MEASUREMENT OF A SANDWICH BOND STRENGTH

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INTRODUCTION

The increasing demand in industry to produce solid-solid bonds has given stimulus to
development of methods of nondestructive testing of such products [1]. The difficulty is to
discriminate and quantitatively describe imperfect interfaces by non-destructive
measurements. In adhesive bond technology the surface preparation of the adherend is most
critical [1]. Ultrasonic measurements seem most promising for NDE of bonds since they are
extremely sensitive to the state of contact at the interface and can be utilized to directly
measure interfacial properties.

The need to characterize imperfectly interfaces is encountered in a wide variety of
scientific and engineering problems. Effective nondestructive testing techniques are
necessary for quality control and in-service inspection of bonding conditions. Many workers
have considered the progressive degradation of the adhesive/adherend interface as a
transition between 'welded' boundary conditions between the adhesive layer and the
adherend in which there is continuity of both normal and tangential displacements across the
interface, and 'slip' boundary conditions in which there is continuity only of the normal
displacements since the slip interface will not transmit shear stresses. More sophisticated
models of the adhesive/adherend interface consider the presence of an isotropic or
anisotropic interlayer of finite thickness between the bulk adherend and adhesive [2]. The
properties of this interlayer may vary as a result of different surface preparation procedures
during manufacture or as a result of in-service degradation. The nondestructive evaluation
task is then to characterize the properties of the interlayer.

For very thin adhesive layers the application of guided waves or leaky guided waves
in the bonded area is required. These types of waves produce shear stresses at the interface
and propagate along the interface; they are therefore sensitive to variations of adhesive quality. The leaky guided waves are substantially attenuated, therefore they yield localized information. Full inspection of the adhesive joint will naturally necessitate the combination of the leaky wave technique with a scanning mechanism.

This work is based on the modified boundary conditions approach. The purpose of this paper is to analyze the possibility of measuring the quality of bonded joints. We present here the results of a series of experiments, in which a number of aluminum samples with bonds of varying thickness and quality were probed using surface travelling ultrasonic waves. These waves were detected by a Michelson interferometer.

PROBLEM PRESENTATION

We consider a two-dimensional case such that the guided wave has no z dependence leading to $\partial / \partial z = 0$. The wave is propagating along the z direction through a three-layer sandwich with the middle layer representing the adhesive layer, indicated by the index 0. The index m denotes the interface between the adhesive and adherend layers. We assume that all materials are linear, homogeneous and isotropic solids.

The longitudinal potential $\phi$ and the transverse potential $\psi$ satisfy the wave equations

$$\nabla^2 \phi = \frac{1}{V_l} \frac{\partial^2 \phi}{\partial t^2}, \quad \nabla^2 \psi = \frac{1}{V_t} \frac{\partial^2 \psi}{\partial t^2}$$

where $V_l$ is the longitudinal wave velocity and $V_t$ is the shear wave velocity in bulk media. We assume that the solutions are time harmonic of the form $\exp(-i\omega t)$ with z dependence of the form $\exp(ikz)$. The propagation constant $k$ has the same value for both potentials in order to satisfy the boundary conditions along z. Those assumptions lead to an incident wave with vertical polarization, $\psi = \psi_z$, thus

$$\frac{d^2 \phi}{dy^2} = \alpha^2 \phi, \quad \frac{d^2 \psi}{dy^2} = \beta^2 \psi$$

where $\alpha^2 = k^2 - k_l^2$, $\beta^2 = k^2 - k_t^2$. $k_l$ and $k_t$ are the bulk propagation constants given by $\omega/V_l$ and $\omega/V_t$ respectively. The solution to the wave equation has the form $\exp(i\alpha y)$ and $\exp(i\beta y)$. We seek for solutions of true guided modes in the middle layer, which will be referred to as the adhesive layer. Thus, the constants $\alpha$ and $\beta$ should be imaginary for the solution in the adhesive layer and real outside that layer. To ensure this condition in the adhesive layer, the velocity has to fulfill the conditions: $V_o < V_{t1}, V_{t2}$ and $V_o < V_{l1}, V_{l2}$. Actually as long as the last condition is fulfilled, a guided mode possessing just a shear potential will exist, and when the first condition is fulfilled as well, the guided mode contains both a shear component and a longitudinal one. Without losing generality, we may assume that $V_{t1}, V_{t2} > V_{l1}, V_{l2}$. Mode solutions for $k_{t1}, k_{t2} < k < k_{t1}, k_{t2}$ correspond to leaky modes through the layer denoted by 2 while mode solutions for $0 < k < k_{t1}, k_{t1}$ are the so-called radiation modes of the waveguide. For these radiation modes $k$ is a continuous variable while the values of allowed $k$ in the guided solutions are discrete.

The potentials take the form of a trigonometric function inside the adhesive layer and an exponential decay in the bulk layers. The time harmonic term will be omitted in the following discussion. We define the normalized velocity $V_n \equiv V/V_o$ where $V$ is the phase
velocity of the wave ($\omega/k$). The normalized velocity has an upper limit determined by
\[ \min\{V_t/V_0, V_s/V_0\}, \]
which in our case reduces to $V_t/V_0$. $V_t$ and $V_s$ are the bulk longitudinal and shear velocities respectively. We described the displacements and stresses in terms of the displacement potentials so that the solutions in each region can be calculated directly.

To investigate the interaction of an ultrasonic wave with the adhesive layer Rokhlin [2] considered an effective shear modulus $\mu_{eff}$ which is a function of the shear modulus of the film and the properties of the adhesive-adherend interfaces. Degradation of the interfacial adhesive joints was simulated by a weak boundary layer where $\mu_{eff}$ was the shear modulus. Another possible approach for modeling the bond strength is the technique presented by Tattersall [3]. He modeled the interfacial forces by a density of springs between the two media, in order to represent any ‘slackness’ at the interface. Others continued his work [4] by analyzing an interface containing cracks or pores. The interface is then represented by a set of springs and masses. They can be thought of as representing extra compliance and mass at the interface. In the present work, the interface between the adhesive and the adherend is modeled as a spring-mass structure. This model modifies the boundary conditions to treat the effect of the finite interfacial stiffness.

In our model we assume that the normal stress and displacement are continuous across the interface. In a quasi-static approach, the shear mechanical behavior of the interface adhesive-adherend is represented by a density of springs with stiffness constant $\kappa$, between the adhesive and adherend. The springs relate the stresses on the faces of the two media to the displacement discontinuity across the interface. In order to correctly include the inertial effects, the mass of the spring is taken into account. For simplicity we consider one portion of this boundary. Fig. 1 shows schematically the model used. The strength of the coupling between the two media is denoted by the parameter $\kappa$. Obviously if $\kappa \to 0$ it characterizes free surfaces (complete unbond), when $\kappa \to \infty$, we revert to the usual case where the conditions correspond to perfect contact. Variations of $\kappa$ allow a continuous transition from the condition of perfect contact to that of no contact. We thus attribute to the finite interfacial stiffness $\kappa$, the integrity of the bond. For the spring-mass model considered here, the following conditions apply

\[ t_{xy}^0 + t_{xy}^1 = 2\kappa(u_x^1 - u_x^2) \]
\[ t_{xy}^1 - t_{xy}^0 = -\frac{m}{2} \omega^2(\frac{u_x^1}{2} + \frac{u_x^0}{2}) \]

where $m = \rho_m h_m$. $\rho_m$ and $h_m$ are the density and thickness of the interface, respectively.

Use of these quasi-static boundary conditions presumes that the ultrasonic wavelength $\lambda$ is
much larger than the dimensions of the interface, $h_m$. The complete boundary conditions for $y = h$ are of the form

$$
t_{y}^{0} = t_{y}^{1}, \\
u_{y}^{0} = u_{y}^{1}, \\
t_{x}^{1} = -\kappa^{+}u_{x}^{0} + \kappa^{-}u_{x}^{1}, \\
t_{x}^{0} = -\kappa^{-}u_{x}^{0} + \kappa^{+}u_{x}^{1} \quad (4)
$$

where

$$
\kappa^{+} = \kappa + \frac{m}{4}\omega^2 \\
\kappa^{-} = \kappa - \frac{m}{4}\omega^2
$$

Use of these quasi-static boundary conditions assumes that the ultrasonic wavelength $\lambda$ is much larger than the thickness of the interface, $h_m$. Substituting these boundary conditions into the displacement and stress expressions, leads to the dispersion matrix equation. We confine ourselves to the solution of symmetric systems in which the two adherends are identical. For this case the potentials have either symmetric or antisymmetric behavior. For the symmetric case, the dispersion equation obtains the form,

$$
\Delta_h^{\alpha_0 \xi_0} t_{\alpha} t_{\beta} + (t_{\alpha} \alpha_0 \beta_0 - t_{\beta} k^2) (\Delta_h^{\beta} \kappa^{-} - \beta_1 k_m \xi_1) + \Delta_L^{\alpha_0 \xi_1} + (k^2 - \alpha_1 \beta_1) \cdot \\
\cdot (\beta_0 k_m \xi_0 - \kappa^{-} \Delta_L^{\alpha_0 \xi_1} + \kappa^{-}[\gamma_0 \gamma_1 - k^2 a_0 a_1 + ik (a_0 \gamma_1 + a_1 \gamma_0)] (t_{\alpha} t_{\beta} \alpha_0 \beta_1 + \alpha_1 \beta_0) + \\
+ 2\kappa^{+}(k \gamma_1 + i a_1 \alpha_1 \beta_1) (k \gamma_0 t_{\beta} + i a_0 \alpha_0 \beta_0 t_{\alpha}) = 0 \quad (5)
$$

where

$$
t_{\alpha} = \tanh(\alpha_0 h) \\
t_{\beta} = \tanh(\beta_0 h) \\
\gamma_i = \mu_i (k^2 + \beta_i^2) \\
a_i = 2\mu_i k \\
k_m = \kappa m \omega^2 \\
\xi_i = \gamma_i + i k a_i
$$

$\Delta_h^{\alpha_0 \xi_0}$ is the expression from the dispersion equation for Rayleigh waves in the layer $i$ and $\Delta_L^{\alpha_0 \xi_1}$ is the expression from the dispersion equation for the symmetric Lamb waves in the layer $i$. For the antisymmetric case, the trigonometric functions $\tan$ should be replaced by the trigonometric functions $\arctan$ in the dispersion equation.

NUMERICAL RESULTS

Consider, as example, the case of two aluminum plates of type $Al2024$, bonded by the $FM73$ adhesive of 100$\mu$m thickness. The properties of $Al2024$ are $\rho_1 = 2.7 gr/cm^3$, $V_1^1 = 6.32 Km/s$, $V_1^2 = 3.13 Km/s$ and for the adhesive $\rho_0 = 1.18 gr/cm^3$, $V_1^1 = 2.25 Km/s$, $V_1^2 = 0.98 Km/s$. The boundary between the adhesive and the adherend plate is usually composed of two very thin layers. One is the Aluminum oxide which has about 100$nm$ thickness and can be disregarded for our purpose and the second layer is the primer with about $h_p = 2.5 \mu m$ thickness and $\rho_p = 0.87 gr/l$. We searched for guided (undamped) waves by restricting the analysis to the real axis. Fig. 2

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Figure 2: Normalized velocity versus normalized thickness for different stiffness constant $\kappa$ shows the influence of interfacial stiffness on the velocity of the first ultrasonic wave mode. $\kappa$ is normalized such that $\kappa = 0$ reduces to the case of delamination, while $\kappa = 1$ represents the case of good bonding. The above results indicate a correlation between the degree of bonding and the guided wave velocity. For low frequencies, $k_t h < 2$, the difference between the various cases reaches its maximum. For very high frequencies, $k_t h > 5$, the power of the wave is localized mainly in the adhesive layer so invalidating any contribution from the boundary. A point of interest is $k_t h = 3.3$ which is the place where the thickness of the layer is equal to $1.05 \cdot \lambda_{us}/2$ where $\lambda_{us}$ is the ultrasonic wavelength. This is the point of the mechanical fundamental mode resonance of the adhesive layer. Here, the velocity is equal for all possible values of $\kappa$. Thus for a determination of the bond strength one should operate away from this region, preferably around $k_t h = 0.5$ and $k_t h = 4$. As the frequency or thickness increases, one observes the asymptotic behavior of the guided wave velocity towards the shear velocity in the adhesive. This may be understood by the fact that when the ratio $h/\lambda$ increases, the wave is surrounded by a bulk-like media and the longitudinal potential vanishes.

**EXPERIMENTAL RESULTS**

The guided wave was generated and detected by the system configuration illustrated in Fig. 3. A $1 MHz$ piezoelectric transducer, which corresponds to $k_t h = 0.32$, was used for the generation of the surface wave. The wave impact on the edge of the adhesive layer
and is split into several different types of waves but with different velocities. Part of the energy of the Rayleigh wave is transformed into the desired guided wave. It propagates through the adhesive layer till it reaches its second edge. Part of the guided wave is now continuing as a surface wave which may in turn be detected. Remote detection of ultrasonic waves is most commonly achieved by means of an optical interferometer. For the present purpose we used one of the most common designs, the Michelson interferometer. The probing beam was tightly focused on the surface of the specimen. In this two beam instrument a laser beam strikes a half-silvered mirror (beam splitter), which splits the beam into two paths. One beam reflects off the specimen, the other off the reference mirror. When the beams recombine, a single fringe occurs across the interference image in the case of parallel beams. Displacements on the surface of the specimen due to ultrasonic vibrations, change the length of the path traveled by the first beam, altering the relation between the two beams which in turn change the intensity of the light incident on the detector.

The materials used are the same as described in the numerical calculations. Several surface treatments were implemented and two different thicknesses were examined. Nine samples of every adhesion type and thickness were verified, their results were averaged. The various types of surface preparation which were used prior to adhesive application, and their future symbol, are chromic acid anodization (A), chromic acid anodization with primer (AP), chromate conversion coating (T), sand blasting (H) and acetone cleaning (AZ).

Two different adhesive thickness were fabricated for each surface treatment by choosing both 0 mm spacer thickness and a 0.1 mm spacer thickness. For each specimen, two signals were monitored and stored in memory. The first signal is the one immediately exiting the piezoelectric transducer, before the wave is arriving to the adhesive layer, called "Reference", and the second one was registered after the wave passed through the adhesive layer, called "After the bond".

The velocity was measured between the two recorded signals, the reference and the signal after the bond. There is some distance which the wave is passing as a Rayleigh wave on the Aluminum material. This time is taken into consideration after a calibration is made in which the exact velocity of the Rayleigh wave is measured. Two parameters are measured and calculated in this case, the relevant distance that the wave is propagating through, the length of the adhesive layer $z$, and the time of propagation through the adhesive layer $t$. 

Figure 3: Principle of the generation and detection of guided waves. $R$ — Rayleigh wave, $B$ — Bulk wave, $G$—Guided wave, $B.S.$ — Optical beam splitter
Figure 4: Calculated velocity and characteristic frequency

The measurement error can be determined by the combined standard uncertainty, [5]. In our case the two input quantities are related, that is, are interdependent. The time and the distance are correlated parameters. This combined standard uncertainty of \( V \) is designated by \( u_V \). The uncertainties of the input parameters \( z \) and \( t \) are \( u(z) = 10 \mu m \) and \( u(t) = 0.1 \mu sec \), respectively. The combined standard uncertainty \( u_V \) for the case where the inputs are correlated with correlation coefficient \( r(z, t) = 1 \), is

\[
 u_V = \sum_{i=1}^{2} \frac{\partial V}{\partial i} u(i) ; \quad i = z, t
\]

Introducing our simple relation \( V = \frac{z}{t} \) into Eq. (6) yields

\[
 u_V = \frac{u(z) + u(t)V}{t}
\]

With the proper known uncertainties for \( z \) and \( t \) given above, the combined uncertainty is about \( u_V = 10 m/sec \) which is 0.5% from the expected measured velocity. This is quite a good accuracy. As already mentioned above, there are nine different measurements performed for every kind of adhesion and spacer. The t-distribution [5] will be used to present the results. The standard deviation is given by

\[
 s = \sqrt{\frac{\sum (V - V_i)^2}{N - 1}}
\]

\( N = 9 \) in our case. The standard uncertainty from the measured velocities is according to the t-distribution \( u_V = s/3 \) and the expanded standard uncertainty is \( U_V = 2.306u_V \). The results will be presented by the average velocity measured \( \bar{V} \) and \( \pm U_V \). This should give a 95% confidence interval.

Two parameters for bond strength evaluation are chosen and calculated. The first one is the velocity of the ultrasonic guided wave and the second is the difference in the characteristic frequency between the two recorded signals. The characteristic frequency is calculated as the weighted mean frequency and the velocity is calculated by the crosscorrelation and LSF methods. The parameters obtained in the experiments are plotted in Fig. 4 with a 95% confidence interval. According to Fig. 4 the best bond quality is obtained
by $A$ and $AP$ type surface treatment, while the worst case is the $H$ type. Actually all the bonds were found to have a reasonable strength, $2.8 < V < 3.1$, which can be explained by the fact that all the samples were prepared as well as possible and no environmental degradation was applied. A perfect bond corresponds to a velocity of $V = 3.2$ and so, even $A$ and $AP$ type are approaching this number but not really reaching it. The delamination case correspond to $V = 2$. All the other types of bonds are between these two extreams.

CONCLUSION

The goal of the present investigation was to examine correlations between the bond strength and features obtained from ultrasonic signals affected by the bonded specimen. The features are obtained from the representation of the signals in both time and frequency domains. The work focuses on theoretical and experimental aspects of model of ultrasonic wave interaction with imperfect interfaces.

The method of utilizing guided ultrasonic wave for bond strength measurement is presented in this work. This technique can be used to easily detect and predict the quality of the bond. The advantage of this technique is that it directly interact with the adhesive layer. Ultrasonic guided waves which propagates through an adhesive layer were detected by an optical interferometer. Specifically, the normal component of the ultrasonic wave has been measured for providing information about the bond strength. The effect of incomplete bonding on the velocity was reported in this paper.

The results indicate that there is a good correlation between the velocity of the guided wave and the bond strength and therefore can be used to classify the interface imperfection. Several bonds were verified and the results are promising.

REFERENCES


