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Development of a low data event timer for monitoring an advancing crack in fracture

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Abstract

Monitoring the crack position and velocity in a fracture specimen can be difficult and laborious. In addition, the data storage requirements can be considerable depending upon the testing conditions. A low data event timer was developed to alleviate these problems. The timer generates a time-stamp when a circuit is broken. A continuous data record is not required, and this greatly reduces the data logging requirements. The test apparatus was applied to cantilever beams bonded with a structural epoxy and tested under different conditions, such as stable to unstable transitions and different temperature extremes. The results indicate that the approach eliminates problems associated with other types of crack measurement and greatly simplifies the measuring process.

Keywords: A. Epoxy/epoxides; B. Fracture mechanics; D. Fracture; Crack location

1. Introduction

One of the more common methods used in fracture mechanics analysis is the energy balance approach. The energy approach assumes that fracture occurs when enough energy is available to exceed the material's resistance to fracture. For linear elastic materials, Irwin put this in terms of a critical energy release rate, G_C, with crack extension occurring when this value is exceeded [1]. In the case of a cracked plate of uniform width that is dead-loaded, the critical energy release rate may be written as

$$G_C = \frac{P_C^2}{2b}\frac{\partial C}{\partial a}, \tag{1}$$

where P_C is the critical load at which crack extension occurs, b is the width of the plate, C is the compliance of the specimen, and a is the crack length.

For nonlinear elastic materials, Rice introduced a critical energy release rate, J, also known as the J-integral [2]. The J-integral can be written in terms of load and displacement for a crack in a plate of uniform thickness as

$$J = \int_0^P \left(\frac{\partial \delta}{\partial a}\right)_P \mathrm{d}P \quad \text{(fixed load condition)}, \tag{2}$$

$$J = \int_0^\delta \left(\frac{\partial P}{\partial a}\right)_\delta \mathrm{d}\delta \quad \text{(fixed displacement condition)}, \tag{3}$$

where δ is the displacement.

Experimental determination of these energy release rates requires knowledge of the load, displacement, and crack position (often as a function of time). Load and displacement measurements are generally determined through the use of load cells and extensometers, respectively. Knowledge of the crack location, or crack velocity in the case of dynamic fracture, can be difficult to measure experimentally, and is usually labor intensive. Generally, there are five approaches used for

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measuring crack location and velocity. These methods are optical, fractography, compliance, acoustic, and potentiometric [3].

Optical methods measure the location of the crack tip by observation of the surface of the test specimen. For slow crack speeds, magnifying instruments used in conjunction with a measuring scale allow for accurate crack velocity measurements. As the crack velocity increases, high-speed recording devices may be required [4,5]. Special techniques such as photoelasticity, Moiré fringes, or shadowgraphy can improve the measurement accuracy [3,6].

Fractography is a post-mortem examination method. The post-failure topography of the fracture surface can yield information about the crack's shape and position. One extension of this technique is to superimpose an ultrasonic shear vibration on the main load [3]. Such an approach allows a direct correlation between crack velocity and microscopic morphology [7].

The compliance method uses a constitutive relation to describe the crack position in terms of the specimen dimensions, modulus, and load. The accuracy of the relation can be improved by inclusion of a strain term, which can be explicitly measured with a strain gage. This technique is usually restricted to special geometries [3].

The acoustic method measures the propagation of a wave through a solid continuum. Regions where the material properties are changing will cause a change in the propagating wave. Artifacts such as a discontinuity will cause a reflection of the wave, which can be experimentally measured [3]. Such methods have been used to measure fracture in a pressure vessel [8].

One of the more common approaches and the one that will remain the topic of this paper is the potentiometric technique. This method measures the change in electrical conductivity of the test material or of gages attached to the specimen. For the former, the potential of the conducting material changes as a crack propagates through it. Through the use of a calibration curve, the crack position and velocity can be established [3]. The latter method measures the variation of electrical resistance of a conductive coating deposited on the crack path [9].

The conductive coating may be placed directly on the test specimen if the material is insulative or onto an insulating support. Generally, the attached gage comes in one of two forms: continuous [3,9,10] or grid [11,12]. An illustration of both gage types can be seen in Fig. 1.

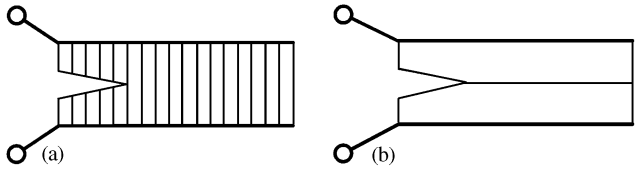

Fig. 1. Conductive gages: (a) grid, (b) continuous.

The resistance grid gives discrete steps in a resistance-versus-time curve, but allows no measurements between each circuit. The continuous gage allows continuous measurements to be made, but has some nonlinear behavior in a resistance-versus-time curve, and a calibration curve is required for each gage geometry.

The primary problem with the potentiometric gages is that they might not track the cracks in the test materials. Possible reasons include test material and insulating layer with different stress–strain behaviors, or conductive material that is too ductile or brittle. Another limitation of the potentiometric gage is that the gage does not track the explicit location of the crack tip. This can present problems if the fracture test requires something besides mode I opening at a single edge of the specimen (e.g., double edge notched tension panels).

One issue that applies to all of the listed testing techniques (i.e., optical, fractography, compliance, acoustic, or potentiometric) is that the sampling rate is proportional to the crack velocity. At very fast crack speeds, the sampling rate is often in the order of microseconds. The data file associated with such a failure event can be of large magnitude and significant data reduction may be required.

One of the more common geometries used in fracture testing is the cantilever beam. The critical mode I fracture energy, G_{IC}, for a cantilever beam is

$$G_{IC} = \frac{P_C^2}{2b}\frac{\partial C}{\partial a}, \tag{4}$$

where P_C is the critical load, b is the width of the beam, C is the compliance of the adherend, and a is the crack position. This relation assumes linear elastic behavior. Mostovoy et al. used simple shear-corrected beam theory to express the fracture energy for adhesively bonded double cantilever beam (DCB) adherends as

$$G_{IC} = \frac{P_C^2}{2Eb^2}\left(\frac{3a^2}{h^3}+\frac{1}{h}\right), \tag{5}$$

where E is Young's modulus of the beams, and h is the beam height [13]. The tapered double cantilever beam (TDCB) specimen is designed so that $\partial C/\partial a$ is a constant. This was done by machining the TDCB adherend so that the term in brackets is constant i.e.,

$$\left(\frac{3a^2}{h^3}+\frac{1}{h}\right) = m, \tag{6}$$

where m is a shape factor. For ASTM D 3433, m is set equal to $35.43\,\mathrm{cm}^{-1}$. The advantage of this geometry is that the crack grows linearly as the adherend is loaded at a constant displacement rate.

At ATK Thiokol, in excess of 2500 adhesive fracture tests of the TDCB variety are conducted annually. The test times vary from a few seconds to several days. Measuring the crack position and velocity of even a small percentage of these tests is difficult because of the