VIBROTHERMOGRAPHY AND ULTRASONIC PULSE-ECHO METHODS
APPLIED TO THE DETECTION OF DAMAGE IN COMPOSITE LAMINATES

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ABSTRACT

It has recently been shown in our laboratories that quasi-isotropic, graphite-epoxy, composite laminates develop a typical damage state that eventually leads to final failure. This damage state cannot be represented by a single through crack that propagates in a self-similar manner in the fashion ordained by fracture mechanics. To the contrary, the damage state is a complex one which begins by transverse cracking in the weakest lamina, continues by an increase in transverse crack density until a stable equilibrium spacing is achieved, proceeds by growth into the adjacent laminae and ends by final, catastrophic failure. In certain stacking sequences, the damage state is further complicated by delamination. Several NDE methods are being developed in our laboratories specifically to identify and quantitatively describe this damage state. The vibrothermography technique uses low amplitude vibrations as a steady state energy source in the composite laminate. The mechanical energy is preferentially absorbed in the region of damage and converted to heat, which can then be detected by thermography. This technique is applicable to detecting delamination. An ultrasonic pulse-echo method utilizing a straightforward diffraction analysis is being developed to detect the transverse cracks which, as they approach and attain an equilibrium spacing, present the appearance of a changing diffraction grating to the ultrasonic beam.

DISCUSSION

Vibrothermography and ultrasonic attenuation techniques have been employed in our laboratory to aid in the understanding of the development of a characteristic damage state in graphite-epoxy laminates. The following figures and photographs indicate the kind of information that one can obtain from these methods. To begin the poster demonstration, a very brief description of the vibrothermography technique is given. Figure 1 is a photograph of the experimental set-up showing a composite panel mounted in a low amplitude shaker. The thermographic camera and television monitor are also shown. Figure 2 a) and b) are photographs taken from edge replicas and show the characteristic damage state, discussed later, of uniform spacing of transverse cracks in the 90° plies and the edge delamination in a [0, ±45, 90] laminate, respectively. A typical thermograph of an edge delamination is shown in Fig. 3. Figure 4 is a thermograph of a specimen taken after static loading to a low load while Fig. 5 is a thermograph of the same specimen after 10,000 cycles of fatigue at the same maximum load level. A boron-epoxy specimen with a circular cut-out was loaded in three-point bending until surface fracturing occurred, Fig. 6. The corresponding thermograph, Fig. 7, indicates large amounts of subsurface damage as well in regions removed from the hole.

An ultrasonic pulse-echo method was used to measure attenuation changes in graphite-epoxy laminates during loading. A description of the observations and a suggested crack and delamination diffraction model to account for the observed changes are followed by a typical experimental observation, Fig. 8. The diffraction model can be used to calculate the expected attenuation downstream of a transducer. Figure 9 is the result for various depths of edge delaminations. Finally, the predicted attenuation as a function of delamination depth is given in Fig. 10.

VIBROTHERMOGRAPHY

Vibrothermography is a nondestructive inspection technique that uses time-resolved thermographic detection of infrared radiation to detect regions of damage in materials. Low amplitude mechanical vibrations are used as a steady state energy input to the material. The interaction of the vibrational stress field with the damaged regions causes local heating to occur (at the site of the damage) which can be detected by video-thermography. This technique has been especially successful in delineating delaminations and similar flaws in composite materials. The accompanying photographs are thermographs of heat patterns developed in graphite-epoxy specimens that were previously subjected to a load-time history as noted. The specimens were then mounted in a shaker which vibrated at approximately 18 kHz with an amplitude that was barely perceptible. Hence the shaker did not cause any additional damage; it simply served as a steady state energy source. Several analytical studies have also been performed in our laboratory to calculate surface heat patterns from subsurface sources and to calculate heat evolved during fatigue loadings.

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Fig. 1. The vibrothermography test set-up

Fig. 2A

Fig. 2B

Fig. 2. A) Transverse cracks in 90° plies, and B) Edge delamination in 90° plies for a graphite-epoxy, [0, ±45, 90]s laminate

Fig. 3. Thermograph made by shaking a graphite-epoxy specimen with an edge delamination. The hot area is the delamination.

Fig. 4. Thermograph of graphite-epoxy specimen after loading statically to 2/3 of ultimate load
Fig. 5. Thermograph of same specimen as in Fig. 4 after 10,000 cycles of fatigue loading to a maximum load 2/3 of ultimate.

Fig. 6. Surface damage on a [0, ±45, 0]s boron epoxy specimen loaded in three point bending.

Fig. 7. Thermograph of specimen shown in Fig. 6 showing sub-surface damage in regions removed from the hole as well as the surface damage across the specimen at the hole.

DIFFRACTION MODEL FOR THE DETECTION OF DAMAGE IN COMPOSITES

Recent work performed in our laboratory has shown that quasi-isotropic graphite-epoxy laminates of the type [0, ±45, 90]s (Type I) or [0, 90, ±45]s (Type II) develop a characteristic damage state. For both types of laminates, transverse cracking occurs first in the 90° plies at a load level of approximately 1/3 of the ultimate load. As the load increases, additional transverse cracks appear in the 90° plies until, at approximately 2/3 of the ultimate load, an equilibrium spacing of transverse cracks has been achieved. With additional load, the cracks in the 90° layers begin to grow into the adjacent 45° layers. These transverse cracks will appear to be a diffraction grating to an ultrasonic wave which is transmitted in a direction perpendicular to the laminate. As shown in the accompanying figures, the attenuation of the ultrasonic wave increases gradually with the load, and hence the number of transverse cracks, until the equilibrium number of cracks has occurred. After this point, the attenuation increases rapidly with load as the cracks begin to open wider and to grow into the adjacent layers.

An elementary diffraction model, following the earlier work of Truell and Papadakis, has been used to calculate the expected attenuation of a longitudinal stress wave caused by the diffraction of the wave. It was assumed that each transverse
crack serves as a rectangular screen across the aperture represented by the transducer. Each screen has a width \( w \) corresponding to the crack opening which is probably physically represented by the projection of the crack onto a plane parallel to the laminate. The number of such screens across the diameter of the transducer corresponds to the number of observed transverse cracks at each load. The calculated attenuation correlates quite well with the experimental observations, showing an increase of attenuation with the number of cracks and with the apparent crack opening.

![Fig. 8. Attenuation versus load for a graphite-epoxy specimen loaded quasistatically.](image)

![Fig. 9. Predicted attenuation due to diffraction effects downstream of a transducer in the presence of delaminations having various depths \( d \) into the field of the transducer.](image)

![Fig. 10. Predicted attenuation as measured by the pulse-echo method as a function of delamination depth.](image)