NONDESTRUCTIVE EVALUATION OF FIBER COMPOSITE LAMINATES

BY THERMOELASTIC EMISSION

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INTRODUCTION

During the rapid cyclic loading of a structure (> .5 Hz), the cyclic variation of surface temperature can be measured with infrared radiometry. The temperature variation is related to the reversible, adiabatic deformation of the material. Adiabatic thermography differs from dissipative thermography, where temperature variations are associated primarily with dissipated energy rather than stored energy. The radiometer system used in the present investigation is capable of resolving local stresses that reflect global stress distributions and macroscopic variations in material properties, including flaws and damage. The present paper emphasizes fundamental aspects of the technique for the nondestructive evaluation of fiber-reinforced composite laminates.

BACKGROUND

During an adiabatic deformation of matter, no heat transfer occurs across the boundary of any control volume. Adiabatic deformation occurs when matter is mechanically excited at a sufficiently high frequency. Under such conditions, energy is reversibly transferred into the material with the load, and it is manifested as a small, variation of temperature at the excitation frequency. Using fundamental principals of thermodynamics, Thomson [1] formulated expression (1), which relates the dilatational stress components, σ_i (i=1,2,3), in homogeneous, isotropic, linear-elastic matter and the resulting adiabatic temperature change, Θ,

$$\Theta = - \frac{T_o \alpha}{c_\sigma} (\sigma_1 + \sigma_2 + \sigma_3) \tag{1}$$

where T_o is the initial temperature of the material, α is the thermal expansion coefficient, and c_σ is the volumetric specific heat at constant stress. Expression (1) implies that the temperature of matter with a positive thermal expansion coefficient will decrease under tension, and increase under compression. Biot [2] gives the counterpart of eq. (1) for anisotropic solids as

$$\Theta = - \frac{T_o}{c_\varepsilon} \alpha_{kl} C_{ijkl} \varepsilon_{ij} \tag{2}$$

where α_{kl} is the thermal expansion tensor, c_ε is the volumetric specific heat at constant strain, C_{ijkl} is the stiffness tensor, and ε_{ij} is the linear strain tensor (summation of repeated indices implied).

Expression (2) can be used to describe the adiabatic temperature change occuring in anisotropic fiber composite materials provided the effective thermoelastic constants of the plies are known [3]. A more realistic approach is to evaluate the heterogeneous deformations and temperature changes of the fiber and matrix constituents separately, and average the temperatures to arrive at the net composite temperature change measured in the laboratory. During an adiabatic deformation, the temperature change in each ply of a laminated composite plate-like structure will be different at a given planar location because of unequal states of stress in the fibers and matrix from ply to ply. This fact is of utmost importance in the interpretation of surface-ply temperature measurements.

The feasibility of stress analysis by thermoelastic measurement depends upon the availability of a temperature transducer with a sensitivity on the order of .001 K and the capability of measuring dynamic temperature variations at frequencies of .5 Hz or higher (depending on the frequency required for adiabatic deformation). One method that meets these criteria is the measurement of infrared surface radiation. Modern infrared radiometers have both the sensitivity and response time required for this application, and have been marketed by the Ometron Co. under the trade name SPATE (Stress Pattern Analysis by Thermal Emission) expressly for stress field measurements. For small temperature variations, δT, the change in photon emittance detected by the radiometer, δQ, is found by differentiating the Stefan-Boltzmann Law, as in eq. (3),

$$(\delta Q) = 3 \, e \, B \, T^2 \, (\delta T) \tag{3}$$

where e is the surface emissivity, B is a constant, and T is the initial surface temperature [4]. The SPATE radiometer produces a voltage directly proportional to the change in surface temperature.

One of the primary advantages of using the infrared sensing technique as opposed to other means of temperature measurement, such as thermocouples, is that it is entirely non-contact. The only specimen preparation required is a thin coat of removable paint that has a high emissivity in the infrared radiation spectrum. An advantage of adiabatic thermoelastic strain measurements over resistance strain gages is the full-field nature of the technique. It can cover a large surface area quickly, and can be used to identify critical regions of the structure that need closer examination -- perhaps with additional, complementary nondestructive evaluation techniques. Recall that other full-field strain measurements techniques, such as brittle coating, photoelastic coating, and moiré interferometry, all require some sort of surface coating to be bonded to the specimen. Another advantage is that high temperature environments pose little problem in infrared radiometry. In fact, not only is the thermoelastic temperature change, Θ, increased by a higher initial material temperature (eqs. 1 and 2), but the change in radiant photon emittance, δQ, is also higher for a given temperature change (eq. 3), resulting in a dynamic stress resolution that improves with T^3.

Considering that fiber composite laminates display anisotropic strength behavior, one significant disadvantage of adiabatic thermoelastic emission measurements is that no directional data for stresses or strains can be obtained for failure analyses. This fact is elucidated by recasting eqs. (1) and (2) in a simplified form for plane-stress conditions,

$$\Theta = K_1\sigma_1 + K_2\sigma_2 \tag{4}$$

from which it is obvious that it is not possible to isolate the individual
components of in-plane stress with a temperature measurement. Rather, the
transducer signal is linearly proportional to a nonuniformly-weighted sum-
mation of dilatational stress components in anisotropic materials ($K_1 \neq K_2$),
and to an equally-weighted summation of dilatational stresses in isotropic
materials ($K_1 = K_2$). This concept is best illustrated graphically, as in
Fig. 1, where each straight line represents the locus of possible combi-
nations of in-plane stress components for a particular temperature
change, Θ_1. Another disadvantage of the present technique is that it is
difficult to maintain an exact temperature calibration with variations in
paint thickness and infrared radiation attenuation between the specimen
and the radiometer. Perhaps the most serious uncertainty in the technique
is the unknown amount of nonadiabatic vs. adiabatic cyclic temperature
variation, which leads to erroneous stress calculations.

As with most other commonly-used strain measurement techniques, adia-
batic thermoelastic measurements are sensitive only to surface deforma-
tions. But, with composite laminates, one must consider that equal lami-
nate strains result in vastly different thermal measurements, depending on
the orientation of the observed ply relative to the global strain field.
Therefore, stacking sequence must be considered when evaluating measure-
ments.

EXPERIMENTAL PROCEDURE

Mechanical testing was carried out with a servo-controlled, hydrauli-
cally-actuated testing machine. Constant amplitude sinusoidal loads were
applied to the specimen at frequencies ranging from .5 to 50 Hz.

The apparatus used to measure the small temperature changes, an Omet-
ron SPATE 8000, consists of an infrared photon detector coupled to a co-
rrelator and computer. The sensitivity of the system is 0.001 K, equiva-
lent to a stress tensor trace of 58 psi in aluminum. The function of the
correlator/computer is to control the detector scan activities and condi-
tion the measured infrared signal such that the sinusoidal temperature
variation occurring at the same frequency as the cyclic load can be deter-
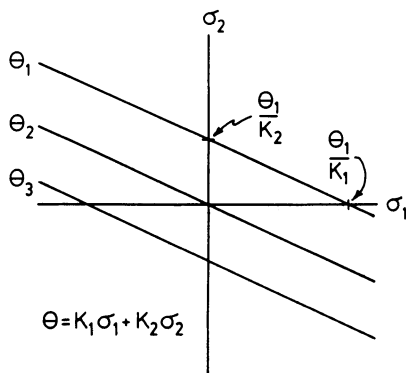mined.

Figure 1. Linear dependence of adiabatic thermoelastic
temperature change on in-plane stress components.

Correlation of the temperature and load signals is accomplished with the use of a lock-in amplifier. A temperature change with no sinusoidal content at the test frequency is rejected. The detector scans the test specimen point-by-point in a raster-like manner, enabling the computer to store the recorded signal at each scan point as a digital quantity. The smallest area that can be sampled at each point is a .02-in. diameter circle. As one might expect, the raster scan can take a long time to complete (up to 2 hours for 1.5- by 2.5-in. scan area). In such cases, it is necessary to cycle the specimen at a sufficiently low load such that neglibible material change occurs during the scan. Cyclic load amplitudes of approximately 30-40% of the ultimate strength were used for graphite/epoxy specimens. Factors influencing the scan time are the scan resolution (the number of data points to be recorded over a given area) and the sample time (the amount of time spent acquiring data at a single position on the specimen). In cases where the signal/noise ratio is small, as with most graphite/epoxy and aramid/epoxy composites, high frequency noise must be reduced by increasing the time constant of low-pass filters. Filtering is necessary since only a single value of temperature change is recorded at each point. A time constant of .3 sec. is generally sufficient to acquire "clean" data with graphite or aramid fiber reinforced plastics. A sample time of about 10 times the time constant is recommended, although factors of 3 or 4 were used for the present work to minimize scan times without excessively sacrificing image quality. Once a scan has been completed, the digital information may be stored on a magnetic disk for future reference. A video monitor enables the operator to observe the results of the scan as each point in the scan is sequentially displayed on a two-dimensional, color-coded contour map of temperature change.

In order to obtain the most consistent scan results, a few procedures are worth noting:

• Minimize variations in surface emissivity by applying a thin, uniform coat of flat black paint to all specimens. The non-reflective nature of the coating also reduces the possibility of reflected heat sources in the laboratory being modulated at the test frequency and, hence, corrupting the data. Note that investigators have suspected that even thin paint coatings act as insulators, particularly at higher frequencies [5,6].

• In all scans that are to be compared with each other, maintain a constant distance between the detector and the specimen in order to minimize variations in the infrared signal attenuation caused by air. Twelve inches was adopted presently to obtain the highest spatial resolution, or smallest focal spot. Obliquity of the detector relative to the surface of the specimen is not critical, provided the angle is less than approximately 55 deg. [6].

• Utilize the smallest focal area and angular increment possible when scanning a specimen for flaws. The smallest angular resolution recommended for the SPATE apparatus is approximately .001 rad. Over a distance of 12 in., this corresponds to a linear translation of .012 in. between each sample point -- small enough to discern matrix cracks in the observed surface ply.

• Maintain a constant sinusoidal load frequency for critical comparisons of test data. The temperature change associated with load depends upon the rate of loading for nonadiabatic deformations. Aside from irregularities associated with load frame resonances (between 30 and 40 Hz, in this case), the deformation of aluminum is nearly adiabatic for load frequencies above 5 Hz (Fig. 2). In contrast, the deforma-

tion of 0-deg. unidirectional graphite/epoxy appears to be nonadiabatic up to 30 Hz (Fig. 2). Frequencies of either 5 or 10 Hz were used for the graphite/epoxy data included herein.

• Expect to obtain spurious data when scanning across an edge of a specimen. The data obtained when the focal area lies partly on and partly off the material are generally inaccurate.

EXPERIMENTS

Adiabatic thermoelastic measurements can be used to nondestructively evaluate the uniformity of the fiber and matrix distribution in graphite/epoxy composites because of the vastly different thermoelastic properties of the fibers and matrix. For example, a typical epoxy resin has a thermal expansion coefficient of 40 $\mu/^0F$, while graphite fibers have longitudinal and transverse thermal expansion coefficients of -.55 $\mu/^0F$ and 5.6 $\mu/^0F$, respectively [7]. Spatial variations in the proportion of fibers and matrix in the surface ply result in a nonuniform thermoelastic emission since the volume fraction of each constituent figures prominently in the overall, measured temperature change. Furthermore, nonuniform macroscopic stress distributions resulting from spatial variations of material properties (including ply thickness and void distribution) also contribute to perturbations in the thermoelastic response. An example of this behavior in a $(0,90)_s$ laminate with highly nonuniform void content and ply thickness is given in Fig. 3.

Adiabatic thermography is also well-suited to the nondestructive evaluation of damage induced by service loads. In fiber-reinforced composite laminates, damage that is large enough to be resolved with the detector takes the form of matrix cracks parallel to the fibers in the surface ply, delamination between plies of different orientation, and ply fracture across fibers in one or more plies. As opposed to most homogeneous materials where overload and fatigue damage is concentrated into a dominant flaw, damage in fiber composites appears as a collection of distinct, but interrelated forms that typically occupy a relatively large volume of material. Hence, the full-field capabilities of the SPATE apparatus are convenient for a quick evaluation of the damage condition of a laminate.
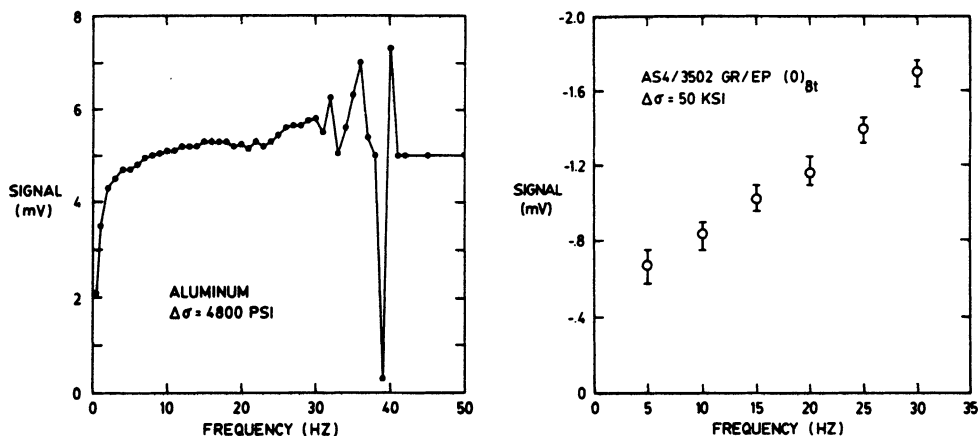

Figure 2. Measured signal (uncalibrated temperature change) at various excitation frequencies with aluminum and unidirectional graphite/epoxy.
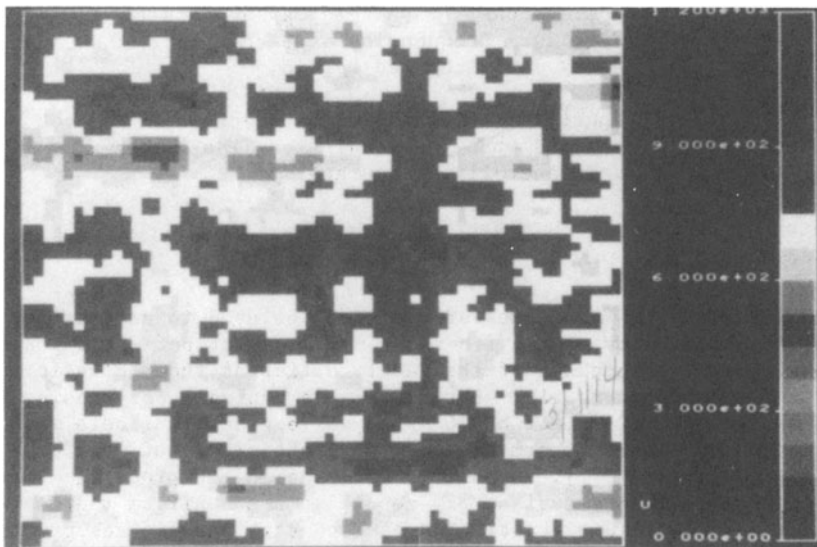
Figure 3. Thermograph of an undamaged $(0,90)_s$ graphite/epoxy laminate.

Figures 4 and 5a illustrate the full-field thermoelastic response of a center-notched graphite/epoxy laminate before and after the appearance of delamination underneath the 0-deg. surface ply. (The ply angle notation is such that positive angles are measured clockwise from the vertical loading axis). Because of the altered stress field in the delaminated surface ply, the thermoelastic response is altered. In this case, high stress concentrations near the notch are relieved by the damage, resulting in significantly reduced thermoelastic measurements over the delaminated area. For comparison with the thermograph, a penetrant-enhanced X-ray radiograph of the same specimen is given in Fig. 5b. Note the additional modes of damage present in the laminate besides surface ply delamination. Matrix cracking in sub-surface plies, however, cannot be resolved in the thermograph because of the relatively small effect of that damage on the thermoelastic emission of the surface ply on which measurements are made.

Matrix cracks parallel to the fibers in the 45-deg. surface ply of a center-notched graphite/epoxy laminate appear as parallel lines of reduced thermal emission (Fig. 6a). The X-ray radiograph (Fig. 6b) confirms the extent of matrix damage in this specimen. Through stereographic radiography, it has been verified that the cracks on the surface of observation are consistently visible in the thermograph. The reason for the reduction in thermal response along the length of a crack is that the crack forms a traction-free surface along its length, reducing the local stress and, consequently, the thermoelastic temperature change in the material adjacent to the crack. Delaminations beneath the surface 45-deg. ply, near the notch, also reduce the thermoelastic emission.

CLOSURE

The measurement of cyclic adiabatic thermoelastic temperature change is an effective technique for the analysis of dynamic stress or strain fields on the surface ply of laminated fiber composite materials. Some advantages of the technique are that it is full field and very quick, requires little specimen preparation, is entirely non-contact, and can cover
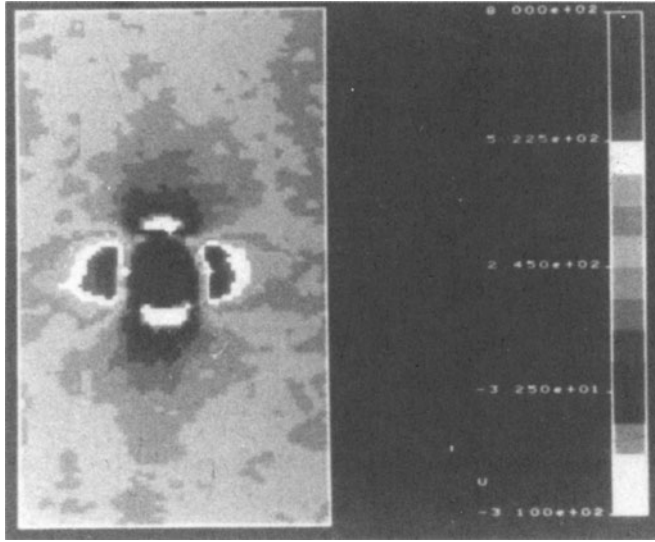
Figure 4. Thermograph of an undamaged $(0,90,\pm45)_s$
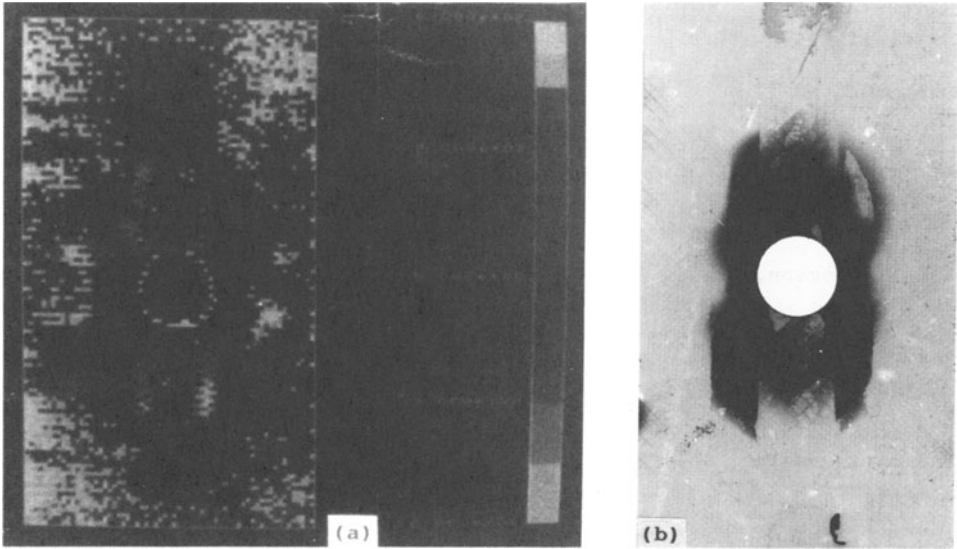graphite/epoxy laminate with a central hole.

Figure 5. Thermograph (a) and X-ray radiograph (b) of a damaged
$(0,90,\pm45)_s$ graphite/epoxy laminate with a central hole.
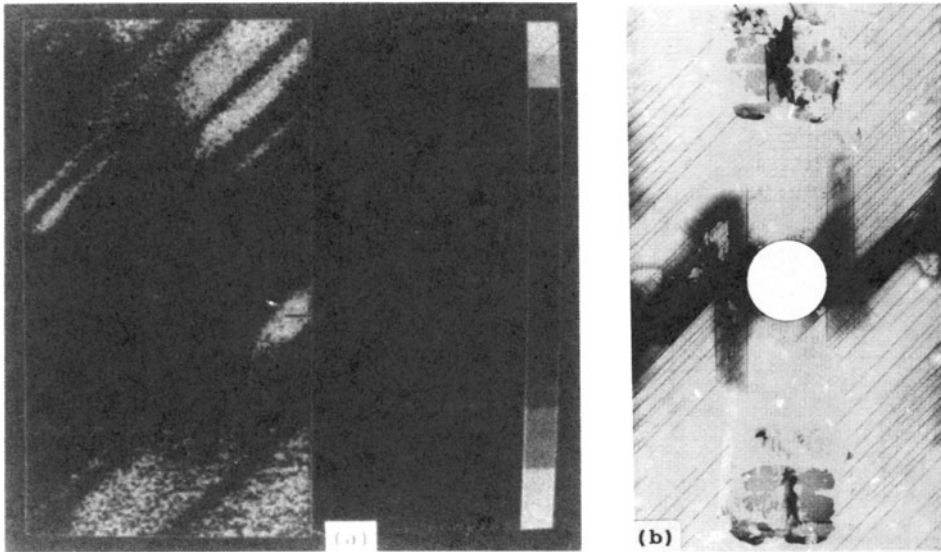
Figure 6. Thermograph (a) and X-ray radiograph (b) of a damaged $(45,90,-45,0)_s$ graphite/epoxy laminate with a central hole.

either a large area (as on a full-scale engineering structure) or a small area (for maximum spatial resolution). Sensitivity to manufacturing irregularities (such as nonuniform resin distribution, void content, and ply thickness) and to service load damage (such as matrix cracking and delamination) has been demonstrated. The surface ply dominates the thermal measurements, and can conceal the presence of sub-surface damage unless that damage significantly alters the deformation of the surface ply. A limitation of the technique is that it is not possible to obtain directional stress or strain components.

ACKNOWLEDGEMENT

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