INTRODUCTION

Performance determination of adhesively bonded systems is a subject of intense interest to both researchers and designers. Attempts to predict adhesive bond performance have mainly focused on nondestructively identifying gross anomalies such as voids or unbounded regions and either correlating these features with destructively determined mechanical performance or using these features in an analytical analysis using concepts such as fracture mechanics or stress concentration.

It is well known that adhesively bonded systems can exhibit variability in mechanical performance even when the systems under evaluation are fabricated identically and appear to lack major anomalies such as those determined by through-transmission untrasonics (voids, disbonds, etc.). Obviously, the ability to nondestructively determine adhesive bond performance is needed if these systems are to be utilized in a load bearing capacity.

The nondestructive evaluation of any materials systems is most successful when the physics of the materials in the system are understood in terms of their interaction with each other during both fabrication and under service loading conditions. The anatomy of a bonded system consists of several material subsystems. The work described in this paper involves a single lap shear bonded configuration (Figure 1a). The anatomy of the bonded system (Figure 1b) consists of the metal adherends, the surface treatment (metal oxide), the low viscosity primer, and finally the adhesive itself (in this paper scrim supported).

The metal adherend surface is surface treated to develop an oxide on the surface of the metal. The low viscosity primer (of similar chemical composition to the adhesive) is applied and allowed to penetrate the porous oxide. Finally, the higher viscosity adhesive chemically bonds to the primer. Stress is theoretically transferred from one adherend to another through mechanical interlock mechanisms and chemical bonds.
The approach used in the work presented in this paper was first to select an adhesively bonded system for evaluation and understand the anatomy of the bonded region. Once the system was selected only the specimens lacking major anomalies (as determined by through-transmission ultrasonics) were saved for evaluation. Once selected, the bonded systems were scanned with an applicable instrumental nondestructive evaluation (NDE) technique. The instrumental NDE technique identifies a material parameter which can be utilized in an analytical analysis to determine mechanical performance. The instrumental NDE technique used in this study was high frequency (MHz) ultrasonic resonance. The resonant response of the bonded area is mapped through the thickness over the surface of the bonded area (normal to the load axis) with a focused ultrasonic transducer. The scanning was continuous with a resolution of approximately 0.02-0.05 square inches.

Once scanned and analyzed, the NDE output is used in closed form analytical expressions which determine the shear and normal stress distributions in the adhesive, along the bond length \( l \) in the direction of the loading axis.
Fig. 2. Finger Panel Assembly

EXPERIMENTAL
SINGLE LAP SHEAR SPECIMEN
FABRICATION

Referring to Figure 1, the single lap shear assembly consisted of Ti-6-4 adherends with a nominal thickness of 0.05 inches. The adherends were chromic acid anodized to develop the surface oxide. The low viscosity primer used was a commercially available epoxy based system (EC 3917, from 3M). The adhesive was a commercially available scrim reinforced toughened epoxy (AF-191, from 3M). The toughening of the brittle epoxy is accomplished through the addition of an elastomeric phase. The lap shear assemblies are fabricated in sheets so that five single lap shear specimens are fabricated simultaneously (see Figure 2). The sheet assembly is layed up on a steel tool to insure proper bondline geometry. The tool with the assembly is then vacuum bagged for autoclave cure per Boeing Materials Specifications (BMS 5-104). It should be noted that this process yields slightly different heating and cooling rates for each side of the bonded joint. In other words, the top face of the bonded region will see a thermal history slightly different than the opposite side residing against the steel tool. After fabrication, the single lap shear specimens are separated, scanned, and subsequently failed in tension in accordance with Boeing Support Specifications (BSS 7202).

ULTRASONIC RESONANCE SCANNING

The technique employed for ultrasonic resonance examination involves the application of an incident burst of sine wave ultrasonic energy to a test part such that the burst width, or time duration, exceeds the round trip transit time of sound through the test part. Methods of extracting material properties information then may be carried out in various ways. One method employed is to sweep the acoustic frequency through a wide range of
frequencies (such as 2-10 MHz) and observe the results of constructive/destructive interference as established between the material's parallel surfaces. Another method, especially suited to "ringing" metallic materials, is to apply the sine wave burst around the materials thickness resonance point, and observing the ring-down signal after the drive energy has ceased. This method is well suited to observing the damping effects of energy absorbing materials which are acoustically coupled to the test material's back surface.

The test equipment employed is a modified Holosonics 200 acoustic holography unit, which is designed specifically for sine burst operation. The original fixed frequency tunable signal source was replaced with a Hewlett Packard 3312A generator.

The pulse-echo output signal is recorded and processed by a Dynacon Systems Ultrasonic Data Recording and Processing System (UDRPS) which digitizes and records the signal along with C-scan coordinate information. The UDRPS, which consists primarily of a Hewlett Packard computer, an ANALOGIC Array processor and a Ramtek 9465 color display system, then reconstructs a high resolution color video display of the recorded C-scan using as rainbow color format with 255 level color resolution.

In addition to amplitude information, point-by-point x-y plots of amplitude vs. frequency may be made to observe frequency shifts resulting from material property variations.

DISCUSSION OF RESULTS

The justification for choosing the Ultrasonic Resonant technique for the instrumental NDE of the bonded systems lies in the technique's potential capability to detect changes in adhesive bond stiffness, through-the-thickness, anywhere over the area of the bonded region. Provided that nondestructively determined information regarding the changes in the elastic modulus of the adhesive was available, it was hypothesized that an approximate closed form solution for adhesive stress distribution could be utilized (such as those available in the literature (1)) to predict the mechanical performance of these "flawless" bonded assemblies.

Five single lap shear specimens were fabricated as described previously. The specimens were scanned at approximately 3 MHz in a continuous mode. Both sides of the bonded region were scanned. Upon inspection of the five specimens (both sides) it was observed that one side of each specimen was significantly more accoustically attenuative than the opposite side. For each specimen, the same side was consistently more attenuative than the other. Recalling the fact that each face of the bonded area saw a slightly different thermal history during fabrication suggests the possibility of a nonuniform distribution of the phases within the cured adhesive system. Another explanation may be the presence of different interfaces on each side of the adhesive possessing variable characteristic impedance ratios. Taking into account the relatively low power used to impart the resonant response through-the-thickness of the bonded area, it is likely that the order in which the imparting signal sees the various characteristic impedance ratios at the interfaces may well determine the strength of the resonant amplitude response. Using techniques available from the field of Acoustics (2), it can be shown that the above assumptions are reasonable.

It is well established that the maximum shear and normal (peel) stresses in a single lap shear configuration exist at the joint edges (1). With this in mind, the Ultrasonic Resonant scans of each specimen were evaluated with respect to the joint edges. With our current hypothesis to describe signal
resonant amplitude attenuation, and the fact that nearly all five specimens failed in such a manner that the lightly attenuated face failed in the oxide, it was felt that only the lightly attenuated face need be considered since it is this face which will bear a majority of the load (due to stiffness considerations). At this point in time it was desired only to determine whether or not the approach used in this paper should be continued. If so, then a more complete assessment of the entire bonded assembly would be warranted. By examining the acoustic response of the joint edge regions only, we assumed a redistribution of stress at the edge as a function of the degree of attenuation and percent area covered of each section of the acoustic response. The response was roughly divided into three levels, blue (lightly attenuated), yellow (attenuated), and red (highly attenuated).

Assuming that the more acoustically attenuated sides of the adhesive system represent interfacial regions which are more acoustically coupled than the less attenuated interface and further, if we observe consistent adhesive failures in the oxide of the interface exhibiting low acoustic attenuation then the following assumptions can be made.

1) The highly damped interfaces represents good acoustical coupling but may possess relatively low stiffness characteristics relative to a lightly damped interface.

2) Using the closed form expressions for shear and peel stress (1) distribution along the joint the calculated fail stresses for the ideal system (described later) can be reduced as a function of the attenuation in the joint edge areas.

3) By shifting load carrying capability from edge to edge and face to face through attenuation knockdowns we can then determine how the stiffer interfacial areas of the joint edges will be overstressed by considering the loaded part with respect to consistent global deformations.

4) By reducing the ideal calculated failure stresses and using these reduced values in the closed form expressions (1) the failure load can then be determined.

An example of a scanned adhesive joint is shown in Figure 3. Figure 3 illustrates a bonded region (shown in the rectangular area) where the interfacial impedance varies over the entire bond. The darker areas are more highly damped than the lighter areas. Obviously the interface in the region of the joint edge is acoustically nonuniform and the stress resulting from uniform strain will tend to concentrate in the lightly damped areas (assuming these interfacial areas to be stiffer than the more acoustically attenuative interfaces).

By determining the failure stresses at the joint edge for a well bonded system (as determined by 3M) knockdowns from these levels could be established by measuring the percent attenuated area at the joint edge and assigning a relative modulus factor as a function of the attenuation. Blue required no knockdown, yellow resulted in a reduction on load carrying capacity of 1/3. Red resulted in a reduction of load carrying capacity of 2/3. Using either the principal maximum shear stress (3) for the well bonded case as the condition to knockdown, the following allowables were determined.

For a nominal adherend thickness of 0.05 inches and an ideal failure load of 2500 lbs (from 3M) the maximum principal shear stress was determined to be 17,595 psi at the joint edge. The principal normal stress at the edge was found to be 26,665 psi. With the failure stresses knocked down (with respect to both interfaces) the failure loads could be calculated using an iterative procedure. The results are shown in Table 1.
Fig. 3. Scanned Adhesive Bond Joint.
TABLE 1. RESULTS

<table>
<thead>
<tr>
<th>Test Specimen</th>
<th>Calculated Failure Load (#)</th>
<th>Destructively Determined Failure Load (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1800</td>
<td>1850</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
<td>2040</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>2125</td>
</tr>
<tr>
<td>4</td>
<td>1600</td>
<td>2100</td>
</tr>
<tr>
<td>5</td>
<td>1900</td>
<td>2100</td>
</tr>
</tbody>
</table>

CONCLUSIONS

As can be seen from Table 1, there appears to be some initial agreement between the calculated failure loads (NDE knockdown) and the destructively determined failure loads. Although additional refinements in waveform analysis and finite element analysis need to be conducted for more reliable results preliminary results are encouraging.

REFERENCES