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F. H. Chang  
*General Dynamics*

R. A. Kline  
*General Dynamics*

J. R. Bell  
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ULTRASONIC EVALUATION OF ADHESIVE BOND STRENGTH USING SPECTROSCOPIC TECHNIQUES

F. H. Chang, R. A. Kline and J. R. Bell
General Dynamics
Fort Worth Division
Fort Worth, Texas 76101

ABSTRACT

In this program statistical analysis of ultrasonically determined parameters was used to identify the features of acoustic wave propagation in adhesively bonded structures which could be used to determine adhesive bond strength. The parameters associated with the interaction of ultrasonic waves with the adhesive-aluminum interfaces and adhesive interlayer which were investigated included bondline transit time, amplitude ratios of reflections from the various interfaces, frequency dependent attenuation and spectral resonance characteristics. Aluminum specimens with both etched and as-received surface preparations were studied. The capabilities of the Fokker bondtester for adhesive strength determination were also assessed. Adaptive learning techniques were used to statistically examine correlation between the observed acoustic properties and shear strength for 394 specimens.

INTRODUCTION

Adhesively bonded structures offer many attractive features in the design of modern aircraft. However, the utilization of these materials has been slowed by the inability to non-destructively evaluate adhesive bond strength. Much of the problem in ultrasonic NDT methods stems from the difficulty in distinguishing changes in acoustic wave propagation in poorly bonded regions, where the adhesive and adherend are in intimate contact but interfacial strength is low, and well bonded regions with high interfacial strength. A NDT methodology which is sensitive to adhesive bond strength must be developed.

In this program spectroscopic techniques were used to study a variety of sonic wave propagation features in adhesively bonded structures. In addition to quantifying the spectral response of the specimens, other acoustic parameters characterizing bondline properties were also determined including travel time through the adhesive and the relative amplitudes of the reflected waves from the various interfaces present. Subsequent to ultrasonic investigation, the specimens were mechanically tested to failure. The measurements were then analyzed to assess the potential of the ultrasonic parameters investigated for adhesive bond strength determination.

EXPERIMENTAL PROCEDURE

For ultrasonic testing adhesively bonded strips (Fig. 1a) were immersed in water and examined with a 10 MHz transducer operated in the pulse-echo mode. In this investigation the use or omission of proper surface treatment, (MEX degreasing, PFL etching) of the aluminum (2024-T81) prior to bonding with Reliabond 398 adhesive, was used to simulate bond strength extremes. Ultrasonic readings were taken at 0.5 inch intervals along the length of the specimen with digitization of the rf waveform and calculation of its Fourier transform for each position. The data processing system is illustrated in Fig 2. After this portion of the investigation was completed, the strips were machined in a single lap shear configuration (Fig. 1b) and tested to failure.

DATA PROCESSING

Acoustic wave propagation in these laminated structures is shown in Fig. 3. From the digitized RF waveform and its Fourier transform, a number of parameters characterizing specimen response could be determined (Fig. 4):

1. t - The time required for sound waves to traverse the adhesive.
2. AR1 - The ratio of amplitudes for the reflected waves A1 and A2.
3. AR2 - Similar to AR1 except for A1 and A3.
4. b2 - The maximum amplitude observed in the Fourier transform of the RF signal.
5. F2 - The frequency at which the maximum amplitude (b2) was observed.
7. f0 - The frequency associated with the anti-resonance of A1 and A2.
8. Q* - F2/b2

* Denotes parameter where spectral asymmetry required measurement on both the low and high frequency sides of the anti-resonance frequency.

ULTRASONIC ATTENUATION/FOKKER BOND TESTER

In addition to the amplitude ratio calculated from the digitized rf waveform, the frequency dependence of the reflected waves A1 and A2 could also be determined from the Fourier transforms of the two signals. Log10 (AR1)-1, indicative of the ultrasonic attenuation, is shown as a function of frequency in Fig. 5a for specimens with treated and untreated surfaces and of identical bondline thickness. Other than the general amplitude reduction (also shown in AR1 calculated from the digitized signal) no dramatic difference in specimen response was observed for the two surface preparations. The bonded laminates were also studied with the Fokker bondtester, a spectroscopic device with the ability to detect gross changes in the resonance characteristics of a piezoelectric probe. No spectral change could be discerned for the two sample preparations.
visions. It was, however, possible to locate artificial defects (Kapton film) located in the bond using the instrument (Fig. 5b, identical settings for the two regions).

SAMPLE DISTRIBUTION

The distribution of shear strengths observed in these specimens is shown in Fig. 6a. As expected, there was a significant difference in the load bearing capability for the two surface treatments. Figures 6b, 6c, and 6d, illustrate the variety in the observed distribution of the ultrasonically determined parameters (and combination of parameters) ranging from virtually no separation in the distributions as in the case of $F_2$ (Fig. 6b) through intermediate separation capability, e.g., $Q_2/Q_1$ (Fig. 6c) with the largest difference observed for $f_0 \log_e (AR_2)^{-1}$, an amplitude ratio with a thickness compensation factor. In general the parameters associated with frequency ($Q_1$, $Q_2$, $B_1$, $B_2$, $F_2$) showed little ability to distinguish between the two surface treatments. Improved resolution capability was observed for the measurements related to signal amplitude ($AR_1$, $AR_2$, $f_0 \log_e (AR_1)^{-1}$, $f_0 \log_e (AR_2)^{-1}$, $D$).

ADAPTIVE LEARNING

Bond strength classification was also examined using an adaptive learning network. For this approach, the behavior of a given parameter is modeled as a multinomial function of other measured quantities with the multinomial coefficients adjusted via an interactive scheme to best fit the actual data. Figures 7a-d illustrate the results obtained for the four parameters (discussed above) as a function of $f_0$, essentially bondline thickness. Ideally, the separation between etched and as-received values should be sufficiently large to accommodate natural fluctuations in the measured quantities and uniform throughout the range of thickness to be encountered. Adaptive learning and sample distribution results are in good qualitative agreement. In no case was it possible to unambiguously discriminate between the two sample treatments using a single measured or calculated parameter. Further statistical studies are now in progress to examine possible improvements in resolution capability with multiple parametric combinations.

CONCLUSIONS

1. The Fokker bondtester was not found to have sufficient sensitivity to adhesive strength variations to adequately serve in the nondestructive evaluation technique investigation conducted in this program.
2. Parameters primarily associated with frequency dependent information (e.g., $Q$ factor, bandwidth) are relatively poor classifiers of bond strength.
3. Parameters associated with signal amplitude (amplitude ratio, resonance depth) showed relatively good resolution capability between strong and weak bonds.
4. No single parameter could unambiguously distinguish well bonded specimens from poorly bonded specimens.
5. Multiple parameter classification offers the possibility of improved bond strength evaluation.
Fig. 3 Wave propagation diagram.

Fig. 4 Ultrasonic parameter identification.

Fig. 5 (a) Frequency dependence of $AR_1$; (b) Fokker bondtester.

Fig. 6 Sample distribution.

Fig. 7 Adaptive learning results - Curve A - FPL etch, Curve B - As received.