NUMERICAL COMPARISON OF EXPERIMENTALLY MEASURED ULTRASOUND THROUGH A MULTILAYERED SPECIMEN

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INTRODUCTION

The integrity of bonded structures is of paramount importance in the safe and reliable operation of aircraft equipment. Fuselages, helicopter rotor blades and nose cones are multilayered composite structures bonded together. The operational readiness and security of these units depend to a large extent on the integrity of the interfacial bonds. Adhesive and cohesive strength studies do not appear promising because failure is really dominated by defects and not by some average physical properties of the adhesive and the interface [1].

Nondestructive evaluation of the bonds and bondlines has experienced very limited success [2]. NDE methods are needed to determine the strength of the bonds *in situ*. Unfortunately, no NDE method has demonstrated the ability to quantitatively state the strength of a bond. Several NDE techniques have been applied to assess adhesive bond quality. They include ultrasonics, acoustic emissions, radiography, holography, nuclear magnetic resonance, eddy current, and thermal imaging [3]. Of these accepted NDE methods only ultrasonics appears to retain a reasonable probability of success in the bondline application [4]. Thermal imaging requires the composite thickness to be small. Otherwise, the thermal image of the interface is completely masked by the diffusion of heat through the substrate. Nuclear magnetic resonance has shown some success in the detection of water within bonds but it has not been able to detect disbonds, foreign matter or weak bonds. Ultrasonic pulse-echo techniques have been shown to reliably detect total disbond regions. Some investigators indicate that the strength of the adhesive layer can be correlated to the attenuation coefficient and velocity of sound in the material [5]. Interfacial and horizontally polarized shear wave measurements have demonstrated the ability to discriminate bond strength [6]. However, the test configurations were highly restrictive and the practical application of the technique is undefined as yet. Leaky Lamb waves technique uses an oblique incident wave.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 10B
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1991

Usually the waves reflect off the interface, however, certain frequencies excite plate waves in the structure. These leaky waves have been shown to interfere with the expected reflection patterns [7]. Determining the correct frequency for destructive interference patterns is not reliable. Researchers have swept the frequencies to find a zone of interference. If one examines multiple frequency responses of the same test configuration small subtleties of the bond integrity can be inferred. This ability to detect weak bonds is still marginal. However, it does indicate that if one could correlate the multiple values obtained from the complex input signals then the probability of characterizing the system configuration would increase.

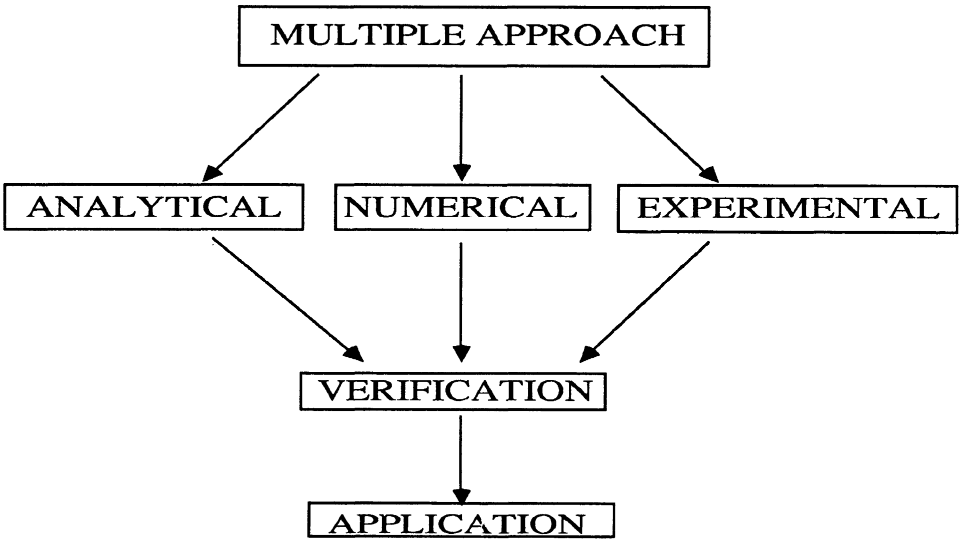


Figure 1. Multiple Approach Strategy for Assessing Bondline Integrity

It is this latter area of ultrasonics cross correlation that we pursue in our work. We have taken a multiple attack strategy involving analytical, numerical, and experimental components as shown in Fig. 1. Analytical analyses have been performed on the transient elastic waves radiating into an elastic half space. Most formulations assume a homogeneous, isotropic continuum with a point or line source [8-10]. A numerical model was developed for solving a complete ultrasonic NDE configuration [11]. This numerical model solves the transient elastodynamic equation of motion in discrete form subject to realistic boundary and initial conditions. For idealized boundary conditions the numerical results can be compared to the analytical solutions. Additionally, from the experimental side, test samples are prepared in a variety of bond configurations. Multiple transducer modes are used to probe the samples. These physical results are compared with the numerical model for verification of the multiple approach stategy. With confidence established in the numerical model, one can use this investigative tool to gain crucial insight into the physical processes of the ultrasound/bondline interaction.

PROBLEM STATEMENT

Our governing equation is the homogeneous elastic wave equation

$$\nabla \overline{\overline{T}} + \overline{f} = \rho \frac{\partial^2 \overline{u}}{\partial t^2} \tag{1}$$

where $\overline{\overline{T}}$ is the stress tensor, $\overline{f}$ are the applied body and surface forces, ρ is the density and $\overline{u}$ is the displacement vector. This elastodynamic equation can be expressed in terms of displacement

$$\mu \nabla^2 \overline{u} + (\lambda + \mu) \nabla\nabla \cdot \overline{u} + \overline{f} = \rho \frac{\partial^2 \overline{u}}{\partial t^2} \tag{2}$$

where μ and λ are Lamé constants. A Galerkin weighted residual method is applied to (2)

$$[M]\{\ddot{U}\} + [K]\{U\} = \{f_B\} + \{f_T\} \tag{3}$$

where [M] is the mass coefficient matrix, [K] is the stiffness matrix and the body and surface forces separated. A central difference is applied to the time component

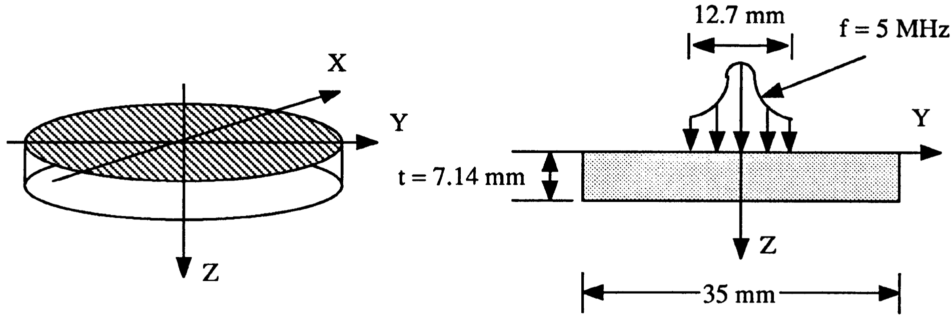
$$\ddot{U}_i^k = \frac{1}{\Delta t^2} (U_i^{k+1} - 2 U_i^k + U_i^{k-1}) \tag{4}$$

The spatial derivatives (subscripts) are explicit at time level k (superscripts) and the mass matrix is lumped for computational efficiency,

$$\{U^{k+1}\} = \Delta t^2 [M]^{-1} (\{f^k\} - [K]\{U^k\}) + 2\{U^k\} - \{U^{k-1}\} \tag{5}$$

RESULTS

The first test configuration was an aluminum sample 7.14 mm thick with a 5MHz pulse-echo longitudinal transducer attached to one surface as shown in Fig. 2. The receiver voltage recorded for this test is displayed in Fig. 3. The numerical simulation of this test involved 500 x 204 elements in the Y and Z directions, respecitvely, with a time step of 2.0 ns, Fig. 2. The realistic transient signal used to simulate the pulsed nature of a piezoelectric transducer has a center frequency of 5MHz, Fig. 4. This simulated force input had a Gaussian distribution with a two standard deviation spread over the simulated transducer diameter.



$\Delta x = 0.035$ mm , $\Delta t = 2.0$ ns, 500 * 204 elements

MATERIAL PROPERTIES OF ALUMINUM

$V_{Long.} = 6260.87$ m/s $V_{Shear} = 6260.87$ m/s $\rho = 2842$ kg/m ^{3}

Figure 2. Aluminum Specimen Without Bondline

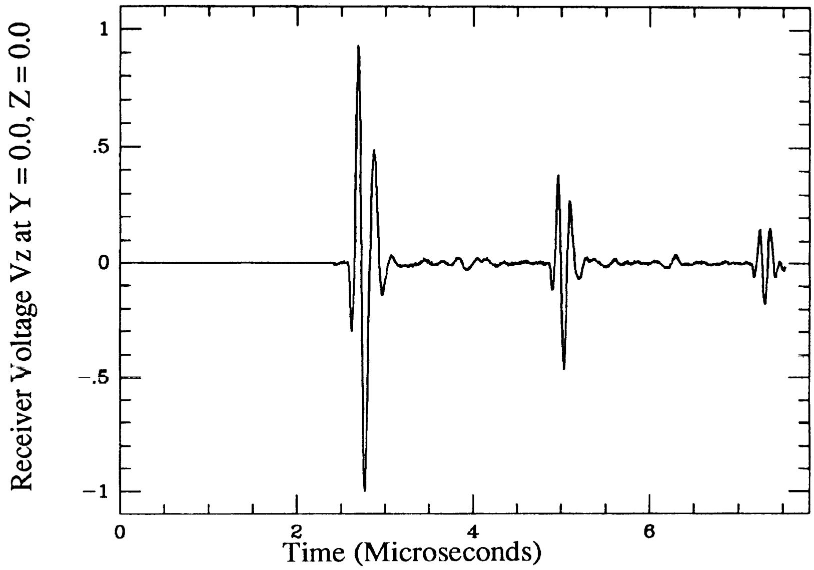


Figure 3. Receiver Voltage as a Function of Time for the Single Specimen Test

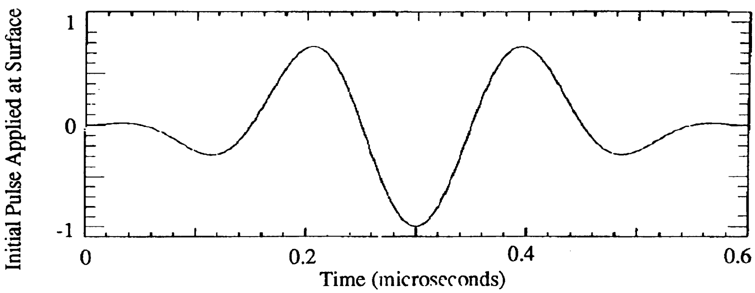


Figure 4. Simulated Piezoelectric Transducer Input

The second time derivative of the numerical displacements were calculated and scaled for comparison with the voltage recorded during the physical tests. Results of the two investigation modes were overlayed in Fig. 5 for the time window spanning the onset of the first reflection through the second longitudinal reflection. The agreement of the numerical simulations with the physical tests is excellent. The frequency responses of the experimental and numerical results are shown in Fig. 6. Note that both responses have a slight shift to the left of the centered 5 MHz input signal, as expected due to the dispersion in the material. The numerical results show excellent agreement with the experimental lower frequencies. However, the higher frequencies displayed in the experimental response are lacking in the numerical simulation. This discrepency is expected since the numerical input did not have the random higher harmonics present in the actual transducer input.

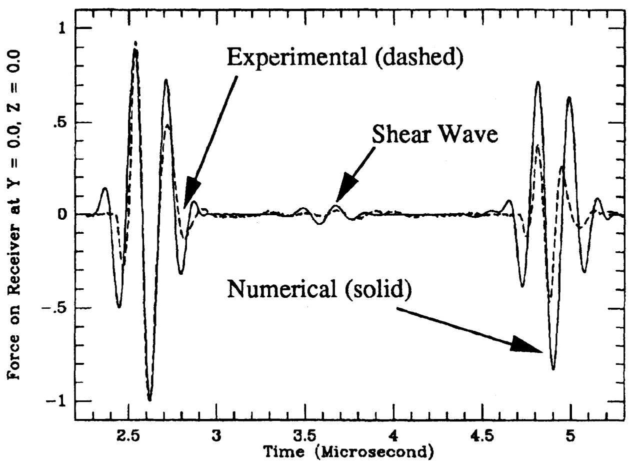


Figure 5. Overlay of Simulated and Physical Results

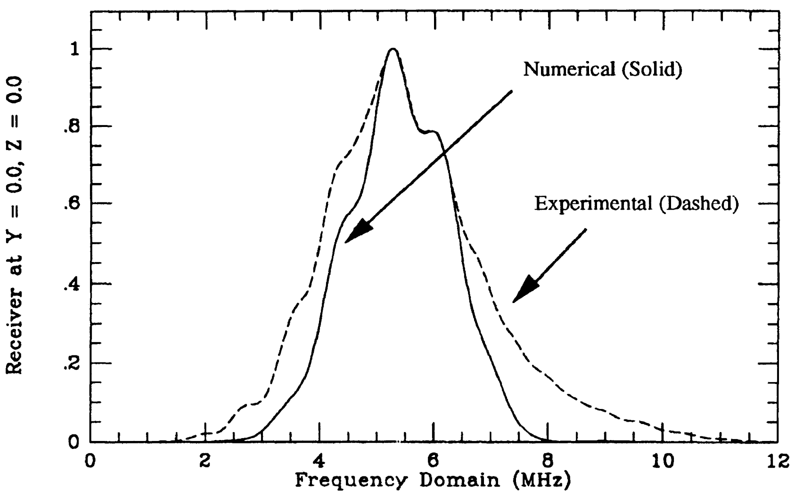
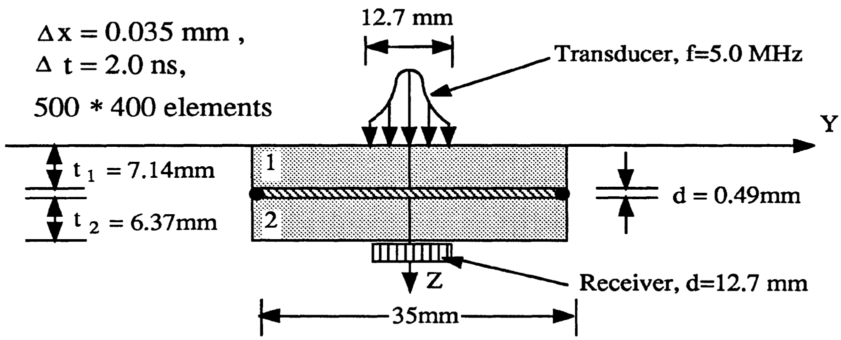


Figure 6. Frequency Responses For Multilayered Sample

The second test configuration involved two aluminum specimens with an interfacial layer of acoustic gel (approx. 500 μm thick), Fig. 7. Pitch-Catch transducers with a center frequency of 5MHz were used. The same numerical inputs as in case one were used. The discretization involved 500 x 400 elements in the Y and Z directions respectively, with a time step of 2 ns, Fig. 7. The receiver voltage and numerical acceleration, $\ddot{u}$, were transformed to the frequency domain and are displayed in Fig. 8. The agreement is excellent in the lower frequencies and again, the numerical results lack higher harmonics.

The Z displacement fields at two time slices (1.5 μs and 3.0 μs) for the multilayered simualtion are shown in Figs. 9 and 10, respectively. At 1.5 μs the longitudinal wave has entered the interfacial region. Higher frequency energy is trapped in the wave guide. A similar interfacial result is clearly evident at 3.0 μs. Note that the numerical simulations provide a "window" to the onset, propagation, and morphology of the elastic wave phenomenon.



AL: $V_{Long.}$ = 6260.87 m/s V_{Shear} = 6260.87 m/s ρ = 2842 kg/m^3

GEL: $V_{Long.}$ = 1490 m/s V_{Shear} = 0 m/s ρ = 1080 kg/m^3

Figure 7. Aluminum Specimen with Acoustic Coupling Gel Bondline

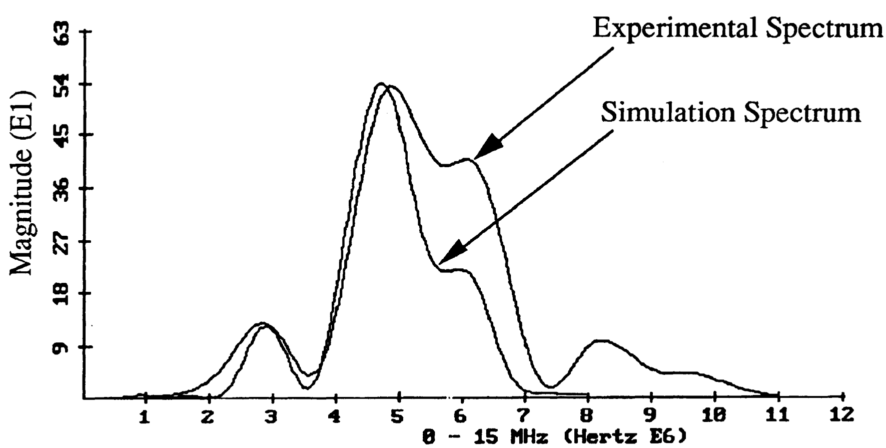


Figure 8. Fourier Transforms of Experimental and Numerical Responses for a Multilayered Configuration

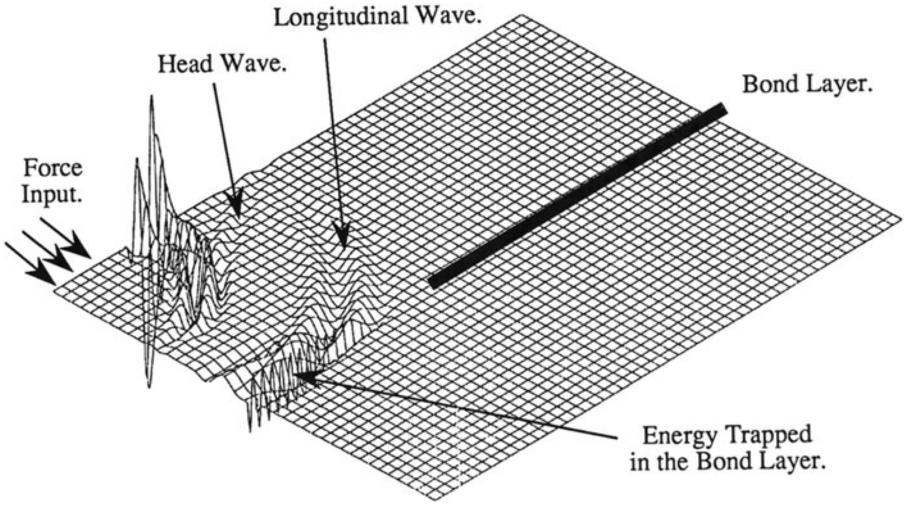


Figure 9. Displacement Field Uz at 1.5 Microseconds

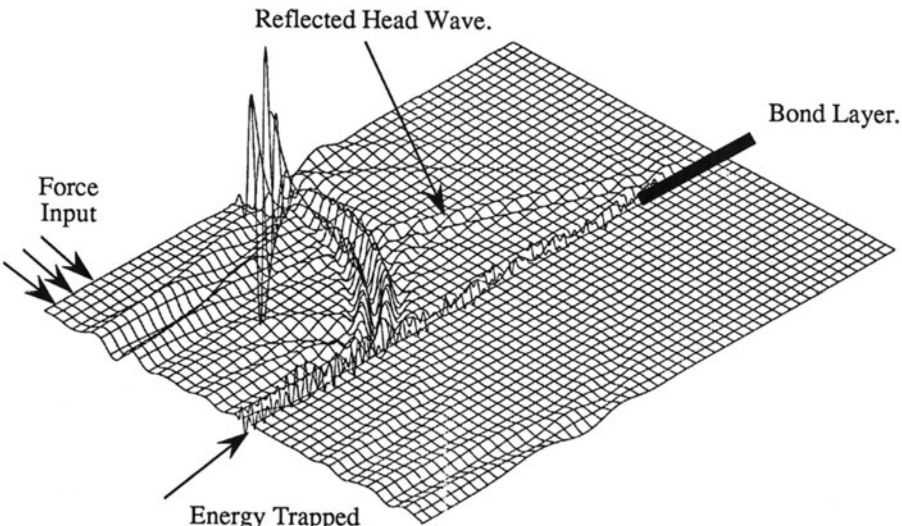


Figure 10. Displacement Field Uz at 3.0 Microseconds.

CONCLUSIONS

An analysis strategy for bondline integrity assessment via ultrasound NDE has been established. This plan utilizes analytical, numerical, and experimental investigations working in harmony. The experimental results can distinguish total disbond situations. Partial disbond testing is ongoing. The numerical simulations exhibit close agreement to experimental results. The simulation mode offers the researcher a transparent view of the elastic wave propagation in an opaque material. This additional insight to the physics should assist in the development of a successful experimental test facility.

ACKNOWLEDGEMENT

This project was supported in part by the U. S. Army Materials Technology Laboratory, Watertown, MA.

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