–129 kHz) concerning (A) PZT sensor (B) gold PVDF sensor (C) silver PVDF sensor.

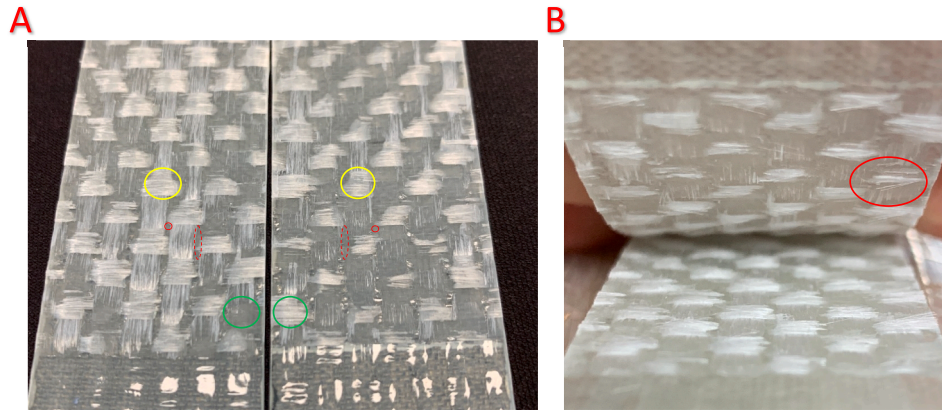


Fig. 9. A specimen subjected to DCB mode I (A) side to side (B) vertically aligned.

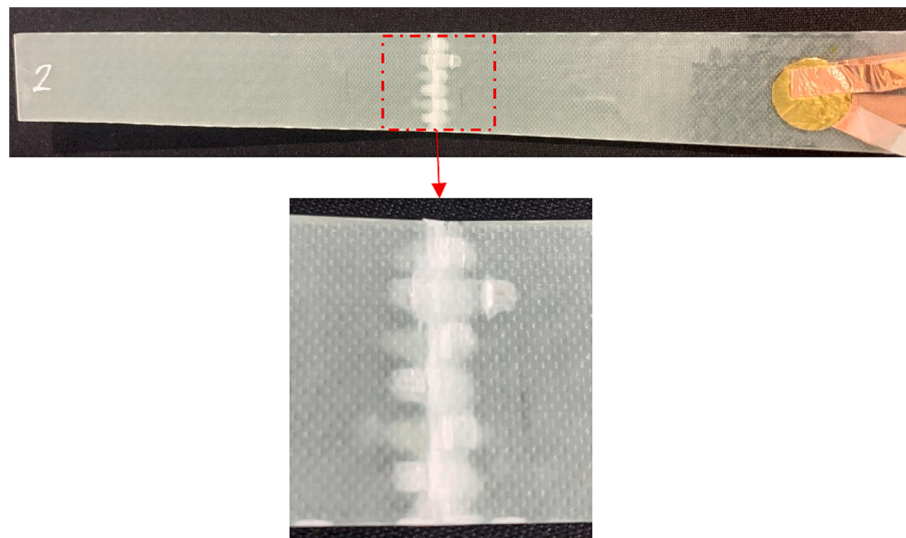


Fig. 10. A specimen subjected to three-point bend test.

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 Fig. 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 Fig. 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

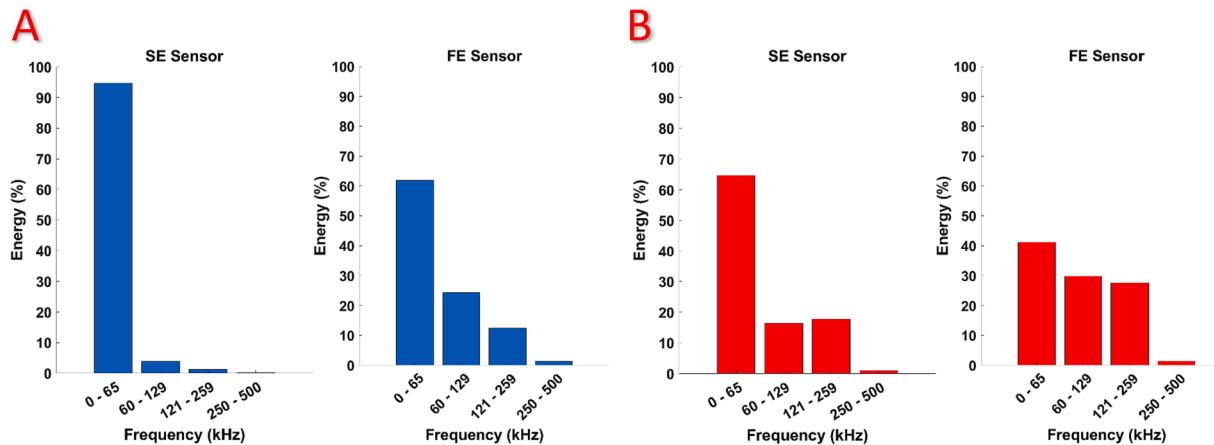


Fig. 11. The frequency energy distribution between the surface embedded (SE) and fully embedded (FE) PZT sensors subjected to DCB mode I testing (A) 8 dB Amplitude difference (B) 0 dB Amplitude difference.

impedance.

3.3. 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. Fig. 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 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. 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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During the preparation of this work the author (Noor Salam Ghadarah) used AI tools to improve the structure and wording of the sentences. After using this tool/service, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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