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Characterizing the damage mechanisms in mode II delamination in glass/epoxy composite using acoustic emission

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Abstract. Mode II delamination propagation is an important damage mode in laminated composites and this paper aims to investigate the behavior of this damage in laminated composite materials using acoustic emission (AE) technique. Three different lay-ups of glass/epoxy composites were subjected to mode II delamination propagation and generated AE signals were recorded. In order to investigate the propagation of delamination behavior of these specimens, AE signals were analyzed using Wavelet Packet Transforms (WPT) and Fast Fourier Transform (FFT). In addition, conventional AE analyses were used to enhance understanding of the propagation of delamination damage. The results indicate that different fracture mechanisms were the main cause of the AE signals. The dominant mechanisms in all the specimens were matrix cracking, fiber/matrix debonding and fiber breakage, with varying percentage of the damage mechanisms for each lay-up. Scanning Electron Microscopy (SEM) observations were in accordance to the AE results.

Keywords: composite material; glass/epoxy; acoustic emission; wavelet packet transform; delamination

1. Introduction

In the last decade, usage of fiber reinforced composite materials for structural applications in the industry has increased drastically. The technology has been applied for many applications, which require high strength and stiffness-to-weight ratio materials (Nikbakht and Choupani 2008). Laminated composite materials are brittle and sensitive to notches or damage. Preventing failure of composite material structures is a significant challenge in engineering design. The dominant type of damage mechanism that occurs in laminated composite structures is interlaminar failure, in particular delamination, which is defined as debonding of nearby lamina. Investigation of dominant damage mechanisms is so challenging work for researchers. So, they try to apply some effective methods to distinguish these damages.

There are some destructive and nondestructive methods for identifying faults in different kinds of materials. An effective method which is used for identifying faults is Acoustic Emission technique. Over the past few years major research developments have been done in application of acoustic emission in numerous engineering fields, including manufacturing, civil, aerospace and material engineering. In order to recognize the main types of damages in composite material, acoustic emission is an effective method. This method can be used for detecting faults and pressure leaks in vessels, tanks, pipes, as well as for monitoring the progression of corrosion in welding (Gholizadeh *et al.* 2015).

Some destructive and nondestructive studies have characterized delamination failures. AE is a powerful technique capable of online monitoring during delamination failure. AE events are related to the fracture modes; in delamination damage, initiation and propagation of the crack are the sources of AE events (Katerelos *et al.* 2009). Some studies use acoustic emission for investigation on composite material in Mode II. Yousefi *et al.* (2014) studied composite material under mode II delamination. They used AE technique. The method they used is consists of a discrete wavelet packet decomposition of AE signals accompanied with a clustering algorithm. This gives the distribution of the normalized AE signal energy on the frequency band. ENF set up have been used to detect mode II delamination on glass epoxy. The results showed that the dominant damage mechanism in all specimens is matrix cracking. Nazmdar *et al.* (2015) investigate to use a novel method called Hilbert transform to correlate acoustic emission signals to their corresponding failure mechanisms. They studied acoustic emission signals subjected to ENF test which simulates mode II delamination on composite material.

In order to resolve design limitations in composite materials it is essential to have adequate information on basic delamination modes. Research have been conducted to extract useful information from AE events (Katerelos *et al.* 2009, De Groot *et al.* 1995), these studies were commonly focused on time features. Since AE events in composite materials are not stationary, characterization of failure modes in time domain is difficult. A time-frequency analysis, using Short Time Fourier Transform (STFT) (De Groot *et al.* 1995), was used for better analysis of AE events

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in which frequency bands, evolving in time, were related to failure mechanisms which occurred during a tensile test on carbon/epoxy materials. Therefore, waveform processing of AE signals based on time-frequency analysis is an ideal analytical method to distinguish fracture mechanisms. Previous studies (Subba Rao and Subramanyam 2008, Qi *et al.* 1997) have illustrated the applicability of Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT) as AE signal discrimination instruments under different loads and types of materials. It is possible with DWT to determine the most energetic levels of decomposition and recognize the frequency bands associated with various damage mechanisms. These techniques have successfully been used to improve discrimination of AE events (Yamaguchi and Oyaizu 1991, Pappas *et al.* 1998, Kostopoulos *et al.* 2003). Ni and Iwamoto (Ni, Iwamoto 2002) used Wavelet Transform (WT) to investigate the relationship between AE signals and damage sources, whereas Marec *et al.* (2008) used CWT and DWT to extract new time-scale descriptors for developing the characterization of failure mechanisms. In some study (Hajizadeh *et al.* 2016), the performance of CT is compared with WT in order to demonstrate the capability of WT and CT in detection of defect types in plate structures.

Some previous work (Shokrieh and Heidari-Rarani 2011) studied delamination propagation in mode-I delamination in multidirectional laminated composite by DCB specimen. They evaluated the beam theories resting on elastic foundations that used to model mode-I delamination. In this study, a compliance based approach was used to calculate critical strain energy release rate. It should be mentioned that a lot of previous works studied damage mechanisms under mode I delamination (Refahi Oskouei *et al.* 2011, Refahi Oskouei *et al.* 2012, Pashmforoush *et al.* 2012, Pappas and Botsis 2016), but there is a lack of studies on damage mechanisms in mode II delamination. Since most of the composite structures are under shearing mode, it is significant for engineers to study mode II delamination. Characterization of damage mechanisms in this mode to have composites with significant toughness, against this type of damage, has made it a necessity to study damage mechanisms in mode II delamination.

In this study, different types of damage mechanisms such as matrix cracking, fiber/matrix debonding and fiber breakage in mode II were investigated. The AE signals related to the types of damage mechanisms were analyzed and the critical load for initiation of delamination was evaluated from AE signal analysis. Frequency analysis of AE waveforms was applied to detect types of fracture mechanisms occurred during mode II. Some previous work (Heidari-Rarani and Ghasemi 2017) studied delamination propagation in ENF specimens with R-curve effects. They indicated that R-curve phenomenon due to fiber bridging may happen in delamination propagation. Therefore, it is necessary to consider the influence of R-curve during the characterization of delamination propagation process. Depending on material type and geometrical dimensions, R-curve effects in ENF specimens can be ignorable or considerable. It should be mentioned that in AE method there are some limitation for considering the R-curve effects.

A Scanning Electron Microscope is a type of electron microscope that creates images of a sample by scanning the surface with a focused beam of electrons. The electrons interact with atoms in the sample, creating various signals that contain information about the sample's composition and surface topography. SEM observations can be used to verify the AE signal results. In this study, SEM observations were used to verify the AE results.

2. Wavelet analysis

WT is a powerful signal processing tool introduced in the mid-1980s (Grossmann and Morlet 1984). A wavelet is a localized wave of effectively limited duration that has a zero average value. Wavelet analysis is the breaking up of a signal into shifted and scaled versions of the mother wavelet. Some studies during the last decade illustrated WT as a suitable method for analyzing AE signals (Qi 2000, Coifman and Meyer 1993). There is a wide range of wavelets with various characteristics (Kaiser 1994, Daubechies 1992, Mallat 1998, Newland 1993) which make wavelet analysis a powerful tool in AE analysis.

In this study, WPT was used to analyze AE waveforms monitored during mode II interlaminar test. In wavelet analysis, a signal splits in 2 components, i.e., approximation and detail, the approximation component has lower frequency range compared with the detail component. WPT is a better tool than DWT as each of the approximation and detail components can split into second level components, and the process is repeatable until having reasonable results (Marec *et al.* 2008, Fotouhi *et al.* 2012, Fotouhi *et al.* 2014, Velayudham *et al.* 2005).

In this study, energy criterion was used to find the dominant components that were related to various failure modes. Eq. (1) describes the relation of energy and frequency mathematically

$$E_i^j(t) = \sum_{\tau=t_0}^{t} (f_i^j(\tau))^2 \, f(\tau), \; f_i^1 \dots f_i^j \tag{1}$$

Where $f(\tau)$, $f_i^1 \dots f_i^j$ and $E_i^1 \dots E_i^j$ stand for an AE signal, the components of the ith level of the decomposed signal and the component energy at level i, respectively. The total energy of a signal has a mathematical form as following

$$E_{total}(t) = \sum_i E_i^j(t) \tag{2}$$

In order to find energy distribution displayed at different components, the ratio of energies at different levels to the total energy, i.e., $P_i^j(t)$, is calculated from Eq. (3).

$$P_i^j(t) = \frac{E_i^j(t)}{E_{total}(t)} \qquad j = 1 \dots 2^j \tag{3}$$

Table 1 Type of specimens

Specimens	Mid-plane	Number of plies
S_1	0, 0	18
S_2	0, 90	18
S_3	+45, -45	18

Table 2 Elastic properties of glass/epoxy laminated composite (unidirectional)

$E_1(GPa)$	43.3
$E_2 = E_3(GPa)$	7.71
$G_{12} = G_{13}(GPa)$	4.1
$G_{23}(GPa)$	2.48
ν_{23}	0.38
$\nu_{12} = \nu_{13}$	0.3

Fig. 1 Experimental setup

3. Experimental procedure

3.1 Testing machine

A calibrated universal testing machine (Hiwa) with the maximum capacity of 49 kN and tunable speed drive of 0.1-500 mm/min was used. All the specimens were tested with a 5 mm/min speed rate.

3.2 Acoustic emission device

Data acquisition system (Physical Acoustic Corporation (PAC) (PCI-2)) with a maximum sampling rate of 40 MHz and AE software (AEWin) were used to store the AE events. A resonant type AE sensor, which is a single crystal piezoelectric transducer from PAC, was used to collect data. With the purpose of providing good acoustic coupling between the sensor and the specimen, the surface of the sensor was coated with grease. The optimum working range of the sensor and the resonance frequency is 100-750 kHz and 513.28 kHz, respectively. The signal was received by the sensor and improved by a pre-amplifier. The threshold, the gain selector of the pre-amplifier and sampling rate were set to 37 dB, 40 dB and 1 MHz, respectively. Signal descriptors such as duration, event energy, rise time, amplitude and counts were recorded by the sensors in a linear pattern with a distance of 70 mm.

3.3 Materials and specimens

The experimental study was performed on composite materials made up of epoxy resin reinforced by 18 layers of E-glass fiber with a volume fraction of 50%. The specimens were prepared by hand lay-up and compression moulds. The thickness of each layer was 0.28 mm. These layers were put together to form a coupon with dimensions of 150×25×5 mm.

A layer of Teflon with a thickness of ~20 μm and dimensions of 25×55 mm was inserted between 9th and 10th layers creating an initial crack of 30 mm. Three types of lay-ups, named S_1, S_2 and S_3, were prepared for experimental tests (see Table 1).

Elastic constant properties of composite materials are given in Table 2.

3.4 MMB test equipment

In this study MMB (Mixed Mode Bending) test set up was used for pure mode II, as shown in Fig. 1. The MMB test method (ASTM Test Method D6671-01 2001, Crews and Reeder 1988) can be used for the same specimen configuration as for mode I, II and mixed-mode delamination tests. Pure mode II loading occurs when loading is in the middle of the specimen. MMB tests were carried out in a universal testing machine with a load cell capacity of 49 kN at 5 mm/min test speed. The utilized load vs. displacement was saved digitally.

4. Result and discussion

The aim of this study is to investigate and characterize mode II delamination damage in laminated composite materials. The results of this study are expressed in two main sections. The first section concentrates on investigating initiation of delamination and detection of damage appeared during propagation of crack by conventional AE parameters such as energy, count, amplitude and hit. In the second section, WT technique is used for analyzing energy percentage of the AE signals in different frequency ranges.

4.1 Mechanical observations and AE behavior

In previous studies, AE amplitude, count and energy were used as the primary AE characteristics for studying delamination damage.

In this study, distribution of AE count and energy were used to investigate the critical load. In Fig. 2, AE count and energy distribution during the test for a typical S_1 is shown, whereas Figs. 3-4 show AE count distribution during the test for S_2 and S_3, respectively. The points having the first high rise in AE count and energy values illustrate the load which causes initiation of major delamination. Creating crack surfaces releases AE energy and as illustrated in Figs. 2-4 there are AE signals with higher AE energy and count quantities compared to the other signals.

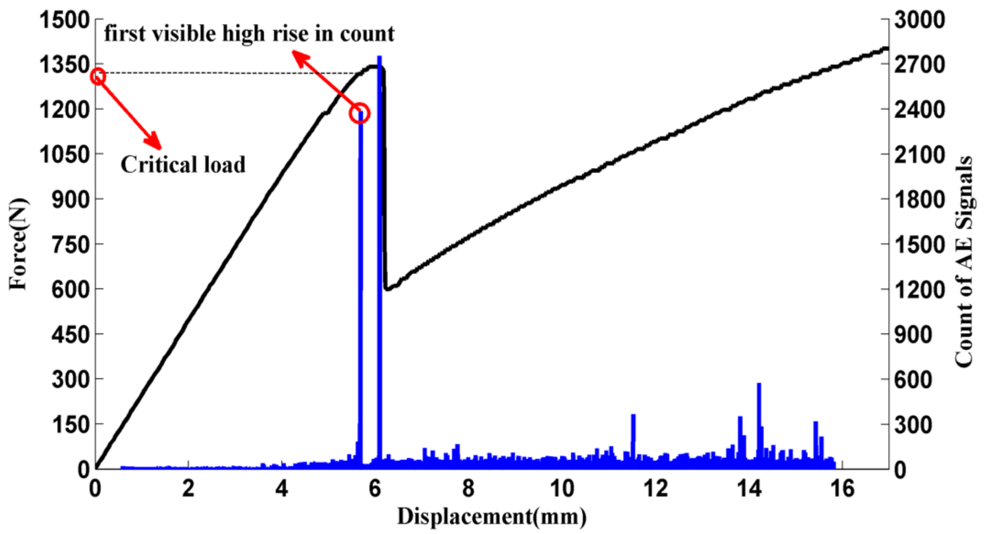


Fig. 2 Determination of critical load, using acoustic emission count distribution technique for S_1

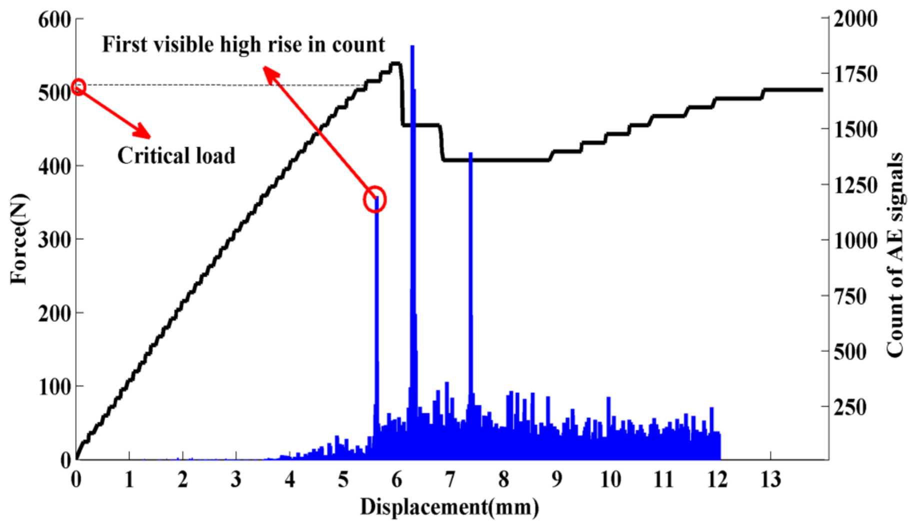


Fig. 3 Determination of critical load, using acoustic emission count distribution technique for S_2

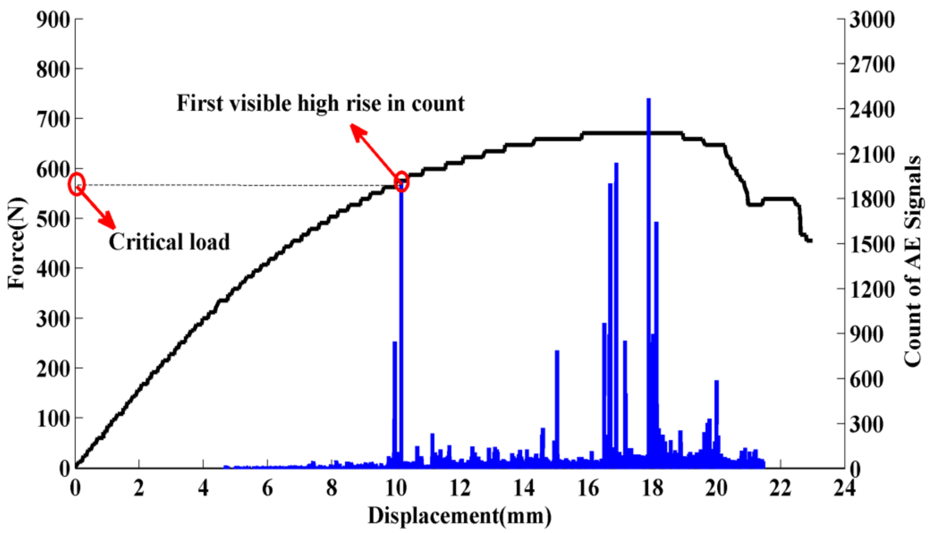


Fig. 4 Determination of critical load, using acoustic emission count distribution technique for S_3

Table 3 Critical load for initiation crack

Specimens	Critical load for crack initiation (N)
S_1	1345
S_2	500
S_3	580

Table 4 AE amplitudes of important fracture mechanisms

Type of damage	Amplitude (db)
Matrix cracking	40-50
Debonding	45-65
Fiber breakage	60-90

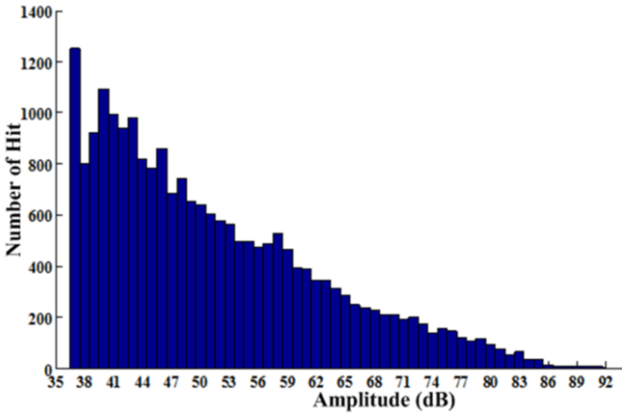


Fig. 5 Hit vs. Amplitude for S_1

Since at the beginning of the test, there is not enough energy to create the crack surfaces, there is no energy release originated at the beginning of the loading. At this phase, the load-displacement relationship is almost linear. Although there are some weak AE signals at the beginning of the test which are associated with friction or other imperfections caused during the manufacturing process. These events do not have any significant effect on the specimen strength. When the mechanical energy reaches to a specific energy, i.e., critical energy for initiation of delamination, there is a sudden release of fracture energy. This is the main cause of first higher AE energy and count quantities (see Figs. 2-4). First nonlinearity point in the load-displacement plot is observed near the first high rise in AE energy. This point is associated with the initiation of delamination. After the initial phase, the load drops off rapidly as a result of sudden crack propagation. By reaching the middle of the specimen (near the indicator tip) force value increases which is due to arresting the crack. By using a distribution diagram of AE count and energy during the loading process, the critical load could be evaluated.

The resulted critical loads for different specimens are summarized in Table 3.

In addition, distributions of hit-amplitude for specimens S_1, S_2 and S_3 are illustrated in Fig. 5. There are some differences between the distributions of hits for the specimens. By testing glass fiber bundles and pure epoxy resin it was found that the low and high ranges of AE amplitude/frequency are related to the matrix cracking and

Table 5 The frequency ranges for main components in third level for S_1, S_2 and S_3

Specimen	Three main components and range of frequency (kHz)		
S_1	DDA3	AAD3	ADD3
	190-250	250-310	310-410
S_2	ADA3	DDA3	AAD3
	110-180	180-250	260-310
S_3	DDA3	AAD3	DAD3
	200-250	250-300	300-400

fiber breakage events, respectively. The range of AE amplitude for fiber/matrix debonding is between the range of fiber breakage and matrix cracking. These results are in a good agreement with the results of previous studies (Ni and Iwamoto 2002, Haselbach and Lauke 2003, Ramirez-Jimenez *et al.* 2004). The ranges of AE amplitude of matrix cracking and fiber breakage are illustrated in Table 4, where the dominant frequency range of the matrix cracking is 180-250 kHz and the dominant frequency range of the fiber breakage is 310-450 kHz.

The results show that, for all the specimens, major numbers of AE signals have the low range of amplitude corresponds with the amplitude ranges of matrix cracking and fiber/matrix debonding. As a result, the dominant damage mechanisms in all the specimens are matrix cracking and fiber/matrix debonding, with varying percentage of the damage mechanisms for each lay-up. Fiber breakage damage has a lower contribution and its percentage in specimen S_1 is more than specimens S_2 and S_3.

4.2 Wavelet analysis and results discussion

As discussed in the previous section, three damage mechanisms e.g., matrix cracking, fiber/matrix debonding and fiber breakage are the main causes of the AE signals. In order to differentiate these damage mechanisms from each other, DWT and WPT were used for signal analyzing. A developed code was used for analyzing the AE signals. The AE signals decomposed into three levels based on entropy criteria (Rao and Bopardikar 1998). There are eight components at the third level and each component at the third level represents a specific frequency range. The frequency content of each component is obtained by FFT method and the results are shown in Figs. 6-8. All the components of the third level are used to determine the dominant energy levels. The total energy of the AE signal is calculated by Eq. (3). The energy distribution in each component is shown in Fig. 9 for specimens S_1.

There are three components with dominant energy distribution, which are related to the damage mechanisms as shown in Table 5. The frequency ranges for these components are illustrated in Table 5.

Considering the WPT results, the dominant damage mechanisms in the specimens are matrix cracking and fiber/matrix debonding, whereas fiber breakage is rarely observed. For all the specimens, the highest energy is distributed at component DDA3 which is related to the

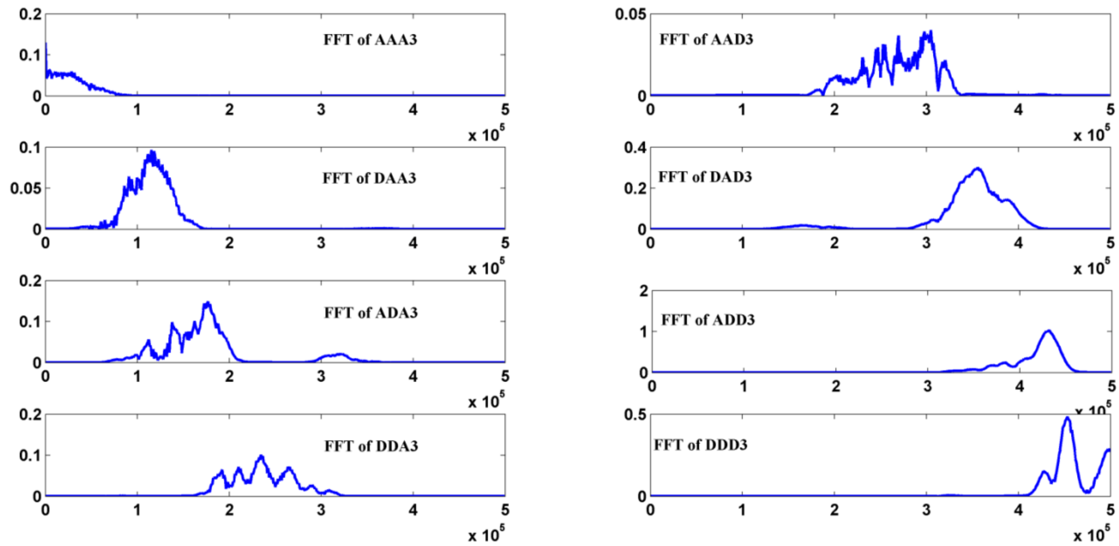


Fig. 6 Third level FFT of the decomposed components for S_1 (FFT amplitude (mV^2/Hz) vs. frequency (Hz))

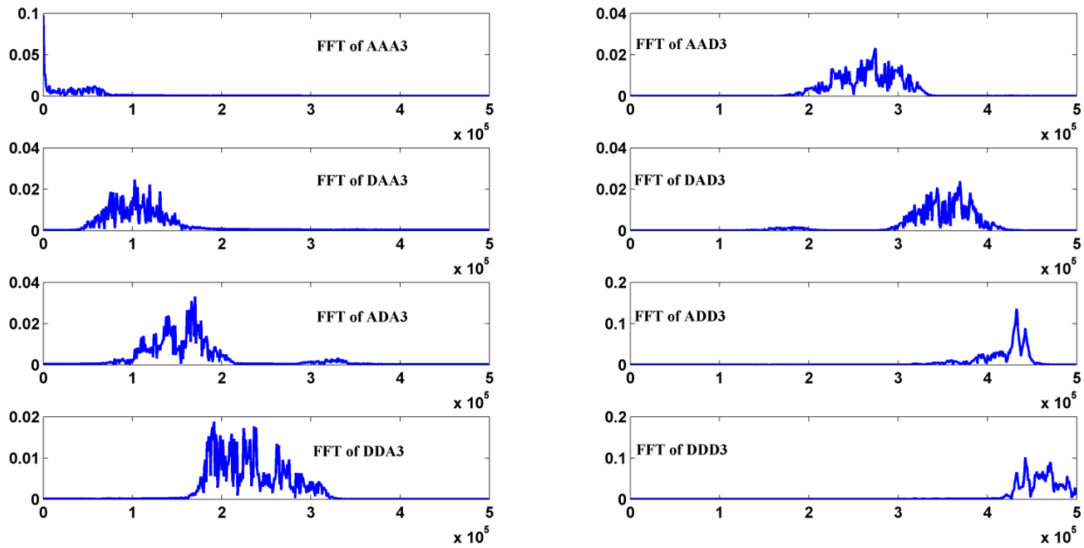


Fig. 7 Third level FFT of the decomposed components for S_2 (FFT amplitude (mV^2/Hz) vs. frequency (Hz))

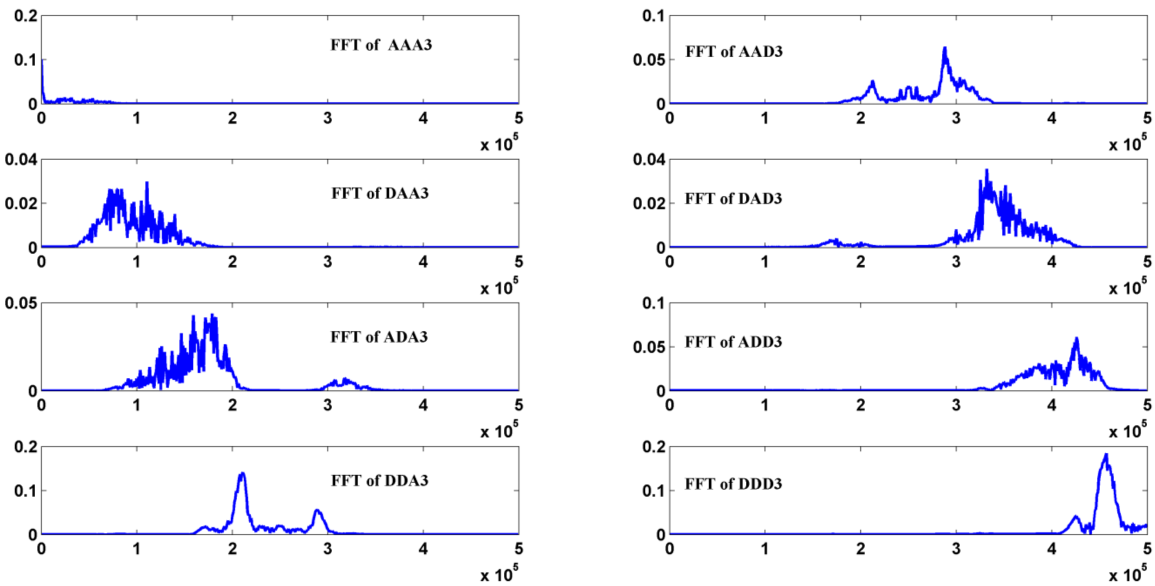


Fig. 8 Third level FFT of the decomposed components for S_3 (FFT amplitude (mV^2/Hz) vs. frequency (Hz))

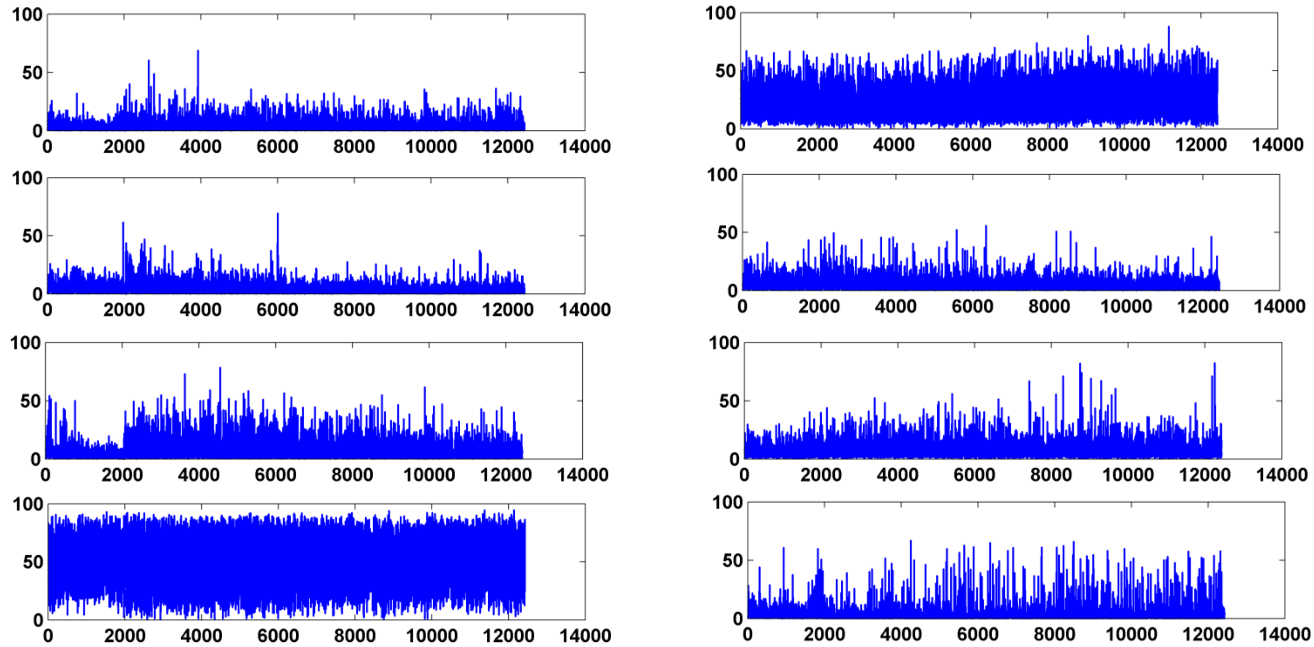
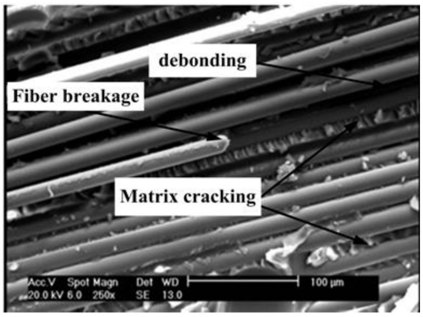
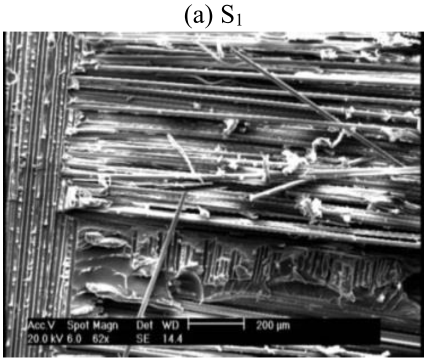


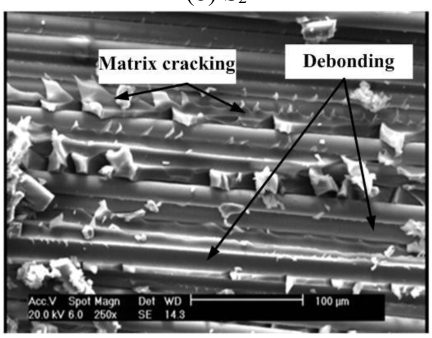
Fig. 9 Energy percentage of each component of third level for S_1 (energy (%) vs. samples)



(a) S_1



(b) S_2



(c) S_2

Fig. 10 SEM observation of dominant failure mechanisms in test for S_1 and S_2

matrix cracking event. In DDA3, A refers to the approximation and D refers to the detail components.

Dominated frequencies at DDA3 are 190-270 kHz, 180-270 kHz and 200-250 kHz for S1, S2 and S3, respectively. The percentage of AE energy related to matrix cracking (DDA3 component) in S3 has its highest value (61.57%), whereas in S1 and S2, the distributed energy is 48.51% and 52.45%, respectively.

4.3 Scanning electron microscope (SEM) results

SEM observations show that matrix cracking, fiber/matrix debonding and fiber breakage are the sources of the AE signals in the investigated laminates. As illustrated in Fig. 10, the dominated failure mechanisms are matrix cracking and fiber/matrix debonding. Fiber breakage also appears, but the percentage of this damage mechanism is low compared to the other types.

It can be seen from Fig. 10 that for S_1 more fiber breakages appeared compared with S_2 and S_3. This due to the fiber bridging phenomenon that appears in S_1 which is a unidirectional laminate. As you can see from the Fig. 10 the dominant damage are matrix cracking and debonding for S_2. We can see from the result, fiber breakage is negligible in mode II delamination propagation where the 0/90 mid-plane is used. In 0/90 interface, fiber length is usually not adequate to allow for bridging, so instead of fiber breakage, fiber debonding happens. It has also been achieved that delamination migration happens for 0/90 lay-up. Delamination growth happens initially along a 0 ply interface then eventually migrates to a neighboring 90 ply interface.

5. Conclusions

In this study, glass/epoxy laminates with different fiber orientations subjected to mode II delamination propagation test were investigated by AE technique. For this purpose, conventional AE parameters such as energy, count, amplitude and hit were used to investigate the propagation of delamination. AE energy and count were used to indicate the critical load for the initiation of delamination. It was found that the amount of the critical load for the unidirectional specimen was more than the other specimens. In addition, WPT was used for analyzing the AE signals and to calculate the energy percentage of the wavelet components. Frequency ranges of the components associated with the fracture mechanisms were also achieved by FFT analysis. The results showed that matrix cracking, fiber breakage and fiber/matrix debonding were the main sources of the AE signals. SEM observations and WPT results indicated that matrix cracking and fiber/matrix debonding was the dominant fracture mechanisms in the investigated layups. It was concluded that the AE method, coupled with signal processing techniques, appears to be a useful tool that is able to monitor the damage evolution and to calculate the interface damage contributing to the overall failure process in mode II delamination.

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