Acoustic Emission of 3D Angle Interlock Glass Fibre Composites

COVER SHEET

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ABSTRACT

It is a big challenge to relate acoustic emission (AE) signal events to specific damage modes developed in composites 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. Because the tested material here is transparent, the development of cracks can be observed in-situ during the test using optical images on the specimen. This paper presents experimental results on the use of AE on 3D AI glass fibre composites for structural health monitoring (SHM) of matrix cracks, during quasi-static tension of flat plates.

INTRODUCTION

Fibre-reinforced composite materials are used extensively in the aerospace industry because of their light weight, superior corrosion resistance and improved fatigue properties when compared to metals. However, the manufacturing costs, production rates and damage tolerance are current challenges faced by the composite industry. Three-dimensional (3D) woven composites have better through-the-thickness properties in comparison to two-dimensional (2D) laminates; they show improved impact damage tolerance, high inter-laminar fracture toughness and reduced notch sensitivity. 3D fabrics were introduced to produce structural composites capable of withstanding multidirectional stresses.

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 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.

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Tests were performed with piezoelectric wafer active sensors (PWAS) bonded on a tensile specimen acting as passive receivers of AE signals. The paper finishes with conclusions and suggestions for further work.

DAMAGE MONITORED BY ACOUSTIC EMISSION

The acoustic emission (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 [1]. 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 [2] 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 [3], discriminating audible types for these three basic damage modes using an AE system. After forty years, Godin et al. [4] 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. 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 [4]. The most popular methods to identify damage are identification by signal amplitude distribution (signal strength) and by signal frequency. TABLE I and TABLE II show a comparison between the amplitude and the frequency distribution model that were encountered in the literature.

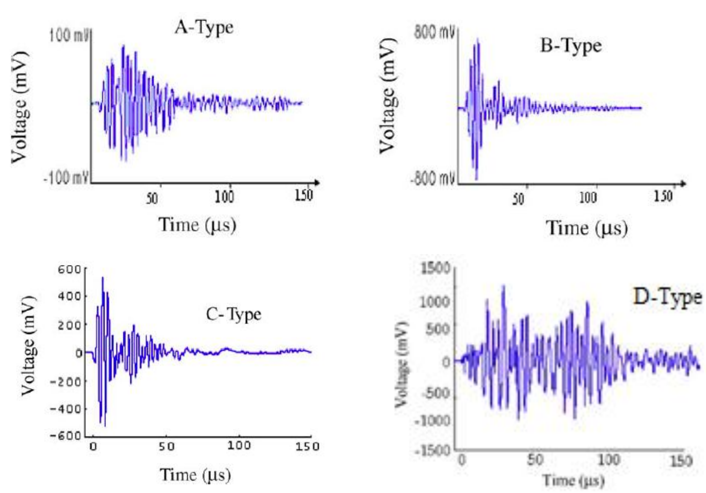


Figure 1: Typical waveforms collected during tensile tests on glass composite: A, B, C, D-types associated with matrix cracking, interface debonding, fibre failure, delamination, respectively [4].

TABLE I: AMPLITUDE DISTRIBUTION ACCORDING TO THE DAMAGE MECHANISM IN COMPOSITE MATERIALS.

Ref.	Matrix cracking	Interface decohesion (fibre/matrix)	Fibre/matrix friction and fibres pull-out	Fibres breakage
[5]	30-45 dB	45-55 dB	--	>55 dB
[6]	60-80 dB	70-90 dB	--	--
[7]	50 dB	--	--	--
[8]	40-70 dB	--	--	60-100 dB
[9]	40-55 dB	--	>80 dB	--
[10]	33-45 dB	50-68 dB	69-86 dB	87-100 dB
[11]	40-78 dB	72-100 dB	--	95-100 dB
[12]	40-55 dB	60-65 dB	65-85 dB	85-95 dB
[4]	35-80 dB	50-80 dB	70-100 dB	--
[13]	<70 dB	<60 dB	--	--
[14]	35-55 dB	55-100 dB	--	35-80 dB
[15]	40-60 dB	50-70 dB	80-100 dB	80-100 dB

All of these studies show the difficulty of identifying damage modes for 2D composites and becomes more complicated for 3D woven composites. Only a small amount of studies has been reported for monitoring evolution of damage and ultimate failure in 3D woven composites. Li et al. [14] 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. [16] investigated AE response in 3D non-crimp orthogonal woven carbon/epoxy composites undergone damage.

However, identifying cracking in the matrix or fibre in addition to delamination need to be investigated further if AE is to be used as an inspection tool in SHM of 3D woven composites. Hence, the present study (qualitative and quantitative) of 3D angle-interlock woven composite damages using AE piezoelectric sensors is undertaken. As these structural woven fabrics are attracting the attention of the aerospace industry, the monitoring of initiation and progression of transverse matrix cracking is of considerable interest and importance, since they can lead to delamination and fibre breakage, which result to ultimate failure.

TABLE II: FREQUENCY DISTRIBUTION ACCORDING TO THE DAMAGE MECHANISMS IN COMPOSITE MATERIALS.

Ref.	Matrix cracking	Interface decohesion (fibre/matrix)	Fibre/matrix friction and fibres pull-out	Fibres breakage
[17]	50-150 kHz	--	--	140-180 kHz
[18]	30-150 kHz	30-100 kHz	180-290 kHz	300-400 kHz
[19]	80-130 kHz	--	250-410 kHz	250-410 kHz
[13]	~ 300 kHz	--	300 kHz	>500 kHz
[20]	50-180 kHz	220-300 kHz	180-220 kHz	>300 kHz
[21]	90-110 kHz	--	200-300 kHz	> 420 kHz
[22]	<50 kHz	200-300 kHz	500-600 kHz	400-500 kHz
[23]	~ 140 kHz	~300 kHz	--	~ 405 kHz
[24]	200-600 kHz	200-350 kHz	0.7-1.1 MHz	>1.5 MHz
[14]	50-80 kHz	50-150 kHz	--	150-500 kHz

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 described in Figure 2.

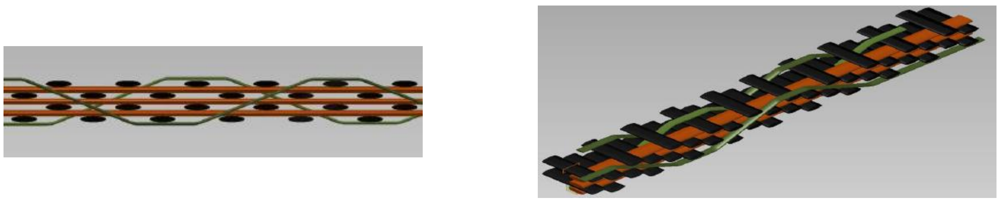


Figure 2: 3D Angle Interlock Woven Composite (front and perspective view) (orange: weft; black: warp; green: binder yarn) (Binder yarn goes all the way through-the-thickness and then returns back).

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, Figure 3. To develop only transverse cracks, the specimen was loaded up to 20% of its ultimate strength (σ_f). During loading, acoustic emission 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. The AE PWAS sensors used in this study were provided by Steminc, further details in [25].

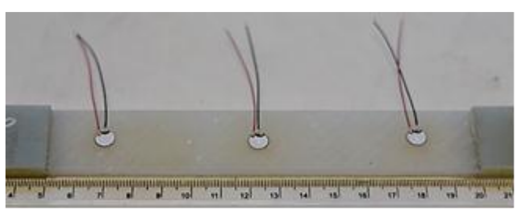


Figure 3: (a) PWAS bonded on a 3D angle interlock glass fibre tensile specimen for acoustic emission.

ANGLE INTERLOCK CRACKING SIMULATION

In the analysis, the 3D Angle Interlock Woven Composite (3DAWC) (Figure 2) is modelled as a (0/90) cross-ply laminate since the crimp mostly occurs at the interlacement points between the weft and binder yarns. In order to check the effect of this simplification on the in-plane properties of the 3DAWC, analytical homogenization technique "orientation averaging model" is used to calculate approximately the elastic material properties [26] and compare it with the experimental data obtained. As shown in Table III, good agreement between the experimental and analytical model is obtained while the last column represents the difference between the calculated values with and without the binder yarns. A larger impact of the through-the-thickness reinforcement is expected on the interlaminar fracture toughness rather than in-plane stiffness properties. An almost 14% increase in E_{33} modulus is predicted when the binder yarns are considered in the analysis.

TABLE III: ELASTIC MATERIAL PROPERTIES OF 3DAWC

	Experiment	With Binder	Without Binder	Difference (%)
E_1	18.52 ± 0.87	17.85	17.33	2.91
E_2	24.83 ± 1.51	24.00	23.48	2.16
E_3	--	12.74	11.00	13.65
G_{12}	--	5.18	4.95	4.50
ν_{12}	--	0.31	0.32	0.68
V_F(%)	$V_F = 50.35 \pm 0.26$; $V_F(\text{warp}) = 31.21 \pm 0.26$; $V_F(\text{weft}) = 15.38 \pm 0.36$; $V_F(\text{binder}) = 3.05 \pm 0.33$			

To determine which constituent part of the 3D woven will experience cracking in the case of uniaxial tension, strain energy density components are calculated for the 3DAWC unit cell when applying 1% strain along the weft direction. The finite element model is run using the COMSOL Multi-physics software package.

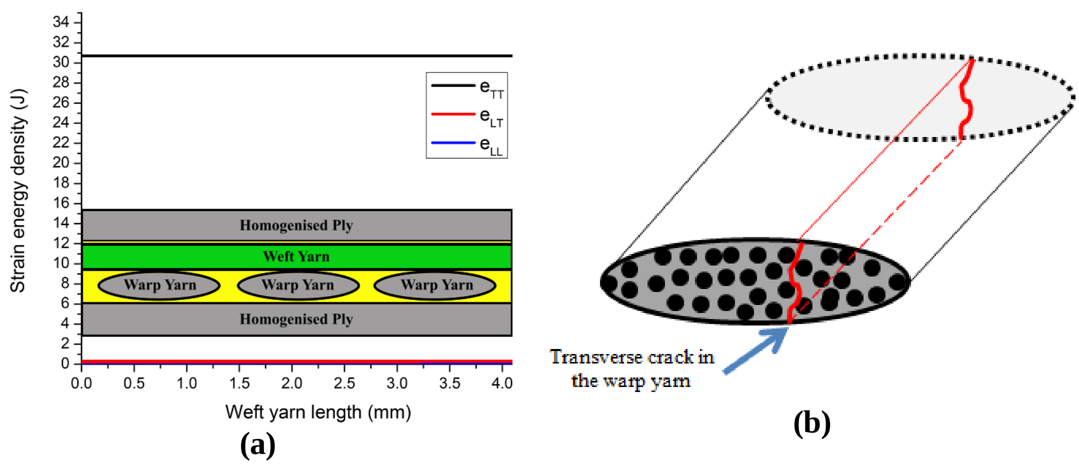


Figure 4: (a) Strain energy release rate along weft yarn (TT: Transverse component; LT: shear component; LL: axial component); (b) crack on a warp yarn cross section (Transverse crack).

Figure 4 shows that the transverse component e_{TT} of the strain energy density is the highest when compared to the longitudinal e_{LL} and shear e_{LT} components. This implies that the strain energy release rate for the transverse component is the one that leads to matrix cracking in the weft yarn under this loading condition. In addition, having a constant energy release rate along the whole yarn length, it suggests that there is no preferable location within the yarn for the crack to start from. This also means that once a crack is initiated in the yarn, it grows instantaneously through the thickness and along the whole yarn length.

RESULTS AND DISCUSSIONS

As mentioned in the previous section, at this applied load only transverse cracking occurs in the studied specimen. Figure 5 shows typical AE waveforms received by the

PWAS#1, #2, and #3, and the associated Fourier transform. 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. [11] 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, which 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 100 to 200 kHz and the second one between 250 and 400 kHz for PWAS#1 and #3. Moreover, a third component is present between 400 to 600 kHz for PWAS#2.

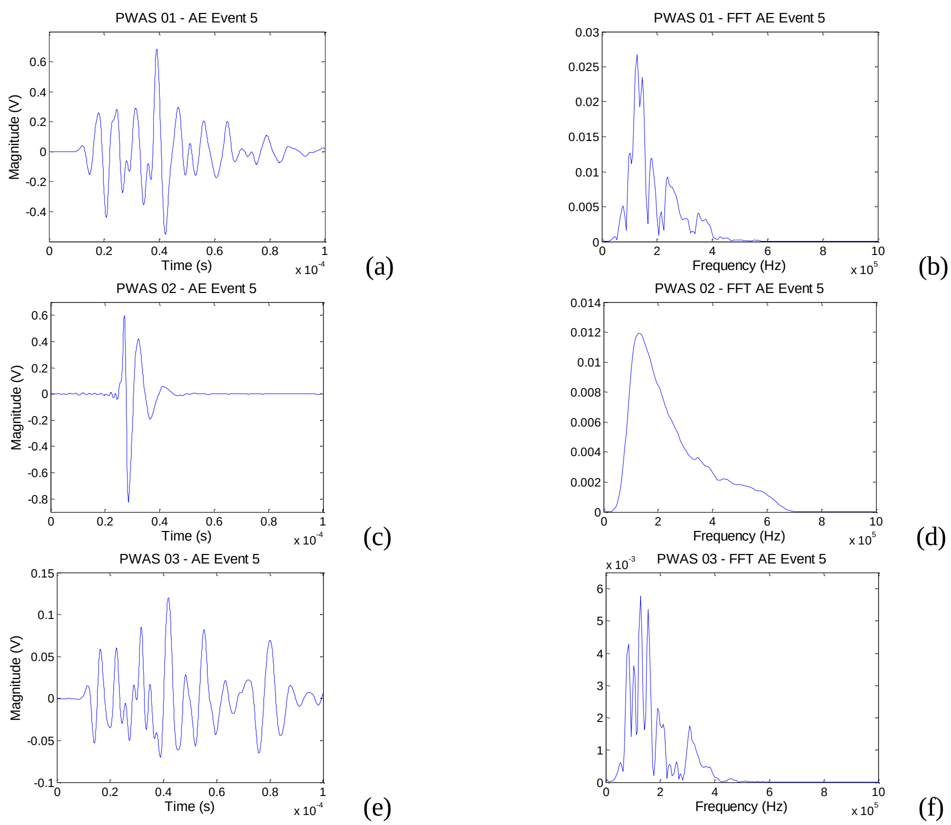
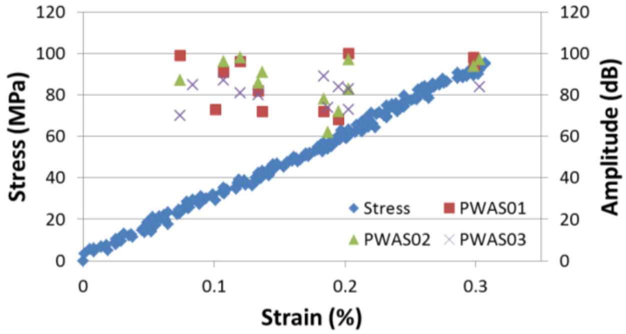
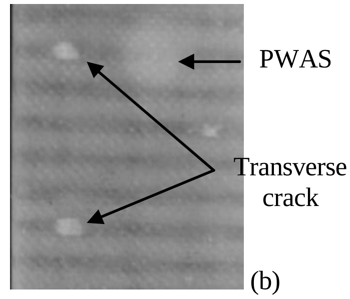


Figure 5: Typical AE waveforms and Fourier Transform from a transverse crack in 3DAI recorded from (a, b) PWAS#1; (c, d) PWAS#2; (e, f) PWAS#3.

The high frequency and the low frequency component correspond to the wave's extensional mode S_0 and to the flexural mode A_0, respectively [27]. This flexural mode 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. The crack initiation for the loading in weft direction occurs in the range of applied strain 0.07…0.1% (Figure 6, showing the data for weft direction loading), a relatively very low level of strain. The amplitude for each AE events (i.e. transverse crack) is between 60 to 100 dB. The signals with lower amplitude were assimilated into noise.



(a)



(b)

Figure 6: (a) stress-strain curve and the amplitude for each PWAS for each AE events; (c) image illustrating developed transverse cracks.

CONCLUDING REMARKS

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. Our preliminary 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 has to be done 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 finite element method need to be performed in order to better understand the damage evolution (that includes delamination, fibre breakage) and ultimate failure of these 3D AI glass composite plates.

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