DEFECTS IN THICK COMPOSITES AND SOME METHODS TO LOCATE THEM

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INTRODUCTION

Nondestructive evaluation (NDE) of thick composites is a difficult task. If ultrasonic techniques are used, such factors as attenuation (preferentially high frequencies); dispersion which causes the ultrasonic wave to change shape as it propagates in the composite; anisotropy (sound velocity a function of direction); material variation (inhomogeneities in composition); and transducer beam spread must be taken into account. Radiographic techniques depend on density differences to produce images. However, in many instances, the density differences produced by defects in composites are not great with the result that many defects go unnoticed. Thermography and shearography are two relatively new NDE techniques but heat flow considerations (for thermography) and stressing a large-thick composite structure sufficiently (for shearography) limit the application of these methods. Regardless of the technique used, the two principal aspects of NDE in a manufacturing environment are defect location and defect sizing.

From analysis and testing, a critical flaw size must be determined for each flaw type. If a flaw is found, it must be correctly sized if the use of composites is to be cost effective. For example, if the flaw is oversized, the part might be unnecessarily rejected.

Methods to locate and size defects in thick composites which we have found successful are discussed in this paper. Also mentioned are techniques we are working on for future NDE applications.

DEFECT LOCATION

Shown in Figure 1 is an ultrasonic through transmission C-scan of a section of a thick walled (2 inch thick) composite cylinder showing fiber waviness. The cylinder is constructed by wrapping composite prepreg tape around the cylinder axis. In some layers, the fiber tape buckles up. This buckling of the layers is called fiber waviness.

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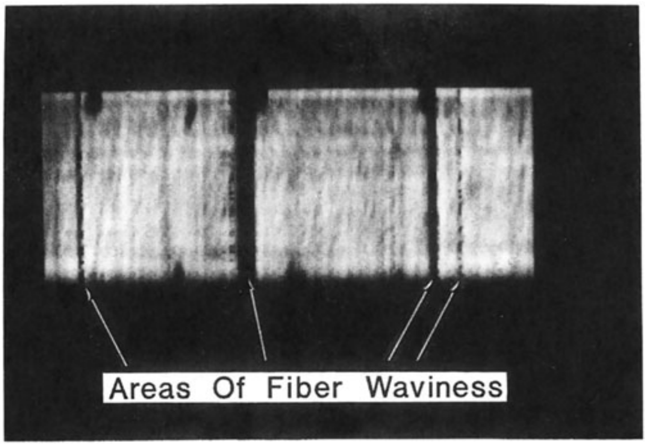
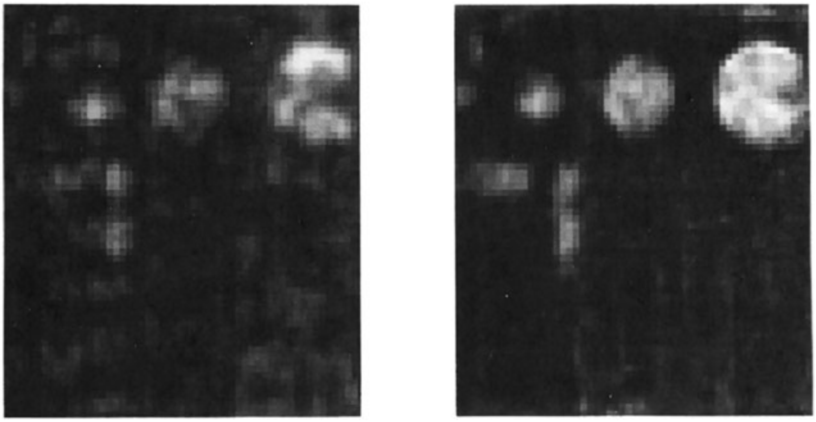


Figure 1. C-Scan of Thick Wall Cylinder Showing Fiber Waviness. Through Transmission Scan With 2.25 MHz Transducer. Two Inch Thick Cylinder Wall.

Ultrasonic through transmission with a 2.25 MHz transducer was used. In this scan, light grey represents areas of high sound transmission and dark grey or black are associated with areas of low sound transmission. Fiber waviness scatters sound away from the forward beam direction and thus less sound is transmitted (i.e. such areas are imaged as dark areas). Such fiber waviness radically affects the compression strength of composites. If the fiber waviness is small compared to the wavelength of sound used, the sound wave will pass by and not detect the waviness. Fiber waviness can be detected provided the sound wave can penetrate the composite and the waviness is on the order of the wavelength of the sound used.

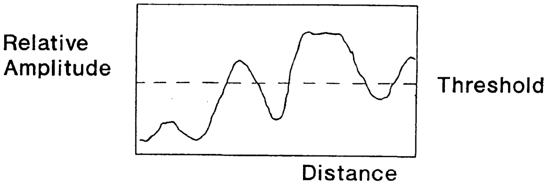
When detecting unbonds between composites and other materials, the material variations in a thick composite itself can distort the ultrasonic scan such that reflections from unbonds are not easily recognized. An example of this difficulty is shown in Figure 2. Here, ultrasonic C-scans of the bonded interface between a graphite/epoxy composite and a rubber composite are shown (each piece is roughly 1.5 inches thick). The pulse echo technique was used to image the interface so that areas of good bonding are dark and areas of unbond are light. The scan shown in part (a) is the interface image using the ultrasonic signal from the interface. Notice that the unbonded areas are not clearly defined. The scan shown in part (b) of the figure is the image formed by the ratio of the interface signal and the signal from the backwall of the second composite. The ratio technique reduces the effects of the ultrasonic signal from the composite, hence only variations in bonding are observed. Notice that the unbonded areas (four circles and 2 rectangles) are better defined in the second scan formed by the ratio technique. The improvement produced by the ratio technique can be understood by referring to Figure 3. Here two B-scans (taken from a line through the four circular unbonds shown in Figure 2) are shown in which ultrasonic signal intensity (arbitrary units) is plotted against distance. In the standard pulse echo case, the peaks of



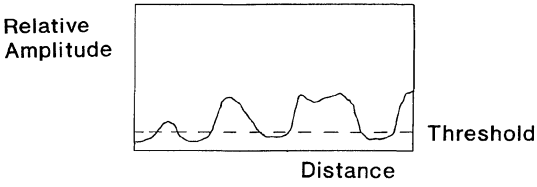
1ST INTERFACE SIGNAL

RATIO: 1ST INTERFACE / BACKWALL

Figure 2. Pulse Echo C-Scans of Thick-Bonded Composite Taken With 0.5 MHz Transducer. Four Circular Unbonds And Two Rectangular Unbonds Are Shown.



a) Standard Pulse Echo



b) Ratio Pulse Echo

Figure 3. B-Scan Data Taken Through the Four Circular Unbonds Shown In Figure 2.

the image corresponding to the two larger unbond images are visible above a threshold but the smaller peak is below the threshold and the image is barely visible in Figure 2 (a). The ratio technique (Figure 3 (b)) separates the peaks somewhat and allows a common threshold to be set which images all three unbonds as shown in Figure 2 (b).

Where more than one bond interface is present, the ultrasonic signal can be gated to image details of the chosen interface. In Figure 4, a pulse echo C-scan of three layers of composite bonded together is shown. A 0.5 MHz, 1.5 inch diameter transducer was used. The scan was gated on the second bonded interface. Notice that the unbonds at the first interface are imaged as dark shadows, while the unbonds at the second interface have a dark ring around them. The reflection coefficient at the interface is positive over a bonded area and is negative in the unbonded area. When the transducer is approximately half on the defect and half off, the contributions from the two reflection coefficients tend to cancel each other and the transducer signal amplitude is a minimum which produces the dark boundary in the image. This phase cancellation always occurs when the downstream material is higher impedance than the upstream material. The ring can be used to size the defect because the defect boundary is now well defined.

Shearography and thermography are two methods which allow large areas to be inspected quickly thus reducing inspection costs. If suspect areas are found, a detailed inspection can be performed by another method, ultrasonics for example. We have successfully used shearography to locate and image unbonds at the interface between two bonded composites as well as to detect delaminations in a composite as shown in Figure 5. The two bonded composites shown in the inset of the Figure are a filament wound piece 1.5 inches thick bonded to a 1.25 inch thick rubber composite. Unbonds were placed at the interface between the two materials and also at 3 levels in the rubber composite.

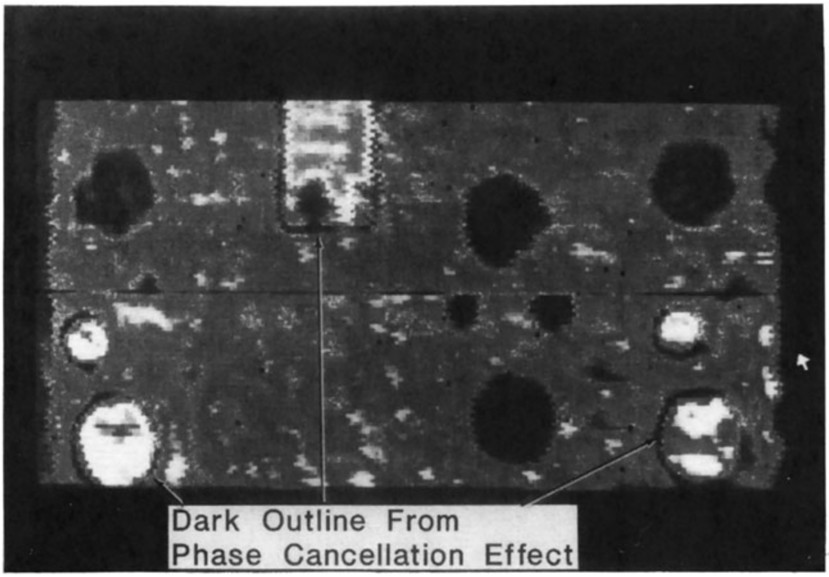


Figure 4. Pulse Echo C-Scan of Three Bonded Composites Showing Unbonds. Scan Gated On Second Interface.

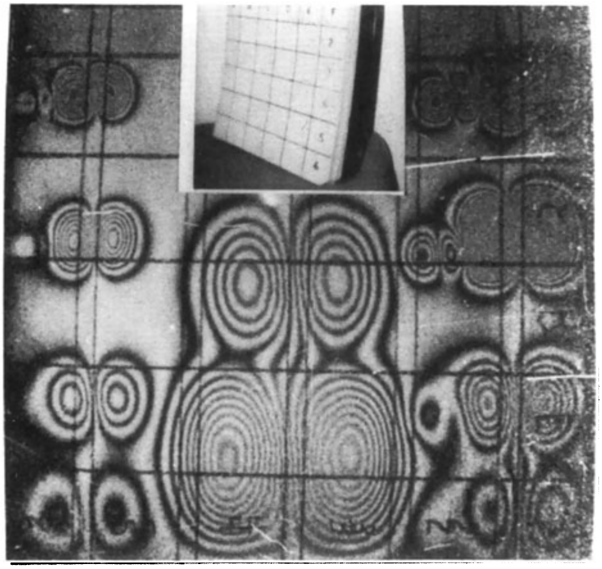


Figure 5. Shearography Results Showing Unbonds Between a 1.5 Inch Thick Filament Wound Composite and a 1 Inch Thick Rubber Composite Sample as Well as In The Rubber Composite.

Shearography images anomalies as fringe concentration pairs, that represent the variation of the out-of-plane displacement of the anomaly areas under loading (vacuum loading in our case). Figure 5 is a double exposure, the first exposure taken with the sample not loaded and the second after vacuum loading. The center of the fringe pair is the center of the anomaly. The relative depth of the anomalies from the observed surface is indicated by the fringe number. The closer to the observed surface the anomaly is, the greater the fringe density.

We have also tried using thermography as a rapid scanning method but have been less successful than with shearography. Shown in Figure 6 is the thermogram of a thick filament wound composite (1.5 inches thick) bonded to a 1.25 inch thick rubber composite. Unbonds were placed at the interface. The sample was heated from the filament wound composite side and observed from the rubber composite side. We could resolve a 4 inch and 2 inch diameter unbond, but could not see a 1 inch or 1/2 inch unbond. We were unsuccessful in observing the unbonds from the filament wound side.

Finding defects is only part of the problem. Defects must also be correctly sized in order to disposition composite parts.

DEFECT SIZING

In order to disposition material in an industrial setting, a defect criteria is necessary because every manufactured composite part has inherent material flaws, if only minute cracks. The question is, how large a flaw of a specific kind can be tolerated without affecting the mechanical strength of the part for the desired application?

Developing the critical flaw size for a manufactured part requires the interplay between design engineering, NDE, and mechanical testing. A case in point will be discussed. Parts were to be cut out of 9 inch x

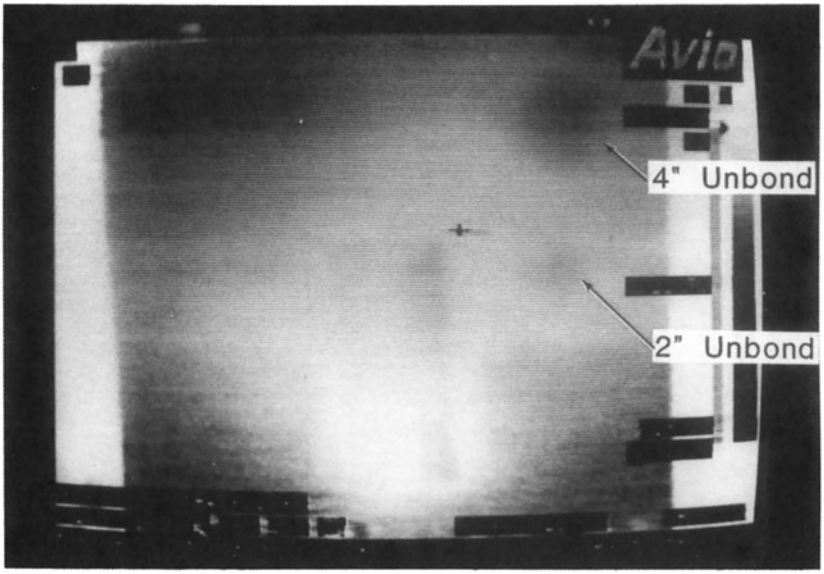
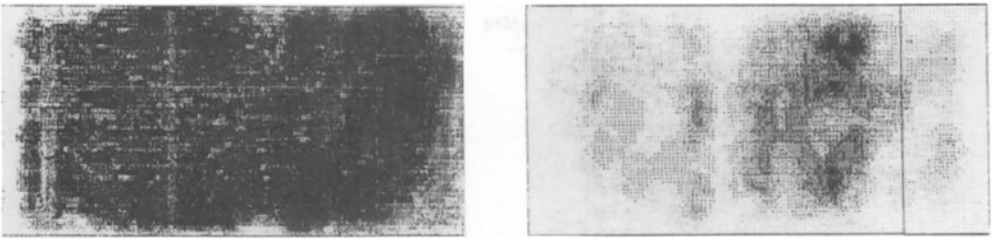


Figure 6. Thermography Results Showing Unbonds Between a 1.5 Inch Thick Filament Wound Composite And a 1.25 Inch Thick Rubber Composite. Thermogram Taken From The Rubber Side.

6 inch x 3/4 inch thick composite panels. Since machining was costly, only those panels that did not have significant porosity were to be used. The key factor is what is significant porosity? These panels were inspected at 10 MHz and 5 MHz with the results as shown in Figure 7. These scans were taken with through transmission and maximum transmission is dark. At 5 MHz, the panel looks good while at 10 MHz, the sound transmission is significantly reduced. The difference in these two scans is the result of small diameter porosity. At 10 MHz the wavelength of the sound in the panel is about 0.25 mm and at 5 MHz it is about 0.50 mm. After a series of mechanical tests, it was determined that for the specific application of this part, porosity smaller than 1.0 mm was not detrimental. Thus the panels were scanned at 2.25 MHz and not a higher frequency.

In general, any defect criteria will have two parts, a maximum allowable defect size and a cumulative total area of defects. For the total cumulative area, there will be a minimum defect size that must be detected. Furthermore, for some applications, the gap caused by the defect must be measured. Since ultrasonics doesn't measure gaps, another technique such as X-ray along the ply direction is used.

To correctly size defects, a "defect" standard is required. It is important that this standard be made of the same material as the part to be inspected. The ideal defect standard would be an actual part with known size defects built in. Such a standard is however costly and typically not done in the composite industry. Generally material of the same type as the part is characterized (sound velocity and attenuation measured in three directions) and then pieces are cut along ply directions. An artificial defect such as a teflon sandwich is glued to one face and the sections glued together. This standard is inspected and the location of the defects verified. Defects are placed at several depths in the standard and also several sizes are used. Our general rule is that we must be able to locate 1/2 the size of any required flaw.



PANEL 162: 5 MHz SCAN **PANEL 162: 10 MHz SCAN**

Figure 7. Through Transmission C-Scans of 3/4 Inch Thick Graphite/Epoxy Composite Panels Showing Relative Amounts of Porosity And Porosity Distribution.

A typical example of a manufactured part is shown in Figure 8. Here a section of a composite cylinder with a outer steel jacket is shown. Inspection of the composite integrity is followed by inspection of the bond between the composite and the steel jacket after assembly. To make a defect standard for this part, a good section of a previously rejected cylinder was used. Cuts along the ply direction were made and a range of defect sizes, simulating delaminations, were inserted at several depths and the pieces were glued together again. A separate standard was made from a section of composite and a section of steel jacket. Unbonds of several sizes were placed at the interface between the steel and the composite and the two glued together with the same gluing procedure as would be used in the actual manufacture of the part.

After verifying that 1/2 the critical flaw size could be detected with the defect standard, inspection of the composite was done by using hand held ultrasonics. The transducer was placed on the outer wall of the cylinder loss of the reflected signal from the inner surface indicated a defect. If a delamination were located, then in order to correctly size the defect, a wedge of the same material as the composite was placed on the outer surface to permit the transducer beam to be perpendicular to the ply direction. Following this inspection, the steel jacket was bonded to the composite and an inspection of the bondline was done using the unbond standard discussed above.

SUMMARY

Thick composites are difficult to inspect. Some of the factors that must be considered are attenuation, dispersion, anisotropy, and material variation. We have used ultrasonic through transmission and pulse echo (generally at low frequencies) to inspect thick composites. In some instances, signal processing techniques such as the signal ratio method or SAFT can be used to enhance the signal-to-noise ratio. The critical flaw sizes must be defined and usually with an interplay between design, NDE, and mechanical testing. To verify that an inspection can detect the critical size defect, it is necessary to use defect standards. These standards must be as representative (material and geometry) of the actual part as possible. Flaw sizing must be accurate in order to make material disposition decisions correctly. We have used new techniques, especially electronic shearography, to rapidly inspect large areas of composites to locate suspect regions.

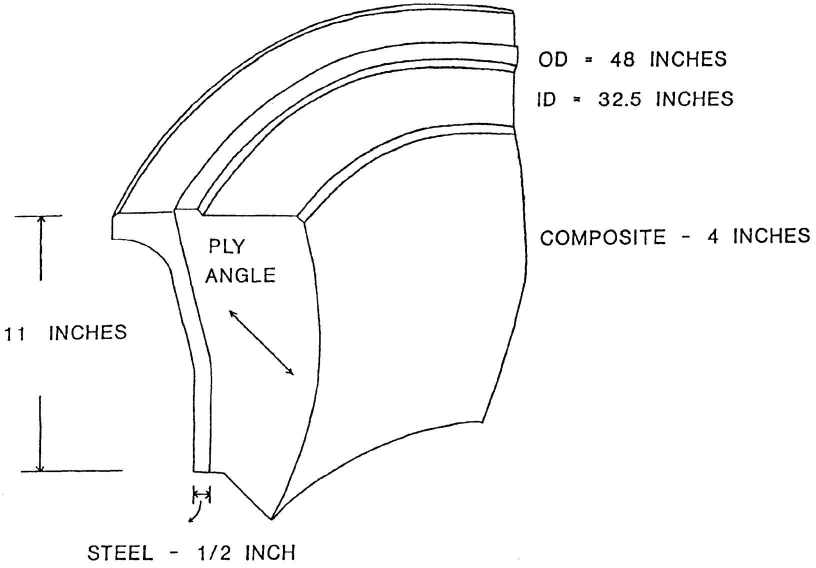


Figure 8. Schematic Drawing of A Section of A Typical Industrial Composite Assembly.

FUTURE WORK

In order to increase ultrasonic penetration of thick multi-layer composites and to improve the signal-to-noise ratio, we are currently conducting experiments with two techniques. The first technique is a low frequency impedance matched receiver, pulser, and transducer system and the second technique is time-delay-spectrometry. We are studying the extension of synthetic aperture focusing to anisotropic materials like composites to improve spatial resolution in imaging and defect sizing. Further experiments using electronic shearography to rapidly inspect large composite areas for suspect regions are planned.