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Localisation and identification of fatigue matrix cracking and delamination in a carbon fibre panel by acoustic emission

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ABSTRACT

Background: The use of Acoustic Emission (AE) as a Structural Health Monitoring (SHM) technique is very attractive thanks to its ability to detect not only damage sources in real-time but also to locate them.
Methods: To demonstrate the AE capabilities on known damage modes, a carbon fibre panel was manufactured with cut fibres in a central location and subjected to fatigue loading to promote matrix cracking. Subsequently, a delamination was created within the panel using an impact load, and the test was continued.
Results: AE signals were located within the crack area in the first part of the test. After impact, AE signals were detected from both areas under fatigue loading; signals from this area were located and used for further analysis with the neural network technique.
Conclusions: The application of an unsupervised neural network based classification technique successfully separated two damage mechanisms, related to matrix cracking and delamination. The results obtained allowed a more detailed understanding of such sources of AE in carbon fibre laminates.

1. Introduction

The growing use of composite materials is encouraged by those industrial sectors in search of lightweight materials, which guarantee the same safety levels and reliability as those in traditional metallic structures. A solution is to equip those structures with an on-board sensing technique, capable of detecting damage. This family of techniques goes under the name of Structural Health Monitoring (SHM), comprising all those systems that monitor, either continuously or at specific moments, the health status of a material, giving an indication to the user about damage developing, damage severity and eventually damage location [1].

Such SHM systems, if appropriately designed, will also allow a reduction in the downtime of assets. Planned, inspection-interval based maintenance will no longer be required in favour of an on-demand maintenance programme. Safety critical structures, such as off-shore wind turbines or aircrafts, will receive the most benefit from this approach to monitoring, since their maintenance downtime represents a large part of their operative cost.

Among the SHM techniques being investigated at the moment, Acoustic Emission (AE) is considered to be a good candidate [2]. AE is based on the observation that materials, when undergoing some type of damage, release energy in the form of short, transient elastic waves in the ultrasound band (100 kHz–1000 kHz). These waves propagate in the structure through the material's bulk and surface, and eventually dissipate due to various phenomena. These waves can be recorded by means of appropriate sensors, usually of the piezoelectric type [3].

AE is classified as a passive Non Destructive Technique (NDT): it does not require signals to be emitted (i.e. to introduce energy in the structure) to detect damage. Instead, it waits for signals to be recorded; those signals originate inside the material by some damage or energy release process. This is a major advantage of AE, as it does not require continuous scanning of the structure or the continuous recording of data in search of a potential defect. This is however also a downside, because it does not provide information about a structure when it is not loaded, unlike other NDTs (like radiography or ultrasound). In other words, the source must be active to be detected; unstressed flaws will not generate AE.

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There are several sources of AE. In metallic structures, AE can arise from crack propagation and plastic deformation [4], as well as from non-detrimental phenomena such as friction and bonding relative movement. Spurious noise sources from parts that are acoustically connected are also a concern. In composite structures, AE sources are associated with the main failure modes of those materials: fibre breakage, matrix cracking, fibre pull-out and delamination [5]. An in-depth analysis of these AE events can lead to source type identification based on waveform characteristics; this is the subject of current extensive research [6]. Especially in composite materials, AE has proved to offer interesting indications to researchers about the development of damage. Static tests, but also fatigue tests [7–9], crack propagation, bond strength tests [10], residual strength tests [11] and many others have benefited from AE monitoring.

For all these applications, the necessity to identify different AE sources emerges. The main concern is to learn how to assess whether and when a specific failure mode occurs in a material; such research is usually aimed at increasing the knowledge regarding failure modes of materials or structures and is directed towards the development of better damage models.

One of the advantages of AE is its ability to localise damage sources by using multiple sensors (three or more for localisation on a plane [3]). Common planar location algorithms usually consider a uniform velocity in the whole plane; then, based on the time of arrival (ToA) of the waveforms, they compute the position by intersection of hyperbolas between sensor pairs. This algorithm is robust for homogeneous materials, provided that the waveforms ToA is computed correctly and the velocity is known with an adequate precision. However, in anisotropic materials, such as Carbon Fibre Reinforced Polymers (CFRP), the wave velocity depends on the orientation of the wavepath with respect to the ply orientation. This makes the ToA technique prone to errors. Moreover, local features (such as material's local inhomogeneities and discontinuities) add uncertainty to the problem. To overcome this issue, a technique called Delta-T was developed [12,13]. Delta-T utilises user-generated maps of ToA differences between sensors, without defining a wave velocity but with the help of a calibration grid. A HSU-Nielsen source [14] is generated at each grid point; subsequently, for each sensor pair, a ToA difference map is computed. The location algorithm then, when receiving a waveform (or, more specifically, the sensor pairs ToA differences) looks up each Delta-T map and identifies the source location. This technique proved to be more accurate than the ToA method in a number of test cases [15].

Commercial AE systems already provide some sort of data compression, by encoding the information contained in each waveform into different parameters, such as peak amplitude, frequency content, duration, energy and some others. Moreover, these parameters are thought to be linked to the kind of damage source that originated the signal. For SHM based on AE, this feature would be helpful because it provides information not only on the event localisation, but also on the activity of specific damage modes.

In composite materials, AE can be generated in a number of ways; the main failure modes include matrix cracking, fibre-matrix debonding, fibre fracture and delaminations. There are differences in the nature of the AE signals due to the source type; this is mainly due to the in-plane or out-of-plane energy content. It is known that matrix cracking and fibre breakage initiate mostly in-plane phenomena and generate extensional waves of higher frequency, while delaminations are dominated by flexural waves of lower frequency [16].

In a delamination, the laminate separates at the interface between two layers, in some cases without indications on the surface (for example, some impacts, although not visible from the impacted surface, may hide large delaminations). Some authors suggest delaminations give rise to high amplitude signals [17], while others point out medium amplitude signals for a $\pm 45^{\circ}$ laminate [18]; authors generally agree on delamination signals having in general a long duration [19], but tend to include debonding within the same classification.

Matrix cracking generally occurs between fibres at the fibre-matrix interface, or as shear failures between plies. These types of matrix failures usually cause hackles, which are visible on the surface. Results have been found to be dependent on material and testing procedure, with some agreement on defining matrix cracking AE as mid-to-high amplitude and low frequency [20], but some studies report low amplitude [17,18,21] and medium frequency [22] fast decay [23] but also slow decay [24].

Finally during loading, some fibres fail in tension. The expected AE signature is an abrupt energy release mechanisms, with high amplitude and fast rise time [18], as it would happen in a brittle crack phenomenon.

As discussed, early approaches based the classification of damage mechanisms on a single AE parameter, typically peak amplitude or frequency content. When trying to overcome some issues, mainly related to signal attenuation as a function of distance, multiple parameters at once have been considered [21,25]. Due to the high amount of data to be processed and difficulties in identifying patterns with traditional statistical techniques, machine

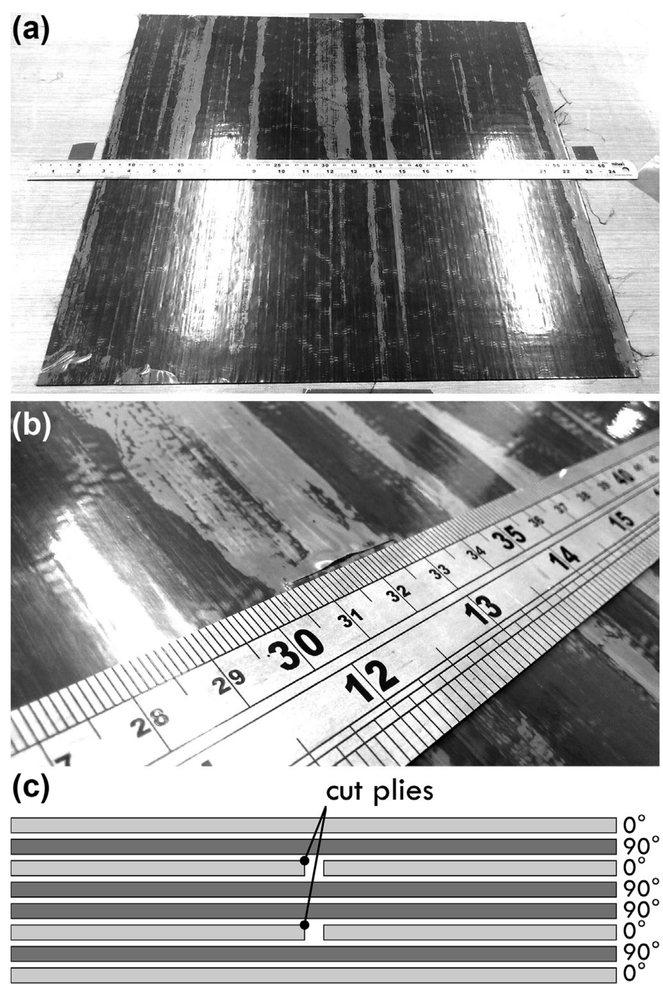

Fig. 1. CFRP panel during layup of the inner plies: entire panel (a), detail of the cut (b) and cut plies schematic (c).