Composites Science and Technology 95 (2014) 21–28

Contents lists available at ScienceDirect

Composites Science and Technology

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

Damage tolerance in glass reinforced polymer laminates

Kenny W. Campbell [a], Peter H. Mott [b,*]

[a] Science Applications International Corporation, La Plata, MD 20646, United States
[b] Chemistry Division, U.S. Naval Research Laboratory, Washington, DC 20375, United States

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 6 January 2014
Accepted 5 February 2014
Available online 11 February 2014

Keywords:
C. Damage mechanics
B. Mechanical properties
A. Glass fibers
D. Acoustic emission

ABSTRACT

Ten glass-reinforced, rubber-toughened polymer laminate panels were tested in 3-point bending in a series of loading–unloading cycles, with increasing deflection. Damage was quantified by the stiffness decrease, hysteresis and residual strain. The threshold for unacceptable damage occurred when the strain reached *ca.* 0.6%. Acoustic emission (AE) was monitored by four sensors on the compressive side of the samples; the correspondence between the damage threshold and different AE measures was explored, with hit strength (i.e., the measured area under the rectified signal envelope, or MARSE) providing the clearest correlation. Separating events with AE hits that were recorded by all four sensors ("associated") from those recorded by three or fewer sensors ("unassociated"), distinguished matrix from fiber damage. Viscoelastic effects were identified by separating hits that occurred during loading from those that occurred during hold and unloading.

1. Introduction

In many applications with unpredictable loading, the superior properties of laminated, glass-reinforced composites are degraded by minor over-straining. Damage affects these composites differently from that of conventional structural materials, such as ductile metals or polymeric glasses. For conventional materials, an uncommon, small over-straining usually causes plastic deformation, with negligible changes to overall mechanical properties; on the other hand for composites, delamination and fiber failure lead to significant reductions in stiffness and strength. Due in part to sensitivity to damage, the design allowable for composites is low – typically 0.3% strain, ¼ that of the fiber failure strain – effacing much of the weight and cost saving [1]. When deformation must exceed these limits, a better understanding of the scope of damage, and its tolerance, is needed to take full advantage of these materials.

Acoustic emission (AE) holds promise as a method to evaluate the health of such structures. For laminated composites there are different types of damage, such as matrix cracking, fiber/matrix disbonding, delamination, and fiber breakage, occurring over different but overlapping ranges of strain. Amplitude sorting [2] has been used to discriminate these types: in tensile loading, this has been corroborated by scanning electron microscopy [3–6] and ultrasonic backscatter [7]; likewise, the correlations have been demonstrated in three-point bending [8]. Faster computers and better software have enabled transient or modal analysis, where different waveforms have been linked to damage types [9–12]. Clustering analysis has been shown to discern damage types from AE signal characteristics [10–14]. Damage has also been related to the AE signal rise angle [15,16]. These studies have demonstrated and improved the diagnostic effectiveness of AE, and through these connections, with consideration to the attenuation [17,18], it is possible to determine the type and extent of damage in a material as it is strained.

Building on these advancements, the purpose of this work is to show how AE may be used to avoid intolerable damage. The tested laminate is commonly used for large marine fabrications (e.g., mast fairings, bow domes, propulsor components, turtleback superstructures, etc. [19]) and is representative of many fiberglass composites [20,21]. During installation it can be necessary to flex an article to higher strains than what normally occurs in service, to where it is possible to generate flaws that weaken the structure. To investigate the potential for installation damage, specimens were subjected to bending cycles with increasing strain, the damage quantified by the stiffness decrease, hysteresis, and residual strain, and correlated to AE data. We consider our findings to be generally applicable to fiber reinforced polymer matrix composites.

2. Experimental

The tested composite was fabricated from 12 plies of Cytec Industries Cycom 5920/1583, a rubber toughened epoxy prepreg

---

* Corresponding author. Tel.: +1 202 767 1720; fax: +1 202 767 0594.
E-mail address: peter.mott@nrl.navy.mil (P.H. Mott).

http://dx.doi.org/10.1016/j.compscitech.2014.02.004
0266-3538/Published by Elsevier Ltd.

reinforced with E-glass fibers, which was developed for immersed saltwater use. The layers contain fibers in the 0° and 90° directions, with all plies laid up with warp directions parallel to the long axis of the sample (an all 0° warp lay-up), and autoclave cured using a proprietary heat and pressure sequence. The cured sheet was cut into panels, with dimensions 470 mm long × 90 mm wide × 5 mm thick.

Ten panels were subjected to 3-point bending as shown in Fig. 1a, using an Instron 5500R test machine. The flexure sequence, shown in Fig. 1b, consisted of slow loading (1.0 mm/min, strain rate $1.2 \times 10^{-5}\ \mathrm{s}^{-1}$) followed by quick unloading (−10.0 mm/min, strain rate $-12 \times 10^{-5}\ \mathrm{s}^{-1}$), and a 10 s hold time between the changes. The maximum deflection grew in each cycle: for the first cycle it was 2 mm, and increased by 1 mm in each succeeding cycle, for ten cycles (11 mm total deflection). After this the samples were flexed to failure. The visible damage occurred near the loading pin, which consisted of fiber failure (~10 mm band), surrounded by delaminations (~35 mm). The stress at the loading pin was found by

$$\sigma = \frac{3Pl}{2wt^2} \tag{1}$$

where P is the load, and l, w, and t are the respective loading span length, sample width and thickness. The strain data were from a Vishay CEA-06-250UW-350 gauge bonded to the tension side, which has a $6.35 \times 4.57\ \mathrm{mm}^2$ sensing area. When the strain exceeded *ca.* 2% this gauge became unreliable, so strains beyond this value were determined from

$$\varepsilon = \frac{6dt}{l^2} \tag{2}$$

where d is the center deflection. This relation was verified by comparing the deflection and strain gauge data at low strain.

The acoustic emission was detected by four Physical Acoustics R15I-AST piezoelectric transducers, with integral preamplifiers, connected to a Physical Acoustics 4-channel μDiSP system. The transducers had resonant frequencies of 125 kHz (plane waves) and 153 kHz (surface waves), and were secured with vinyl tape using Sonotech Ul tragel II as a coupling medium. A sketch of the hit voltage $V(t)$ is shown in Fig. 2, identifying the threshold V_T, duration t_D, and hit strength found from the measured area under the rectified signal envelope (MARSE). The amplitude is (in $\mathrm{dB_{AE}}$)

$$A = 20 \log \frac{V_M}{V_R} - G \tag{3}$$

where V_M is the maximum hit voltage, V_R is a 1.0 μV reference at the preamplifier input, and G is the preamplifier gain, which was fixed by transducer circuitry to 40 $\mathrm{dB_{AE}}$. The amplitude threshold was set to 45 $\mathrm{dB_{AE}}$ ($V_T = 17.8$ mV), which discards the noise from the loading fixture, as determined by experiment. The hit strength (i.e., MARSE) is computed by integrating the rectified peak signal voltages $|V_P(t)|$ over the time the amplitude exceeds the threshold, i.e., the hit duration:

$$M = \int_{t_0}^{t_1} |V_P(t)|\,dt. \tag{4}$$

In strict terms M is not energy, but nevertheless it is proportional to the hit energy as it accounts for both amplitude and duration.

Amplitude attenuation was determined from pencil lead breaks carried out at 50 mm intervals along the sample. The result, 0.033 $\mathrm{dB_{AE}}$/mm, indicates that from an event under the center load pin, where almost all damage occurs, the amplitude difference between the outermost and innermost detectors is *ca.* 3.1 $\mathrm{dB_{AE}}$. Given the data scatter, this difference was acceptable.

Using linear beam theory, it can be shown that this loading geometry limits the transverse shear stress to 1.2% of the tensile

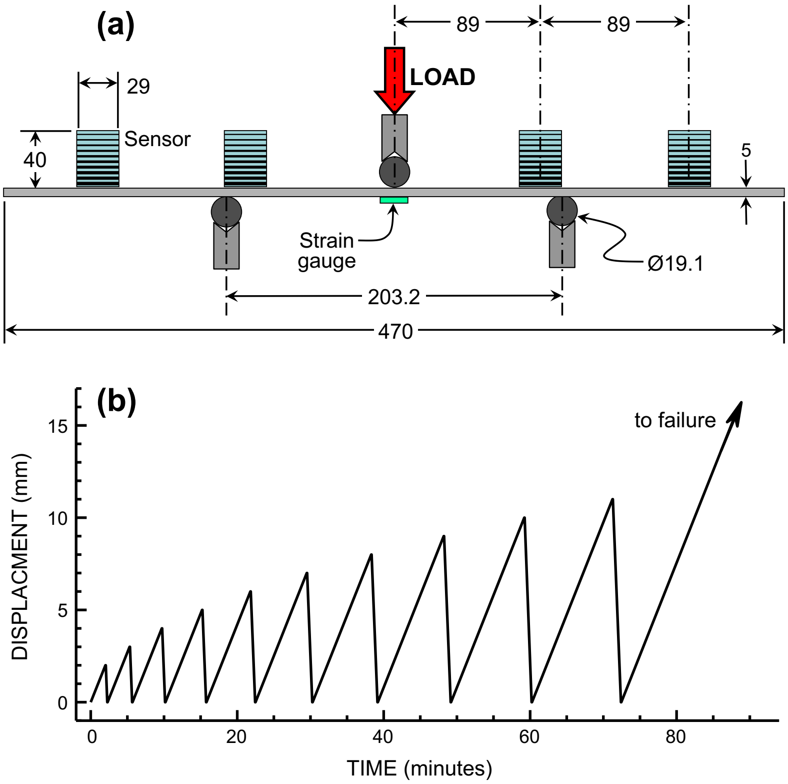

Fig. 1. (a) Schematic of loading. Dimensions are in mm; sample width (normal to page) was 90 mm. (b) Load pin displacement: the respective loading and unloading rates were 1.0 and −10.0 mm/min, corresponding to strain rates of 1.3×10^{-3} and $-13 \times 10^{-3}\ \mathrm{s}^{-1}$.