DEFECT AND DAMAGE CHARACTERIZATION IN COMPOSITE MATERIALS

I. M. Daniel, S. C. Wooh and J. W. Lee

Northwestern University

Evanston, IL 60201

INTRODUCTION

Defects may be introduced in composites during processing and fabrication. They include contaminants, porosity, inclusions, delaminations, and nonuniform fiber and matrix distributions. Damage induced in service under loading and environmental variations includes matrix cracking, delamination, fiber breakage, and dispersed defects, such as matrix ageing and degradation.

A variety of nondestructive evaluation methods have been used for composites, but the most effective and practical ones are ultrasonic and radiographic methods. These methods can be supplemented by others, such as acoustic emission, interferometric, and wave propagation techniques. The sensitivity and effectiveness of such NDE methods are discussed in connection with three applications: thick composites, metal-matrix composites, and fatigue damage.

THICK COMPOSITES

New structural applications of polymer matrix composites require the use of thick sections, up to 7.62 cm (3 in.) in thickness. Fabrication of thick composites poses a great challenge. These composites are susceptible to defects due to thermal gradients and nonuniform resin bleeding during curing. Typical anticipated defects are matrix cracking and delaminations. Conventional nondestructive techniques usually must be adapted to the case of thicker composite laminates.

To study the detectability of delaminations, a thick composite laminate was prepared. A 10.2 × 15.2 cm (4 × 6 in.) 150-ply thick unidirectional graphite/epoxy plate was prepared with 7.9 mm (0.31 in.) diameter and 0.025 mm (0.001 in.) thick mylar inclusions. These inclusions were embedded between the plies at various locations through the thickness.

The conventional pulse echo technique using a focused transducer was not suitable in this case. An unfocused 5 MHz transducer, 1.71 cm (0.75 in.) in diameter, was used to obtain the A-scans shown in Fig. 1. These scans were sufficient in detecting the through-the-thickness location of the mylar inclusions. Furthermore, they can be used to determine the wave propagation velocity in the thickness direction, $C_3 = 3{,}040\ \mathrm{ms}^{-1}$ (119,800 in./sec).

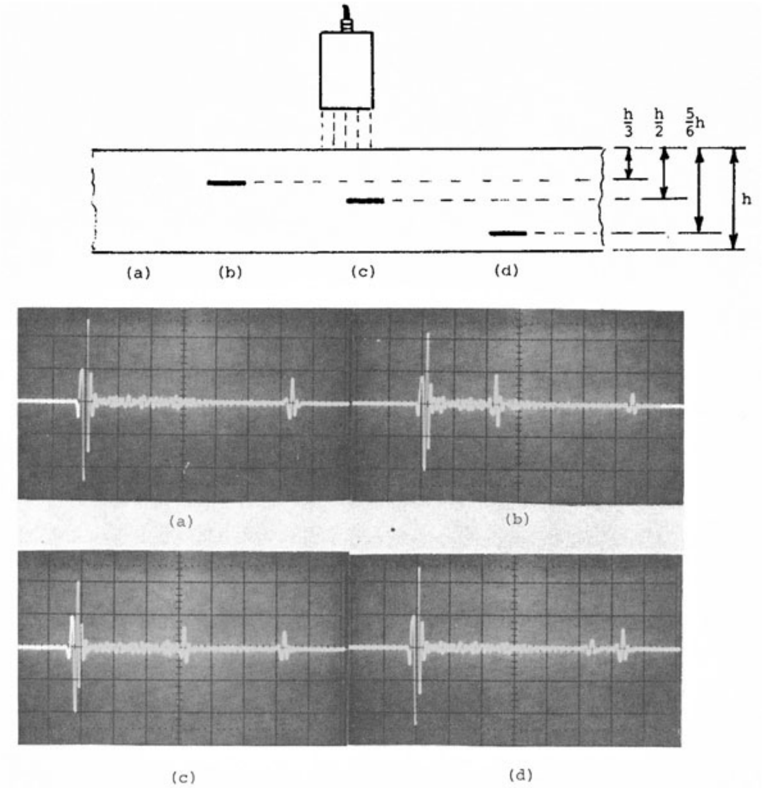


Fig. 1. A-scans at four different locations in unidirectional 150-ply graphite/epoxy laminate with embedded 7.9 mm (0.31 in.) diam., 0.025 mm (0.001 in.) thick inclusions.

The planar characterization of the inclusions could not be achieved by the pulse echo method with either focused or unfocused transducers. In the case of unfocused transducers the difficulty was due primarily to the fact that the beam diameter was larger than the defect diameter. A practical solution to this problem was obtained by using a through-transmission technique utilizing an unfocused transmitting transducer and a focused receiving transducer as shown in Fig. 2. The receiving transducer was focused on the back surface of the specimen to detect the shadow of the defect. Results of this modified C-scanning are shown in Fig. 3.

Another common defect in thick composites is transverse matrix cracking in crossply laminates. Some of these cracks appear during the cooldown stage of the curing process due to thermal gradients and the anisotropic thermal expansion of the various plies. Cracking also occurs during subsequent exposure to low temperature and during mechanical loading. When the in-plane dimensions of the laminate are relatively small, it is possible to detect matrix cracks by conventional penetrant-enhanced X-radiography (Fig. 4). For large plates, however, it may not be possible for the X-ray opaque penetrant to reach all cracks. A new ultrasonic technique and an analytical model have been developed recently for matrix crack characterization in thick composites [1].

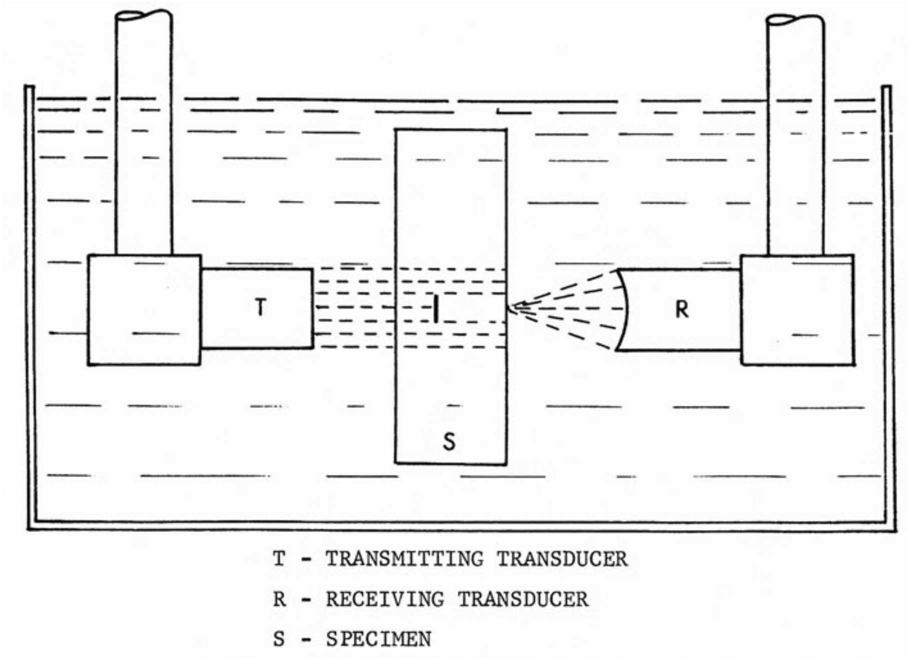


Fig. 2. Ultrasonic through transmission method for detection of embedded flaws in thick composite laminates.

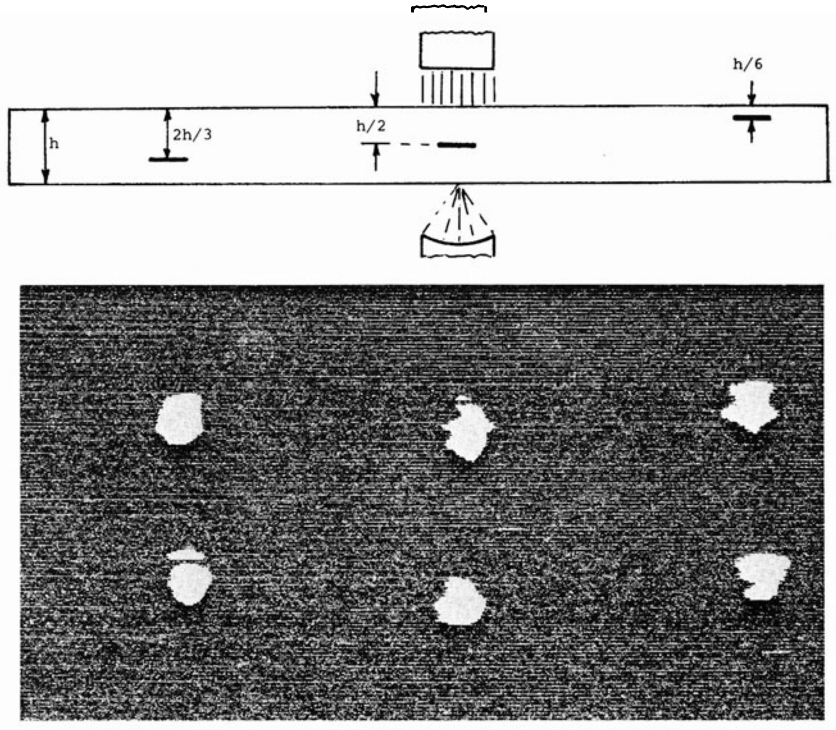
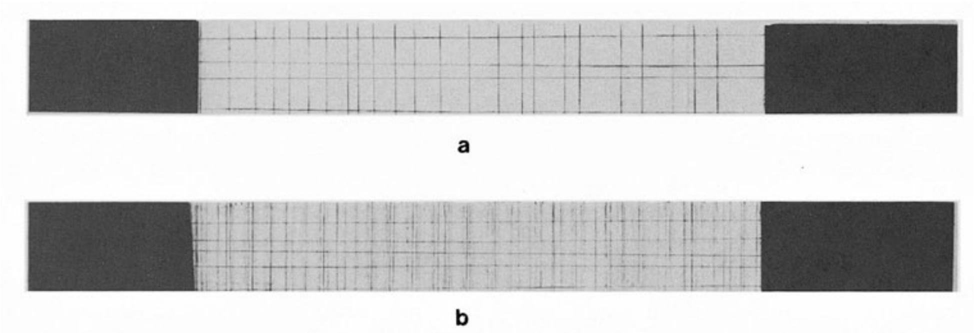


Fig. 3. Through transmission C-scan of 150-ply graphite/epoxy laminate with embedded 7.9 mm (0.31 in.) diam., 0.025 mm (0.001 in.) thick inclusions.



b

Fig. 4. X-radiographs of $[0_{10}/90_{10}]_s$ AS4/3501-6 graphite/epoxy specimens.
(a) After thermal shock from 394 degK (250°F) to 255 degK (0°F)
(b) After application of 449 MPa (65 ksi) tensile stress.

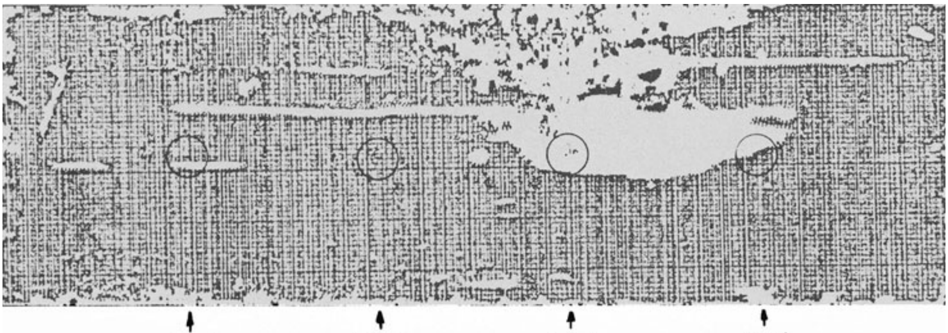
METAL-MATRIX COMPOSITES

Metal-matrix composites have some advantages over polymeric matrix materials. In general, they exhibit high shear strength and modulus, high transverse tensile strength, excellent stability over a wide temperature range, strength retention, excellent fatigue and creep properties, and high impact strength. Composite systems that have been investigated to date include boron/aluminum, borsic/aluminum, graphite/aluminum, FP (aluminum oxide)/aluminum, and FP/magnesium. Fabrication of these composites is more involved than that of polymeric matrix composites, therefore, nondestructive inspection is even more important.

Manufacturing defects encountered in metal-matrix composites are similar to those of organic matrix composites. They include: fiber matrix debonding, porosity, fiber misalignment, fiber fracture, nonuniform fiber distribution, and matrix fracture. Available nondestructive methods must be adapted for each material and defect type.

An example of the application of various NDE methods to the detection of porosity is illustrated in Fig. 5 [2]. The specimen was a unidirectional 8-ply FP/magnesium plate of dimensions 12.7 × 3.8 × 0.64 cm (5 × 1.5 × 0.25 in.). The conventional C-scan, obtained with a 15 MHz focused transducer in the pulse echo mode, delineates clearly the regions of high porosity. Ultrasonic attenuation measurements were made at various points along the centerline of the specimen. A method based on the attenuation of a train of echoes was used to obtain an attenuation coefficient for the material in terms of decibels per cm. It can be seen that this coefficient increases with increasing porosity area within the ultrasonic beam. Thus, the attenuation coefficient increases from 0.44 dB/cm in the undamaged region to 0.81 dB/cm in the porous region.

In addition to attenuation, the wave propagation velocities were measured at the same locations along the specimen centerline. The wave velocity is proportional to the square root of the ratio of the stiffness over density. Although both stiffness and density are expected to decrease in the porous region, it appears that the velocity does vary with extent of damage. The wave velocity decreases from 6771 m/s in the undamaged region to 6120 m/s in the flawed region as seen in Fig. 5.



	3-1-1	3-1-2	3-1-3	3-1-4
Ultrasonic Attenuation (dB/cm)	0.52	0.44	0.81	0.55
Wave Propagation Velocity (m/s)	6679	6771	6120	6723

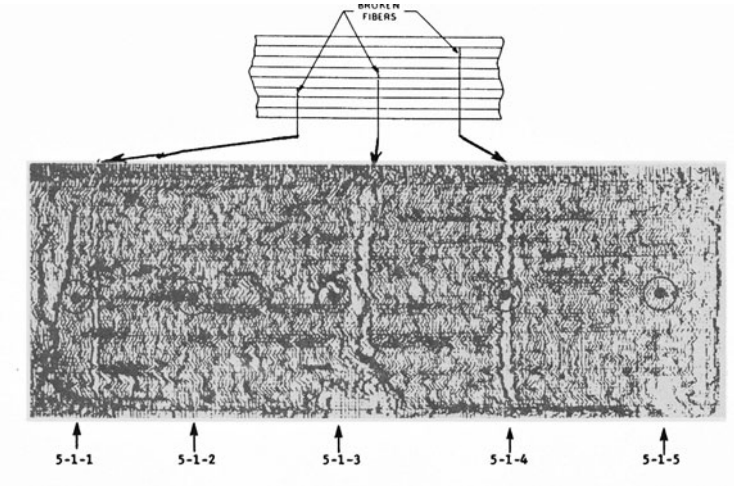
Fig. 5. C-scan, ultrasonic attenuation and wave propagation velocities for FP/Mg specimen with porosity.

Another type of flaw investigated was fiber fracture. Figure 6 shows a sketch of an FP/magnesium specimen with fiber fractures in the second, fourth and sixth plies from the top. Conventional ultrasonic scanning does not reveal such flaws. However, analog scanning with a 15 MHz focused transducer was effective in detecting the locations of the fiber fractures (Fig. 6).

FATIGUE DAMAGE

Nondestructive evaluation is very important in characterizing and monitoring damage development in composites under cyclic loading. Damage development consists of three stages, initiation, growth, and localization leading to ultimate failure. In crossply laminates damage consists of transverse matrix cracking, longitudinal matrix cracking, delaminations at the intersections of matrix cracks, and fiber fractures [3,4]. Damage mechanisms and damage development depend on the cyclic stress level and thereby on the state of damage produced during the first loading cycle. Damage development consists of three stages: (1) damage occurring during the first fatigue cycle consisting of transverse matrix cracking, (2) damage developing during the first 80% of the logarithmic lifetime of the material and consisting of multiplication of transverse matrix cracks up to a limiting crack density, and (3) damage occurring in the last 20% of the logarithmic lifetime and consisting of longitudinal matrix cracking, local delaminations and fiber fractures.

The fatigue damage discussed above can best be characterized by penetrant-enhanced X-radiography as illustrated in Fig. 7. This method can be complemented by ultrasonic backscattering as shown in Fig. 8. Fatigue damage can also be characterized in terms of the residual axial modulus as a function of fatigue lifetime. The reduction in residual modulus is closely associated with damage development. A typical curve for normalized residual



ULTRASONIC WAVE ATTENUATION FOR FP/Mg SPECIMEN WITH FIBER FRACTURE BY WATER DELAY LINE TECHNIQUE.

Inspection Location	Material Attenuation dB/cm	 (dB/in.)
5-1-1	0.32	(0.80)
5-1-2	0.32	(0.80)
5-1-3	0.25	(0.62)
5-1-4	0.42	(1.06)
5-1-5	0.35	(0.89)

Fig. 6. Analog C-scan of FP/magnesium specimen with Fiber Fracture.

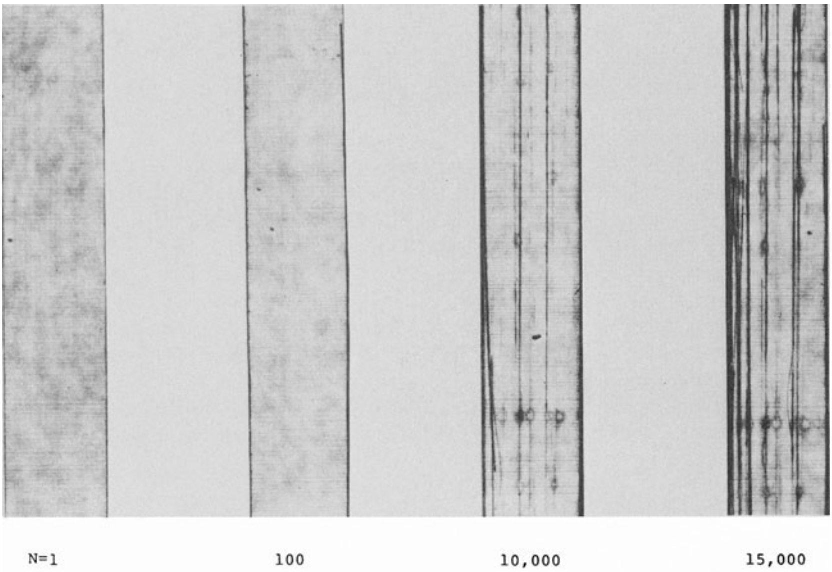


Fig. 7. X-radiographs of a $[0/90_2]_s$ graphite/epoxy laminate subjected to fatigue loading at 662 MPa (96 ksi) for various numbers of cycles.

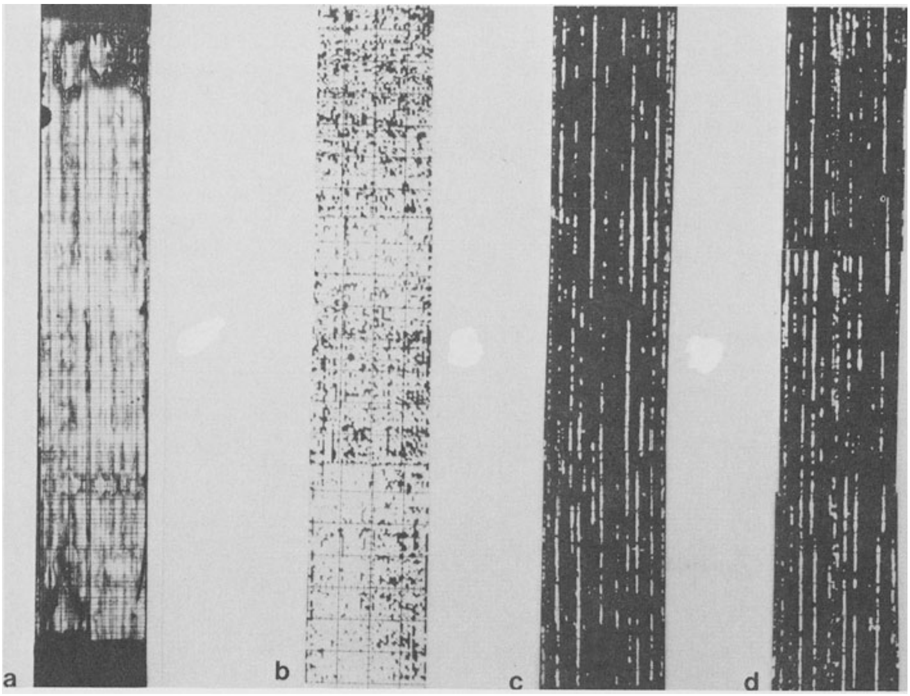


Fig 8. Damage in $[0/90_2]_s$ AS4/3501-6 graphite/epoxy laminate cycled at 518 MPa (75 ksi) for 7.5 × 10^6 cycles. (a) X-radiograph, (b) transverse cracking detected by backscattering C-scan, (c) longitudinal cracking in upper layer detected by backscattering C-scan, (d) longitudinal cracking in lower layer detected by backscattering C-scan.

modulus displays characteristic features associated with the three stages of damage development discussed before (Fig. 9).

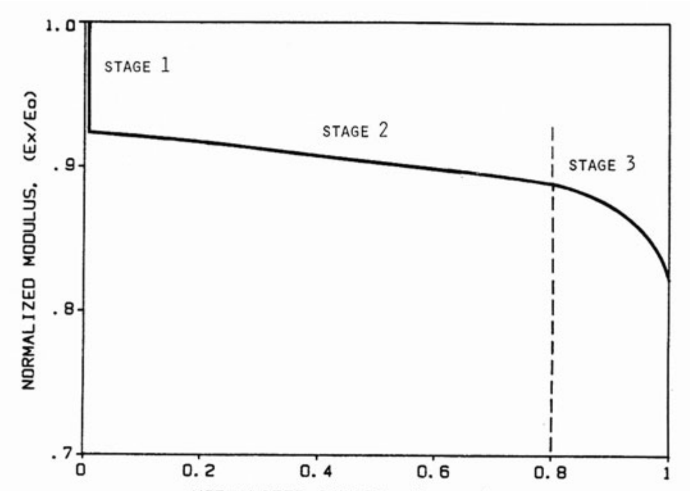


Fig. 9. Typical curve of normalized residual axial modulus for $[0/90_2]_s$ graphite/epoxy laminate with characteristic features corresponding to three stages of damage development.

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