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De Araujo Alves Lima, R., Gulino, M., & De Freitas, S. T. (2025). Advanced Techniques for Accurate Crack Length Monitoring in BI-Material Adhesively Bonded Joints. In *Proceedings - 2025 IEEE International Workshop on Metrology for Green Technologies, Renewable Energy and Ecological Sustainability, MetroGREENST 2025* (pp. 304-308). IEEE. https://doi.org/10.1109/MetroGREENST67435.2025.11429016

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2025 IEEE International Workshop on Metrology for Green Technologies, Renewable Energy and Ecological Sustainability (MetroGREENST) | 979-8-3315-9635-4/25/$31.00 ©2025 IEEE | DOI: 10.1109/METROGREENST67435.2025.11429016

Advanced Techniques for Accurate Crack Length Monitoring in Bi-Material Adhesively Bonded Joints

1st Rosemere de Araujo Alves Lima
IDMEC, Instituto Superior Técnico
Universidade de Lisboa
Lisbon, Portugal
rosemere.lima@tecnico.ulisboa.pt

2nd Michele Gulino
Department of Engineering for Industrial Systems and Technologies
University of Parma
Parma, Italy
michele.gulino@unipr.it

3rd Sofia Teixeira de Freitas
IDMEC, Instituto Superior Técnico
Universidade de Lisboa
Lisbon, Portugal
Faculty of Aerospace Engineering
Delft University of Technology
Delft, the Netherlands
sofia.teixeira.freitas@tecnico.ulisboa.pt

Abstract—***Driven by sustainability goals outlined in the European Green Deal, most of the industrial sectors (i.e. automotive, aerospace and civil infrastructures) require reliable, lightweight, and durable materials. Accurate crack detection significantly extends the operational life of bonded structural components, reducing maintenance, waste, and environmental impact.***

This study presents acoustic emission (AE) techniques for accurately monitoring crack length in adhesively bonded joints, primarily targeting Titanium-Carbon Fiber Reinforced Polymer (Ti-CFRP) bi-material specimens, with Titanium-Titanium (Ti-Ti) joints included as a benchmark.

Titanium Ti6Al4V substrates fabricated via Laser Powder Bed Fusion (LPBF) were prepared with various surface conditions: as-printed and sandblasted. The mode I fracture toughness was evaluated via Double Cantilever Beam tests, which were supported by continuous AE monitoring with high-resolution equipment capturing around 200,000 waveforms.

Principal Component Analysis and machine learning techniques, including Self-Organising Maps and K-means clustering, classified AE signals into clusters associated with damage or background noise. A linear localisation algorithm tracked crack initiation and growth phases. Results validated the accuracy of AE signals to localise crack propagation under the bi-material quasi-static mode I load condition. The study highlights AE's potential for precise and sustainable structural health monitoring, informing future numerical modelling to predict joint durability.

Keywords—Adhesively Bonded Joints, Crack Measurement, Acoustic Emission, Principal Component Analysis, Self-Organising Maps, Ti-CFRP.

I. Introduction

Adhesively bonded joints—particularly those combining dissimilar materials such as Titanium–Carbon Fiber Reinforced Polymer (Ti–CFRP) and Titanium–Titanium (Ti–Ti)—are widely used in aerospace, automotive, and renewable energy sectors due to their superior fracture toughness and damage tolerance [1, 2]. As global efforts intensify toward sustainability, the demand for lightweight, durable, and energy-efficient structural components continues to grow.

The integration of advanced materials, such as 3D-printed metallic substrates and composite laminates, offers significant potential for weight reduction, contributing to lower energy consumption and emissions in transportation and manufacturing [3]. However, ensuring the long-term reliability of these bonded structures requires precise monitoring of crack initiation and propagation [4].

This study presents a robust experimental methodology to accurately detect and quantify crack growth in bi-material adhesively bonded joints. By enabling detailed analysis of damage evolution, the proposed approach supports the development of safer, longer-lasting structures with reduced maintenance needs, lower environmental impact, and enhanced recyclability.

II. Materials and Methods

Titanium Ti6Al4V substrates were fabricated via Laser Powder Bed Fusion (LPBF) with an M290 system (EOS Gmbh, Krailling, Germany), and supplied by 3TAdditive Manufacturing Ltd (Newbury, United Kingdom). A Ti6Al4V powder of an average particle diameter of 37.3 µm was used for the substrates and the following printing parameters were selected: (a) building angle of 90◦, (b) laser scan speed of 1250 mm/s, (c) layer thickness of 60 µm, (d) spot size of 80 µm, and (e) laser power of 190 W. The post-printing stress-relieving treatment was carried out in a vacuum furnace (1.3x10-3 mBar maximum air pressure), for 4h at 800°C.

It is worth mentioning that LPBF was selected due to its ability to produce components with inherently rough surfaces. This characteristic enhances mechanical interlocking and improves adhesion performance in bonded joints [1,5].

Surface conditions included as-printed (untreated), mechanically sandblasted, and oxidised (formation of an oxide layer after the parts' printing). Two bonding strategies were explored: secondary bonding (Ti6Al4V-Ti6Al4V) and co-bonding (Ti6Al4V-CFRP). The joints were bonded with Structil ST 1035 supported epoxy film adhesive. The adhesive thickness relied on the carrier mat thickness (0.1 mm) to avoid excess resin bleeding, as is common practice in industrial applications.

Fracture toughness was evaluated using Double Cantilever Beam (DCB) tests under quasi-static mode-I loading, with continuous load-displacement recording to calculate critical strain energy release rates. Digital Image Correlation and visual evaluation through a travelling microscope were performed (Figure 1).

Marie Curie Postdoctoral Fellowship: REVOLUTION_WIND - grant agreement ID:101153013.

Fundação para a Ciência e a Tecnologia (FCT) for its financial support via the project LAETA Base Funding (10.54499/UIDB/50022/2020).

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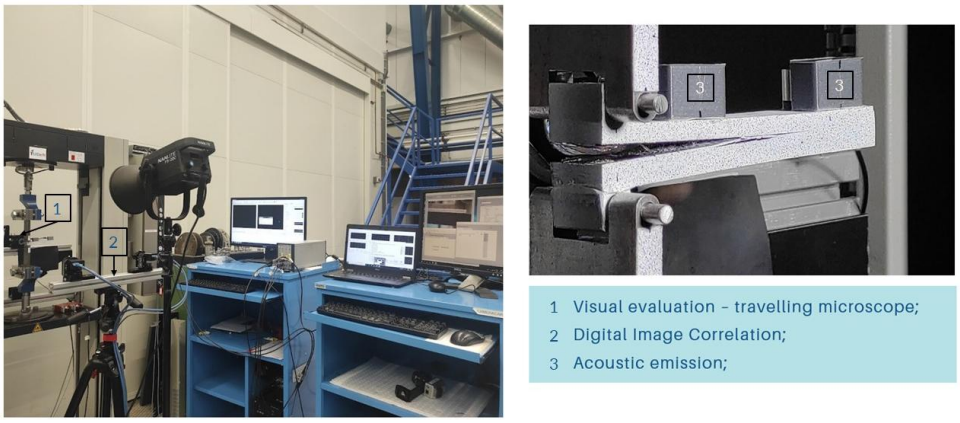


Figure 1: Experimental set-up for quasi-static mode I fracture toughness characterisation.

The results related to the specimens' fracture toughness are detailed in previous work by the authors [1]. In summary, the findings showed that, in the absence of oxidation, as-printed titanium joints exhibited, on average, a 13% higher fracture toughness than their sandblasted counterparts. In contrast, when oxidation was present, sandblasting proved beneficial, resulting in a 64% average increase in fracture toughness compared to untreated joints.

An Acoustic Emission (AE) monitoring system was implemented, including an eight-channel Vallen ASMY-6 acquisition unit, two Vallen VS150-M piezoelectric sensors, and a 34 dB Vallen AEP5 preamplifier. Key AE system parameters included a sampling frequency of 10 MS/s, an amplitude threshold of 34 dB, a rearm time of 2.5 ms, and a 25 kHz high-pass filter.

Pencil Lead Break Test (PLBT) was performed to identify the dominant frequency content of the artificially generated signals and to assist in determining the wave propagation velocity within the bi-material joints.

The acoustic emission (AE) system continuously monitored crack evolution within the joints throughout the quasi-static tests, capturing a large volume of waveforms associated with both crack propagation and background noise. As a result, an efficient post-processing methodology was essential.

The acquired data advanced signal processing through Principal Component Analysis (PCA) for feature extraction and dimensionality reduction. PCA enabled the identification of the most significant principal components, enhancing the interpretability of complex multivariate data by isolating the most relevant features [6].

Following this, unsupervised machine learning techniques were employed to cluster the AE signals, as detailed in the scheme of Figure 2. Two clustering methods were applied: Self-Organizing Maps (SOM) and K-means clustering. SOM is a type of artificial neural network that maps high-dimensional data into a lower-dimensional (usually 2D) space while preserving the topological relationships between data points. This approach enables intuitive visualization and identification of clusters with similar characteristics.

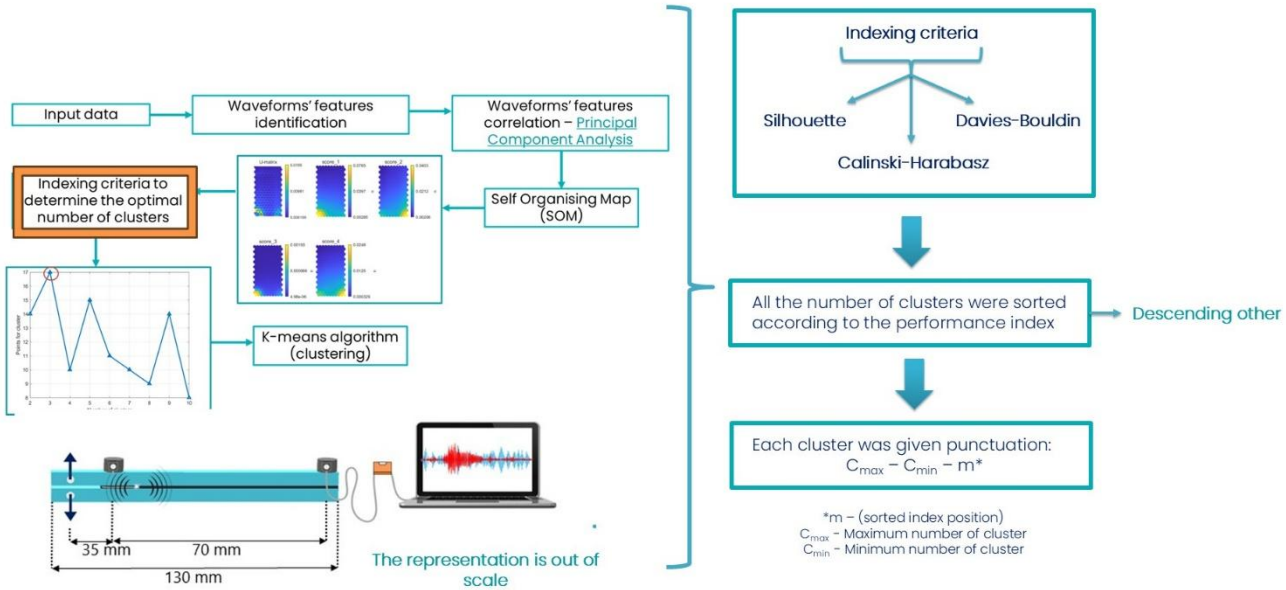


Figure 2: Acoustic emission post-processing for data clustering.

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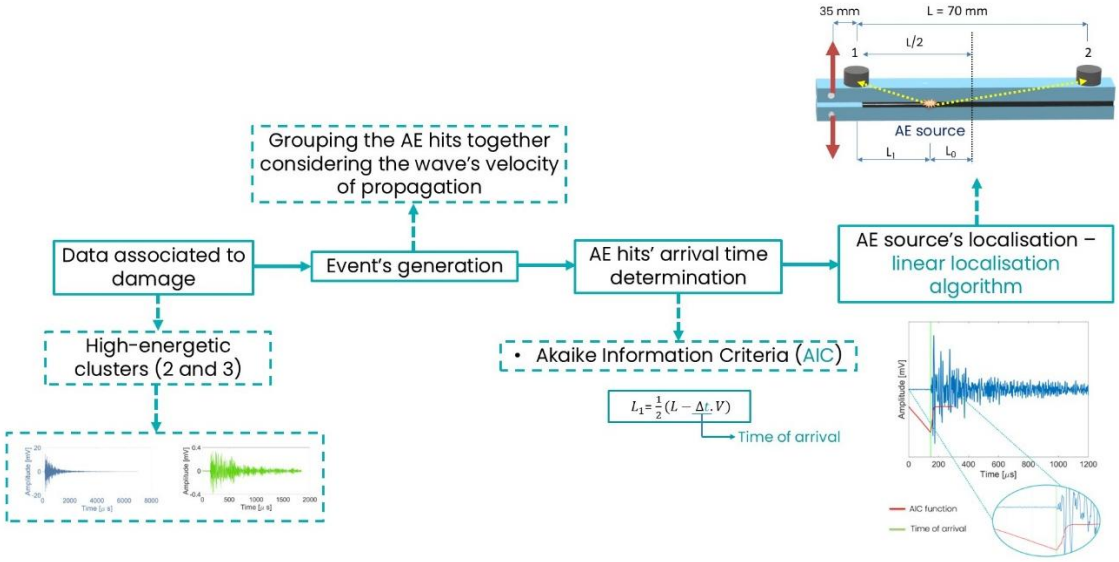


Figure 3: Acoustic emission hits localisation flowchart.

In contrast, K-means clustering partitions the data into k groups by minimizing intra-cluster variance [7]. It iteratively assigns each data point to the nearest centroid and updates the centroid positions until convergence, providing a fast and efficient method for grouping similar signals.

To determine the optimal number of clusters for the K-means algorithm, an indexing criterion was employed, including Davies-Bouldin, Calinski-Harabasz, and Silhouette indexes [8]. This approach helped identify and isolate high-energy clusters indicative of damage events.

Acoustic Emission hits associated with damage events were localized using a linear localisation algorithm, which estimates the source position of each event based on time-of-arrival (ToA) differences across multiple sensors. To ensure accurate ToA detection, the Akaike Information Criterion (AIC) picker was applied [7]. Prior to AIC analysis, each AE waveform was transformed using the Hilbert transform, with a time window set to twice the pre-trigger duration. The AIC function was then computed over this interval, and the onset time of the AE event was identified as the point where the AIC function reaches its minimum. Once ToAs and wave propagation velocity were determined, the source position of each AE event could be precisely localized. The flowchart used to locate the AE hits is detailed in Figure 3.

III. RESULTS AND DISCUSSION

Figure 4 shows the representative load versus displacement curve of co-bonded titanium-composite joints sandblasted, in function of the cumulative energy and acoustic emission hits assessed during the quasi-static mode I fracture tests.

As illustrated in Figure 4, negligible acoustic emission activity is observed prior to the maximum load peak. Upon reaching this peak, a pronounced increase in AE hits occurs, resulting in a steep rise in cumulative energy. This trend indicates the onset of crack propagation and its subsequent development. It is worth noting that around 70000 waveforms were recorded for each specimen, representing a huge amount of data that can be related to damage propagation and background noise.

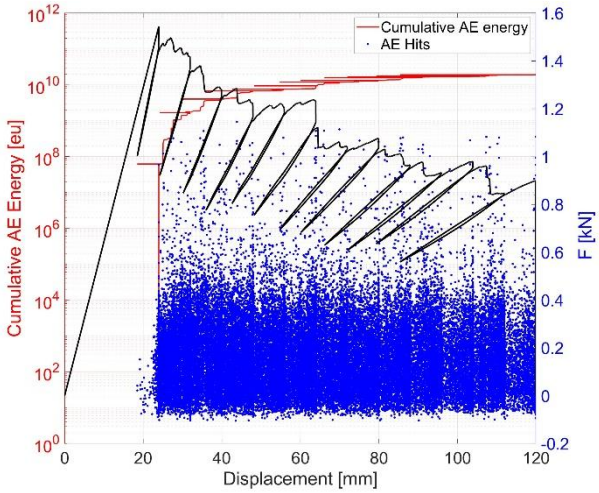


Figure 4: Experimental load versus displacement curve in function of the cumulative energy and hits assessed.

The developed methodologies provided highly accurate crack length measurements and successfully distinguished background noise from damage-related AE signals. The AE features of energy, duration and frequency were used for the dataset clustering process.

High-energy clusters consistently associated with actual damage and fracture events were used for event creation and final source localisation. Figure 5 presents the load–crack length relationship for the co-bonded titanium–composite joint, obtained through visual inspection, the analytical CBBM, and the AE localisation method. The AE localisation results were further classified by energy, amplitude, and duration in an attempt to establish a stronger correlation with the crack length measurements derived experimentally and analytically.

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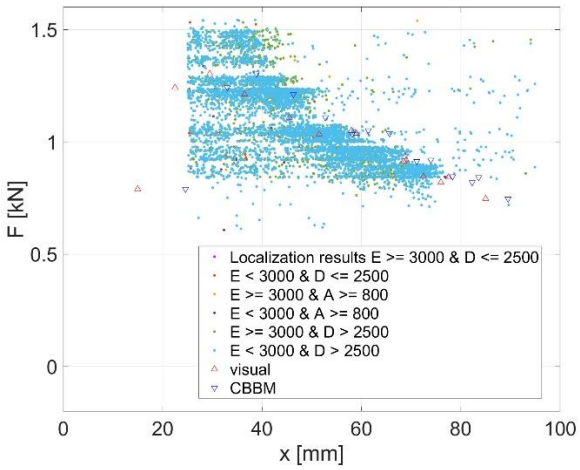


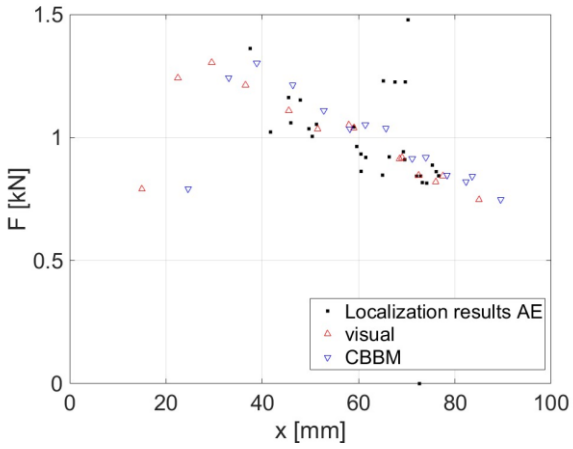
Figure 5: Crack-tip localisation using acoustic emission monitoring results divided by energy, amplitude and duration levels.

As can be observed in Figure 5, the AE located events are scattered and provide a dense cloud of points that reflect continuous monitoring of fracture processes. The high density of points between the visual and CBBM analytical crack length measurements suggest a reasonable correlation between them.

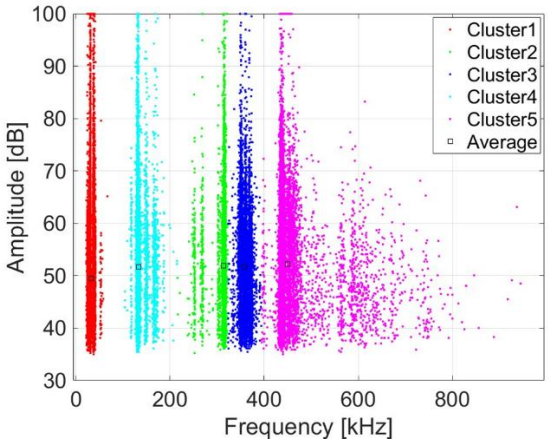
To refine the crack propagation monitoring, an engineering approach was applied by considering only the progressive crack front position. This prevented the inclusion of AE sources located behind the already developed crack or originating from AE reflections.

Linear localisation demonstrated strong agreement between AE-based localisation, analytical calculations, and physical observations, underscoring the accuracy and reliability of the AE methodology in identifying crack positions and lengths, as illustrated in Figure 6(a).

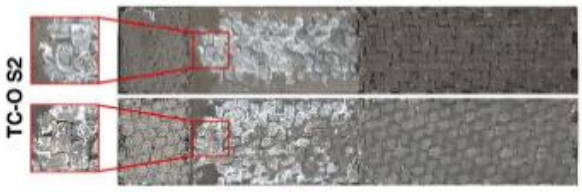
Clustering results from AE analyses clearly illustrate distinct groups that can be potentially associated with damage events and background noise, see Figure 6 (b). As observed in this figure, the groups are main divided in different frequency groups, well-known characteristic of the acoustic emission hits generated in composite materials (i.e. matrix cracking and fiber breaking) [6].



(a)



(b)

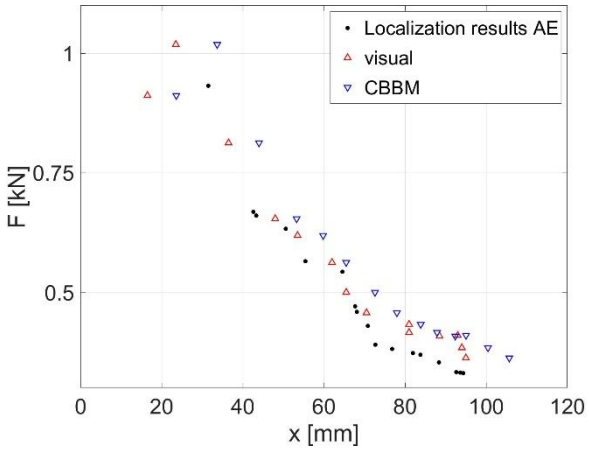


(c)

Figure 6: (a) Crack-tip localisation using acoustic emission monitoring results, (b) clustering of acoustic emission data and (c) fracture surface – co-bonded titanium-composite joints sandblasted.

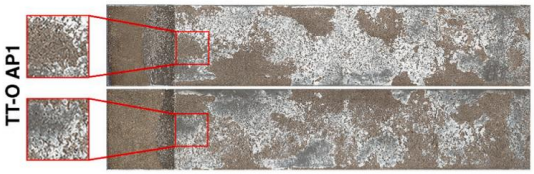
Indeed, drawing attention to Figure 6 (c), the fracture surface of the co-bonded titanium-composite joint presents a mainly cohesive failure at the first half of the specimen, followed by a crack deflection towards the composite substrate first plies.

Figure 7 (a) illustrates the AE hit locations for the secondary-bonded titanium–titanium as-printed joints, while Figure 7 (b) presents the corresponding fracture surface. These results demonstrate that, despite the use of a different bonding technique and substrate materials, the crack development and propagation could still be continuously monitored during the quasi-static DCB tests.



(a)

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(b)

Figure 7: (a) Crack-tip localisation using acoustic emission monitoring results, and (b) fracture surface – as-printed secondary bonded titanium-titanium joints.

A detailed analysis of the AE waveforms confirmed the presence of distinct characteristics linked to crack initiation and propagation phases, enabling robust discrimination between damage-related activity and background noise. These findings confirm the capability of AE monitoring to provide early detection and accurate tracking of crack evolution, thereby reinforcing the accuracy and reliability of the methodology.

Moreover, comparative analyses across different surface treatments and bonding strategies demonstrated substantial effects on fracture resistance. In particular, oxidized substrates and sandblasted surfaces exhibited superior performance, identifying them as optimal approaches for surface preparation in bonded joints. These results highlight the critical role of controlled surface morphology and treatment processes in enhancing joint reliability and extending service life.

IV. CONCLUSIONS

This study demonstrated that integrating AE monitoring with advanced clustering techniques significantly improves the accuracy of crack length measurement in adhesively bonded joints. Linear AE localization showed excellent agreement with visual and analytical methods, confirming its reliability in identifying crack-tip positions and propagation paths. The unsupervised clustering of AE signals enabled robust discrimination between damage events and background noise, while fracture surface observations validated the correspondence between AE waveform characteristics and underlying failure mechanisms.

The methodology proved effective across different material systems (Ti–CFRP and Ti–Ti) and surface treatments, with oxidized and sandblasted substrates showing superior fracture resistance. These findings underline the importance of surface preparation in enhancing joint durability.

Despite the promising results, the following limitations should be mentioned: (a) Limited Geometries and Materials: The dataset is currently constrained to specific geometries (DCB) and material combinations (Ti-Ti and Ti-CFRP). This limits the generalizability of the trained machine learning models across different joint configurations or composite systems; and (b) Sensor Configuration Sensitivity: AE localisation is highly dependent on precise sensor placement and material-specific wave speeds. Any variation in sensor arrangement or bonding defects may affect accuracy.

Therefore, future investigations extending this methodology to dynamic loading scenarios and mixed-mode fracture conditions to evaluate the robustness of AE signal classification under complex stress states would be novel and highly interesting to extend the use of the acoustic emission method in real-world applications. Additionally, expanding the AE database using multiple joint geometries and composite material systems would improve the generalizability of the clustering models and reduce the gap between the scientific knowledge and the industrial application of such methodologies.

ACKNOWLEDGMENT

The authors would like to acknowledge the Marie Curie Postdoctoral Fellowship for the project REVOLUTION_WIND. DOI: 10.3030/101153013. Moreover, a special acknowledgment for the support provided by Bercella Srl and 3 T-Additive manufacturing that kindly offered the materials for this research.

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