International Journal of Current Engineering and Technology
ISSN 2277 - 4106

Available at http://inpressco.com/category/ijcet

Research Article

Investigation of Failure Modes in Glass/Polyester Composites by Means of Acoustic Emission

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Accepted 8 Dec. 2012, Available online 1March 2013, **Vol.3, No.1(March 2013)**

Abstract

The non-destructive Acoustic Emission (AE) techniques acquire and analyze the signals emitted from the deformation or fracture of materials under external loading. In this study, the AE techniques with statistical analysis were used to study the damage process of composite laminate under buckling loads. Different damage mechanisms are activated within the composite laminate during loading scenario. These ''damage entities'' are acting in different space and time scales within the service life of the structure and may be interdependent. It has been argued that different damage mechanisms attribute distinct acoustic behaviour to the composite system. Loading of composite laminates in particular leads to the accumulation of distinct damage mechanisms, such as matrix cracking, delamination between successive plies and fiber rupture at the final stage of loading. Buckling is consisted of two main stages including delamination and fracture. The complex failure mechanisms that are commonly considered as the distinctive characteristic of composites are being amenable to nondestructive test advance. The tested of glass/polyester composite specimens include three lay-up patterns: $[0^0/90^0]_{6s}$, and $[0^0]_{6s}$. Each specimen includes 12 layers, and the thickness of each layer is about 0.416 mm. Moreover, the microscopic properties of different composite specimens after fracture are watched and analyzed by scanning electron microscope (SEM). Based on the SEM conception, the controlling failure mechanisms of composites including the splitting matrix cracking, fiber/matrix interface debonding, fiber pull-out and breakage as well as delamination are identified.

Keywords: *Acoustic Emission, Signal Processing, Buckling, Failure modes, SEM.*

1. Introduction

Nowadays, the Acoustic Emission (AE) technique [Huguet S., Godin N., Gaertner R., Salmon L., Villard D., 2002] has been extensively applied to detect internal damage in structures and materials. This technique can provide insights on concrete damage behaviors under various loading cases such as flexural, cyclic, impact, freezing–thawing, fatigue loading and even under chemical influence like corrosion [Pollock AA., 1989; Labuz JF., Cattaneo S., Chen L-H. 2001; Morton TM., Harrington RM., Bjeletich JG. 1973 ; Berkovits A., Fang D. 1995].

Thus far, the procedures for implementing the AE technique have already been documented and published by several organizations including the American Society of Mechanical Engineers (ASMEs) and the American Society for Testing and Materials (ASTMs). The AE damage detection of concrete has been conducted by analyzing parameters of AE signals such as hits, counts, duration time, amplitude, energy, and rise time [Ohno K., Ohtsu M. 2010; Farid Uddin AKM., Numata K., Shimasaki J., Shigeishi M., Ohtsu M. 2004; Grosse CU., Finck F. 2006]. A promising technique in addressing this challenge is acoustic emission (AE), which is the transient energy spontaneously released by incremental crack growth. Compared to other non-destructive testing (NDT) techniques, AE has the advantage of real-time, continuous monitoring of in-service structures [Abazary, S. and A. R. Oskouei 2012; Loutas TH., Kostopoulos V. 2009 ; Daneshmehr A, Asa A, and Abazary S. 2012; Oskouei AR., Zucchelli A., Ahmadi M., Minak G. 2011].

However, the previously referenced authors do not provide such evidence after they classified the AE signals. Therefore, our purpose is to use a methodology with the aim of identifying the acoustic signatures of the damage mechanisms. Based on the our previous work [Oskouei A.R., Ahmadi M. 2010], for that purpose, tensile stresses have been applied on samples of pure resin, fiber and of composite under different conditions that were expected to produce preferential damage mechanisms, such as matrix cracking, fiber breakage and debonding. The benefit of

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classification of the cracking mode is twofold. Since the time sequence of the mechanisms is known (transverse cracking–delamination–fiber rupture), classifications enable to evaluate the remaining life for the structural component and act as a warning against final failure [Scholey JJ., Wilcox PD., Wisnom MR., Friswell MI. 2010].

Additionally, it is possible to tailor the properties of the constituent phases and their interface using proper design or materials so as to optimize the resistance against the specific failure modes. In the engineering field, the shape of the AE waveforms is reported to be characteristic of the fracture mode. Shear events are characterized by longer Rise Time (RT, time delay between the first threshold crossing and the maximum peak) and usually lower peak amplitude (A, voltage of the largest cycle) than tensile events [Shiotani T., Ohtsu M., Ikeda K. 2001; Soulioti DV., Barkoula NM., Paipetis AS., Matikas TE., Shiotani T., Aggelis DG. 2009].

This is examined by the RA (RT/A) value which is defined as the ratio of the RT to the waveform Amplitude, A (expressed in V, see Figure 1) [Ohtsu M. Recommendation of RILEM TC 212-ACD, 1998]. It has been shown that lower RA values, indicate tensile nature of fracture events . Another technique that has been used for structural integrity monitoring is UT. Pulse velocity has been correlated to damage and strength offering rough but valuable information because the damage condition influences the mechanical properties and hence wave speed [Popovics S. 2001; Van Hauwaert A., Thimus JF., Delannay F. 1998].

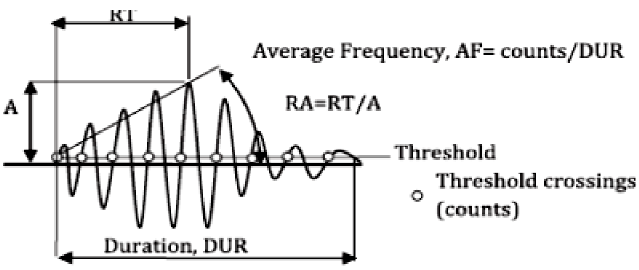

Fig. 1, Typical AE waveform with basic parameters[17].

2. Experimental Procedure

2.1 Material and Specimens Preparation

The tested glass/polyester composite specimens include four lay-up patterns: $[0^0/90^0]_{6s}$, $[Woven]_{6s}$ and $[0^0]_{6s}$. The woven fabric and unidirectional fibers material are as follows: density of 195 g/m^2, tensile strength warp: 386 n/cm weft: 486 n/cm, thickness 0.28 mm and weave is plain. The properties of the polyester resin as a matrix material is density of 1020-1040 kg/m^3. The laminates were prepared by hand lay-up. To prevent slip during loading, end tabs in 20 mm x 30 mm length were glued at the same ends of specimens.The composites specimens dimension and lay-up of 2 specimens are listed in Table 1, each specimen includes 12 layers, and the thickness of each layer is about 0.416 mm.

Table 1: Sizes and lay-up patterns for 2 specimens.

Number	lay-up patterns
1	$[0/90]_{6s}$
2	$[0]_{6s}$

2.2 AE Equipment

Acoustic emission software AE Win and a data acquisition system (PAC) PCI-2 with a maximum sampling rate of 40 MHz were used to record AE events. A broadband, resonant type, single-crystal piezoelectric transducer from physical Acoustic Corporation (PAC), called PICO, was used as the AE sensor. The sensor had a resonance frequency of 513.28 kHz and an optimum operating range of 100-750 kHz. The surface of the sensor was covered with grease to provide good acoustic coupling between the specimen and the sensor. The signal was detected by the sensor and enhanced by a 2/4/6-AST pre-amplifier. The gain selector of the preamplifier was set to 40 dB.

The test sampling rate was 1 MHz with 16 bits of resolution between 10 and 100 dB. Prior to the damage check, the data acquisition system was calibrated for each kind of specimen, according to a pencil lead break procedure. A repeatable acoustic wave then generated a lead breakage in the specimen on its surface. At the same time, the velocity and attenuation of the AE waves measured. The lead breakage operation was repeated several times and the sensors. After the calibration step, AE signals were captured during mechanical testing. Signal descriptors, such as amplitude, duration, rise time, counts, and energy, were calculated by the AE software (AE Win) .

2.3 Testing Machine

A properly calibrated test machine was used. All the specimens are loaded in 5 mm/min. Figure 2, shows the composite specimen positioned for acoustic emission test. the data acquisition system was calibrated for each kind of specimen, according to a pencil lead break procedure. A repeatable acoustic wave then generated a lead breakage in the specimen on its surface. At the same time, the velocity and attenuation of the AE waves were measured. The lead breakage operation was repeated several times and at different locations between the sensors. After the calibration step, AE signals were captured during mechanical testing. Signal descriptors, such as amplitude, duration, rise time, counts, and energy, were calculated by the AE software (AEWin).

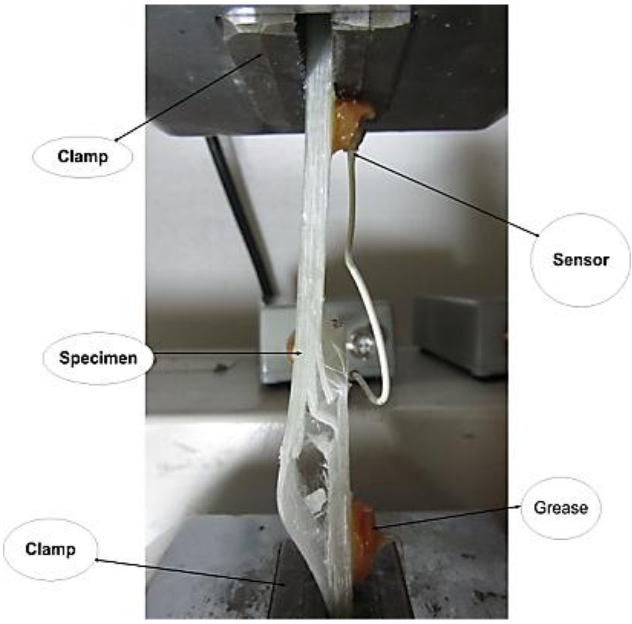

Fig. 2 Composite specimen positioned for acoustic emission test.

3. Scanning electron microscopy (SEM)

For more comprehension of fracture mechanisms, have been observed by SEM. The primary modes of damage observed in the specimens tested are illustrated in the photomicroscographs of the fracture surfaces as shown in Figures 5 and 7. Figure 5, showed matrix cracking, fiber-matrix debonding, fiber pull out-and breakage in a $[0/90]_{6s}$ specimen. In a $[0]_{6s}$ specimen, fiber breakage, fiber pull-out and breakage, matrix cracking were observed as shown in Figure 7.

4. Results and Discussion

For completeness and comparison a survey of the literature on characterization of failure modes in composites is presented in brief. And it had been stated that the signal amplitudes (40–55 dB), (60–65 dB), (65–85 dB), and (85–95 dB) correspond to matrix cracking, interface fracture, fiber-pull out, and fiber fracture, respectively [Ely T., M., and Hill E., K. 1995]. Huguet et al [Huguet s., Godin N., Gaertner R., Salmon L., and Villard D. 2002], explain the peak amplitude distribution of AE signals generated because of the occurrence of different failure mechanisms in glass/epoxy composites. The authors identify the failure modes of glass fiber reinforced plastic composites using a hybrid artificial neural network [Bar H., N., Bhat M., R., and Murthy C. R. L. 2004]. Hamstad demonstrates the applications of a wide band piezo polymer sensor for composites [Hamstad M., A. 1995].

The event duration and rise time distributions with the increment of load are discussed in subsequent sections. The time axis is equivalent to load as the experiments were carried out at a constant load rate.

4.1 Acoustic Emission Representation for Composite Specimen $[0/90]_{6s}$.

The data acquired and recorded from buckle tests, carried out on the set of specimens to characterize different damage mechanism. Thus, the high-amplitude signals beyond 80 dB representing the longitudinal fiber breakage are also mixed with the middle and low-amplitude signals showing the progressive matrix cracking and interface failure. The controlling failure mechanisms include the matrix cracking, fiber/matrix interface debonding, delamination and fiber breakage, shown in Figure 3.

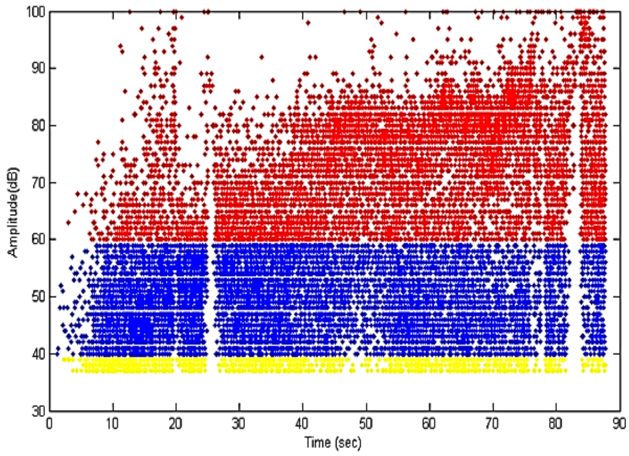

Fig. 3, Acoustic emission response for composite specimen$[0/90]_{6s}$: time-amplitude curve.

The distribution of P-FRQ of the acquired AE signals generated in unidirectional laminates is shown in Figure 4. AE monitoring of pure matrix cracking under loading shows that the dominant frequency range of signals is at a lower level (I) than the dominant frequency range of fiber bundle breakage (III). Thus, the frequency range (II) is considered for the debonding process between fiber and matrix interfaces [Oskouei AR., Heidary H., Ahmadi M., Farajpur M. 2012; Abazary S., Asa A., and Daneshmehr A. 2012].

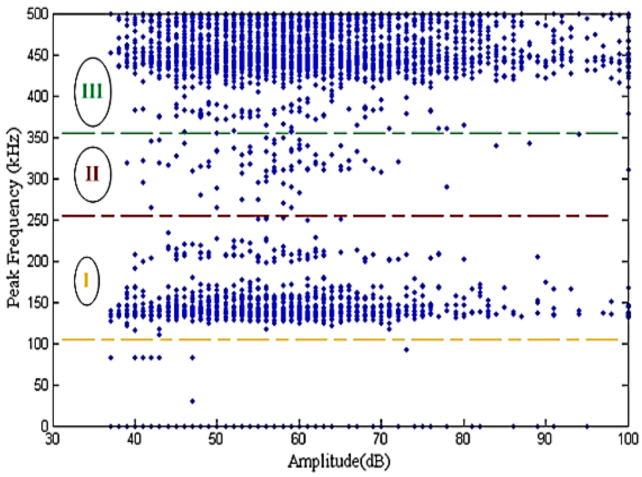

Fig. 4, AE signal peack frequency-amplitude distribution.

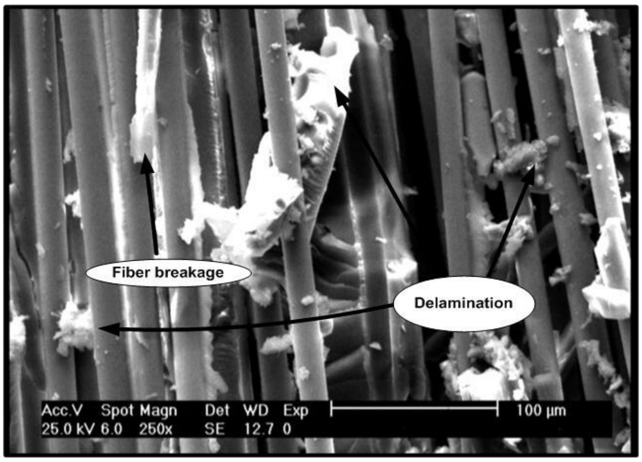

Fig. 5, Microstructure of composite spesimen-1 after fracture by scanning electron microscope.

4.1 Acoustic Emission Representation for Composite Specimen $[0]_{6s}$.

According to the figure 7 in region (I), the failure started with the power failure in the region (II) more,finally, in region (III), fiber failure occurs.

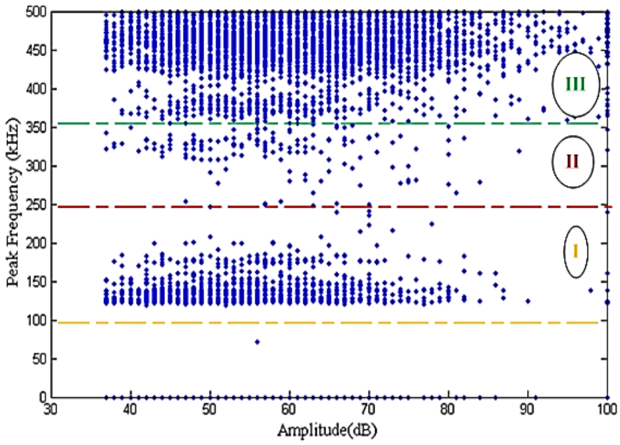

Fig. 6, AE signal peak frequency-amplitude distribution.

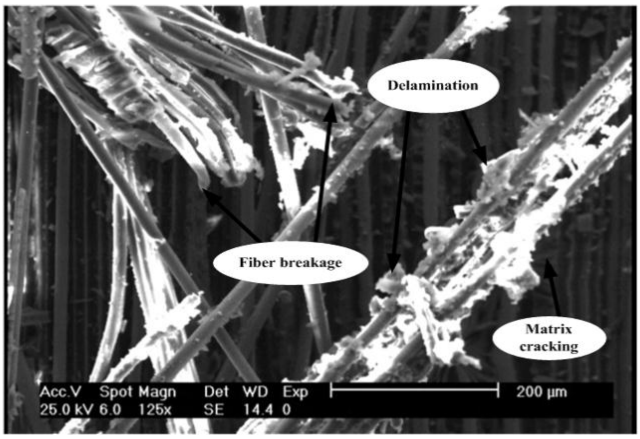

Fig. 7, Microstructure of composite spesimen-2 after fracture by scanning electron microscope

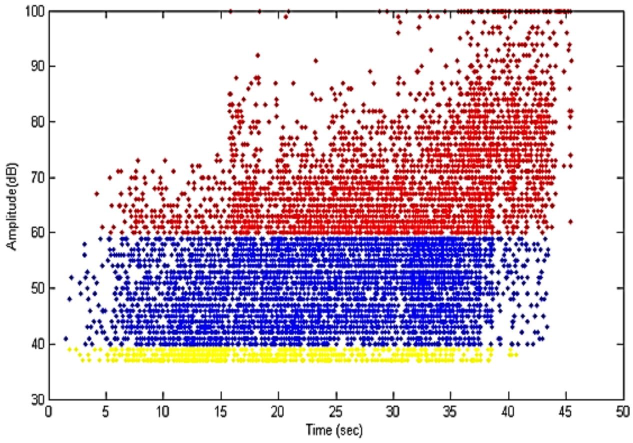

Fig. 8, Acoustic emission response for composite specimen$[0]_{6s}$: time-amplitude curve

Conclusions

This research focuses on the failure mechanisms and damage evolution of glass/polyester composite laminates by combining the buckling experiments and acoustic emission tests.

Effect of two lay-up patterns: Duration, Rise Time, amplitude and Peak Frequency are explored. The real-time acoustic emission response is analyzed from the view of composite micromechanics. From the analysis, the following conclusions are obtained:

Although the controlling failure modes can be- identified, the complete separation of all appearing failure mechanisms is not easily realized because of the complex interactions among them. Here, we summarize the amplitude range for each failure mode. The amplitude of the matrix cracking, fiber/matrix interface debonding, delamination, and fiber pull-out and breakage are about 40-60 dB, 50-70 dB, 60-80 dB and 80-100 dB, respectively. However, the amplitude range varies from different composites, sizes and lay-up patterns even for the same failure mode.

The frequency range for each damage determined. For matrix cracking, the dominant frequency range of signals is at a lower level (100-250 kHz) .Thus, the frequency range 250-350 kHz is considered for the debonding between fiber and matrix interfaces. The dominant frequency range of fiber bundle breakage (400-500 kHz).

The results presented show that different failure mechanisms have different characteristics which can be studied utilizing the AE parametric data.

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