AN ULTRASONIC TECHNIQUE TO DETECT NONLINEAR BEHAVIOR RELATED TO DEGRADATION OF ADHESIVE BONDS

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INTRODUCTION

Quantitative nondestructive evaluation of degradation of adhesive bonds remains one of the most challenging problems in nondestructive evaluation. The objective of this work is to attempt a new approach to the solution of this problem.

Comprehensive reviews of progress in the NDE of adhesive bonds up to the early 90's can be found in Refs. [1,2]. In recent years, techniques based on the detection of nonlinear behavior have received increasing attention [3,4,5]. In these early stages of the study of nonlinear behavior of adhesive bonds, most of the research has been of a theoretical nature. Several models have been suggested and theoretically investigated by Thompson and Thompson [2]. An in-depth theoretical investigation using a spring model has been performed by Achenbach and Parikh [3]. These studies have shown some promise that the investigation of nonlinear effects may be useful to evaluate the residual strength of adhesive bond.

In some cases, strength degradation of adhesive bonds has been correlated with a reduction of the effective modulus of the bond, i.e., with a reduction of the slope of the linear traction-displacement ($Q - \Delta$) curve across the bond. In other cases, degradation can be observed as a reduction of the linear portion of that curve with no change in initial slope. Our work presented here is based on the assumption that failure of adhesive bonds is initiated at the point where nonlinear behavior starts.

The first kind of bond degradation is easier to detect than the second kind, since the reduction of modulus results in a change of acoustic impedance contrast between adherend and adhesive layers. A difficulty arises because the adhesive layer is usually very thin, around $100\mu m$. Separation of the reflected signals from the bottom and top adherend/adhesive interfaces is extremely difficult [6]. Very high frequencies have to be used for this separation [7]. Because of the difficulty of the

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very thin layer, we view the two reflected signals as a single signal by replacing the thin bond layer by a layer of springs. The second case of bond degradation is even more difficult to detect because ultrasonic measurements may not be directly affected by the nonlinear behavior. In this work, an external factor is introduced to stimulate the interaction of nonlinear effects with an ultrasonic signal. The external factor is that a load is applied to move the bond response to the nonlinear portion of the $Q - \Delta$ curve. In the work presented here a static load is applied during ultrasonic measurements.

NONLINEAR BEHAVIOR

The application of a prestress Q to the bond yields a gross displacement Δ across the bond thickness. If an ultrasonic disturbance is introduced in the loaded specimen, then the total stress and total displacement are $Q + q$ and $\Delta + \delta$, where q and δ are the stress and displacement due to the ultrasonic disturbance. Let us define a function $Q(\Delta)$ for the nonlinear elastic relation between the traction and displacement across an adhesive layer. The general behavior of $Q(\Delta)$ curve is as shown in Fig. 1. The degradation of the adhesive layer can be defined as the reduction of the slope of the $Q - \Delta$ curve and as the reduction of the linear part of the $Q - \Delta$ curve before the onset of nonlinearity.

At any local point, the slope of a $Q - \Delta$ curve is defined as $\frac{dQ}{d\Delta}$. Because the small disturbance generated by an ultrasonic wave produces a small stress field and a small displacement, it gives us a convenient way to obtain this slope at any local point. At any local point, we can make the following linear approximation

$$\frac{dQ}{d\Delta} \approx \frac{q}{\delta} = \beta \tag{1}$$

THEORETICAL MODEL

The theoretical investigation of Ref. [3], which assumes that the adhesive bond has been pulled in the nonlinear range by a static prestress, uses a spring model to relate the incident signal and the reflected signal.

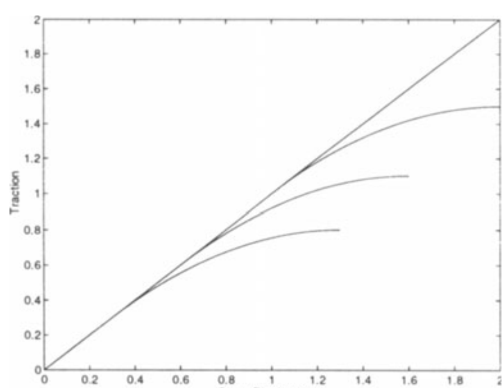

Fig.1 Typical Traction (Q) Displacement (Δ) Curve

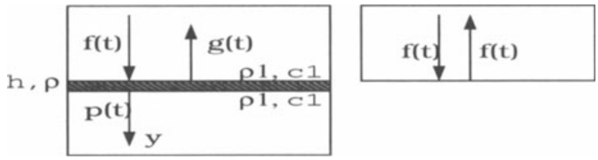

Fig.2 Illustration of Wave Motion.

Let's consider a special case for the spring model (Fig. 2), in which the adherends are the same material. At the bond surface $y = 0$, the following conditions are satisfied

$$\sigma_y|_{y=0^+} - \sigma_y|_{y=0^-} = \frac{1}{2}\rho h[\ddot{\nu}|_{y=0^+} + \ddot{\nu}|_{y=0^-}] \tag{2}$$

$$\sigma_y^0 = \frac{1}{2}[\sigma_{y|y=0^+} + \sigma_{y|y=0^-}] \tag{3}$$

$$\delta = \nu|_{y=0^+} - \nu|_{y=0^-} \tag{4}$$

where ρ, h are the mass density and thickness of the layer, σ_y is the normal stress, ν is the displacement in the y direction, and δ is the gross displacement across the layer.

It is assumed that the bond is prestressed and that for a small perturbation introduced by an ultrasonic signal, a linear elastic equation holds between the superposed traction and the superposed displacement across the adhesive layer

$$\sigma_y^0 = q = \beta\delta \tag{5}$$

where β is a constant, namely the local slope of the nonlinear elastic relation.

If a plane harmonic longitudinal wave is incident from $y < 0$, we can write the general form of incident, reflected and transmitted displacements as follows

$$\nu^I(y,t) = f(t - y/c_1) = Fe^{i(\omega t - ky)} \tag{6}$$

$$\nu^R(y,t) = g(t + y/c_1) = Ge^{i(\omega t + ky)} \tag{7}$$

$$\nu^T(y,t) = p(t - y/c_1) = Pe^{i(\omega t - ky)} \tag{8}$$

where c_1 is the wave velocity of the adherends, ω is the angular frequency of the harmonic wave, k is the wave number.

In terms of f, g, p, the interface conditions in the displacements and stresses follow from Eqs. (2)-(8) as

$$\nu|_{y=0^+} = p(t) = Pe^{i\omega t} \tag{9}$$

$$\nu|_{y=0^-} = f(t) + g(t) = (F + G)e^{i\omega t} \tag{10}$$

$$\sigma_y|_{y=0^+} = -\rho_1 c_1 \dot{p}(t) = -\rho_1 c_1 i\omega Pe^{i\omega t} \tag{11}$$

$$\sigma_y|_{y=0^-} = -\rho_1 c_1[\dot{f}(t) - \dot{g}(t)] = -\rho_1 c_1 i\omega[F - G]e^{i\omega t} \tag{12}$$

$$\delta = \Delta e^{i\omega t} \tag{13}$$

By using the above relations, and equations (2) and (4), we find

$$\Delta = [P - F - G] \tag{14}$$

$$\rho_1 c_1 i\omega[P - F + G] = \frac{1}{2}\rho h \omega^2 [P + F + G] \tag{15}$$

By using Eq. (3), we can obtain

$$-\rho_1 c_1 i\omega[P + F - G] = 2\beta\Delta \tag{16}$$

In order to simplify the expressions, we define

$$\beta_0 = \frac{\rho_1^2 c_1^2}{\frac{1}{2}\rho h}; \qquad \omega_0 = \frac{\rho_1 c_1}{\frac{1}{2}\rho h} \tag{17}$$

where

$$\beta = \gamma\beta_0; \qquad \omega = \bar{\omega}\omega_0 \tag{18}$$

By using the above simplifications, we obtain

$$G = H(\omega)F = \left(\frac{i\bar{\omega}}{i\bar{\omega} + 2\gamma} - \frac{i\bar{\omega}}{i\bar{\omega} + 1}\right)F \tag{19}$$

where $H(\omega)$ can be viewed as the transfer function relating input F and output G.

If we define the Fourier Transform of $f(t)$ as $F(\omega)$, the reflected signal g^s can be written as

$$g^s(t) = \int_{-\infty}^{\infty} H(\omega)F(\omega)e^{-i\omega t} d\omega \tag{20}$$

EXPERIMENT

Experiment and Specimen

The configuration for the pulse-echo experiment is shown in Fig. 3(a). A Panametrics Ultrasonic Pulser/Receiver (Model 5055PR) was used to excite the ultrasonic transducer. An ultrasonic transducer with a central frequency of 5 MHz was used. A Digital Oscilloscope (Tektronix TDS520) was employed for data acquisition. Data from the oscilloscope was acquired by a computer through a General Purpose Interface Bus (GPIB). The sampling frequency was 250 MHz.

Figure 3 (b) shows the specimen. Both adherends were aluminum cylinders with a thickness of 1.00 inch. The bonding area was selected as a region with a diameter of 0.75 inch. The adhesive layer was made of an epoxy resin supplied by the Dow Chemical Company. Two different kinds of adhesive layers were prepared. One kind of layer consisted of 70% DER 331, 30% DER 732. The curing agent was DEH 24, 13% in weight. the second kind was 50% DER 331, 50% DER 732 with 13% DEH24 curing agent in weight. An aluminum tube was used as the transducer holder and water tank. The transducer was placed inside the water-filled tube. Three evenly spaced screws can be used to align the transducer to guarantee normal incidence of a longitudinal wave. The aluminum tube was connected to the sandwiched bond specimen by an adhesive layer. Sulfuric acid dichromate etch [8] was used for the preparation of the bond surfaces.

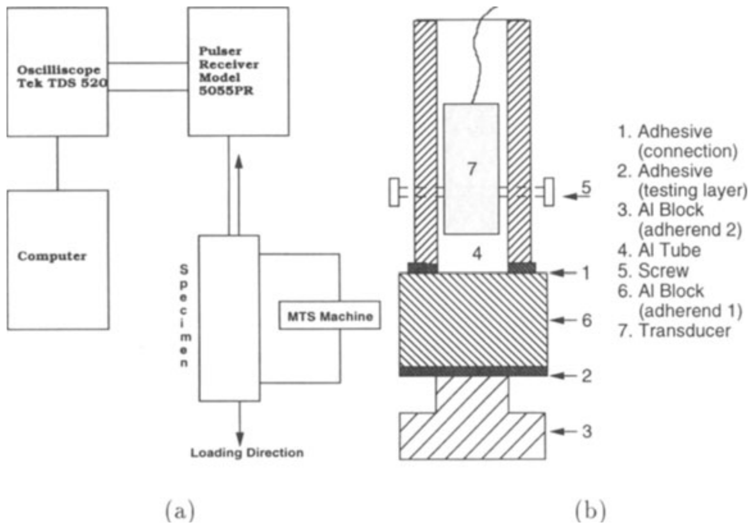

Fig. 3. Illustration of Experiment Setup and Specimen

The Inverse Problem

The inverse problem is formulated as follows: For a known incident signal $f(t)$, we can use Eq. (20) to simulate a signal $g^s(t)$ for a fixed parameter γ. If we define an error function as

$$Error(\gamma) = \sum_{t=0}^{t=T} (g(t) - g^s(t, \gamma))^2 \tag{21}$$

where T is the duration of signal $g(t)$, we can determine the best value of the parameter γ by minimizing the error function. This parameter γ represents the property of the adhesive layer that is to be determined.

To simulate $g^s(t)$, we need to know the incident signal $f(t)$. By virtue of near 100% reflection at an aluminum-air interface, the reflected signal from the aluminum-air back surface was used as incident signal $f(t)$. The measured signal $g(t)$ was the actual signal reflected from the bond (Fig. 1).

The model was tested on the two different adhesive layers mentioned above. The parameter γ was obtained as 0.0129 and 0.0156 for the 50-50 and the 70-30 epoxy layer, respectively. Figure 4 (a) shows the error vs. the parameter γ for the $50-50$ adhesive layer. Figure 4 (b) shows the simulated signal $g^s(t)$ and the measured signal $g(t)$ for the best parameter γ for the $50-50$ adhesive layer. From Fig. 3(a), it can be seen that the error increases as the parameter deviates from the best fit parameter. From the comparison of the simulated and measured signals, it is noted that good agreement between these two signals has been achieved.

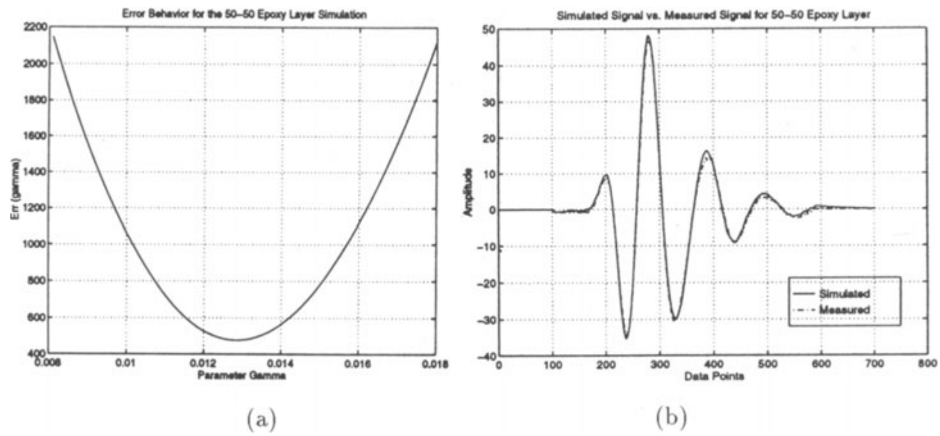

Fig. 4 Error Behavior and Simulation Results

From Eq. (5) , it is straight forward to define an effective modulus M_{eff} as

$$M_{eff} = \beta h = \gamma \beta_0 h = 2\rho_1^2 c_1^2 \gamma / \rho \tag{22}$$

In this manner, the inverse scheme yields effective moduli of 6.83 GPa and 8.04 GPa for the 50-50 and the 70-30 epoxy layers, respectively.

The velocities of these two different layers were also measured using samples of the adhesive materials. The velocities were obtained as $2.42 km/s$ and $2.65 km/s$ for the 50-50 and the 70-30 epoxy layers, respectively. Using the standard relation $\lambda + 2\mu = \rho c^2$, the elastic constant $\lambda + 2\mu$ was obtained as $6.50 GPa$ and $8.01 GPa$ respectively, which are values very close to the measured results.

From this section it can concluded that the theoretical model can reliably calculate the effective modulus of the adhesive layer through simulation of the reflected signal $g(t)$.

Results

To study the nonlinear behavior under a static load, a tensile load was applied to the specimen. The loading direction is specified in Fig. 3(a). The static tensile loading was applied through a MTS machine during ultrasonic testing. The machine clamped both ends of the specimen shown in Fig. 3(b).

Degradation was generated by applying different fatigue cycles to the specimen. For this study, 3 groups of specimen were prepared for each kind of adhesive layer. For the first group, no fatigue cycles were applied. The second group was subjected to $50K$ fatigue cycles. The third group was subjected to $100K$ cycles. The different fatigue cycles were applied to generate different severities of deterioration of the adhesive layer. The waveform for the cyclic fatigue was a sine wave centered at $-200 lbs$ with an amplitude of $100 lbs$ ($i.e.$ $100 - 300 lbs$ compression). The frequency of the sine waveform was $2.0 Hz$.

For the $50-50$ epoxy layer, the reflected signal kept very steady except for a very small fluctuation, less than 1%, when a static load up to $1000lbs$ was applied to the non-fatigued specimen. This means that the effective modulus has not changed because the $Q-\Delta$ curve is still in the linear range. However, for the $50K$ cycle fatigued specimen, once the load exceed $500lbs$, a clearly detectable change in the reflected signal can be seen. This means that the nonlinear part has been reached. For the $100K$ cycle fatigued specimen, the nonlinearity happens earlier, at 200 lbs.

Figure 5(a) shows the calculated effective moduli vs. the applied load. Figure 5(b) is the reconstruction of the stress-strain relation for the $50-50$ epoxy layers. For the $70-30$ epoxy layer, the results are of the same form as the $50-50$ epoxy layer, but the critical load level where nonlinear behavior starts is lower.

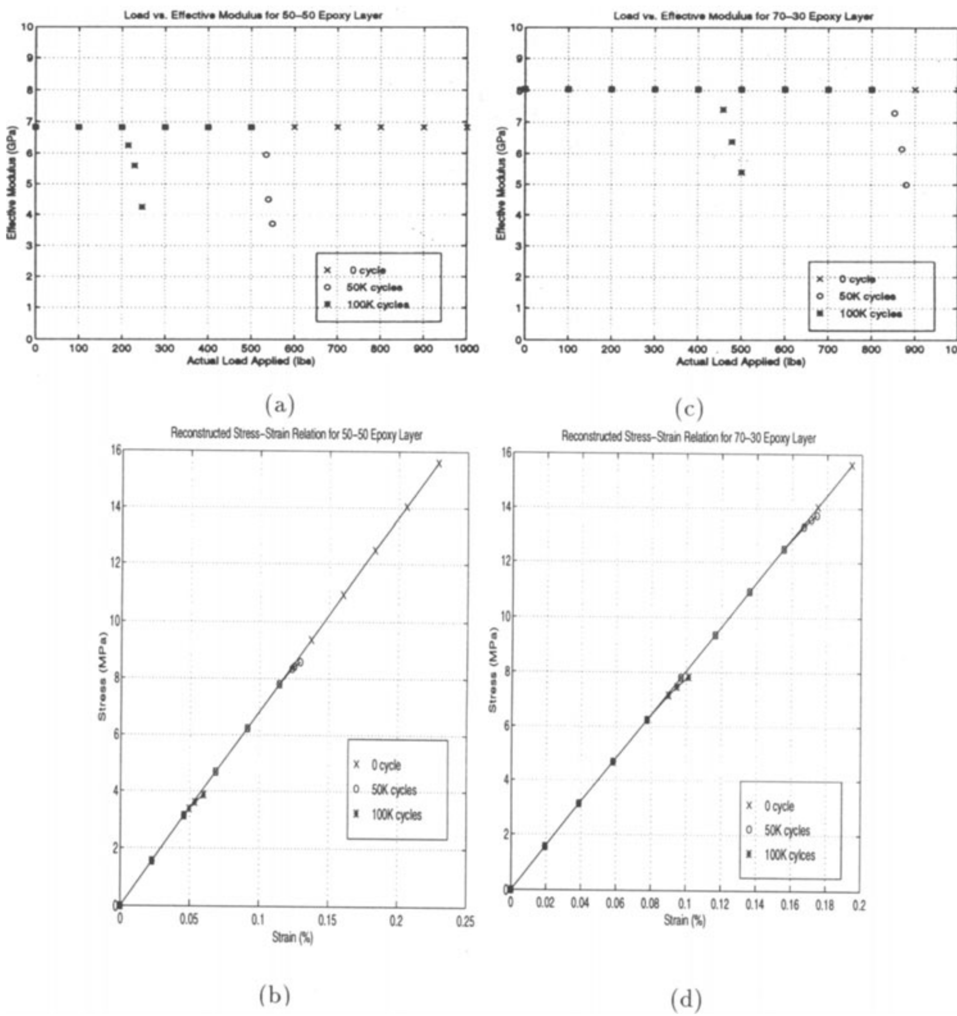

Fig.5 Experiment Results

Figure 5(c) shows the effective moduli vs. the applied load. Figure 5(d) is the reconstruction of the stress-strain relation for the $70 - 30$ epoxy layer.

From Fig. 5 (a) to (d), it can be seen that for a given type of epoxy layer, the $50K$ fatigue cycles clearly reduce the load at which nonlinearity starts. $100K$ fatigue cycles reduce this load further. However, for both cases, the deteriorated layers didn't show any difference of modulus in the linear range as compared to the non-deteriorated layer.

From the results of this section it may be concluded that the degradation can be characterized by the reduction of the linear portion of the traction-displacement curve.

CONCLUSIONS

A comparison of experimental and simulated results based on a theoretical model was used to obtain the effective modulus of the adhesive layer. The onset of nonlinear behavior of adhesive bonds was detected. The results show that the degradation due to cyclic fatigue can be detected by the reduction of the linear portion of the stress-strain curve without any change of slope in the linear range. Further work aimed at the implementation of dynamic loading to the specimen while the specimen is being tested ultrasonically is currently under consideration.

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