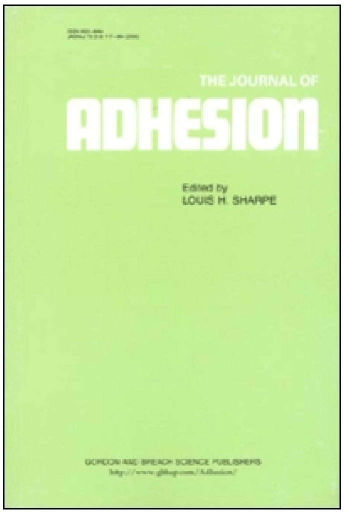

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Modeling Concepts for Studying Ultrasonic Wave Interaction with Adhesive Bonds

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Recent research has shown that such adhesive bondline defects as chemical segregation, variation in cure, gas entrapment or inadequate surface preparation are responsible for many adhesively bonded structural failures. Analytical models have been developed in this work that can be used to relate these "flaws" to the manner in which they affect the reflection of an ultrasonic pulse from such a bondline. The results of this study provide a substantial resource base for extended research through which ultrasonic inspection can become a reliable NDT technique for bond strength determination.

INTRODUCTION

The need for adhesives as a structural joining technique is of great importance today. The world consumption of resins and synthetic adhesives is increasing rapidly. A major limitation on the use of structural adhesives, however, is the determination of the ultimate strength after completion of the bond. Rose and Meyer[1] review some of the studies which have been conducted in an attempt to evaluate bond strength. Work in this paper is not concerned with the specific detection problems of voids or debonds in the adhesive, but rather the development of analytical models that can be used to relate anomalies associated with low load failures in an adhesive bond having no voids or debonds to the interaction of an ultrasonic pulse with that bond.

Models are developed in this work that allow us to study the basic ultrasonic wave interaction mechanisms with an adhesive bond. It is hoped that this basic understanding will enable us to select suitable ultrasonic inspection methods and signal processing techniques that will advance the state of the art of ultrasonic inspection from a mere flaw detection tool to a quantitative bond characterization tool.

The models developed in this work represent a first step toward establishing accurate and reliable ultrasonic inspection techniques in the adhesive bond evaluation process.

MOTIVATION FOR THE DEVELOPMENT OF ANALYTICAL MODELS

The failure of an adhesive bond generally falls into one of two categories; adhesive failures and cohesive failures. A failure is adhesive in nature if it occurs along one of the interfaces between the adhesive and the substrate. A cohesive failure exists if the failure occurs entirely within one of the components making up the bond system—the two substrates and the adhesive layer itself.

Studies have shown[2] that many interfacial type failures occur due to the lack of proper interfacial preparation or subsequent surface contamination resulting in a weak intervening layer at the adhesive-substrate boundary. When a failure is adhesive in nature, the ultimate load is usually relatively low compared to the nominal strength of the adhesive.

Cohesive failures, on the other hand, generally occur at much higher loads; ideally at the predicted strength of the weakest member of the bond system. The portion of this work concerned with cohesive failures deals with those that occur within the adhesive at loads below the nominal strength of the adhesive. Studies have also shown[3] that in many cases these failures are caused by a migration of certain chemical components of the adhesive to the adhesive-substrate interface. This migration causes a deviation from the designed chemical balance through the adhesive which could definitely alter the ultimate strength of the adhesive.

Another possible cause of a cohesive failure is the entrapment of gas bubbles[4] in the adhesive during manufacturing. These bubbles cause reduced load transfer area in the adhesive and also produce stress concentration which can seriously decrease the load carrying ability of the adhesive. By properly controlling ambient pressures prior to and during the bonding process, however, these gas bubbles can usually be eliminated from the completed bond. Whether they have been eliminated cannot be determined nondestructively once the cure cycle has been completed.

These anomalies which have been characteristic of bond failure were used in the development of the analytical models discussed in the next section. Since the anomalies also represent a variation in the mechanical characteristics of the adhesive, they will cause a variation in the interaction of an ultrasonic wave with the adhesive layer.

Analytical models

Several theoretical models of the adhesive bond layer have been developed herein that utilize the physical property variations that may exist in an adhesively bonded system to study the ultrasonic wave interaction with that adhesive layer. In conjunction with the elastic wave theoretical analysis, they provide an essential step in obtaining a thorough understanding of the nondestructive testing possibilities for adhesive bonds. Computer programs discussed in more detail by Rose and Meyer,[1] have been developed that can be used to calculate the theoretical ultrasonic reflection from the adhesive layer as a function of modeled bond parameters and ultrasonic input wave characteristics. By varying these input values, relevant trends in the resulting ultrasonic signals with the various bondline properties can be determined.

Reference bond model

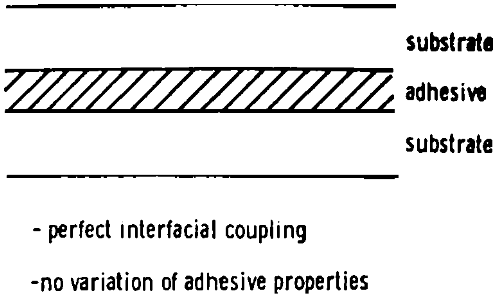
The first approximation of an adhesive bondline is to consider the adhesive layer as a homogeneous, isotropic layer with isotropic substrate layers on either side, as depicted in Figure 1a. Perfect wave coupling is assumed to exist at the interfaces. Using this model, major differences in the ultrasonic reflection due to different adhesive material properties or bond thickness can be detected. Obviously, variations due to slight anomalies that may exist within the adhesive or at the bond substrate interface cannot be studied with this model.

The three-layer model of the adhesive bond represents a theoretically ideal situation with respect to the reflection and transmission of ultrasonic waves from the bond layer. It is this model that will be used as a reference for comparison with possible material property gradients and surface treatment problems that may occur under more realistic circumstances.

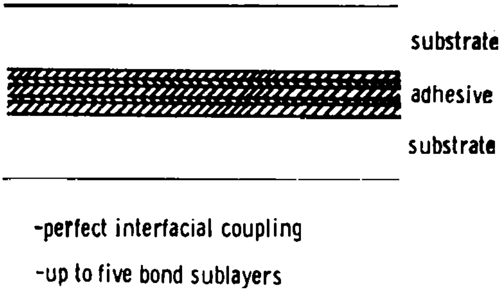
Material property gradient model

The chemical migration, gas entrapment and cure variation problems, in addition to decreasing the strength of the adhesive bond, will cause some sort of mechanical property variation through the thickness of the adhesive. It is this variation which will affect the transmission and reflection of ultrasonic waves through the adhesive. Since the variation can be related to the cohesive strength of the bond, then the bond strength can also be related to the variation in the ultrasonic reflection.

The N-layer model considers variations of this type by assuming that the adhesive layer consists of several sublayers—each of a uniform thickness as shown in Figure 1b. By altering the characteristics of these layers, property variations through the bond thickness can be modeled. Ideal coupling is again assumed to exist at the adhesive-substrate interface.



a.) Reference Bond Model



b.) Property Gradient Model

FIGURE 1 Models for adhesive bond analysis.

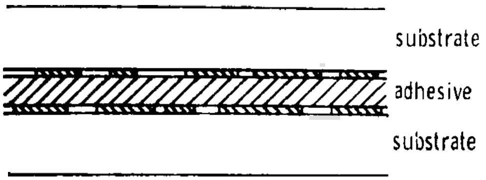
Surface preparation model

As discussed earlier, it is well known that proper surface preparation is required if adequate and consistent bond strengths are to be expected. It is, however, very difficult to determine the quality of the surface treatment once the bond has been assembled.

Let us consider the possibility that poor or inadequate surface preparation allows the assembly of a bond with oxides or contaminants remaining on the substrate surface. These surface contaminants may result in microscopic points of non-bonding uniformly distributed over the adhesive-substrate interface. These non-bond points will not only affect the strength of the overall bond but also affect the wave coupling between the substrate and the adhesive. One method of modeling adhesive-substrate interface flaws is to assume that the contact between the adhesive and the substrate is not continuous but consists of many points of contact separated by microscopic voids as shown in Figure 1c. Stronger bonds might be considered as having a higher total contact area. The results obtained from this model will aid in the detection of weak bonds resulting from interface flaws such as an inadequate or improper surface preparation.

Combined property gradient and surface preparation model

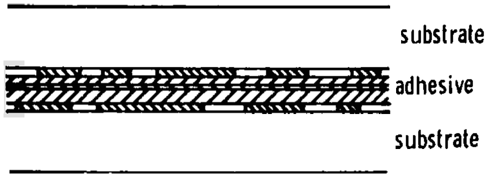
The fourth model, shown in Figure 1d is simply a combination of the previous two models and can be used in studying the interactive effects of those two types of bond anomalies.



-possible variation of interfacial coupling

-no variation of adhesive properties

c.) Surface Preparation Model



- possible variation of interfacial coupling
- possible variation of adhesive properties

d.) Combined Property Gradient and Surface Preparation Model

FIGURE 1 Models for adhesive bond analysis

ULTRASONIC WAVE ANALYSIS

Before computing the ultrasonic reflection from an adhesive bondline, let us first consider the problem of determining the reflection of a continuous plane wave. The solution consists of solving the governing wave equation in each material and matching stresses and displacements at the interface.

In determining the reflection from a material layer, such as the reference model, the total reflection will be the sum of the reflections from both the first and second interfaces, taking into account the phase lag of the reflection from the second interface with respect to the reflection from the first.

When it is desired to determine the reflection from a multiple layer system such as the Gradient Model, the procedure is similar to that outlined above except that it is more complex. The number of individual reflections that must be considered increases tremendously with the number of layers. In the particular case of the Gradient Model it is reasonable to assume the variation in the mechanical properties of one bond sublayer with respect to the next will be small. The reflection coefficient at the interface between any two adhesive sublayers will therefore also be small in magnitude. Internal reflections which have been reflected from any two internal interfaces and will be very small in magnitude since the amplitude will depend on the product of two small coefficients. Neglecting the second order internal reflections simplifies calculation of the reflection yet still yields characteristics of the material gradient in the adhesive.

In the analysis of the Surface Preparation Model the conventional reflection and transmission coefficients are no longer valid due to the presence of the equivalent area discontinuity at the interface. It must be pointed out that this model is not meant to imply that junction of the adhesive and substrate consists of small "bridges" as depicted in Figure 1c. As mentioned earlier, poor substrate surface preparation might produce an adhesive-substrate containing microscopic nonbond areas or areas of poor intermolecular contact uniformly distributed over the interface. The model is a representation of an equivalent contact area reduction which will affect the ultrasonic wave reflection and transmission in a similar manner.

The equations for the reflection and transmission amplitudes of a stress wave at a discontinuity in both area and material properties can be developed by again solving the wave equation in each section and matching stresses and particle velocities at the interface. This problem has been discussed by Ripperger and Abramson[5] for a bar and by Mortimer, Rose and Blum[6] and Rose and Mortimer[7] for a shell type structure. Assuming that

1) damping and dispersion effects are negligible in the individual layers
2) plane sections remain plane
3) deformations are linear and elastic

the solution of this problem yields

$$\frac{R}{I}=\frac{\rho_2 c_2 A_2-\rho_1 c_1 A_1}{\rho_2 c_2 A_2+\rho_1 c_1 A_1} \tag{1}$$

and

$$\frac{T}{I} = \frac{2\rho_2 c_2 A_2}{\rho_2 c_2 A_2 + \rho_1 c_1 A_1} \tag{2}$$

It can be seen that if the areas of each material at the interface are identical, the equations shown above reduce to the conventional reflection and transmission coefficients.

In order to analyze the Surface Preparation Model, it is only necessary to substitute these new equations in place of the traditional ones for each interface. By assigning the outside two bond sublayers an equivalent area reduction, the corresponding effect on the incident stress wave can be determined.

COMPUTER PROGRAM

A computer program was written to generate the theoretical reflection of an input pulse from one of the bond models. Starting with a particular pulse shape, the input is first transformed to the frequency domain through the use of the Cooley–Tukey Fast Fourier Transform algorithm[8]. Each of the Fourier components of the input pulse is considered separately and its interaction with the particular bond computed. The program is written such that the bondline can be divided into as many as five sublayers allowing each to have its own mechanical properties, such as elastic modulus and density and geometric properties such as thickness and equivalent area as discussed for the model. The program computes the magnitude of each reflection from energy having traversed the bondline no more than eight times. The energy is usually dissipated by this time and any reflection occurring thereafter is small enough to be considered negligible. A record is maintained of the time delays of each reflection for reconstruction purposes in the time domain. When the reflection of each Fourier component is computed, they are added in the time domain to obtain the total reflection from the bond. The analysis of any one of the bond models can be accomplished using the same program by adjusting the number of bond sub-layers and the properties of each to suit.

The amplitude-time echo from the bond layer $h(t)$ is the convolution of the input signal, $f(t)$ with the reflectivity characteristics of the bondline, $g(t)$, as;

$$h(t) = f(t) * g(t) \tag{3}$$

In the frequency domain, convolution is characterized by multiplication:

$$H(W) = F(W)\ G(W) \tag{4}$$

Since we are interested primarily in determining bondline properties, we will allow the input spectrum $F(W)$ to be unity over some desired frequency range. As the extent of the frequency range is increased, the corresponding pulse in the time domain will approach a Dirac delta. The reflection spectrum $H(W)$ in such a case is identically equal to the spectral characteristics of the bond $G(W)$. By performing a Fourier inversion using a phase reference, the reflection characteristics of the bond in the time domain could be determined. Seydel and Frederick[9] discuss a technique similar to this for resolving echoes from reflectors very close to each other. Once the reflected spectrum from the unit amplitude input spectrum is determined, the reflected spectrum for an arbitrary input can be determined, the reflected spectrum for an arbitrary input can be determined using Eq. (4) above.

SAMPLE RESULTS

Computer runs were made for several possible situations that could be encountered in the study of material property gradient and surface treatment

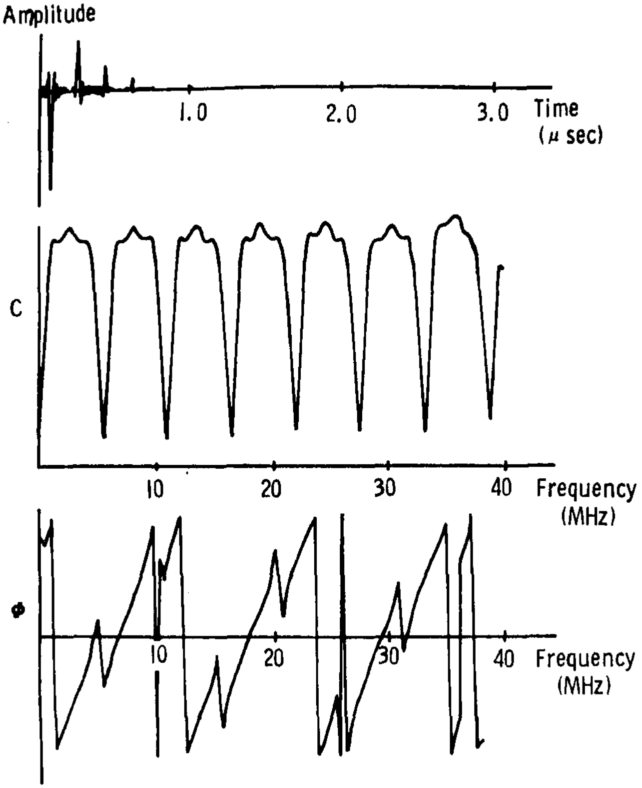


FIGURE 2a Theoretical reflection for the reference bondline.

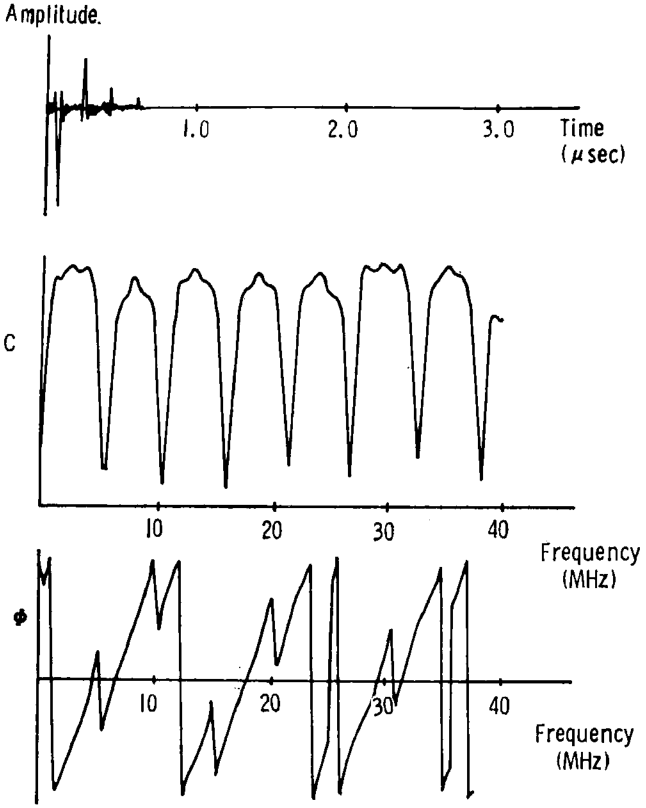


FIGURE 2b Theoretical reflection for a density gradient bondline.

problems. Typical results, shown in Figure 2, indicate the characteristic trends in both time and frequency domains associated with the particular adhesive properties modeled. The upper trace is the computer generated amplitude-time reflection of the "white noise" input pulse from the particular bondline being studied. The center and lower curves are the amplitude-frequency and phase-frequency profiles respectively. The phase amplitude is restricted to angles between $-\pi$ and π and therefore the "jumps" in the curve from π to $-\pi$ are not related to the bondline characteristics. Figure 2a shows the reflection from the reference bondline model. Brekhovskikh[10] demonstrated that the location of the "spectral depressions", frequencies at which the amplitude of reflection becomes very small, for a single layer could be related to the ratio of layer thickness and wave length in the layer. A phase discontinuity also apparently related to layer thickness occurs at various locations in the phase profile. Figure 2b represents the reflection from a

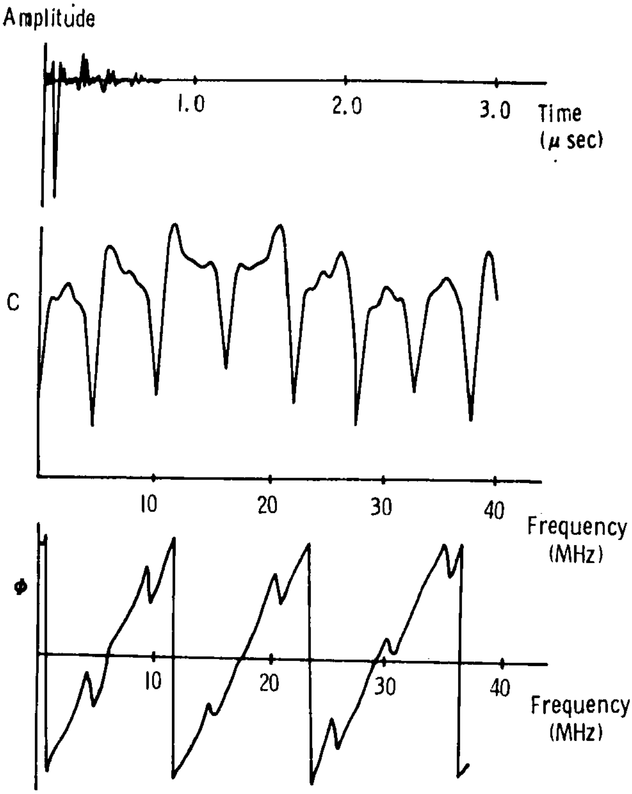


FIGURE 2c Theoretical reflection for a bondline having improperly prepared substrate interfaces.

bondline having a density gradient while Figure 2c demonstrates the effect of a poor quality interface. The layer properties used in these model calculations are given in Table I.

Mast and Rose[11] mention that, in many cases, showing a variation exists in the reflection from a "flawed" specimen may be sufficient for the evaluation process. For instance, if these results for property gradient bands are compared in the time domain with the reference bond, it will be found that the differences are very small and in some cases almost undetectable visually. If, however, the Fourier Transform functions are compared, it will be found that the differences are more noticeable. For example, a comparison of the results for the reference bond and a density gradient bondline, are shown in Figure 3. Although the amplitude-time curves are almost indistinguishable, there are very noticeable differences in the Fourier curves. The Fourier amplitude curve in Figure 3 shows a significant spectral depression shift in the 28 MHz region. In the Gradient model the "spectral depressions" can no longer be used to indicate the properties of a single layer since the bond now consists of a system of many sub-layers. The spectral profile has been altered by this variation. The Fourier phase curve in Figure 3 also shows more easily detected differences although they are spread over a wider frequency range.

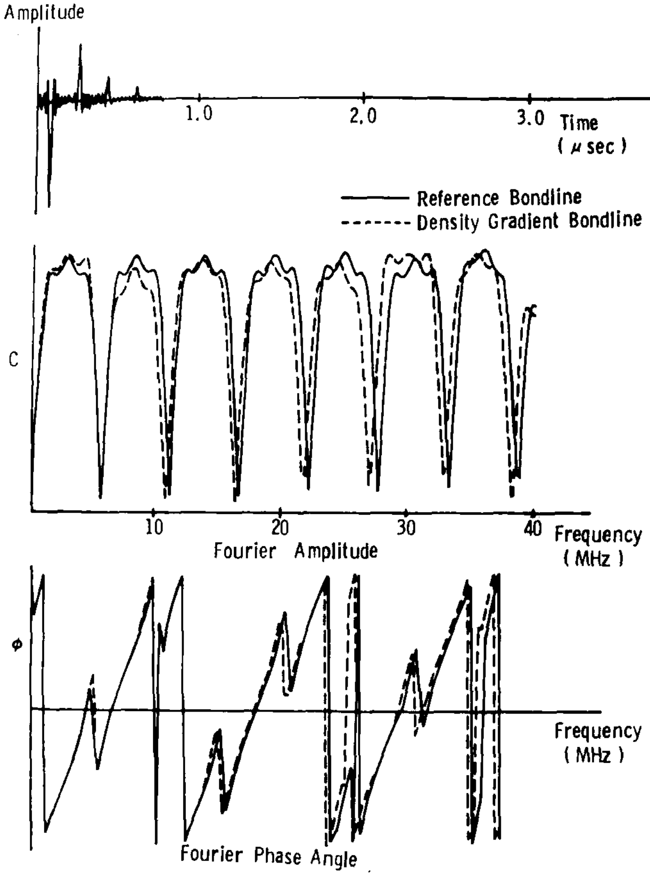


FIGURE 3 Comparison of the reflections from the reference bondline and the density gradient bondline.

Results for the model of interface flaws indicate more drastic amplitude changes in the time domain as well as the frequency domain, possibly implying less need for sophisticated signal processing techniques.

TABLE I

Bondline data for computer model analysis

Type of bondline modeled	Numbers of bond sublayers	Thickness of bond sublayers cm	Equivalent area of bond sublayers	ρ gm/cm^3	c cm/sec
Reference bondline	1	0.025	1.0	1.18	0.267×10^6
Density gradient bondline	5	0.004166	1.0	1.42	0.239×10^6
		0.004166	1.0	1.18	0.267×10^6
		0.008333	1.0	0.944	0.292×10^6
		0.004166	1.0	1.18	0.267×10^6
		0.004166	1.0	1.42	0.239×10^6
Poor quality interface bondline	3	0.0042	0.50	1.18	0.267×10^6
		0.0166	1.00	1.18	0.267×10^6
		0.0042	0.50	1.18	0.267×10^6

CONCLUDING REMARKS

Analytical models were developed that can be used to relate bondline anomalies to the manner in which these anomalies will affect the reflection of an ultrasonic pulse. The models demonstrate two types of effects that can be expected as a function of such bondline properties as density or modulus gradients, inadequate adhesive cure, or inadequate surface preparation:

a) Obvious effects—the amplitude—time and amplitude—frequency response help in selecting the optimum transducer for experimental inspection by illustrating the theoretical effects of the particular flaw on a "white noise" input pulse. By observing the characteristic changes in the theoretical reflection, desirable qualities of the experimental inspection system can be established.

b) Non obvious effects—the computer results using the bond models provide training and test data sets that can be used in future signal processing analysis and pattern recognition studies to detect variations that may not be noticeable visually.

Use of the adhesive bond models demonstrates that the variations in the ultrasonic reflections may be small and that care must be taken not to overlook these small differences in the ultrasonic reflection signal patterns. Careful signal analysis may avoid more advanced and perhaps complex signal processing and pattern recognition work.

The work conducted in this study also provides a substantial resource base for extended research. Future work should be directed toward the development and implementation of new analytical models which better characterize an adhesive bondline with respect to factors such as attenuation, dispersion, and viscoelastic effects. Attention should be given to shear wave interaction with the bondline so that possible effects due to moisture absorption could be minimized. Efforts should also be made to manufacture ultrasonic inspection equipment to specifications suitable to research specifications. This, in itself, could eliminate the need to restrict data comparison to those results obtained during one data acquisition session.

Future work should also be directed toward the development of high speed data acquisition and analysis systems which will allow the inspection of the bond at several points, especially near the ends. The strength evaluation at each point should be weighted in accordance with its position and the expected stress distribution for the bond. A technique called "simulearning", introduced by Rose, Mast and Niklas[12] could be of value here.

With this advancement in the state-of-the-art, ultrasonic inspection could become a reliable quantitative technique for the determination of bond strength in the not too distant future.

Acknowledgement

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List of Symbols

A_i = cross sectional area of the ith material
I = amplitude of the incident wave
R = amplitude of the reflected wave
T = amplitude of the transmitted wave
c_i = wave velocity in the ith material
ρ_i = density of the ith material

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