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F. H. Chang
General Dynamics

R. A. Kline
General Dynamics

J. R. Bell
General Dynamics

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Ultrasonic Evaluation of Adhesive Bond Strength Using Spectroscopic Techniques

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 preparation 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.

Keywords
Nondestructive Evaluation

Disciplines
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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 preparation 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 nondestructively 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, (MEK degreasing, FPL etching) of the aluminum (2024-T81) prior to bonding with Reliabond 398 adhesive, was used to simulate bond strength extremes. Ultrasound 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. \( AR_1 \) - The ratio of amplitudes for the reflected waves \( A_1 \) and \( A_2 \).
3. \( AR_2 \) - Similar to \( AR_1 \) except for \( A_1 \) and \( A_3 \).
4. \( b_2 \) - The maximum amplitude observed in the Fourier transform of the RF signal.
5. \( F_2 \) - The frequency at which the maximum amplitude \( b_2 \) was observed.
6. \( B/2^* \) - The half bandwidth associated with the anti-resonance of \( A_1 \) and \( A_2 \).
7. \( f_0 \) - The frequency associated with the anti-resonance of \( A_1 \) and \( A_2 \).
8. \( Q^* \) - \( f_0/b_2 \)
9. \( \alpha \) - The anti-resonance depth.

* Denotes parameter where spectral symmetry 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 \( A_1 \) and \( A_2 \) could also be determined from the Fourier transforms of the two signals. Log \( \alpha \) \( (AR_1)^{-1} \), 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 \( AR_1 \) 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 prepara-
tions. It was, however, possible to locate arti-
ficial 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 ex-
pected, there was a significant difference in the
load bearing capability for the two surface treat-
ments. Figures 6b, 6c, and 6d, illustrate the
variety in the observed distribution of the ultra-
sonically determined parameters (and combination
of parameters) ranging from virtually no sepa-
ration in the distributions as in the case of $F_2$
(Fig. 6b) through intermediate separation capa-
Bigity, e.g., $Q_2/Q_1$ (Fig. 6c) with the largest
difference observed for $f_0 \log_{10} (AR_2)^{-1}$,
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 ($AR_1$, $AR_2$, $f_0$
$\log_{10} (AR_1)^{-1}$, $f_0 \log_{10} (AR_2)^{-1}$, $D$).

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 mea-
sured 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 thick-
ness. 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 qual-
itative 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 reso-
lution capability with multiple parametric combi-
nations.

CONCLUSIONS

1. The Fokker bondtester was not found to
have sufficient sensitivity to adhesive strength
variations to adequately serve in the nondestruc-
tive evaluation technique investigation conducted
in this program.
2. Parameters primarily associated with fre-
quency dependent information (e.g., $Q$ factor,
bandwidth) are relatively poor classifiers of bond
strength.
3. Parameters associated with signal amplitu-
de (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 evalua-
tion.
Fig. 3 Wave propagation diagram.

Fig. 4 Ultrasonic parameter identification.

Fig. 5 a) Frequency dependence of $\text{AR}_1$; b) Fokker bondtester.

Fig. 6 Sample distribution.

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