DEFECT QUANTIFICATION IN 3D ANGLE INTERLOCK GLASS FIBRE COMPOSITES USING ACOUSTIC EMISSION

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Abstract
In addition to manufacturing cost and production rates, damage tolerance has become a major issue for the composites industry. Three-dimensional (3D) woven composites have superior through-thickness properties compared to two-dimensional (2D) laminate, for example, improved impact damage tolerance, high interlaminar fracture toughness and reduced notch sensitivity. The performance of 3D woven preforms is dependent on the fabric architecture which is determined by the binding pattern. Different combinations of 3D woven preforms can be produced given the variation of the binding pattern. They can be classified into angle interlock and orthogonal interlock according to the binder orientation, or through-the-thickness and layer-to-layer if the penetration depth of binders is involved.

For this study, angle interlock (AI) structures with through-thickness and layer-to-layer binding were manufactured. Monitoring of acoustic emission (AE) during mechanical loading is an effective and widely used tool in the study of damage processes in glass fiber-reinforced composites. Tests were performed with piezoelectric sensors bonded on a tensile specimen acting as passive receivers of AE signals. A new set of experimental data has been generated which will be useful for validating multi-physics numerical models, providing insight into the damage behaviour of novel 3D AI glass fibre composites, and may ultimately lead to more effective material selection and determination of design limits. The paper finishes with conclusions and suggestions for further work.

1 INTRODUCTION

It is a big challenge to relate acoustic emission (AE) signal events to specific damage modes developed in composite materials under hygro-thermo-mechanical loading. This study provides further insight into the AE monitoring of a 3D angle interlock (AI) glass fibre composite and has revealed the complex nature of the relationship between the principal characteristics of recorded AE events on the one hand and the mechanical behaviour of the material on the other.

Monitoring of acoustic emission (AE) during mechanical loading is an effective and widely

used tool in the study of damage processes in glass fiber-reinforced composites. This study provides further insight into the AE monitoring of 3D AI glass fibre composites. Tests were performed with piezoelectric sensors bonded on a tensile specimen acting as passive receivers of AE signals. These signals are carefully analysed to identify resin cracks in the warp yarn and relate to crack density. The paper finishes with discussion and suggestions for near future work.

1.1 Acoustic emission in composite materials

AE is a passive SHM technique that can be used for many applications. When crack grows, energy is released at the crack tip in form of waves. AE sensors can be used to measure these waves. Several sensors in combination can be used to estimate the severity of the crack and its location. Most publications show results from fatigue cracks in bulk materials and qualitative results from real structures. However, there is limited literature presenting quantitative results from plate-like structures and a lot of the experiments are based on simulated AE sources, e.g., pencil lead breaks [1]. One aim of this paper is to analyse the elastic waves generated from transverse cracks (TC) in a 3D angle interlock composite structures subjected to tensile loading.

The AE method allows the detection and location of damage using specific localisation algorithms. Knowledge of the propagation velocity and attenuation of the AE wave is required. However, contrary to metallic material, the anisotropic nature of composite material gives a large range of propagation velocity due to fibre orientation. Moreover, the attenuation of the AE waves is more complex than in a homogeneous material [2]. In addition, in a same composite material, wave attenuation is more significant in cracked than in healthy state, which will complicate the signal processing after few damage modes have developed, especially for the amplitude distribution. Qualifying damage started first in 2D composites and Mehan and Mullin in 1968 [3] managed to identify three basic failure mechanisms: (i) fiber fracture; (ii) matrix cracking; (iii) and fibre/matrix interfacial debonding. The authors reported the application of AE in composites in 1971 [4], discriminating audible types for these three basic damage modes using an AE system. After forty years, Godin et al. [5] conducted mapping of cross-ply glass/epoxy composites during tensile tests. They have classified four different acoustic signatures of failure and determined four conventional analyses of AE signals as depicted in Figure 1.
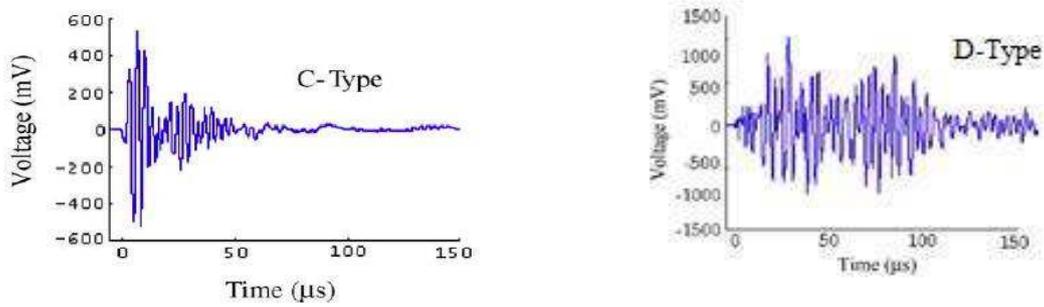

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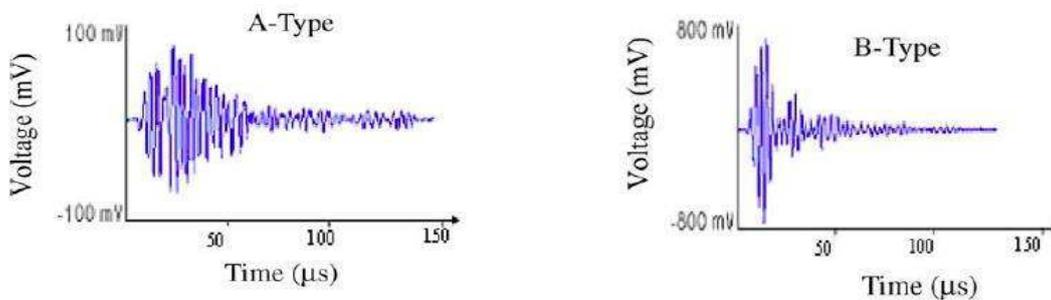
Figure 1: Typical waveforms collected during tensile tests of a glass/epoxy composite: A, B, C, D-types associated with matrix cracking, interface debonding, fibre failure, delamination, respectively [5].

Typical waveforms with A-Type (slow increase times at about 10-20 µs) signals associated with matrix cracking, B-Type (sharp rising, lasted for 10 µs and abruptly decreasing) with fibre/matrix interface de-bonding, C-Type associated with fibre failure, and D-Type (long rising times, high amplitudes, and very long durations) with delamination [5]. The most popular methods to identify damage are identification by signal amplitude distribution (signal strength) and by signal frequency and has been reviewed in a previous study [6].

This study showed the difficulty of identifying damage modes for 2D composites and becomes more complicated for 3D woven composites. Only a small number of investigations has been reported for monitoring evolution of damage and ultimate failure in 3D woven composites. Li et al. [7] studied AE signals for 3D non-crimp orthogonal woven glass/epoxy composites from cluster analysis point of view. These clusters are based on different parameters of peak amplitude, peak frequency, and RA value (rise time divided by peak amplitude). From their investigation, cluster 1 (low frequency, low amplitude events) and 2 (moderate frequency, low amplitude) is correlated to matrix cracking, cluster 3 (low to moderate frequency with high amplitude) with fibre and matrix de-bonding, and cluster 4 (high frequency) with delamination and fibre breakage. Lomov et al. [8] investigated AE response in 3D non-crimp orthogonal woven carbon/epoxy composites undergone damage.

1.2 Guided waves

Guided waves are very widespread in structural health monitoring (SHM) applications: Guided waves are important for SHM applications because they have the ability to travel without much energy loss over large areas. This property makes them well suited for ultrasonic inspection of bridges, aircraft, ships, missiles, pressure vessels, pipelines, etc. In plates, ultrasonic guided waves propagate as Lamb waves and as shear horizontal waves (SH). Ultrasonic guided waves in plates were first described by Lamb (1917). A detailed study of Lamb waves has been given by Viktorov [9], Achenbach [10], Graff [11], Rose [12] and Dieulesaint and Royer [13]. Lamb waves are of two varieties, symmetric modes (S) and anti-symmetric modes (A). At low values of the frequency-thickness product, fd , the fundamental symmetric mode, S0, is similar to axial waves whereas the fundamental anti-symmetric mode, A0, looks like flexural waves. Work has been done to establish analytically the dispersion curves in isotropic plates [13, 14], to validate the results experimentally and to study the effect of dispersion over long distances [15]. Lamb wave propagation was used by many authors [16-18] using piezoelectric disks as transmitters and receivers to measure the changes in the signal received from a structure having a defect. However, the signal processing is complex due to multiple reflections. Today the majority of work concerns the propagation of Lamb waves in thin isotropic structures. For this reason it is very important to study the Lamb wave

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propagation from an acoustic emission point of view in 3D composite materials to understand the difficulties in analysing these waves in order to be able to qualify and quantify the defects in such structural configurations.

2 MATERIALS PRESENTATIONS AND EXPERIMENTAL SET-UP

In this study, a 3D angle interlock (AI) S2 glass woven composite plate with through-thickness binding was infused using bi-functional epoxy resin (LY564) and hardener (XB3486) supplied by Huntsman. In the AI configuration, the binder goes all the way through-the-thickness and then returns back. According to the binding pattern, shown in Figure 2, one binder yarn is inserted after every three layers of weft (yarn). This structure consists of 4 layers of warp (fibres parallel to weaving direction or at 0º) and 3 layers of weft (fibres transverse to weaving direction or at 90º), which are held together by the binders (through-thickness fibres) inserted in the weft direction at regular intervals as illustrated in Figure 2.

Figure 2: 3D Angle Interlock Woven Composite (through thickness and planar view) (orange: weft; black: warp; green: binder yarn) (Binder yarn goes all the way through-the-thickness and then returns back).

Tensile testing was carried out according to ASTM standard D3039, on specimens 250 mm long and 25 mm wide. The tensile load was applied in the weft direction. A non-contact video extensometer was used to measure the strain developed while the specimen was loaded in an Instron 5982 R2680 testing machine. Three piezoelectric wafer active sensors (PWAS) bonded on the specimen were acting as AE receivers. To develop only transverse cracks, the specimen was loaded up to 20% of its ultimate strength (σ_f). During loading, AE signals were recorded and the PWAS were able to pick up AE signal of good strength at a frequency range 100–700 kHz. The acquisition of the signals was performed using software 'AEWin' from Mistras with a sampling rate of 10 MHz and 20 dB pre-amplification.

3 AE SIMULATION

Simulation of AE was realised using the ABAQUS/implicit software which has multi-physics piezoelectric elements. FEM modelling was used to simulate the elastic wave emitted by the transverse crack growth. These can be used to compare with the results obtained from the experiment. The ABAQUS model is shown in Figure 3. Eight nodes linear piezoelectric brick elements were used to simulate the PWAS. Implicit solver methods of solution are used in order to simulate the real voltage/amplitude received signal [19]. The use of multi-physics finite element method (MP-FEM) is explored to model the reception of the elastic wave as electric signal recorded at a PWAS receiver (R-PWAS). The piezoelectric material properties were assigned to the PWAS as described in ref [20]. PWAS has a density of $\rho = 7600$ kg.m^{-3} diameter of 7 mm, and thickness of 500 μm. The Rayleigh damping used in the simulation is from ref [2]. To simulate the energy released by the transverse crack a two-point source force was applied between PWAS#1 and PWAS#2.
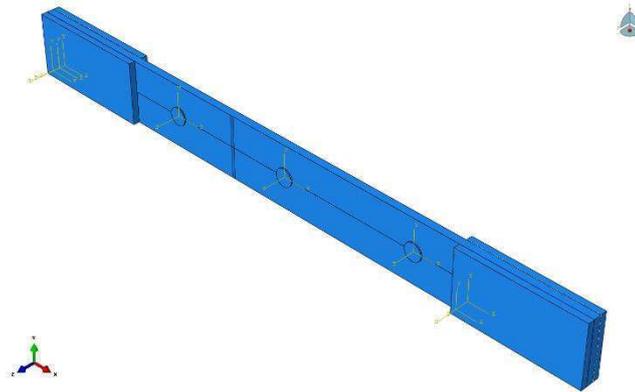
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Figure 3: ABAQUS model of the 3D woven composite with 3 PWAS bonded on the top to record the AE events from the simulated transverse crack.

4 RESULSTS AND DISCUSSION

4.1 Multi-physics finite element simulation

Figure 4 shows image snapshots of overall displacement amplitude of the guided wave pattern in the plate taken at 10-μs intervals. Multiple guided waves modes are present. At $t = 10\,\mu s$, one sees the waves just starting from the transverse crack. By $t = 20\,\mu s$, most of the wave has already being reflected from the edges of the tensile specimen.
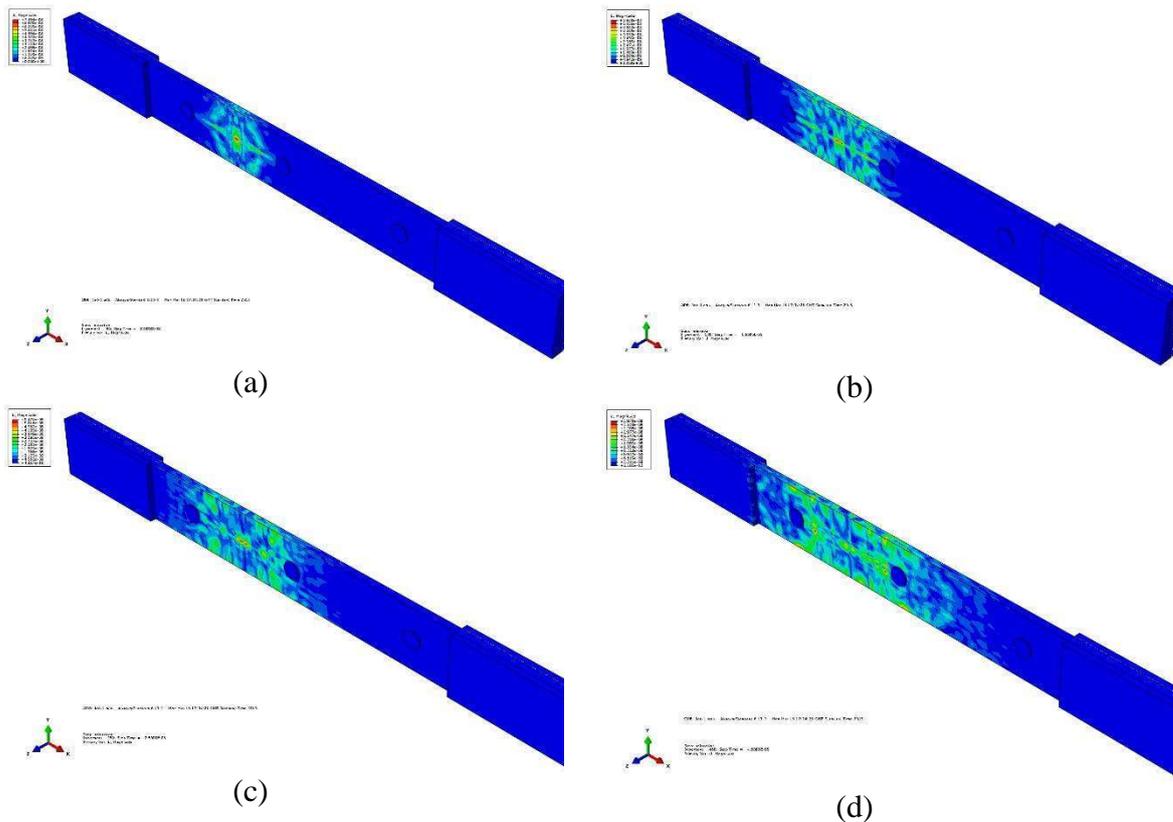

(a)

(b)

(c)

(d)

Figure 4: Snapshot of the MP-FEM simulation of guided waves generated by a pair of point forces simulating an AE by the transverse crack in a 3D AI composite tensile specimen at (a) 10μs; (b) 20μs; (c) 30μs; (d) 40μs.

The simulated AE signal caused by the simulated transverse crack excitation as captured at

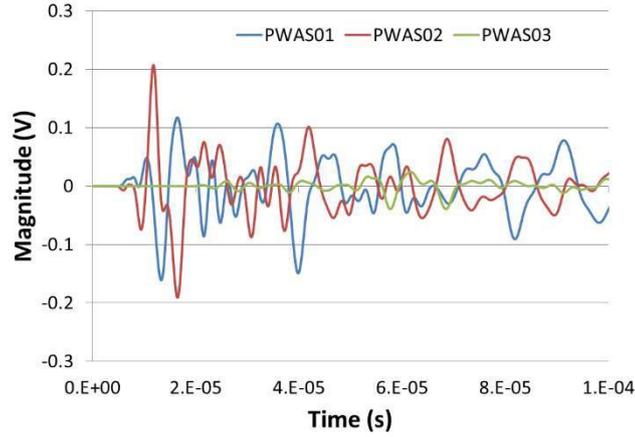PWAS#1, 2, and 3 are shown in Figure 5.

Figure 5: Received signal: Output voltage against time for PWAS#01, 02, and 03.

To better understand these signals, the discrete wavelet transform (DWT) is used. The DWT of a time signal s(t) is the result of the convolution product between the signal s(t) and a family of "daughter wavelets" $\gamma_{m,k}(t)$, $DWT_{m,k} = \int_0^\infty s(t)\gamma_{m,k}(t)dt$. The main particularity of the DWT is that the result obtained with each daughter wavelet corresponds to the time behaviour of the signal in a frequency band corresponding to dilatation factor m. Each response is called the decomposition level. A number of different bases have been proposed to construct a family of wavelets. A good solution for analysis and decomposition can be obtained with the Morlet wavelet. The application of discrete wavelet analysis to the acquired AE signals resulted in its decomposition into six different levels. Each level represents a specific frequency range, and the frequency range increases with increasing wavelet level.

The decomposed AE signals in level 1 to 5 are shown in Figure 6 for the PWAS#01. The Fourier spectrum of the Figure 6 signals is shown in Figure 7. The frequency spectra for DWT levels 1 through 5 are centered at about 68 kHz, 120 kHz, 200 kHz, 340 kHz, and 650 kHz, respectively. At frequencies 68 kHz, 120 kHz, and 200 kHz (Morlet wavelet levels 1, 2, and 3), three modes exist, the fundamental symmetric mode (S0), the fundamental anti-symmetric mode (A0), and the fundamental shear mode (SH0). However, with the PWAS receiver geometry and properties, the SH mode cannot be caught by these sensors [2]. Moreover, analysing the tuning curves (not in this paper), at 68 kHz the amplitude of the A0 mode is much higher than the S0 mode, and its travel speed is slower. At 120 kHz, the amplitude of A0 and S0 are almost the same, and at 200 kHz, the amplitude of the S0 is much higher than the A0. To conclude, the component at low frequency (below 120 kHz) is dominated by the fundamental anti-symmetric mode A0. At 340 kHz (Morlet wavelet level 4), four modes exist, S0, A0, A1 and S1; at 650 kHz (Morlet wavelet level 5), six modes exist, S0, S1, S2, A0, A1, and A2. So at these frequencies, the distinction of the different wave packets and the signal processing are very complex. Moreover, the amplitude is distributed such that it is the highest in level 1 and lowest in level 5 as shown in Figure 6. The FFT of the original signal shows that the amplitude of the signal is higher for the frequency lower than 160 kHz, which mean that the transverse crack develop more flexural (i.e. A0) than extensional (i.e. S0) motion.
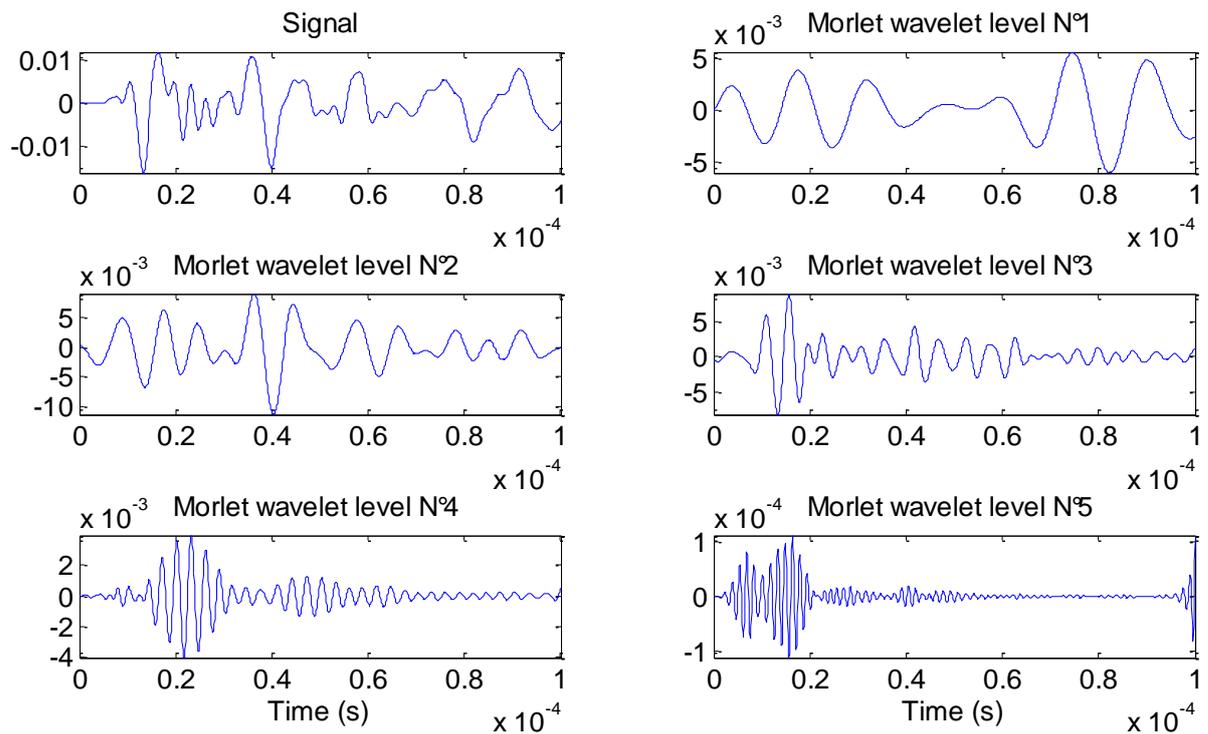
Figure 6: Discrete wavelet transform of the simulated signal received by the PWAS#1.
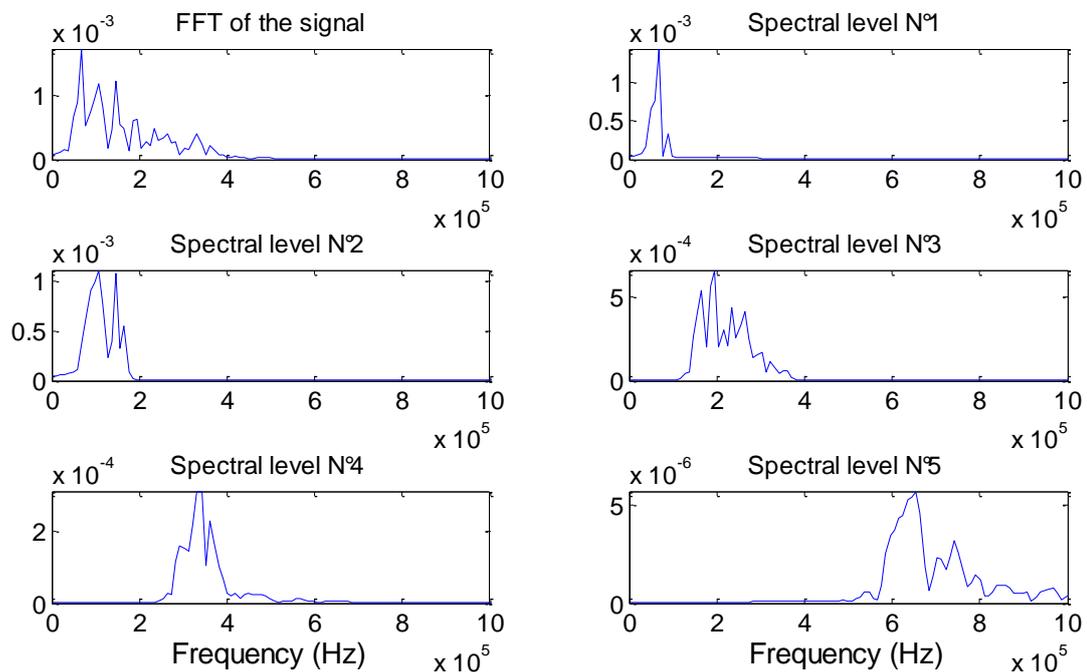

Figure 7: Frequency spectra for the different wavelet level (PWAS#1).

4.2 Experiments

As mentioned in our preliminary work [6], at this applied tensile load only transverse cracking occurs in the studied specimen. Figure 8 shows typical AE waveforms received by the PWAS#1, #2, and #3, and the associated Fourier transform.
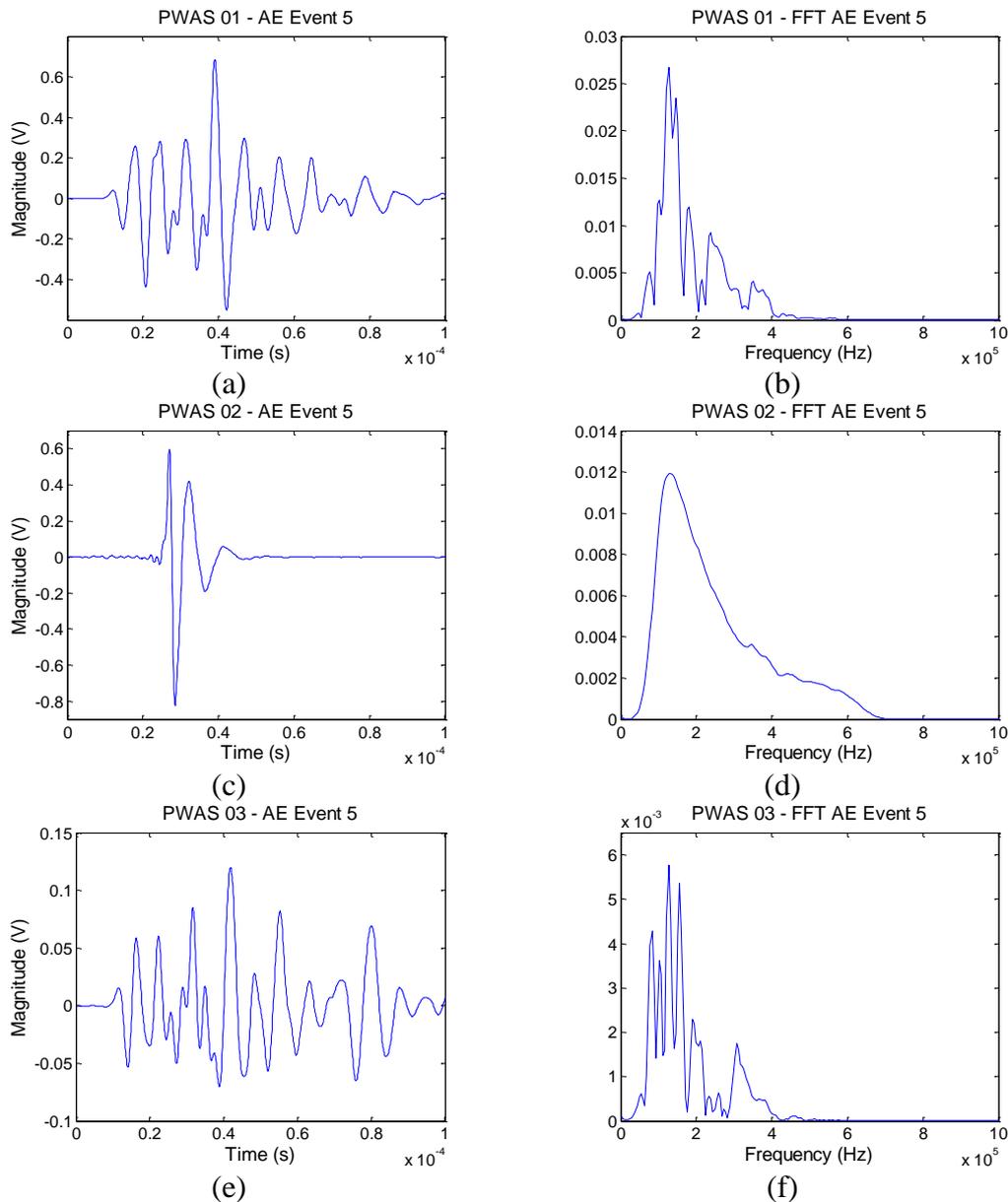
Figure 8: Typical AE waveforms and Fourier Transform from a transverse crack in 3DAI recorded from (a, b) PWAS#1; (c, d) PWAS#2; (e, f) PWAS#3.

In this particular example, the transverse crack occurs closer to PWAS#2 than the other sensors. This signal looks sharper and stronger than those obtained by PWAS#1 and #3. Masmoudi et al. [21] classified this very energetic signals with amplitude above 94 dB to fibre breaking. However, in our case no fibre breakage occurs, only the transverse crack in the warp yarn develops as previously simulated. The amplitudes of this particular events are 96, 98, 81 dB for PWAS#1, #2, and #3, respectively. The amplitude decreases with the travel length due to the high damping coefficient in this 3DAI composite materials. Moreover, the frequency components of these signals show clearly two major components, the first one between 70 to 180 kHz and the second one between 200 to 400 kHz for PWAS#1 and #3. Moreover, a third component is present between 400 to 600 kHz for PWAS#2. The high frequency and the low frequency component correspond to the wave's extensional mode S0 and to the flexural mode

A0, respectively, as showed in the MP-FEM simulation. This flexural mode A0 has higher amplitude than the extensional mode. It seems that the transverse cracks generate more flexural motion than extensional motion. This presence of a flexural mode would indicate that the crack does not develop symmetrically about the mid-plane of the 3D AI laminate. Moreover, the amplitude for each AE events is between 60 to 100 dB. The signals with lower amplitude were assimilated into noise.

The results shown earlier have proven that transverse matrix cracking signals do exhibit a clear flexural mode. In most cases, however, the extensional mode was also clearly present. For the transverse matrix crack signals this is caused by their asymmetric growth through the thickness. Matrix cracks most often initiate at one of the outer plies and grow through the thickness to the other side of the specimen. These results in a particle motion which is in plane, but asymmetric about the mid-plane, thus resulting in a flexural mode. The large flexural mode observed during this test can be explained by the same principle: transverse cracks will occur preferably in the zone of maximum tensile stress. AE waves generated there will thus cause an in plane motion, but the motion will be asymmetric about the mid-plane. This will again result in a flexural component.

5 CONCLUSION

Transverse crack in the warp yarn was detected and quantified in a 3D angle interlock woven glass composite plate during a tensile test using piezoelectric wafer active sensors bonded on the surface of the sample. AE simulation has been conducted with the MP-FEM approach. The AE event was simulated as a pulse of defined duration and amplitude. The simulated electrical signal was measured at a receiver PWAS using the MP-FEM capability with the piezoelectric element. Morlet wavelet transforms and their FFT frequencies were used to process the signal in order to define and separate the different modes that composed the AE signal. These results show that the amplitude of the AE signal depends on the distance between the crack and the sensor (affected by damping). A complete study on the guided wave propagation and the attenuation effect is required in order to increase the accuracy of the results. Moreover, for our materials the amplitude of the AE signal form this transverse crack is between 60 and 100 dB. The frequency component with the highest amplitude is between 100 to 200 kHz.

Although some good progress has been demonstrated, there are still some outstanding questions which need to be answered. A complete experimental research program and a MP-FEM method need to be fully performed in order to better understand the damage evolution (that includes multiple matrix cracks, delamination, and fibre breakage) and ultimate failure of these 3D AI glass composite plates.

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