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Delamination evaluation of composite laminates with different interface fiber orientations using acoustic emission features and micro visualization

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ABSTRACT

This study aims to investigate the sequence of initiation and evolution of different damage mechanisms during the DCB standard test procedure on specimens with different interface fiber orientation using Acoustic Emission (AE) data analysis and microscopic imaging methods. For this purpose, a series of experiments based on standard ASTM D5528 were performed on 24 layer glass epoxy multidirectional specimens with $[[\pm\vartheta/0_5]_{As}]_{As}$ layup, in which ϑ *is* 0. 30. 45 *and* 60. The acoustic data were then acquired with two AE sensors and the whole test procedure was observed by two digital cameras, which were focused on specimen edges. The results show that the initiation and evolution process of matrix cracking as the first activated damage mechanism greatly depends on the interface fiber orientation. Also, load-displacement curves and AE data can be well correlated with microscopic observation in all stages of damage initiation, evolution and propagation. Although the standard nonlinear point as crack initiation onset predict an equal fracture energy for all cases, however AE analyses and microscopic observations show early damage initiation and evolution in 45 and 60-degree interfaces.

1. Introduction

Fiber reinforced composite materials in industrial applications, such as civil structures and automotive industry have been utilized tremendously in recent years due to their higher strength and stiffness compared to conventional materials [1]. One of the most restricting problems of utilizing composite materials is the damage mechanisms of delamination. Plies of different orientations can be considered as a major source of delamination due to in-plane ply stiffness coefficients change through the thickness. Fracture mechanics have been used as an efficient approach to characterize delamination initiation and propagation. To this aim, the critical energy release rate (G_{Ic}) has been used as a criterion for multidirectional (MD) specimens. Some studies showed that the measured initiation G_{Ic} is almost independent of the fiber interface orientation [2–5], while others stated that it causes the increasing of G_{Ic} [6–10] or even may decrease [11–14] with respect to fiber orientation changes. Therefore, more researches should be conducted in the field of delamination characterization in MD composite laminates. To this aim, Acoustic emission (AE) is a capable methodology for delamination detection of composite structures [15].

AE as a nondestructive method has been utilized to detect damage mechanisms in different applications by detecting the released energy due to these events in a structure [16–23]. Also, the delamination as the consequence of damage evolution between two adjacent plies sometimes can be detected very hard and late because it occurs beneath the surface of the specimen [1,24]. In this case, AE can be utilized as an efficient approach for delamination characterization. The reliability of AE in delamination detection is studied by some authors [25–27]. Some other researches have already been conducted to determine initiation of delamination using different AE based methods such as acoustical features and Sentry function [28–33]. Yousefi et al. [34] predicted delamination growth using a power law relation between cumulative AE energy and micro visualization data. In Refs. [35,36], AE features have been implemented to evaluate delamination growth behavior of

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composite materials. Romhany et al. [37] obtained an AE localization algorithm to measure the delamination propagation using double cantilever beam specimens. They found that AE is a capable approach for delamination detection in composite laminates. Paget [38] used AE method for detection of damage mechanisms occurring in the carbon/epoxy specimens. From the literature review and to the author' knowledge, in most cases, AE method was not utilized to characterize delamination in the case of different fiber orientations. In this case, AE features can be used as an effective tool to obtain much more precise results. Finally, results of such studies can lead to acquiring sufficient knowledge in order to increase the reliability of composite structures with cost-effective, time-saving and more accurate methods.

Herein this study, the initiation, evolution and propagation of different damage mechanisms including matrix cracking, fiber-matrix debonding and fiber breakage in multidirectional laminates with different interface fiber orientations will be investigated and a detailed analogy between The AE data and damage features observed on fracture surfaces will be presented for delamination initiation and propagation. .

2. Experimental procedures

2.1. Specimen preparation

To eliminate the effect of stacking sequence, a 24 layers laminate with stacking configuration of $[[\pm\vartheta/0_5]_s]_{As}$ with angles 0, 30, 45, 60 has been utilized. In lay-ups design, three factors must be considered. The first is to eliminate the bending twisting coupling. The second is to decrease the difference of stiffness of two cantilevers and the third is to reduce the thermal residual stresses. In this configuration not only does the overall flexural stiffness of the laminates remain within an acceptable range but also the effect of bending-bending and bending-twisting couplings can be minimized [7,14,39,40].

E-glass fabric with a specific mass of 200 gr/m^2 and a thickness of 0.2 mm with less than 10% fibers in weft direction was used through Vacuum Infusion Process (VIP) to manufacture each 230 $\times$ 300 $\times$ 4.8 mm laminate with EPL 1012 Epoxy resin. Laminates were kept at room temperature for about ten days to reach their ultimate strength as described by producer company. Material properties of the laminate are summarized in Table 1. The initial delamination was introduced by inserting a 40 μm thickness of PTFE strip with a width of 20 mm between 12th and 13th layers during layup process.

Specimens with a dimension of 25 $\times$ 175 $\times$ 4.8 mm were cut by water jet cutting process from each laminate and sanded carefully to eliminate any source of matrix cracking at specimen edges and also better visual investigations. The loading hinges according to standard ASTM D5528 [41], were bonded by cyanoacrylate adhesive after sufficient surface preparation. The thickness of PTFE strip was relatively small enough not to generate a resin rich area in front of the crack tip.

Table 1
Laminate stiffness properties.

E_{11}	22.443	GPa
$E_{22} = E_{33}$	9.041	GPa
$G_{12} = G_{23} = G_{31}$	3.318	GPa
$\nu_{12} = \nu_{13}$	0.21	
ν_{23}	0.4	

2.2. Test procedure

The Double Cantilever Beam (DCB) test was performed according to ASTM standard D5528 [41] with DARTEC servo-hydraulic universal testing machine with a crosshead speed of 1 mm/min. Load-displacement data were recorded at the same time by a data acquisition system. A digital video camera with high optical zoom was also set to record the crack length data during the test. A digital microscope (with a 215$\times$ zoom) was also provided to focus to the other edge of the specimen to record the crack initiation and propagation process. Also, two AE sensors were embedded on the upper surface of the specimen in 20 mm ahead and 80 mm back of the crack tip for further investigations. The test setup and corresponding equipment are illustrated in Fig. 1.

2.3. AE sensors

The generated AE signals were recorded using two AE sensors. The threshold of AE signals captured during tests was adjusted to 35 dB. The resonance frequency of the single-crystal piezoelectric AE sensor was 513.28 kHz. An optimum operating range of these sensors were 100–750 kHz. The 2/4/6-AST preamplifier with a gain selector of 40 dB was utilized to enhance acoustical signals. The sampling rate of AE data acquisition board was set to 40 MS/S (Mega Samples per Second). In order to calibrate AE sensors, the pencil lead break method was implemented according to ASTM E976-10 [42] standard prior to each test. Vacuum grease was also used to cover the contact surface between sensors and specimens to create good acoustical coupling.

3. Result and discussion

3.1. Damage mechanisms frequency bands

Based on the literature review, the dominant damage mechanisms of composite materials, when subjected to DCB test, are fiber breakage, matrix cracking and fiber-matrix debonding [26,34–36].

Based on previous research [36], the frequency content of AE signals was analyzed using Hilbert Transform (HT) concept the results show that matrix cracking events have been limited to the frequencies [62.5–187.5 kHz] and frequencies between 350 and 500 Hz are referred to fiber breakage. According to previous research [35], fiber-matrix debonding occurs between these two band. Although HT analysis introduces these bands for each damage mechanism, however, it can be seen that the presented band for fiber-matrix debonding is very conservative and most of this event happened with some frequencies between 200 and 230 Hz.

3.2. Event analysis

Fig. 5 presents changes of cumulative AE energy and counts and load during the test procedure. In this figure time has a linear relation with displacement, thus the horizontal axis of all graphs can be easily replaced with displacement.

As it is noticeable in Fig. 2, in every specific range of time, the trend and the rate of changes in cumulative AE energy are similar to those of cumulative AE counts. This confirms that more events cause more energy emission. Also, the relation of the load curve with the cumulative AE energy and count is considerable in Fig. 2. For all cases, abrupt changes in load in a specific time period lead in a similar increase in the AE energy rate. This would be consequent of an increase in the rate of acoustic events occurred in the corresponding range of time. The green dashed lines show some points in which this relation can be highlighted better for different interface orientations. Another similarity in the behavior of all cases