DEFECT CHARACTERIZATION IN THICK COMPOSITES BY ULTRASOUND

David K. Hsu and Ali Minachi
Center for NDE
Iowa State University
Ames, IA 50011

INTRODUCTION

In today's application of composites, thick composites are beginning to be used for load bearing structural members. The nondestructive evaluation of composites relies heavily on ultrasound as the probing field, but the ultrasonic NDE of thick composites poses new challenges. First, to penetrate a large thickness of composite one must use ultrasound of low frequencies, but the long wavelengths at low frequencies afford only poor resolution. Secondly, with increasing thickness, the anisotropy of the material assumes a greater importance and certain simplifying assumptions acceptable in thin composites are no longer valid. Moreover, in pulsed ultrasonic measurement of thick composites, the high total attenuation associated with the large thickness and its frequency dependence often changes the spectral content of the pulses considerably [1].

The main objectives of this paper are to use ultrasonic techniques to evaluate the porosity content and to measure delamination sizes in thick composites. Porosity has been known to degrade the mechanical properties of composites; porosity occurring between the plies is particularly detrimental to the interlaminar shear strength of laminates. A method was developed previously for estimating porosity content in thin laminates [2,3], in which the void content was related linearly to the slope of the attenuation versus frequency curve (da/df, or the "attenuation slope"). The utility of this method for quantifying void content in thick composites is now explored.

Ultrasound has been most effective in detecting and mapping out delaminations in composite laminates. In a thick composite, however, delaminations present a dilemma between sensitivity and resolution. For lower attenuation and therefore better penetration in thick composites, it is necessary to use low frequency ultrasound, but the resolving power of low frequency waves is poor and the large transducer size may become comparable to or even greater than the delamination size. A model-based method that optimizes the sensitivity-resolution trade-off for thick composite inspection would therefore be very desirable. In this work an effort is made to develop flaw sizing methods when the transducer is comparable in size or even larger than the delaminations one wishes to size.

Porosity Evaluation in Thick Composites

In previous studies of porosity quantification by ultrasonic attenuation measurements, it was found that the frequency dependence of attenuation in composite laminates containing porosity was usually linear in the low megahertz range. Furthermore, based on a simple model and
experimental data, the slope \( (\frac{da}{df}) \) of the linear section of the attenuation versus frequency curve was correlated to the volume fraction of porosity [2]:

\[
\text{Void content (\%)} = k(\frac{da}{df})
\]  

(1)

where \( da/df \) is expressed in \((\text{cm MHz})^{-1}\). The numerical value of constant \( k \) depends on the void morphology; it is approximately equal to 4 for spherical voids (e.g. those often occurring in woven composite laminates) and approximately equal to 2 for flat elongated voids (e.g., those in laminates made of unidirectional prepreg tapes.)

The samples used in the study of porosity in thick composites were pieces of a graphite/epoxy filament wound case (FWC) of a large rocket motor made by Hercules. The samples were 1.4" thick, with a slight curvature, and the fiber directions were at 90\(^\circ\) (hoop) and ± 33.5\(^\circ\) from the axial direction of the case. The ultrasonic attenuation was measured using the through transmission of a broadband pulse in an immersion test setup. Pairs of 1 MHz, 1" diameter and 2.25 MHz, 0.5" diameter transducers were used in data acquisition. The attenuation versus frequency curves were obtained by comparing the spectrum of the sample signal with that of a reference signal transmitted through water only using the usual "log-difference" method. Transmission loss at the interfaces was accounted for, and beam spreading was corrected using the sound velocity normal to the laminates. Measurements were repeated using different transducer separation distances and using transducers of different center frequency and diameter, the variations in \( da/df \) obtained were less than ± 10 \%.

Measurement results in 1.4" thick composites containing porosity showed that the attenuation versus frequency curves were quite linear over the frequency range of 0.3 to 1.5 MHz. Figure 1 shows the results obtained from one location of the sample with \( da/df = 1.76 \) (cm MHz)\(^{-1}\). Two one-inch-square areas of a sample showing different attenuation were examined and the average \( da/df \) values were found to be approximately 1.3 (cm MHz)\(^{-1}\) and 1.8 (cm MHz)\(^{-1}\), respectively. Using Eq. (1),

![Fig. 1. Ultrasonic attenuation as a function of frequency of a 1.4" thick filament wound graphite/epoxy containing porosity. Dots are experimental data and solid line is the least squares fit.](image-url)
the predicted void contents were 2.6% and 3.6%, respectively, if the voids were flat long cylinders. However, if the voids were spherical, the predicted void contents would be higher: approximately 5.2% and 7.2%, respectively. These two areas were subsequently cut out and acid digestion analysis was performed to determine the void content. Acid digestion results showed that both areas had approximately 4.4% voids.

Since the estimation of void content from \( \Delta a/\Delta f \) depended on the void morphology, a penetrant solution of gold chloride in ether was applied to an adjacent area, followed by pyrolytic deplying, to examine the void shape. Combined with optical microscopy of cross-section surfaces, these examinations showed a great variety of void size and shape but the large flat and long voids seemed to account for most of the volume. The complexity of void morphology was believed to be the principal difficulty in estimating the porosity content using ultrasound. However, consistent with the expected trend based on void morphology, the acid digestion values fell between the two extremes and were closer to those for flat, long voids. More work is clearly needed in order to improve the quantitative evaluation of complex shaped voids.

**Sizing of Delaminations in Thick Composites**

In thick composites the large thickness and the frequency dependence of ultrasonic attenuation have the combined effect of a low pass filter and it is pertinent to examine the interaction between defects and long wavelength components of the interrogating fields. An important parameter in sizing a delamination ultrasonically is the width of the beam at the plane of delamination. In the extreme case where the delamination is much greater than the beam width, a simple C-scan will reveal the extent of the delamination and the flaw size can be obtained from the coordinates at the half-amplitude points of the echo signal. In the other extreme case where the beam width is much greater than the flaw size and a C-scan will simply map out the beam profile at the depth of the flaw for the particular experimental conditions. Such a scan contains little flaw information.

In thick composites, the most interesting and likely situation is probably the intermediate case when the beam width and the delamination size are of the same order of magnitude. (For frequencies of a few megahertz, flaw sizes of the order of 1/4" to 1" in diameter would fall in this case). In this regime a pulse-echo line scan across a delamination usually produces a bell-shaped signal amplitude versus position curve. The separation of the half-amplitude points (full width at half maximum), however, usually cannot be related to the delamination size in a simple manner because the width of the bell-shaped curve depends on a large number of parameters. These include the transducer size, the flaw depth, the water path length, the attenuation and elastic anisotropy of the composite, and, of course, the flaw size.

Experimentally the sample was a 2 cm thick laminate of 0/90 graphite/epoxy matting containing six 0.25" diameter simulated delaminations in the form of double Teflon film implants at the midplane. The sample was made by LTV Aerospace and Defense Company. A number of transducers were used in the line scan of the delaminations. To accentuate the effects of thick composites, some of the line scans were made with an additional 2" thick (280 plies) 0/90 graphite/epoxy laminate on top of the 2 cm sample. The 2" piece was practically void free and the signal-to-noise ratio of the pulse-echo signal was therefore acceptable even at a flaw depth of 2.4" (total path length 4.8"). Figure 2 shows the amplitude versus lateral distance curves with and without the additional 2" using a 5 MHz center frequency, 1/2" diameter planar transducer. The full width at half maximum of both scan curves overestimated the nominal 0.25" flaw size, and the overestimation was worse with the extra 2" thickness, as expected. Table I summarizes the flaw sizing results based on the half amplitude points of broadband ultrasonic pulses. As expected, the best size estimate was obtained using a focused transducer. Since the flaws were circular, conventional C-scans conveyed the same information as the line scans.
Fig. 2. Line scan results of a 0.25" diameter delamination in thick composites.

Table 1. Full-width-half-maximum sizes of a 0.25" delamination

<table>
<thead>
<tr>
<th></th>
<th>1 MHz, 1&quot; dia. unfocused</th>
<th>5 MHz, 1/2&quot; dia unfocused</th>
<th>5 MHz, 1/2&quot; dia 4&quot; focus</th>
</tr>
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<tr>
<td>Without extra 2&quot; GR/EP</td>
<td>0.45&quot;</td>
<td>0.33&quot;</td>
<td>0.27&quot;</td>
</tr>
<tr>
<td>With extra 2&quot; GR/EP</td>
<td>0.53&quot;</td>
<td>0.44&quot;</td>
<td>*</td>
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* Insufficient focal length for measurement at this flaw depth.

An Iterative Delamination Sizing Method

When the relative size of the delamination in a composite and the ultrasonic beam width are unknown, an iterative approach may be used to estimate the delamination size. In this method the experimental amplitude-versus-distance curve is compared to a computed amplitude-versus-distance curve first for a trial flaw size. The flaw size that gave a calculated curve closest to the experimental curve in the least squares sense is taken to be the estimated size.

Calculation of the amplitude versus distance curve for a delamination is generally difficult because it depends on the spectral content of the ultrasonic pulse and the elastic anisotropy (or slowness surface) of the composite. In this work the curve was computed for a single frequency and the comparison with experiment was done using the corresponding Fourier component of the measured flaw signal. Since a complete knowledge of the slowness surface of the matted 0/90 laminate was not available, a parabolic fit to the slowness of a unidirectional laminate was used as an approximation in the calculation. (Work is
currently underway to measure the stiffness matrix and to construct the slowness surface of the sample.) The assumption was also made that the delaminations were circular, flat and parallel to the plies.

The displacement field at the delamination was calculated with the Gauss-Hermite beam model [4,5] using the transducer size, water path and delamination depth of the experiment. In the pulse-echo test this field was reflected back to the transducer. Based on Auld's reciprocity principle, the field received by the transducer can be written as

\[ R = K \int_{S} u^2 \cdot n \, dS \]  \hspace{1cm} (2)

where \( u \) is the displacement field on the delamination, \( n \) is the normal unit vector to the delamination surface \( S \), \( dS \) is an area element of \( S \) containing the point with the displacement field \( u \), and \( K \) is a constant multiplicative factor irrelevant to the present iteration scheme. In comparing the measured and computed amplitude-distance curves, both were normalized to unity at their respective maximum.

The procedure for the iterative sizing is shown schematically in Fig. 3. At each transducer position in the line scan, an FFT was performed on the time domain flaw signal and the amplitude of a selected frequency (usually near the center frequency of the received ultrasonic pulse) was extracted to produce the amplitude versus distance curve. A theoretical curve was then computed using an initial guess of the delamination size, and the difference between the measured and computed curves was found. The flaw size was varied to minimize this difference and thereby determine the delamination size. The minimization routine used was a Fibonacci search with the golden section. Convergence usually took no more than 10 iterations using any reasonable but very forgiving initial guess.

Fig. 3. Schematic diagram showing the steps of the iterative sizing of delaminations in composites.
To test the iterative sizing method, three different transducers were used to size one of the six nominally 0.25" diameter simulated delaminations in the 2 cm thick 0/90 matted composite. Using a 0.5" diameter planar transducer with a center frequency of 2.25 MHz, and a water path of 4 cm, the 2 MHz signal amplitude versus distance is shown in Fig. 4. Also shown is the iterated amplitude-distance curve that gave the best fit to the experimental data. This iteration yielded 0.277" as the estimated delamination diameter. The same delamination was then sized using two focused transducers and agreements similar to that in Fig. 4 were obtained. The sizing results on this 0.25" flaw are summarized in Table II. As can be seen, the iterative sizing method produced satisfactory results for a variety of transducer size, focus and frequency. Using the 2.25 MHz, 0.5" diameter planar transducer, the other five 0.25" delaminations were also sized with the iterative method. The estimated diameters ranged from 0.256" to 0.284".

Finally, to provide an indication of the sensitivity of the iterative sizing method, a measured amplitude versus distance curve is compared in Fig. 5 with computed curves for several different flaw sizes. As can be seen, when the estimated size deviated from the correct value, the difference between the measured and computed amplitude versus distance curves began to increase.

Table II  Iterative sizing results for a 0.25" delamination

<table>
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<tr>
<th>Transducer parameters</th>
<th>Frequency component</th>
<th>Diameter estimate</th>
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<tr>
<td>5 MHz, 0.5&quot; dia. 4&quot; focus</td>
<td>2.5 MHz</td>
<td>0.272&quot;</td>
</tr>
<tr>
<td>2.25 MHz 0.75&quot; dia. 4&quot; focus</td>
<td>2 MHz</td>
<td>0.266&quot;</td>
</tr>
<tr>
<td>2.25 MHz 0.5&quot; dia. planar</td>
<td>2 MHz</td>
<td>0.277&quot;</td>
</tr>
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</table>

Fig. 4.  Computed best fit (solid line) for the 2 MHz component of a 0.25" delamination echo obtained by a 2.25 MHz, 0.5" diameter planar transducer. Dots are experimental data. This fit gave a size estimate of 0.277".
Fig. 5. Comparison between experimental results (dots) and computed results (solid lines) for delamination diameters of 0.2", 0.3", 0.4" and 0.5" using the 2.5 MHz component of the flaw echo obtained with a 5 MHz, 0.5" diameter transducer with a 4" focal length in water.

CONCLUSIONS

Ultrasonic NDE methods were applied to thick composites to evaluate two classes of defects: porosity and delamination. The attenuation versus frequency curve at low frequency (around 1 MHz) was essentially linear. Quantitative prediction of volume percent of voids was more difficult because of the broad range of void size and shape in the filament wound composite used. Sizing of delaminations in thick composites was achieved using an iterative method which minimized the difference between the experimental amplitude versus distance curve and the theoretical curve computed with Gauss-Hermite beam model.

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REFERENCES


