EFFECT OF DEBONDING IN FIBER-REINFORCED COMPOSITES
ON ULTRASONIC BACKSCATTERING

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INTRODUCTION

With the increased use of new high strength materials such as fiber-reinforced composites, the need for NDE methods is obvious, especially in industries such as the aerospace industry. The particular defect studied here (debonding of fiber from the matrix) is particularly important as it is often the earliest sign of fatigue damage in fiber-reinforced laminates [9]. Having an ability to detect such damage is clearly necessary and the application of ultrasound may provide a cheap and rapid method of detection. This paper presents two theoretical models of the effect of debonds on ultrasonic backscattering, and compares them with the experimental results from scale models of a single debonded fiber.

THEORY

Much work has been published on scattering from cylindrical and spherical scatters in fluids [1,2,3,4] but there is little in the literature on the similar problem for a solid scatterer embedded in a solid matrix. White [5] investigated the angular dependence of the monochromatic scattering by a cylindrical void at normal incidence for both longitudinal and shear incident waves in a solid matrix. The approach outlined here is concerned with broadband longitudinal radiation at normal incidence on a solid cylinder in a solid matrix.

The quantity calculated is the backscattering form function (BSFF) for the backscattered longitudinal wave. This relates the amount of scattered pressure, \( p_c \), to the incident pressure, \( p_0 \):

\[
p_c = p_0 \left[ \frac{a}{2r} \right]^{1/2} f(\infty, \pi) e^{i(kr - \omega t)}
\]  

(1)

where \( f(\infty, \pi) \) is the backscattered form function [10].
The BSFF depends on the elastic properties of both the matrix and the scatterer as well as the boundary conditions that exist at the interface. For a well-bonded fiber these are;

\[
\begin{align*}
\nu_{r1} &= \nu_{r2} & \text{continuity of radial velocity (2)} \\
\nu_{\theta 1} &= \nu_{\theta 2} & \text{continuity of tangential velocity (3)} \\
\sigma_{r1} &= \sigma_{r2} & \text{continuity of radial stress (4)} \\
\sigma_{\theta 1} &= \sigma_{\theta 2} & \text{continuity of tangential stress (5)}
\end{align*}
\]

It has been assumed that the materials used are lossless and the effect of thermal waves on backscattering is negligible.

By altering the boundary conditions at the interface the BSFF can be expected to change also. Two different models of the debonding have been considered, the first assumes that a thin air filled shell surrounds the fiber basically acting as a crack. The effect of introducing a thin air shell is shown in Fig. 1, the backscattered from function is displayed as a function of \(ka\) where \(k\) is the wave number and \(a\) is the radius of the scatterer. The basic shape is essentially the same as for an air filled cylindrical void, even with the shell set to a thickness of 1nm the backscattering remains basically the same. In the low \(ka\) region (below \(ka = 0.2\)) a sharp resonance occurs for the thin air shell. The size and position of this resonance depend upon the thickness of the shell. Typically as the shell thickness is reduced this resonance shifts to higher \(ka\). Further analysis needs to be done but it is thought that this may be some kind of whispering gallery mode although a similar resonance has been attributed to movement of the inclusion [7].

For the second model tangential slip has been allowed at the interface of the fiber and matrix. The approach follows Mal and Bose [6] with the boundary conditions given by;

![Fig. 1. Backscattering from a glass cylinder in a perspex matrix.](image-url)
\[ \sigma_{r1} = \sigma_{r2} \]  
\[ u_{r1} = u_{r2} \]  
\[ \sigma_{g1} = \sigma_{g2} \]  
\[ \sigma_{g1} = K[u_{g1} - u_{g2}] \]

K is in general a complex number which is related to the shear modulus of a layer of thickness \( \delta \) by;

\[
\text{shear modulus} = K\delta
\]

For simplicity in the calculations presented here, K has been kept real. It can be shown that for \( K \) tending to \( \infty \) then the case for perfect bonding is reached, conversely for \( K = 0 \) the situation of perfect slip is achieved. Fig. 2 shows the result of the inclusion of slip for a glass cylinder embedded in a matrix of perspex, the wave speeds (longitudinal and shear) and densities, are listed in [8].

It was found that with \( K \) set to the order of \( 10^{15} \) that the result was effectively the same as for a perfectly bonded cylinder.

At \( K = 5.0 \times 10^{13} \) differences to the bonded curve are now quite obvious. Below \( ka = 3 \) there is a general reduction in the amplitude of the feature but the overall shape remains the same. The resonance between \( ka = 5 \) and \( 6 \) has now become a double resonance of a lower amplitude and above \( ka = 7 \) there are further small changes in the size and shape of the structure compared to the bonded curve. With \( K \) set to \( 1.0 \times 10^{13} \), the curve becomes basically the same as for perfect slip with \( K = 0 \) (see Fig. 2).

![Fig. 2. Effect of interfacial slip on ultrasonic backscattering.](image-url)
In the region below $ka = 3$ there has been a further reduction of the peak with a knee introduced around $ka = 1.5$, this trend occurs smoothly as $K$ is reduced. At $ka = 3$ there is now a very pronounced resonance which is in stark contrast to the sharp dip seen for the bonded curve. There are a number of other sharp deviations from a bonded curve notably around $ka = 8.0$.

The two models, thin air shell and slip model, give quite different results. Both have obvious short comings, the thin air shell model assumes a continuous air shell surrounding the fiber with no contact, this is a highly unlikely situation. For the slip model account needs to be taken of the frictional losses. This may be done by allowing $K$ to become complex and is currently under investigation. In order to determine which aspects of these models best describe debonding and its effect on ultrasonic backscattering an experimental investigation on a scale model of a single fiber has been studied.

**EXPERIMENTAL INVESTIGATION**

The scale models used were a single wire of either Copper or steel wire embedded in a cold-setting epoxy resin (Araldite: HY 951 hardener, MY 753 resin). As all the theoretical results are a function of $ka$ the experimental model can be scaled using a larger fiber (approximately 0.36mm radius) and lower frequencies to look for the effects predicted by the theory.

The basic technique used was a pulse-echo technique with a broadband transducer being excited by a short duration high voltage pulse, frequency components of the incident wave range from 3 MHz to 10 MHz. This leads to a corresponding $ka$ range for a 0.36 mm radius scatterer of $2 < ka < 8$. The backscattered signal is captured on a digitizing CRO and then time-averaged to improve signal to noise ratio. The digitized signal is transferred to a personal computer for Fourier transforming and dividing out the transducer’s frequency response (obtained from the pulse received from a large plain reflector). The result is the scatterer’s frequency response. The backscattered form function is then obtained by allowing for cylindrical spreading of the backscattered signal and for transmission through the front face of the epoxy block.

Results for a well-bonded wire are in good agreement with theory. Fig. 3 shows the results for the copper wire. The positions of the features in the measured backscattered form function agree very well, especially the position of the troughs. There is a systematic error with the experimental points too high but from $ka = 3$ to $ka = 7.5$ the relative sizes of the resonances matches those predicted by the theory. Below $ka = 3$ and above $ka = 7.5$ the experimental points are significantly higher. This is due to a signal processing artifact, where the sensitivity level of the transducer is becoming quite low and is leading to errors when dividing the scatterer’s response by the transducer response.

The copper wire was now debonded from the matrix by physically pulling the wire from the block. Although crude, this method ensured the wire was debonded. The wire was then carefully inserted and the experiment repeated. The result of this measurement is shown in Fig. 4.

The immediate striking feature is that the two curves are very similar in the relative sizes and shapes of the resonances. In addition there is an apparent shift of the debonded curve to higher $ka$ in comparison with the curve for the well bonded wire. This is particularly noticeable for the troughs at $ka = 4$ and at $ka = 7$. However the overall structure is basically the same as that for the well-bonded wire. It is only in direct comparison that the differences become clearly apparent.
A further experiment was conducted on separate specimen (Copper wire in epoxy resin). This time however the wire was not completely pulled out. The debonded region extended some two thirds to three quarters the length of the wire. This could easily be identified with the naked eye and by viewing the block through crossed polarized filters. A sharp change in the birefringence patterns could be seen at the end of the debonded region. Two sets of measurements were made, firstly on the debonded region far from the still bonded wire and secondly much closer to the bonded wire but without the incident beam impinging on this area. Primarily this was done to produce two sets of data that would concur and create confidence in the results.
The results from the two regions of debonded wire are displayed in Fig. 5a and 5b. Both sets of results show a transition from a curve that bears little relation to the expected form function for a bonded wire, to one that is distinctly similar to the expected scattering for a bonded wire. The major difference between Fig. 5a (upper wire) and 5b (lower wire) is that the transition was seen to occur much faster for the upper region of the debonded wire.

In Fig. 5a the curve obtained immediately after debonding clearly shows little similarity to that for a bonded wire (c.f. Fig. 3). After approximately an hour it can be seen that in the region below $ka = 5$ the two main resonances have been picked out with the one at $ka = 4$ still quite small. The trough at $ka = 3.5$ has shifted to higher $ka$ by approximately the same amount as was seen in Fig. 4, ($\Delta ka = 0.17$). After about 1 day the upper region of the debonded wire (Fig. 5a) shows a much larger peak at $ka = 4$ and a sharp trough at $ka = 7.5$. In the range $5.0 < ka < 7.5$ the two peaks seen in Fig. 3 are much reduced.

For the lower debonded region (Fig. 5b) the curve obtained immediately after and one hour after debonding are very similar above $ka = 3.5$, the two sharp troughs at $ka = 3.5$ and $ka = 6.5$ are picked out well. Once again these features are shifted to higher $ka$ with respect to a well bonded wire, by $ka = 0.17$. It is only after a day subsequent to being debonded that the results for the lower wire approach those for a bonded wire, and this is only true for the region below $ka = 5$. As for the upper region of the wire there are some oscillations in the structure from $ka = 5$ to $ka = 7.5$.

As a function of time the scattering is clearly tending to a stable situation which is very similar to the backscattering from a well-bonded wire. It appears that the wire having debonded and stretched then proceeds to relax back to a stable situation in good contact with the matrix material. This is further implied by the way that the upper portion of the debonded wire, which was subject to a greater strain than the lower) relaxed faster than the lower region of the debonded wire. Even after a day (and indeed a week) the scattering from the debonded region remains the same. There are some structural changes in the backscattered spectra, the knee in the peak at $ka = 4$ and in the region $5.0 < ka < 7.0$, which are presumably linked to the conditions now existing at the interface and the effect of damage in the matrix material.
around the wire. In addition there is the shift to higher $ka$ of the curves for debonded wires (partial debonds and total pull out). This may be due to the effect of a thin shell of damage making the effective radius of the scatterer larger, this is to some degree born out by $\Delta ka$ remaining relatively constant.

**CONCLUSION**

Of the two theoretical models discussed, the thin air shell model does not appear to be a realistic description of the effect of debonding on the ultrasonic backscattering. The slip model has predicted lower levels of backscattering (when the parameters for the scale models were input) but still did not show any of the features seen in the measured form functions for the scale models. However, of the two theoretical models the latter does seem the more promising and the introduction of frictional losses may well make this a more realistic description. The experimental results show that debonding can be detected with some very unexpected features occurring such as the shift to higher $ka$ and the observed relaxation of the wire. However until theory and experiment can be brought into closer agreement it is unlikely that scattering measurements can be used as an NDE technique for the detection of debonding.

**REFERENCES**

10. R. Hickling, JASA 30, p. 137.