COMBINED INVESTIGATION OF EDDY CURRENT AND ULTRASONIC TECHNIQUES FOR COMPOSITE MATERIALS NDE

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INTRODUCTION

Advanced composites are not without a trade-off. Their increased designability brings an increase in the complexity of their internal geometry and, as a result, possible modes of failure. When two or more isotropic materials are combined in a composite, the isotropic failure modes may also combine. In a laminate, matrix delamination, cracking and crazing, and voids and porosity, will often combine with fiber breakage, shattering, waviness, and separation to bring about ultimate structural failure. This combining of failure modes can result in defect boundaries of different sizes, corresponding to the failure of each composite component. Consequently, more than one NDE technique is needed to investigate the integrity of the composite component.

This paper discusses a dual-technology NDE (eddy current (EC) and ultrasonics (UT)) study of graphite/epoxy composite samples. Both eddy current and ultrasonic C-scans were made to characterize the effects of mechanical impact damage, high temperature thermal damage and the presence of various types of inserts placed within composite samples that were laminated in various stacking sequences. The eddy currents induced in the samples are sensitive to the conducting graphite fibers while the ultrasonic wave propagation is mainly influenced by the material properties of the insulating matrix and the fiber/matrix interfaces. Thus, the two techniques are complementary and yield a more complete picture of the state of the composite component.

EXPERIMENTS

Two ultrasonic techniques were used to study the samples. The first was a standard pulse-echo attenuation technique with an iterative scanning strategy to optimize the resulting ultrasonic image. Here optimizing means achieving the finest resolution of detectable features with the greatest pixel value difference between them for maximum image contrast. This was accomplished by maximizing the effective dynamic range, to produce the widest normalized value scale, and having the maximum number of peak amplitudes fall within that range such that amplitude response fluctuations and, therefore, acquired pixel value differences, were also a maximum. To obtain the widest raw-data histogram value scale, and the best image resolution for the least ultrasonic scatter, the scanned region was kept within all specimen boundaries. A value scale ranging from 0 - 1254, was created by using two receivers that were set for maximum linear gain. A spectrum analyzer was then used to check for distortion.

Lamb waves were also used to demonstrate their feasibility for investigating the effect of thermal-damage on the Lamb wave phase velocity [1]. The phase velocity of the Lamb wave is sensitive to the density of the material, the elastic constant in the propagation direction and Poisson's ratios for strains normal and parallel to the propagation direction [2]. The test setup consists of a single transmission and multi-receivers separated by a fixed distance for pitch-catch time of flight measurements.

To characterize any damage to the fibers in the composite samples a series of eddy current scans were also performed. A standard eddy current instrument along with a with a 6 mm (0.25 inch) diameter spring loaded probe was used to scan over the surface of the composite samples. The probe contained a ferrite core and has a nominal operating range of 2.5-6 MHz. For the samples studied this was the frequency range needed for three standard depths of penetration to fall within the thickness of the samples. The tester was balanced on a "good" part of the sample and was adjusted so that lift-off signals moved along the horizontal (the real impedance axis). This effectively separated the resistive component (horizontal) from the reactive component (vertical) and each was recorded separately as the probe was mechanically scanned over the surface of the samples.

To obtain a fairly wide diversity of defects three distinct types of samples were studied. The first set of samples were part of a graphite composites NDE study between the Mc Donnell-Douglas Aerospace Division, St. Louis, Mo., and the US Navy. They consisted of twelve 15.2 x 16.5 cm^2 (6.0 x 6.5 in^2), 16 ply, [0]8s, unidirectional, AS4/977-3, laminates under-coated with Mil-P-85582 primer with one side top-coated with MMS-420 gloss white paint and the other coated with color #36320 flat grey paint. The white sides were exposed to a 20.3 x 15.2 cm^2 (8.0 x 6.0 in^2) heat blanket, while an insulating blanket was used to retard heat transfer from the grey sides. It is not known if uniform temperatures were actually maintained over the entire surface of each panels, as temperatures were only monitored at the center of each panels surface.

A graphite composite sample from Boeing was also examined. The sample contained 48 plies with a periodically repeated fiber orientation of +45°, 90°, -45° and 0° and overall dimensions of 30 x 45 cm^2 (12 x 18 in^2). Defects were introduced into the sample as a series of 1.27 cm^2 (0.5 in^2) non-conducting inserts that were placed at different levels within the composite.

Finally, an impact damage composite sample was investigated. The sample was a graphite/epoxy sample several plies thick with overall dimensions of 10 x 25 x 0.3 cm^3 (4 x

10 x 0.125 in^3). Further documentation on the panel is limited. The impact damage was such that it is not directly visible to the unaided eye.

RESULTS AND DISCUSSION

Fig. 1 displays the optimized ultrasonic attenuation results for the thermally exposed panels. The image shown in the figure contains four panels one of which is an unexposed control panel. The three remaining panels were subjected to a temperature of 537°C (1000°F) for a period of 3 minutes before testing. Their were also variations in how quickly the final temperature was reached providing changes in the net energy absorbed by the plates, but this effect will not be considered in this paper. The ultrasonic data highlights noticeable “hot-spots” (areas of greatest apparent thermal effect) with sharp boundaries. Outside these “hot” regions the samples appear very similar to the unexposed control panel. The hot-spots originate in about the same location and are similar in shape. Differences in their shapes correlate well with differences in the net absorbed thermal energy. All the UT images show little thermal degradation outside the hot-spot boundaries. Inside the boundaries there is a narrow transition region surrounding a region of randomly scattered data values (the cause of which is believed to be porosity due to the pyrolysis of the epoxy matrix).

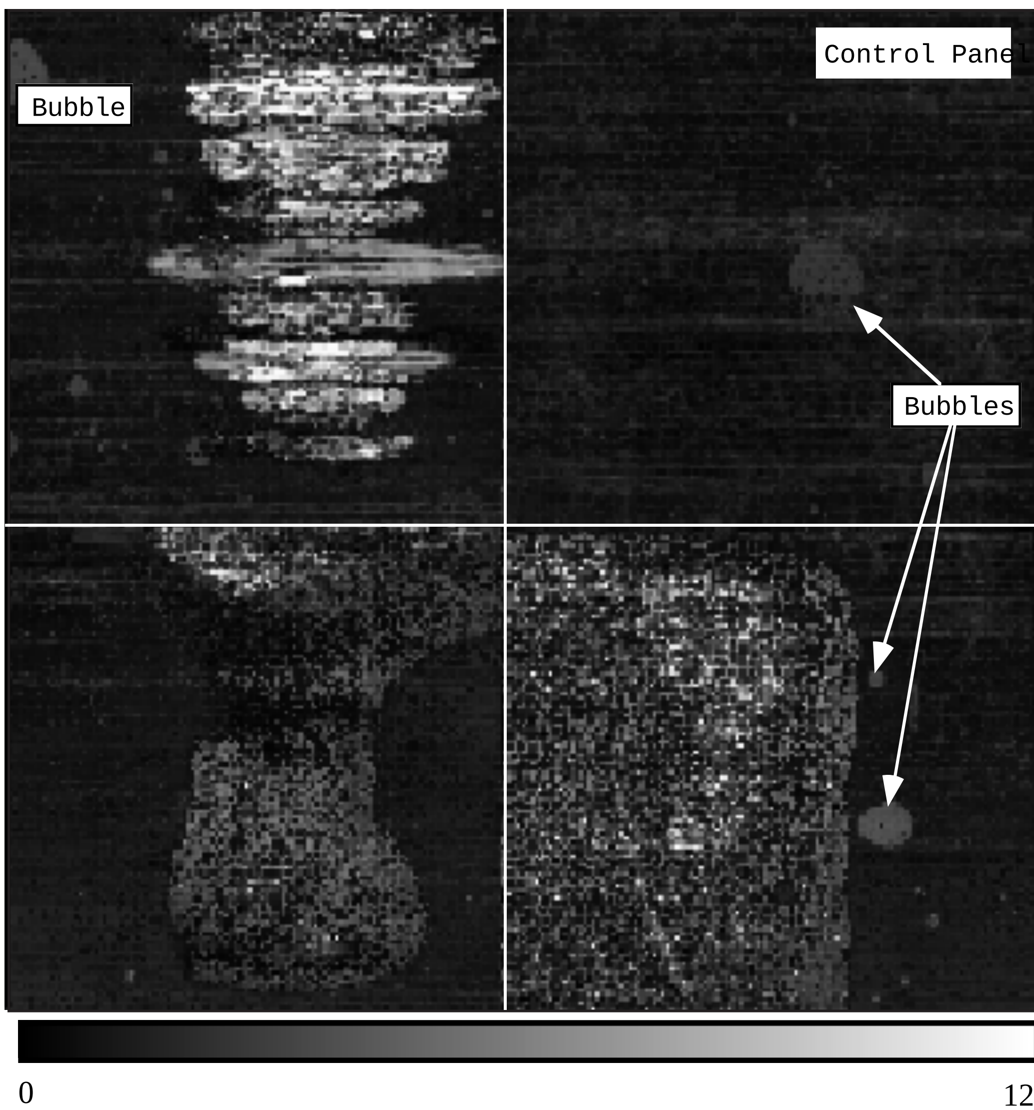


Fig. 1. Ultrasonic attenuation image (Normal mode, planform orientation) or three thermal-damaged composite panels along with an unexposed control panel.

The samples were also studied with Lamb waves and the results are provided in Fig. 2 below. Although the results are preliminary this figure shows a definite decrease in the overall velocity of the ultrasonic wave as a function of the final sample temperature. At lower temperatures the data is not as well correlated, but this is probably due to sample anisotropy, transducer separation or uncertainty in the group velocity measurements.

The samples were also scanned using an eddy current probe. The panels were scanned on both sides with a spring-loaded probe operating at 4.0MHz, 4.5MHz, 5.0MHz, and 6.0MHz. Typical results are given in Fig. 3 below. The images show impedance measure-

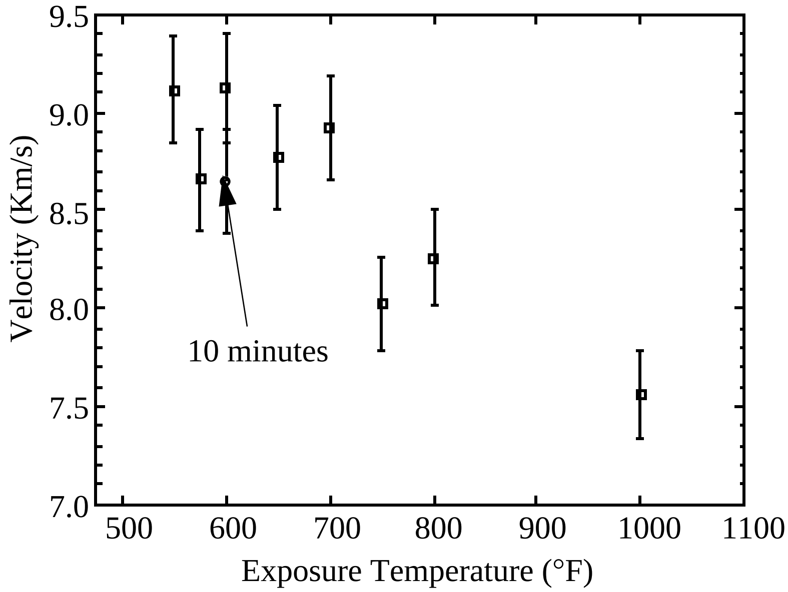


Fig. 2. Lamb wave velocity results for thermal-damaged samples. The exposure temperature was maintained for an average of 3 minutes except where noted.

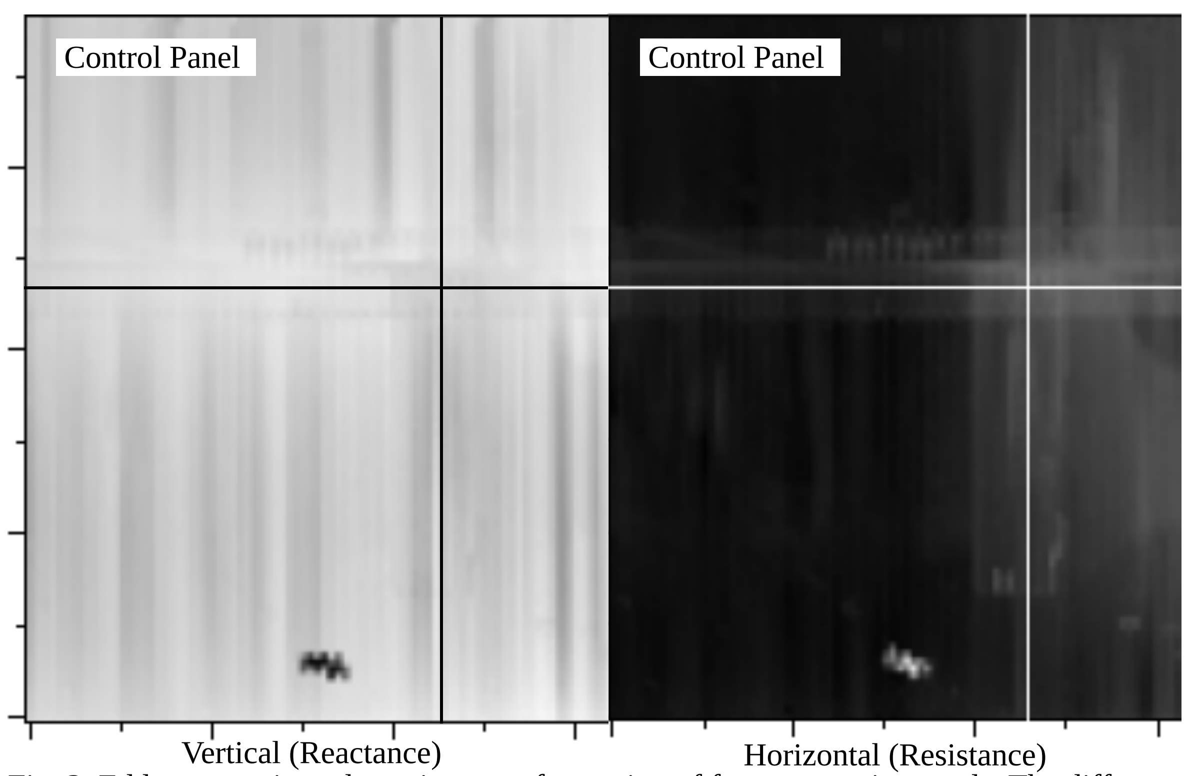
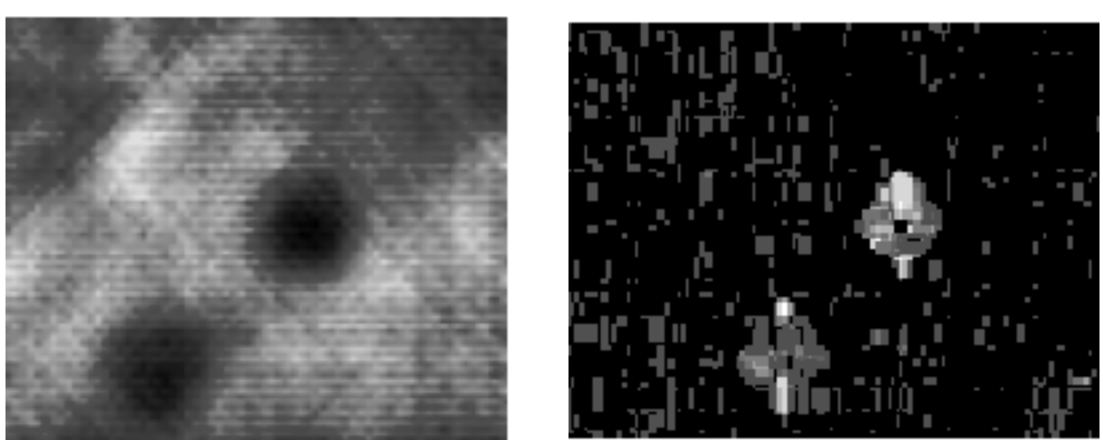


Fig. 3. Eddy current impedance images of a portion of four composite panels. The different panels are distinguished by the horizontal and vertical lines. The probe was operated at 4.0MHz.

ments from an EC probe that is scanned over an undamaged control panel and portions of three thermal-damaged panels. The impedance results are displayed using images of the horizontal (changes in the horizontal results are the same as changes in lift-off which corresponds to resistance changes) and vertical images from the impedance plane values. The results do not show any repeatable differences between the samples. Variations in the Resistance plot can be accounted for by surface roughness and wear tape at sample boundaries which also add to the probe lift-off. Since the only electrically conductive material in the panels are the graphite fibers it is reasonable to assume that the fibers are not severely damaged.

Impacting a laminate locally alters both fibers and matrix, causing cracking, delaminations, fiber displacement and shattering. While normal mode ultrasonics are affected by all these alterations, this technology is more matrix-sensitive than fiber-sensitive. On the other hand, the conductive fibers in the insulating matrix, allow eddy current imaging to isolate the fiber effects. Therefore, maintainability criteria should require the coordinated use of both EC and UT technologies (with a possible third technology to isolate matrix cracking). Fig. 4 illustrates some of the benefits of coordinating the two technologies. The UT attenuation scan shows not only the delamination patterns and their shapes due to stacking sequence, but it also gives evidence of random scatterers like voids and porosity. On the other hand, the impedance image (vertical component shown), which was made from the side opposite to where the impacting occurred, more clearly shows fiber orientation and a significant impedance change due to fiber displacement and, possibly, shattering. It is important to note the defect images are not very similar in shape. This can have adverse implications if one plans to use only one imaging technology to map defect boundaries.

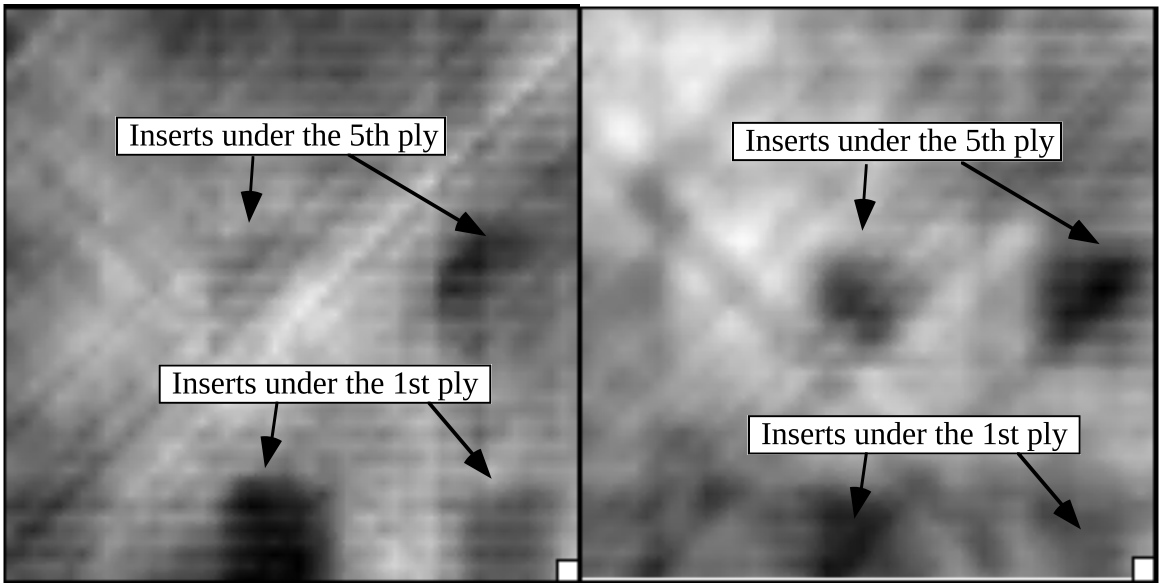
In Fig. 5 we show eddy current images of non-conducting inserts in a graphite/epoxy composite panel. This is important because it shows a sensitivity in the EC response to delaminations and not just from broken fibers. Surface roughness measurements of the same specimen show significant variation corresponding to the locations of the non-conducting inserts and a line scan of the variations is shown in Fig. 6. The changes in the eddy current signal due to the inserts are caused by fiber displacement. This effect is similar to thickness change variations observed using eddy currents in isotropic conductors. This result should be considered when interpreting the images of delamination patterns, particularly from impact, which is a major cause of fiber displacement.



Eddy current image

Ultrasonic image

Fig. 4. Impact damaged composite sample imaged using ultrasonic attenuation and eddy current impedance measurements. The ultrasonic data was taken at 5.86MHz and the EC results were performed at 4.0MHz.



Real part of the normalized impedance Imaginary part of the normalized impedance

Fig. 5. Image of the probe impedance of a 2.5MHz eddy current probe scanned over a composite sample containing non-conductive inserts. The scan region is 7.6 cm^2 (3 in^2).

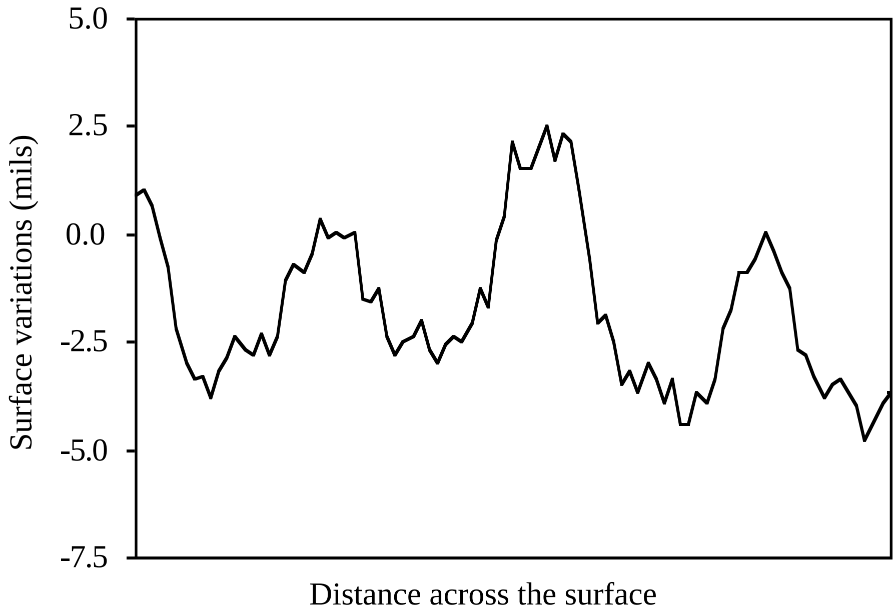


Fig. 6. Surface roughness variations along a line containing three inserts located at the fifth ply in the composite sample.

SUMMARY

The objective of this paper was to show the need for coordinated use of two or more NDE technologies to detect and assess composite defects. For the thermal-damaged panels, UT studies indicate that the thermal effects are confined to the hot-spots with no detectable degradation outside those regions. This result was partially validated by the Lamb wave analysis. There is a definite decrease in the wave velocity as the maximum sustained temperature is decreased, however, the results are subject to error as indicated by the error bars in the figure. In considering the eddy current results it appears that the sample degradation is limited to the matrix material and does not significantly effect the fibers. The only indications observed by the EC inspection were resistive and caused by lift-off changes from the adhesive tape securing the panels together and the roughening of the paint at the hot-spots due to burning. The reactive images are virtually featureless with the exception of indications due to the reference markers (metal tabs), and edge effects. The implication is that the fibers are not effected by exposure to heat. The above conclusions are preliminary and will be tested further in the near future. Uncoated panels with larger planforms will be fabricated to obtain better Lamb wave performance and for EC/UT responses unaffected by the charring paint.

The impact and insert study served to isolate the effects of delamination damage from EC indications, implying the possibility of correlating the results with ultrasonic data. Furthermore, the greater EC sensitivity to fiber damage affords the ability to find the two different boundaries due to both damage types occurring at one site, a typical impact effect.

Composite damage occurs in a variety of modes. The interaction of damage modes can conceal their individual signatures from a single NDE technology. Therefore, accurate assessment is more likely when two or more NDE technologies are used to sort them out. Although this study was limited to graphite/epoxy laminates, the multiple NDE technology approach can be adapted to other composite types even those requiring a different NDE technology combination.

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