NOVEL INSTRUMENTATION FOR RAPID ASSESSMENT OF INTERNAL DAMAGE IN COMPOSITE MATERIALS

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Abstract

Novel instrumentation interfaced to a mechanical tapping probe for dental applications has been developed that can locally determine the damping capacity of material samples and structures. The present system is portable and can quickly access surfaces that are difficult to reach with other nondestructive techniques. The measured values of local damping capacity may be used to locate and assess internal damage as indicated by comparisons with ultrasonic scans of the specimens. The relationship between internal delamination/microcracking and damping capacity in composites makes the present system acutely sensitive for assessing the extent of damage in these materials.

Introduction

One of the difficulties in using composites in engineering structures concerns the detection of internal damage comprised of microcracking and delamination [1, 2]. Composites are generally more susceptible to damage development than are unreinforced metals, particularly when under stresses that approach the tensile strength of the material. For example, damage can result in an airframe structure from an unexpected impact or overload situation such as a hard landing. Since the damage is often within the structure of the composite, it can be difficult to detect from an examination of the external surfaces. Thus, nondestructive testing systems that can economically detect internal damage in composites are needed for the safe operation of advanced engineering structures.

The sudden application of force on a solid body generally results in a stress wave that propagates from the impacted surface. The deformation of all solids undergoing impact has both an elastic and inelastic character [3]. Energy is conserved by the elastic mode of deformation which facilitates the propagation of the stress wave. By contrast, the inelastic mode of deformation dissipates the energy of the stress wave as it propagates. The relative extent to which a material deforms inelastically and dampens strain energy may be characterized as its loss coefficient, η, given by

$$\eta = \frac{D}{2\pi U} \qquad (1)$$

where D is the total energy dissipated per unit volume and U is the input energy per unit volume generated by the applied stress [3]. The energy of an elastic wave is dissipated after it has traveled a relatively short distance in inelastic materials with a high loss coefficient. By contrast, stress waves in elastic materials with a low loss coefficient may travel long distances with very little dissipation [3]. In general, microstructural processes that give rise to internal friction increase the loss coefficient of a material. Such processes include the sliding of free surfaces that can exist within the solid. In composite materials, internal damage will generate such free surfaces, especially when the damage is in the form of broken fibers and delaminations. Thus, as a composite material is damaged in this manner, it is reasonable to conclude that its damping capacity, as characterized by its loss coefficient, should increase in the damaged region.

Novel instrumentation that uses an impact probe for making nondestructive quantitative measurements of damping capacity in engineering materials has been optimized in this present work for use in the detection of internal damage in fiber-reinforced composite materials. Damping test machines are generally large and bulky, and they require test specimens be cut to specific dimensions [4]. The method described in the present paper is able to test a specimen cut to practically any size and shape. The present test system is portable, lightweight, and low in cost. In addition, the present system does not require a liquid couplant, which is typically necessary for conventional ultrasonic inspection methods. It is anticipated that the present instrumentation would be particularly advantageous at locations that are difficult to access or where liquid couplants cannot be used. Thus, the present instrumentation provides a convenient and economic method for detecting changes in the mechanical properties of components qualitatively and accurately in a non-destructive manner. Evidence indicating the capabilities of this instrumentation for detecting internal damage in fiber-reinforced composite materials is presented in the following.

Experimental

Materials

The model materials that were used to calibrate the experimental system were acrylic [polymethylmethacrylate (PMMA)] and commercial purity aluminum. These materials have well characterized energy loss coefficient values that are listed in the published literature [3].

The composite materials that were tested were toughened epoxy resin reinforced with carbon fibers, R6376/T500-12K, from CIBA GEIGY Composites Division. The laminations consisted of 24 plies with an orientation of $[45/90/-45/0]_{3S}$.

Test Procedure

The experimental system consists of a hand-held probe that is part of a Siemens Periotest device originally developed for making qualitative assessments of the rigidity of natural teeth and dentures. The present system integrates this device with a desktop computer equipped with a high speed data acquisition board and custom virtual instrumentation software based on the LabVIEW graphical programming language (See Figure 1). To test

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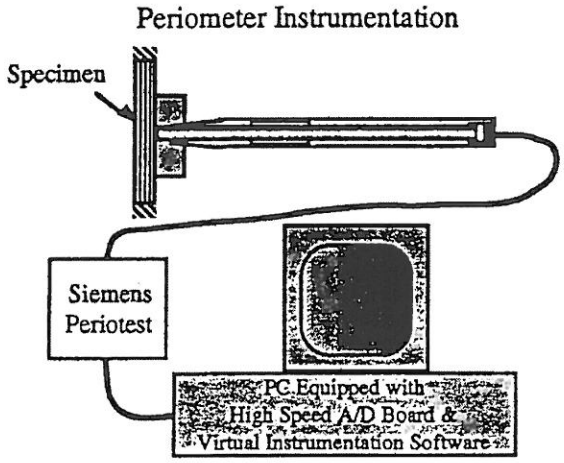

Figure 1: Schematic of Novel Instrumentation

a composite sample, the tip of the probe is placed perpendicular to the specimen and activated with the push of a button. A rod is then driven by an electromagnetic coil to impact the specimen 16 times in four seconds. A signal corresponding to the shock wave resulting from each impact is sent to the computer via the high speed data acquisition board. The computer analyzes 10 of the 16 impacts and quantitatively determines the damping capacity of the specimen beneath the probe.

Test specimens used in the present experiments were fixed in a table vice equipped with plastic chucks prior to testing. The vice was tightened to the same torque for each specimen through the use of a torque wrench to insure consistent external conditions. A grid was drawn on each sample for accurate placement of the impact probe. Additionally, the tip of the impact probe was fitted with a circular plate to facilitate perpendicular alignment to the specimen.

Each specimen was tested in 13 separate locations in order to develop a damage profile (Figure 2). Equidistant readings on each specimen were averaged to account for the asymmetric damage field surrounding the impact site.

Determination Of The Energy Loss Coefficient.

The value of the input energy, U, for the present system is assumed to be approximately equal to the kinetic energy of the impact rod just prior to contact with the specimen [5]. The energy dissipated, D, is defined to be

$$D = U - E_\varepsilon - D_p \tag{2}$$

where E_ε is the elastic strain energy conserved and Dp is the energy dissipated by sources external to the specimen. Substituting Eq. (2) into Eq. (1), the loss coefficient is given as

$$\eta = \frac{1}{2\pi}\left[1 - \frac{E_\varepsilon + D_p}{U}\right] \quad . \tag{3}$$

The kinetic energy of the rod prior to impact was determined by measuring the mass and velocity of the impact rod just prior to

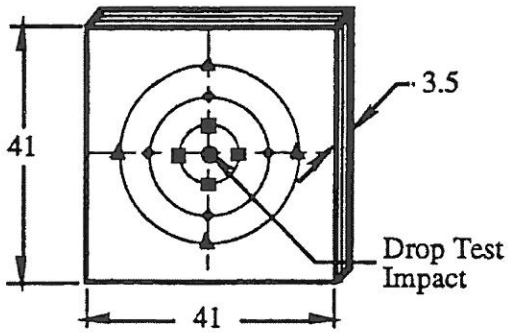

Figure 2: Dimensions of the present composite specimens. Each specimen was tested along the orthogonal center-lines shown. All dimensions are in mm.

contact with the specimen. The average value of U was determined to be approximately 3.25×10^{-6} J.

Calibrating the experimental system

The acceleration of the rod before and during impact was measured for two model materials, acrylic and aluminum, with known damping characteristics to calibrate the experimental instrumentation [6]. The statistical variation of the material measurements was determined with data which provided an assessment of the overall accuracy of the instrumentation. The standard deviation of the data for each measurement was determined for both the maximum strain energy returned from the specimen and η. The elastic strain energy conserved is given by

$$E_\varepsilon = CF^2 \tag{4}$$

where the constant C is the effective elastic modulus of the impact rod and F is the impact force determined by the product of the maximum acceleration in the stress wave resulting from the impact and the mass of the rod [4]. The value of D_p should not vary significantly with different material specimens since it primarily depends on energy losses in the Periotest probe, geometry of the specimen, and specimen gripping arrangement. Thus, it is reasonable to assume that D_p is constant for a given sample geometry and grip configuration. To determine the values of C and D_p for a given testing configuration, it was necessary to measure the elastic strain energy conserved for two model materials that have known loss coefficient values. By substituting Eq. (4) into Eq. (3) and rearranging terms, the value of C is then given by

$$C = \frac{2\pi U(\eta_1 - \eta_2)}{F_1 - F_2} \tag{5}$$

where the subscripts 1 and 2 refer to the acrylic and aluminum model materials respectively. The value of D_p is then given by

$$D_p = U(1 - 2\pi\eta) - CF^2 \tag{6}$$

for either of the two model materials. It was noted that destructive interference from reflected stress waves could result in errors when the aluminum sample was impacted at the center. This problem is easily remedied by impacting the sample at a location that is slightly off-center. It was also necessary to leave the Periotest unit on for 15 minutes prior to testing to avoid electronic drift effects.

Induced Damage In The Composite Materials

Damage was induced in the composite samples by subjecting them to a standard direct impact drop weight test. A hemispherical tip of 16.1 mm diameter with a mass of 5.34 kg was dropped from various heights resulting in damage to the centers of four samples from impact energies of 35, 81, 127, and 173 J. Ultrasonic C -scans, using a Kraut Kramer Branson scanner with a 5 MHz transducer, were performed on each test specimen after damage testing. Comparisons between the data from the C-scans and the data obtained with the present impact system were then conducted.

Experimental Results

Energy Loss Coefficient Values For The Composite Materials

Figure 3 shows the values of η for the composite material specimens given by the experimental system. These results confirm two significant phenomena regarding the damaged samples. First, the graphs show that more energy dissipation is measured for damage resulting from higher impact energies. This increase in damping capacity is to be expected since greater damage provides more sources of internal friction. Secondly, as the probe was positioned to test points away from the drop test impact site, energy dissipation decreases correctly correlating with the decreasing gradient of damage.

C-scan results provide a qualitative assessment of damage for comparion with the present loss coefficient values.

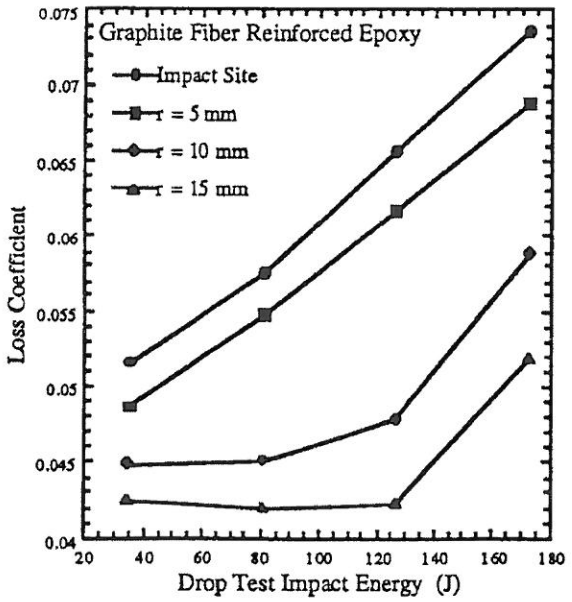

Figure 3: Loss Coefficient as a function of the impact energy for the drop test used to induce damage in the specimen. The measurements are average values taken at the same distance from the impact site, r, in four orthogonal directions as indicated in Figure 2.

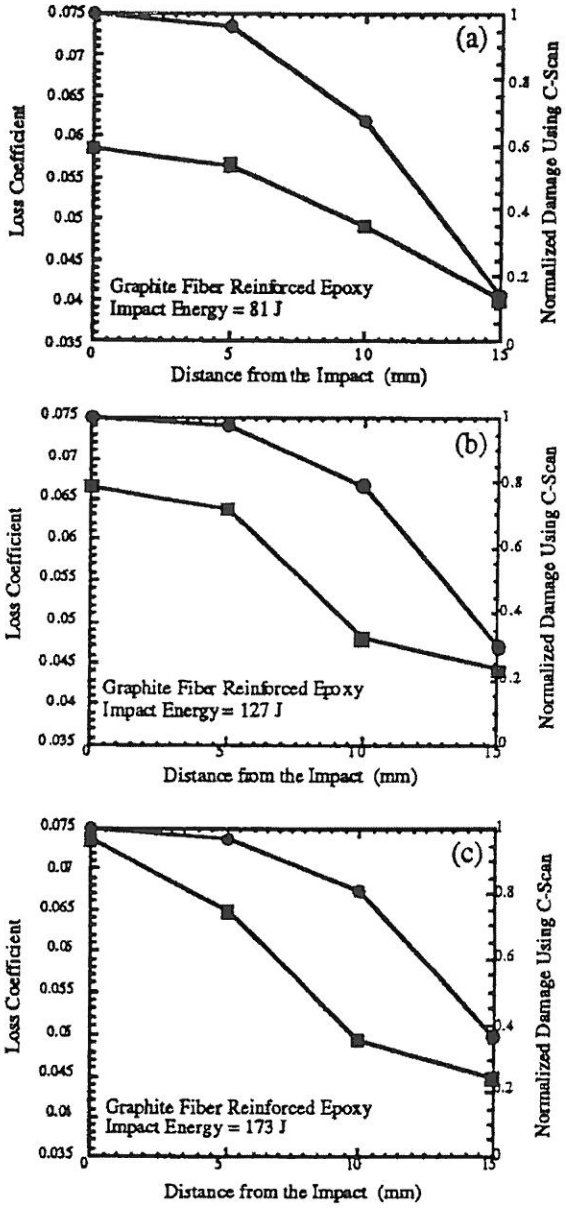

Figure 4: Loss Coefficient and normalized damage values for C-Scan measurements vs. distance from impact sites. Drop test impact energy for each sample is (a) 81, (b) 127, and (c) 173 J. The square symbols correspond to the loss coefficient and the circles correspond to the C-scan measurements.

A pulse-echo C-scan intensity map [7] consisting of an linear color scale to represent different degrees of damage was performed for each of the specimens. These results were quantified by calculating a normalized damage parameter, which is the ratio of the C-scan intensity for each location over the intensity corresponding to the maximum damage as indicated by the color scale. A comparison of the results indicates good agreement between the data for the two non-destructive testing systems as shown in Figures 4. We also note that the loss coefficient values appear to be sensitive to the extent of damage at the drop test

impact site while no variation with impact energy is observed for the normalized C-scan values at this position This difference in the results is discussed further in the following section.

Discussion

For the present instrumentation, 10 probe impacts are analyzed to determine a single averaged value of η. Typically, the standard deviation of the 10 readings is less than 0.1% of the measured value. If the standard deviation was greater than this due to accidental movement of the probe during testing, the measurement was repeated. Additionally, each location was tested four times and then averaged to compensate for slight variations in pressure and alignment. With practice an operator can consistently reproduce accurate results when holding the probe by hand.

To maximize the accuracy of the system, the clamped edges of the composite material should be smooth and free of extraneous fibers since damaged edges on a specimen can give rise to additional damping. Further, more consistent results are obtained when the Periotest probe is held against the specimen using a mechanical fixture. This procedure eliminates slight movements and pressure variations which can occur during hand-held operation. However, this movement typically becomes insignificant with regard to the accuracy of the results once the operator has had a minimal amount of experience in handling the probe.

Internal damage in graphite-fiber reinforced PMCs can result in two significant sources of increased energy dissipation. First, internal friction from the sliding of crack and delamination surfaces can result in increased energy damping. Second, increased energy dissipation results as more of the stress is supported by the polymer matrix due to fiber breakage. We note that the deformation of the polymer matrix generally dissipates more energy than the reinforcing fibers. Thus, damping capacity should increase as the ratio of intact fibers to matrix decreases.. This suggests that the observed dependence of damping capacity on extent of damage should be valid regardless of the level of damage. On the other hand, the present C-scan method detects damage by the amplitude of acoustic waves that travel through the damaged region after being reflected from the back surface of the sample [7]. Once the damage reaches a level that prevents the reflected acoustic signal from traversing the specimen, further damage is not detected. This effect is demonstrated in Figure 4 which indicates a constant C-scan reading at the drop test impact site despite an increased level of impact energy. The sensitivity of the present instrumentation is not limited in this manner with respect to damage level as demonstrated by the increasing value of the loss coefficient at the impact site with increasing impact energy.

Conclusions

The present instrumentation is capable of accurately determining damping capacity in terms of the loss coefficient, η, in a graphite fiber reinforced PMC. Measurements of η increase with decreasing distance to the impact site for drop tested composite samples. Values of η are also found to increase with increasing drop impact energy for these samples. Comparisons of these results with ultrasonic C-scan data further confirm that the local values of η determined with the present instrumentation can be used to assess the spatial distribution of internal damage in PMCs.

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