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Criticality of degradation in composite materials subjected to cyclic loading

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ABSTRACT

Degradation of composite materials subject to cyclic loading is a multi-step process involving micro-cracks formation and progression until failure occurs. In this paper, the signatures of acoustic emission (AE) response emanating from composite specimens subjected to fully-reversed bending fatigue are studied. The composite is glass/epoxy (G10/FR4) laminates and the experiments cover different frequencies and displacement amplitudes. Results are presented for AE energy, counts and amplitudes. It is shown that the distribution of the cumulative AE amplitude can be described by a power law. Further, examination of the evolution of the probability density function (PDF) of the AE energy (counts) reveals two scaling zones wherein the transition from the low energy (count) to high energy (count) regime is identified. The low-energy phase represents very low damage or damage-free state of the laminate characterized by a power law with an exponent of $\alpha_E = 1.8 \pm 0.05$. In these series of experiments, AE energy release and AE counts follow the statistics and power laws that do not depend on the operational conditions.

1. Introduction

Recent research on the fracture of heterogeneous materials at the micro level [1] shows that the advancement of degradation is accompanied with bursts that follow a universal power-law distribution [2]. Decaying power laws are observed in the response of materials—in both simulations and experiments—subjected to the loading- and straining procedures [3–10].

Irrespective of the type of loading and the underlying damage mechanisms, material degradation is always accompanied with dissipation of strain energy [11–15]. A portion of this released energy is in the form of the acoustic emissions which itself is a subcategory of a broader phenomenon called the crackling noise [16–18] . This phenomenon is known to occur in diverse range of systems including paper crumpling [19], Barkhausen magnetic noise [20], earthquakes [21], systems with interfacial and sliding friction [22], intermittent plastic flow [23] and fracture of materials [24,25].

Recent research shows that AE signals emanating from fracture of different materials exhibit a behavior that can be described by decaying power law distribution [26–32]. For example, experiments on polyurethane foams conducted by Deschanel et al. [26] reveal that AE energy in creep and tensile experiments can be characterized by power law. Experiments dealing with fracture of paper samples with a small notch in tensile tests by Salminen et al. [27] also revealed that the energy distribution of AE signals exhibits a power law with an exponent of $\alpha = -1.25$. Similarly, the burst distribution in propagation of the interfacial crack along the weak plane of a block of Plexiglas is reported to follow a power law distribution with $\alpha = -1.7$ [28]. The crackling dynamics observed in [28] was later modeled by Laurson et al. [29] and Bonamy et al. [30] who classified this phenomenon as a self-organized critical phase transition [30].

The observation of the power-law behavior associated with the AE signatures is not confined to problems involving fracture and crack propagation. It is also seen in plastic deformation and dislocation dynamics of crystalline materials. For instance, the energy distribution of the acoustic emissions measured from single ice crystals under constant-stress creep tests exhibits a decaying power law with $\alpha = -1.6$ [6].

The applicability of power law in characterizing acoustic emission appears to be scale free and independent of the details of the system. While the AE signatures associated with the fracture of diverse array of materials are known to exhibit scale-free trend, relevant information on the behavior of materials subjected to cyclic fatigue loading is scarce. It is of interest to exploit the evolution of the acoustic emissions in the degradation of materials with microfracture(s) due to cyclic fatigue. For this purpose, woven glass/epoxy laminates are examined by means of AE. We seek to determine if there exists a scaling function which holds throughout the life of the laminates for different operational variables. We also present statistical behavior of AE features to examine the applicability of the concept of self-organized criticality to the fatigue fracture of the laminates.

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The outline of the paper is as follows. The specifications of the laminates are provided in Section 2. Experimental procedure and the typical behavior of the AE descriptors in a fully-reverse fatigue experiment are presented in Section 3. Also presented in Section 3 is the Scanning Electron Microscope (SEM) images taken from the fatigued surface of the specimens. Section 4 gives the statistical analyses on the AE features and their power law behavior followed by concluding remarks in Section 5.

2. Materials

Specimens tested are made of glass/epoxy (G10/FR4)—an unbalanced woven fabric composite with plain weave-and-aligned configuration— stacked in fifteen layers within the thickness of 3 mm. The structure of this type of composite is formed by interlacing two sets of orthogonal yarns (warp and weft) as shown in Fig. 1a. Two unidirectional layers stacked in [0°/90°] made of continuous filament glass cloth in epoxy resin binder form each woven layer. The specimens are prepared with on-axis stacking sequences in which warp and weft directions are aligned with the load direction. They are manufactured based upon the ASTM STP 566 for use in reverse-bending fatigue tests with a similar configuration reported in Refs. [33,34]. For a detailed description of the woven types of composites refer to [35]. The G10/FR4 crosswise elastic modulus and the lengthwise elastic modulus in flexure are 15.1 MPa and 18.6 MPa, respectively. The crosswise and lengthwise flexural strength are 310 MPa and 379 MPa, respectively.

A woven composite laminate has internal defects in both macro- and micro-scale due to its specific structure and manufacturing procedure (Fig. 1b). From a chronological perspective, in the tested woven glass/epoxy, the initial surface damage starts from the crossover points where wefts cross the warps and results in micro crack advancement and coalescence. Hence, this layered material is susceptible to debonding and interlayer stress concentration.

3. Experimental procedure

3.1. Apparatus and data acquisition

The description of the bending fatigue apparatus is reported elsewhere [33]. Briefly, the specimen is clamped at one end and the other end is oscillated with a specified amplitude and frequency. A PCI-2, a two-channel AE system which samples up to a rate of 10 MHz, measures the acoustic emissions from the specimen during the entire test, i.e., until failure occurs.

The emitted waves are detected by a wide-band piezoelectric sensor and converted to an electrical signal. The AE sensor, a *WSa* model manufactured by Physical Acoustic Corporation, is a wide band AE sensor that has a frequency range of 100–900 kHz. The sensor is in 19.02 mm diameter with a stainless steel body and a ceramic face end. The temperature stability of the sensor is in the range of −65 °C to 175 °C. It is acoustically coupled to the specimen using a gel-type ultrasonic couplant and is firmly attached to the specimen. The received signals are amplified with 40 dB pre-amplification. The threshold level on AE counts is set to 45 dB and the Peak Definition Time (PDT), Hit Definition Time (HDT) and Hit Lockout Time (HLT) are set to 50, 200, 300, respectively. Post-processing is performed on the measured data before performing statistical analysis. For example, AE data with average frequency—the ratio of the counts over duration—above 450 kHz are eliminated from the analysis. Signals of zero energy are also filtered out according to the filtering rules on AE signals measured from composite; See Refs. [36,37].

The extracted AE features are counts, amplitudes, energy and average frequency. The counts are defined as the number of times that the AE amplitudes exceed a preset level (threshold) and the energy is derived via integration of the rectified voltage signal over the duration of the AE signal and is computed by AEwin software. The AE energy emanates from the elastic energy release and the energy release due to fracturing processes that occur during the cyclic loading [38–40].

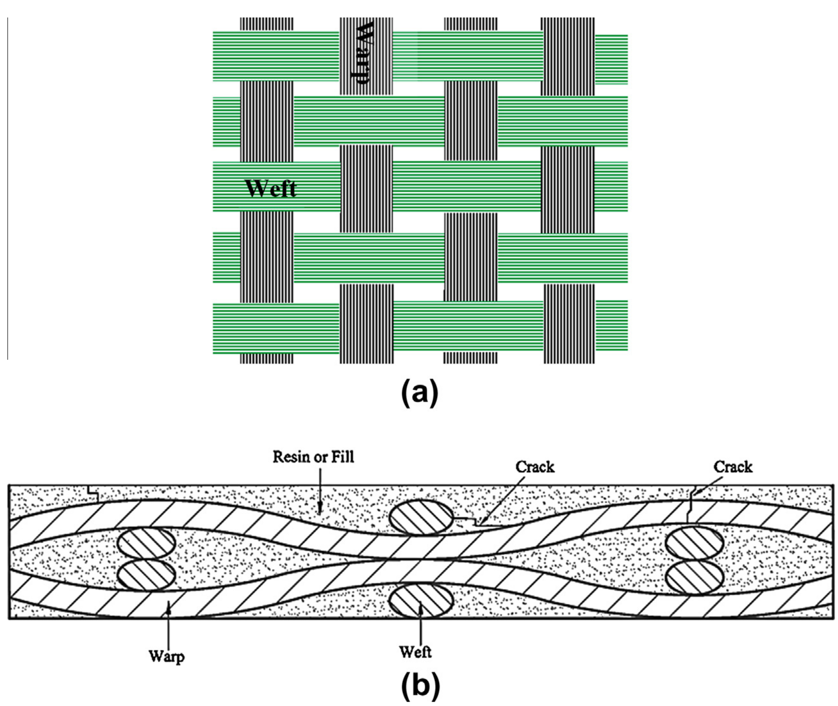

Fig. 1. (a) Plain weave pattern of each layer (without matrix). (b) Illustration of cracks that appear within the laminate in different cycles of operation. Due to specific design of the woven types of composites, the locations where the warps pass over the weft are sites of stress concentration from where initial surface cracks start.