Composites Science and Technology 116 (2015) 26–32

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Transverse cracking in carbon fiber reinforced polymer composites: Modal acoustic emission and peak frequency analysis

Christopher Baker [a], Gregory N. Morscher [a,*], Vijay V. Pujar [b], Joseph R. Lemanski [b]

[a] Mechanical Engineering Department, University of Akron, Akron, OH, United States
[b] Aerostructures, UTC Aerospace Systems, Chula Vista, CA, United States

ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form 13 April 2015
Accepted 6 May 2015
Available online 12 May 2015

Keywords:
A. Carbon fibers
A. Polymer-matrix composites (PMCs)
B. Matrix cracking
D. Acoustic emission

ABSTRACT

The initiation and propagation of cracks in carbon-fiber reinforced toughened epoxy polymer composite laminates were studied using modal acoustic emission and waveform energies, coupled with peak frequency data and correlated to matrix crack density in the transverse direction. Composites of four different ply layups were studied. Results show the placement of the 90° ply (e.g., on the surface or internal) as well as the number of adjacent 90° plies directly influence the applied stress load at which transverse cracks are formed and the resulting stress distribution. Results for matrix cracking show that peak frequency data alone was unable to fully characterize the damage initiation, contrary to prior studies. However, based on modal acoustic emission principles, coupling the peak frequency data with acoustic energy of waveforms, effectively corresponded to the stress-dependent number of 90° ply transverse cracks and the through-the-thickness location of the 90° ply. This information can be very useful to understand stress-dependent transverse cracking in a given 90° ply or to develop optimal lay-up sequences to maximize composite properties.

1. Introduction

Carbon-fiber reinforced polymer (CFRP) composites are becoming widely used in defense, civil transport and other commercial industries. The need to accurately assess and predict damage mechanisms in composite systems is important for their design and implementation [1].

Damage progression in CFRP systems is dependent on several factors. While the matrix, fiber and fiber-matrix interface constituents have an obvious impact on the initiation and progression of damage, there are several design factors that also play a significant role. These include the fiber tow sizes, fiber architecture, fiber orientation and the lay-up sequence. An understanding of these design considerations presents significant opportunities for optimizing composites design to maximize their properties to meet the application requirements, and is being evaluated extensively. Many *in situ* and non-destructive evaluation techniques have been utilized to better understand damage evolution in composites [2,3]. Modal Acoustic Emission (MAE) is one of these techniques which has demonstrated utility throughout many composite systems, including those with metal, polymer and ceramic matrices [4–7]. It has been suggested by many that peak frequency analysis of waveforms generated in AE is an accurate way of categorizing damage types [8–11]. De Groot [8] and, more recently, Gutkin [8] and Arumugam [10], have presented interesting results correlating peak frequency (the frequency with the highest magnitude in the FFT spectrum) of fracture-generated acoustic emission and damage mechanisms. As summarized in Table 1, all these studies show similar trends in the relative frequency levels and the damage types, i.e. low frequencies for matrix cracks, high frequencies for fiber fracture, etc. The studies differed, however, in the actual frequency values for the damage types, and arrived at a different frequency spectrum for each damage type.

In this study, damage evolution via the use of MAE and peak frequency analysis is explored with respect to damage accumulation in different composite layups. MAE is a waveform based acoustic emission method which takes into account multiple modes or frequencies. Two dominant modes in thin plates are readily detected by MAE, the lowest order symmetric wave, known as the extensional (typically higher frequency), and the lowest order anti-symmetric wave, or flexural (typically lower frequency). Thus, it is critical in modal acoustic emission [4,5] to capture AE waveforms with wide frequency band sensors to ensure all meaningful wave modes are being captured. Surgeon and Wevers [6] and Johnson and Gudmundson [7] have proposed classification systems based on MAE acquisition, but are largely qualitative in

* Corresponding author.

http://dx.doi.org/10.1016/j.compscitech.2015.05.005
0266-3538/

Table 1
Summary of peak frequency findings of three different studies.

	Matrix crack (kHz)	Delamination (kHz)	Fiber/matrix debonding (kHz)	Fiber pull-out (kHz)	Fiber fracture (kHz)
De Groot (CFRP 6376)	50–175	225–300	–	175–225	300–525
Ramirez–Jimenez (GFRP)	–	–	80–110	200–300	425–525
Gutkin (CFRP IM7/8552)	0–50	50–150	200–300	500–600	400–500

nature. The latter work identified that transverse matrix cracks often have different waveform content, suggesting that they were possibly due to laminate layup and fracture geometry.

In this study, laminate composites with the same constituent content but different lay-up configurations were tested in tension. Transverse plies were the plies oriented 90° to the loading direction and were observed to be the primary region of transverse crack formation. Coupons with back-to-back 90° plies generated transverse matrix cracks around the composite centerline. Composites with surface 90° plies generated transverse surface cracks. The study compared these two systems to investigate whether there is a difference in acoustic response based on crack location. Acoustic emission was monitored for other composite layups, including layups with ±45° plies, during tensile testing with the intention of examining damage mechanisms and damage locations in these different composite laminate constructions, and understand their correlation to excitation or propagation of certain modal frequencies. Post-test microscopy was performed on failed specimens as well as specimens subject to intermediate tensile stress loads in interrupted tensile tests to understand the damage mechanisms, the location and type of damage initiation and the progression of damage as a function of stress.

2. Experimental

The composite system investigated was comprised of unidirectional AS4, high strength PAN carbon fiber plies preimpregnated with 8552 toughened epoxy resin, supplied by Hexcel Corporation.[1] Composite laminates were fabricated by UTC Aerospace Systems at their Riverside, CA, location utilizing conventional hand lay-up procedures and a standard 350 °F autoclave cure cycle.

Various ply layups were investigated, whose configurations are shown schematically in Fig. 1. Note that 0° fiber/ply orientation pertains to the loading direction and 90°, the perpendicular. Fiber volume fraction was nominally 60% of the total volume for all layup configurations. All panels featured symmetric layups, but the relative volume fraction of 0°, 45° and 90° plies varied in each panel, as shown in Fig. 1. Panel 2 had only 16 plies; all other panels had 24 plies. Panels 1, 2 and 3 featured instances of two adjacent 90 plies, referred to hereafter as double 90° plies. All panels had several instances of single 90° plies, referred to hereafter as single 90° plies. The number of such plies and their relative location varied among these panels. Panels 1 and 3 had only one instance of double 90 plies, which occurred along the midplane. Panel 2 featured double 90 plies on the surface and in the interior but not in the midplane. Both Panels 3 and 4 featured an alternating 0/90 symmetric lay-up with identical volume fraction of 0 and 90 plies. The only difference between Panels 3 and 4 was that Panel 3 featured 0 plies on the surface, while Panel 4 featured 90 plies on the surface. As a result, Panel 3 had a double 90 plies along the midplane, while Panel 4 had a double 0 plies.

Rectangular test coupons were tested according to ASTM D 3039 [12]. Specimens were 10″ long, and either 12.7, 25.4 or 38.1 mm wide. The specimens were each fixed with fiberglass tabs on either end with aero-grade Loctite E-120HP epoxy and cured in an oven in air at ~100°F for an hour to cure the epoxy. Tensile tests were carried out using an Instron[2] 5585 Series screw-driven test frame with a ±100 kN load cell. Strain was measured using a 1″ extensometer with 50% travel. Loading rate was 0.05″/min, and elastic moduli were measured from data acquired from 5 to 50 MPa. The acoustic emission system was a Fracture Wave Detector manufactured by Digital Wave Corporation.[3] Three or four wide-band sensors (50 kHz–2.0 MHz) were used, and the sampling rate for the system was set to 10 MHz to ensure all sensor output data was being recorded. 1024 data points for each waveform was recorded including 256 pre-trigger points. Sensor placement for the tensile tests is shown in Fig. 2. Data analysis, including Fast-Fourier Transforms (FFTs) and peak frequency identification, was performed in MATLAB on the signal captured from the sensor closest to the middle of the gage section, i.e., closest to the source event. The MATLAB script took raw waveform data, performed Fast Fourier Transforms on the appropriate gage events and output respective peak frequencies. Outer sensor separation was typically ~80 mm, and calibrated source location was carried out using a technique described in Morscher [13]. Only events in the middle ±20 mm of the specimen were used in the acoustic analysis, i.e., AE events which triggered the interior sensor(s), to ensure that no acoustic events were due to the machine or grip area. Threshold voltage for source location was set to 50 mV, which appeared to be the optimal level for filtering out noise and capturing true, relevant signals. The typical extensional velocities are also shown in Table 2.

3. Results and discussion

3.1. Mechanical behavior and acoustic response

Typical stress–strain curves are shown in Fig. 3a. The mechanical and acoustic emission parameters for each panel are summarized in Table 2. Note that only one of the specimens failed in the gage section which was from Panel 1 and failed at 739 MPa. The rest of the specimens evaluated in this study failed either in the grips, outside the ±20 mm central region of the specimen where AE was evaluated, or did not fail due to the lack of capacity of the load cell. Therefore, for the most part the tensile tests can be considered as "interrupted" and represented different levels of maximum stress experienced for each composite. This enabled characterization of different levels of stress-dependent damage for specimens from the same panel. There were 3 different widths (12.7, 25.4 and 38.1 mm) of composites tested; however, there did not seem to be an impact of width on the resulting acoustic emission profile.

Representative examples of cumulative acoustic energy (i.e., the sum of energies of each successive acoustic gage event) during tensile loading are shown in Fig. 3b. Note that panel 2 had the earliest onset of acoustic events, followed by panels 1, 4 and 3 and is tabulated in Table 2. The stress for the first AE event (Table 2) corresponds to the lowest stress at which an AE event is detected from the gage section. Similarly, the first "loud" event stress

[1] Hexcel Corporation, Stamford CT

[2] Instron, Norwood, MA

[3] Digital Wave Corp, Englewood, CO