Innovative Use of Adhesive Interface Characteristics to Nondestructively Quantify the Strength of Bonded Joints

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ABSTRACT

Advances in structural adhesives have permitted engineers to contemplate the use of bonded joints in areas that have long been dominated by mechanical fasteners and welds. Although strength, modulus, and toughness have been improved in modern adhesives, the typical concerns with using these polymers still exist. These include concerns over long-term durability and an inability to quantify bond strength (i.e., identify weak bonds) in adhesive joints. Bond deterioration in aging structures and bond strength in original construction are now critical issues that require more than simple flaw detection. Whether the structure involves metallic or composite materials, it is necessary to extend inspections beyond the detection of disbond flaws to include an assessment of the strength of the bond. Use of advanced nondestructive inspection (NDI) methods to measure the mechanical properties of a bonded joint and associated correlations with post-inspection failure tests have provided some clues regarding the key parameters involved in assessing bond strength. Recent advances in ultrasonic- and thermographic-based inspection methods have shown promise for measuring such properties. Specialized noise reduction and signal enhancement schemes have allowed thermographic interrogations to image the subtle differences between bond lines of various strengths. Similarly, specialized ultrasonic (UT) inspection techniques, including laser UT, guided waves, UT spectroscopy, and resonance methods, can be coupled with unique signal analysis algorithms to accurately characterize the properties of weak interfacial bonds. The generation of sufficient energy input levels to derive bond strength variations, the production of sufficient technique sensitivity to measure such minor response variations, and the difficulty in manufacturing repeatable weak bond specimens are all issues that exacerbate these investigations. The key to evaluating the bond strength lies in the ability to exploit the critical characteristics of weak bonds such as nonlinear responses, poor transmission of shear waves, and changes in response to stiffness-based interrogations. This paper will present several ongoing efforts that have identified promising methods for quantifying bond strength and discuss some completed studies that provide a foundation for further evolution in weak bond assessments.

Introduction

The benefits provided by adhesive joints, such as improved strength, better load transfer corrosion resistance and improved durability, coupled with the evolution of advanced adhesives has allowed many traditional fastened joints to be replaced with bonded joints. Thus, the ability to not only detect disbonds but also to quantify the strength of bonded joints is critical to adhesive applications in automotive, aerospace, and civil industries. Furthermore, the rapidly-expanding role of composites in structures has increased the importance of NDI methods capable of identifying interply delaminations and disbonds in laminate-to-laminate joints and has produced a need for NDI methods that can quantify bond strength. Bond deterioration in aging structures and bond strength in original construction are now critical issues that require more than simple flaw detection. While extensive

development has been completed to mature the detection of delaminations or fiber fracture flaws in composites, the problem of assessing weak bonds has not been solved by the NDI community. Use of advanced inspection methods to measure the mechanical properties of a bonded joint and associated correlations with post-inspection failure tests have provided some clues regarding the key parameters involved in assessing bond strength. Figure 1 shows a number of sample structures that are now being designed with an emphasis on bonded joints. Figure 2 shows specific metal and composite structures that use film and paste adhesives in their construction.

Adhesive bonding is an important joining tool for modern structures. Structural adhesives can greatly increase the strength as well as stiffness of joints and can significantly improve the crash performance of vehicles. Structural adhesives also allow more efficient structures to be designed that may be difficult to weld or where fasteners reduce fatigue performance. Structural adhesives will play an increasingly important role in the joining of dissimilar materials such as aluminum (Al) to steel or magnesium (Mg) to other metals: The adhesive acts both as a galvanic barrier and as a stress spreader on materials that are more brittle. This study was directed at filling a major technical gap for adhesives: how to determine whether an adhesive bond in a structure will perform as designed without actually destroying the bond.

Most disbonds, which are regions possessing no adhesive strength, involve inhomogeneous areas or other discontinuities that can disrupt an interrogating signal. As a result, traditional ultrasonic and thermographic inspection methods are quite capable of detecting such flaws. However, weak bonds or kissing disbonds, which may provide homogeneous, intimate contact but no adhesive strength, are much more difficult to identify [1,2]. Due to the presence of a weak bond, ultimate strength tests would produce cohesive failure but at a reduced level such that the full potential of adhesive joint is not achieved. Figure 3 depicts various mechanisms that can result in a weakened bond. Contaminants can weaken the adhesive-to-adherend interface or react with the adhesive itself to reduce its performance. Environmental conditions may also reduce the properties of the adhesive such that the global strength of the bonded joint is reduced.

Inspection Options Must Exploit the Unique Features of Weak Bonds

This paper presents results from studies to: 1) create fabrication methods to reliably generate realistic weak bond specimens and 2) develop NDI methods – and complimentary signal analysis schemes – to characterize weak bonds and quantify their strength [3]. The NDI methods that were investigated include: pulse-echo UT, thermography with signal enhancement, oblique and shear-wave resonance, mechanical impedance analysis, laser-peening, laser UT, swept-frequency UT spectroscopy, nonlinear harmonic generation, oblique incidence ultrasound, and guided waves.

At present, the quality control of adhesive joints relies on the robust control of the adhesive preparation and its application. However, there is no method available to test the overall quality of the joints other than destructive testing. Given a specific adhesive, the overall performance of an adhesive joint is determined by four properties: the total adhesive area, the location of the adhesive within the joint, the thickness of the adhesive, and the specific strength of the metal/adhesive bond.

A variety of ultrasonic and transient infrared methods have been developed over the last several decades that can detect the presence of adhesive or the complete lack of adhesion in an adhesive joint. These methods rely upon the reflection or transmission of heat or sound at the adhesive/panel interfaces. These are essentially elastic interrogation methods. By contrast, there are no widely-accepted means to detect “kissing bonds” in which there is intimate (molecular) contact between the panels and the adhesive layer but in which there is reduced specific bond strength (force per unit of

bonded area). Kissing bonds can occur under a variety of conditions including inadequate surface preparation, surface contamination, adhesive degradation, adhesive contamination, or environmental aging (typically corrosion, moisture intrusion, and thermal cycling). The difficulty is that a nondestructive bond-strength method needs to determine the strength for the area without actually breaking the bond. In practice, the bond-strength test methods probe some inelastic or anelastic feature of the interfaces which correlates with the bond strength.

Recent advances in ultrasonic- and thermographic-based inspection methods have shown promise for measuring such properties [4]. Vibrothermography uses the effect of externally-induced vibrations to excite a structure and observe the resulting heat patterns within the material. This approach may be sensitive enough to reveal subtle material differences associated with weak bonds such that the monitored thermal field can be correlated with the strength of the bond (properties of bond material). Similarly, specialized ultrasonic (UT) inspection techniques, including laser UT, guided waves, UT spectroscopy, and resonance methods, can be coupled with unique signal analysis algorithms to accurately characterize the properties of weak interfacial bonds [5]. The generation of sufficient energy input levels to derive bond strength variations, the production of sufficient technique sensitivity to measure such minor, and often nonlinear, response variations, and the difficulty in manufacturing repeatable weak bond specimens are all issues that exacerbate these investigations. This paper will present several ongoing efforts to quantify bond strength and review a number of completed studies that provide a foundation for further evolution in weak bond assessments.

Different damage mechanisms (for example, water ingress, corrosion, and contamination) potentially have different effects on the mechanical properties of the bond interface and the adhesive itself. NDI methods may react to specific types of mechanical changes and material configurations so it is important to understand the weak bond mechanism in each case so that the proper NDI method can be deployed. Some weak bond cases may result from a decrease in the adhesive modulus so a method that determines modulus is a possible option. Or if the stress-strain curve becomes nonlinear, then nonlinear ultrasonics may prove useful. In instances where the modulus remains unchanged as the failure strength decreases, such techniques may become unsuitable. Potential ultrasonic methods can be divided into two categories depending on whether they interrogate the out-of-plane or in-plane stress-strain characteristics with respect to the bond interface. Generally these two characteristics are measured using compression waves and shear waves respectively. Compression-wave methods can look at the nonlinear response of a weak interfacial bond. While other methods may exploit the poor transmission of shear waves across a zero-volume disbond.

Some NDI methods rely on the general correlation between fatigue strength and viscoelastic losses. This is a scientifically sound approach, but the methods are difficult to implement for large, curved panels which are typical in the automotive world. Recently there have been two new proposals: laser "shot peening" and vibrothermography. The latter method looks especially promising and raises the possibility that other hybrid, non-linear methods that either probe the interfaces when they are strained or measure viscoelastic losses might be attractive to measure bond strength [6,7].

Approach to Weak Bond Characterization

A suite of customized applications of advanced NDI techniques, coupled with signal analysis, were applied to characterize bonds that are non-ideal and, thus, possess strengths that are less than optimum. The ideal result is data that can be calibrated to quantify the strength of a bond. Data analysis was used to highlight subtle changes in the structure's response and signal trends in order to link such differences to bond quality parameters. In order to obtain data that contains the small variation in bond line response, it was necessary to optimize the excitation used for the inspection.

This includes both the frequency content and the magnitude of the excitation. Such optimization schemes considered the goal of keeping the inspections truly nondestructive; excessive excitation may damage the bond line. The source of the weak bond can stem from changes in the adhesive or a non-optimum interface between the adhesive and the adherend. This study focused on the expected sources of poor bonding at the adhesive-to-adherend interface.

When assessing weak bonds, the source of the weak bond can stem from changes in the adhesive or a non-optimum interface between the adhesive and the adherend. One side aspect of this work determined if off-design cures produce changes in the material properties of adhesives and to use NDI methods to monitor such changes. By considering changes in the adhesive, these effects can be uncoupled in subsequent tests on bonded structures. Similarly, the effects of contaminants and other sources of weak bonds at the adhesive-to-surface interface were studied. Results from mechanical property tests were intercompared. In this manner, NDI testing on the complete structure focused on the *interface region* to better identify/quantify a weak bond. The data analysis looked at subtle changes in the response and signal trends in order to link such differences to bond quality parameters.

Figure 1: Sample Applications for Bonded Joints – Clockwise from Upper Left: Aircraft, Spacecraft, Wind Turbines, Automobiles, Pipelines, and Bridges

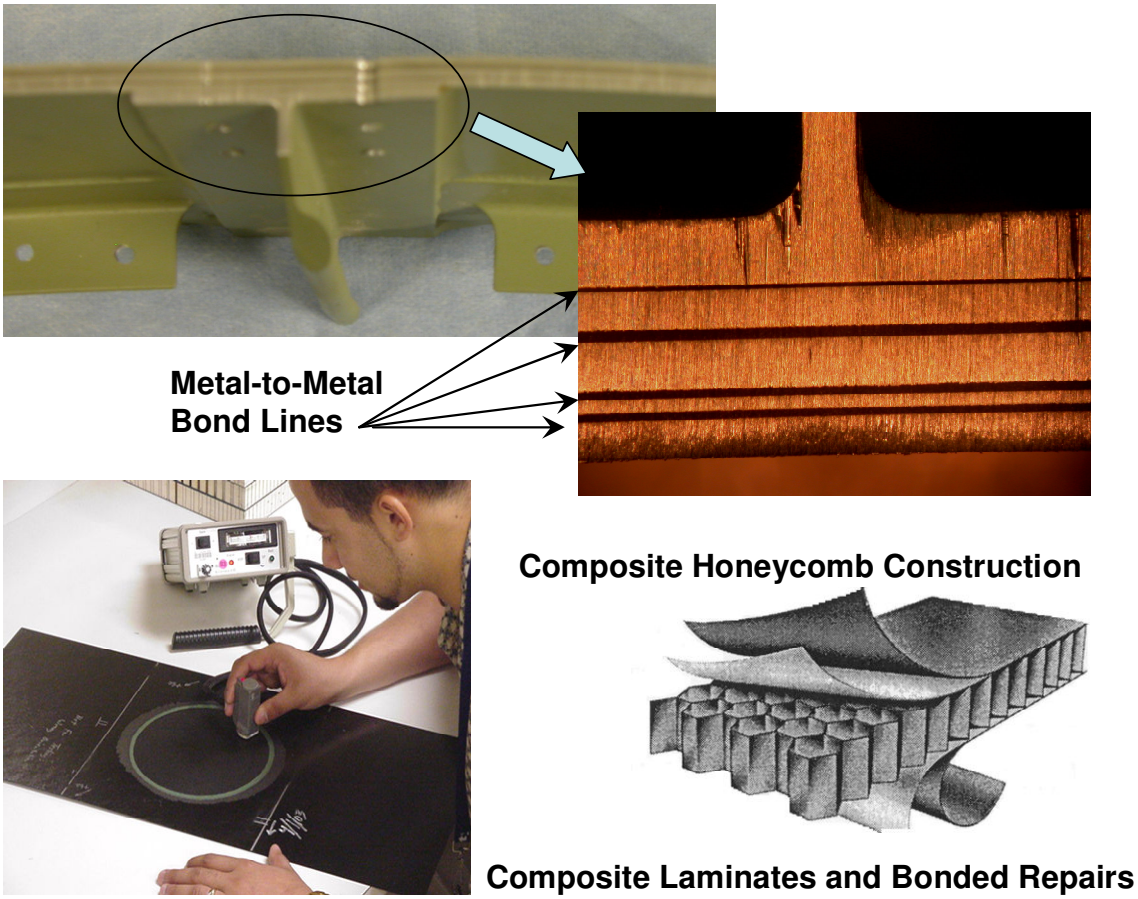

Figure 2: Bonded Joints in Metals and Composites

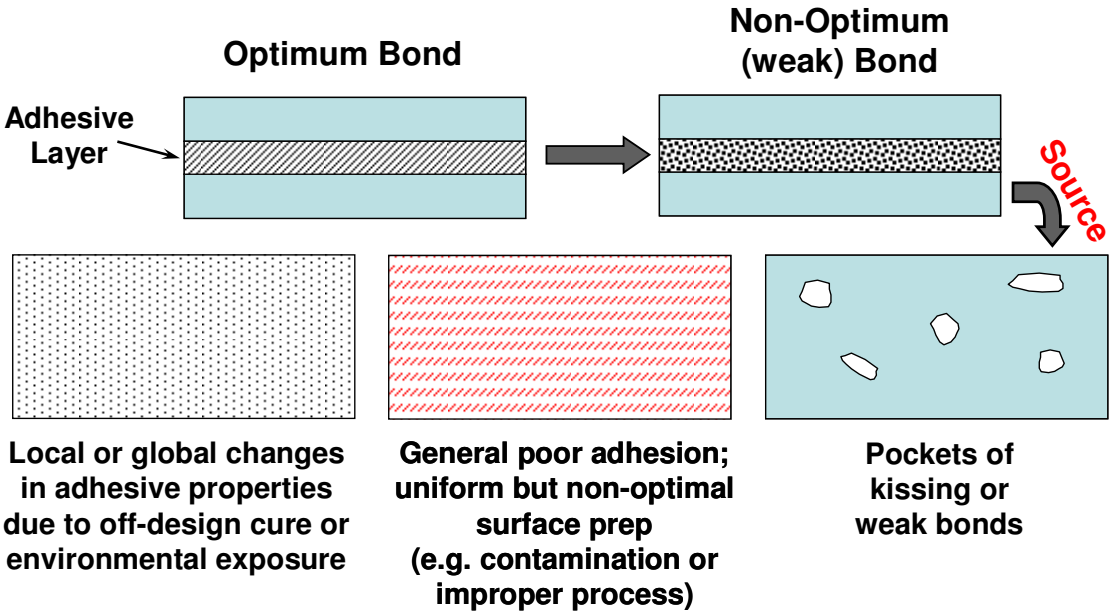

Figure 3: Mechanisms of Weak Bonds

Generating Reliable Weak Bonds

The first challenge in this effort was to be able to create weak bonds with the adhesives used in the automotive industry in such a way that the strength results would be repeatable with some small level of variation. This was done by fabricating a series of lap joint coupons that are made of two galvanized steel adherends with a 1-inch overlap and a 1" x 1" bond area as shown in Figure 4. The thickness of the steel plate was 1.5 mm (0.060") and the thickness of the standard bond line was 0.40 mm (0.016"). The coupons were prepared using specific methods designed to produce various levels of weak bonds. The methods that were evaluated in this study included 30 different configurations and included: 1) various levels of grease thicknesses, 2) grease with thinner layers of adhesive, 3) different mold releases with various levels of coverage, 4) diluted mold release, 5) non-optimum cure profiles (varying in temperature and time), 6) hot-wet conditioning, 7) application of different contaminants (water, wax, sand, Vaseline, 8) oil application with various levels of coverage, 9) less than 100% adhesive coverage, and 10) baking powder with various levels of coverage.

Various contaminants were applied to one side of one steel plate, in the lap splice overlap region, to produce changes in the interface properties between the steel surface and the adhesive layer. Some contaminants, such as grease, were uniformly applied across the bond area. Highly sensitive scales were used to determine the thickness of each grease application. For other contaminants, such as mold release and baking powder, the applications were sometimes uniformly applied and other times distributed across the bond area. Controlled distribution of contaminants was produced by applying the medium through screens which were machined to ensure a specified amount of surface area coverage. The bond line thickness was controlled by placing carefully-selected gage wires adjacent to the bond region and then applying a uniform clamping pressure to the steel plates when the paste adhesive was in a soft, uncured state. After the adhesive was cured, the wires were removed and the bond line thickness of each specimen was measured to ensure less than 5% deviation in the bond thickness.

These specimens were then tested for strength by completing a failure test (tensile) in a uniaxial mechanical test machine as shown in Figure 5. All the test results were analyzed to determine the consistency (variance of strength), and the percentage of the full bond strength for each of the specific weak bond methods. It should be noted that a series of pristine coupons were fabricated in the same manner as the weak bond methods in order to provide strength and variance results for comparison purposes. There are several mechanisms at work when the weak bonds are formed by the different contamination methods. It is believed that they affect bond strength in different ways. The grease affected the interface between the adhesive and the steel. The baking powder and mold release also affected the interface but appeared to have some effect on the adhesive as well which resulted in local changes in the adhesive interface - primarily many tiny porosity pockets - which decrease the overall bond strength. While one may view this as a change in composition of the adhesive one can also view this as a representative degradation in adhesive (or adhesive interface) due to a reaction with contaminants.

The weak bond methods that showed the least amount of variance in strength results were then put into percentage of full strength bins (e.g. 10%, 30%, 50%). The final percentage of full strength bins used were 10%, 30%, 50%, 70%, and 90%. More coupons were fabricated and tested (strength tests) on the ten, selected weak bond methods to insure repeatability (i.e. small deviation in strength). Table 1 shows the final selection of weak bond methods that were used for inspection purposes. Over 300 coupons were fabricated and tested to arrive at the final weak bond test set. Thus, there are 10 specimens in each NDI set with bond strengths in each of the following categories: 10% bond strength

(2 types), 30% bond strength (2 types), 50% bond strength (2 types), 70% bond strength (2 types), 90% bond strength (1 type), 100% bond strength (1 type).

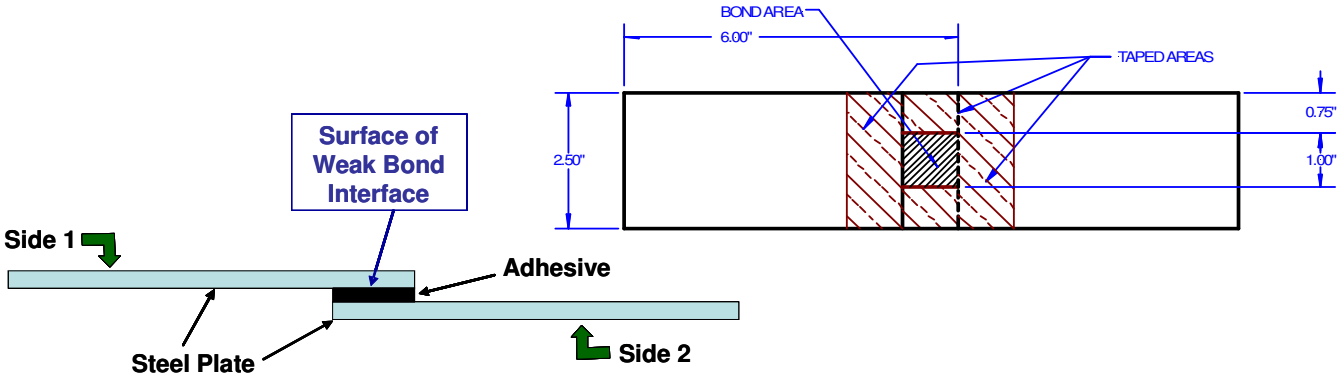

Figure 4: Weak Bond Lap Splice Test Specimen

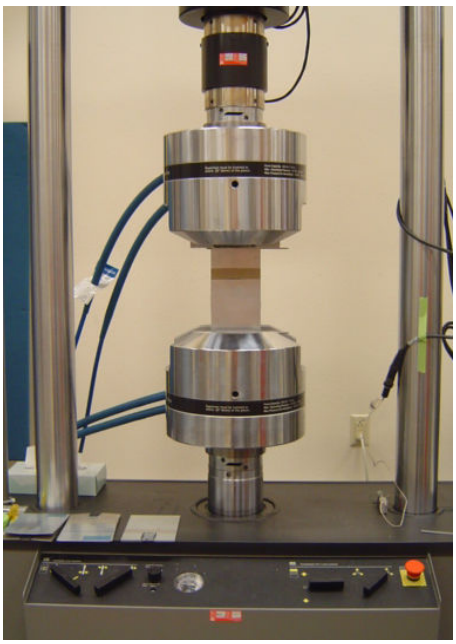

Figure 5: Weak Bond Specimen Mounted in Uniaxial Mechanical Test Machine to Determine Bond Strength

Nondestructive Characterization of Weak Bonds

Based on previous experience in related weak bond studies, along with research into promising inspection methods, a suite of NDI methods were selected to study the weak bond specimens. The suite of NDI techniques evaluated were: 1) pulse-echo UT, 2) phased array UT, 3) nonlinear harmonic generation, 4) swept-frequency UT spectroscopy, 5) oblique and shear-wave resonance, 6) laser shot peening, 7) through transmission UT (immersion and air-coupled), 8) flash thermography with signal enhancement, 9) laser UT, 10) mechanical impedance analysis, 11) oblique incidence ultrasound, and 12) guided waves. Some techniques did not show any promise for assessing weak bonds, some

techniques were able to identify the severely weak bonds (less than 20%), some techniques showed some trends but did not provide the resolution to make any clear indications of weak bonds and some methods clearly showed delineation in bond strength. Some of the most promising and sensitive methods will be described here.

USCAR Weak Bond Coupon Specimen Test Matrix				
Specimen No.	**Description**	**No. of Strength Tests Completed**	**Avg. Strength (lbs./kN)**	**% of Bond Strength**
T-PRI-7F-X	Pristine	10	3,349/14.9	100%
T-MO-RE-MS-25-zzF-X	Full Strength mold release (Miller-Steph. 25% cov.)	10	2,946/13.1	88%
T-GRE-100-01-zzF-X	100% Grease Applic. (0.01mm thk.)	13	2,066/9.2	62%
T-MO-RE-MS-50-zzF-X	Full Strength mold release (Miller-Steph. 50% cov.)	10	1,931/8.6	58%
T-PWD-10-zzF-X	Baking powder 10% coverage w/screen	13	1,552/6.9	46%
T-SC-25-7F-X	25% Screen Applic. of Adhesive	10	1,530/6.8	46%
T-PWD-25-zzF-X	Baking powder 25% coverage w/ screen	13	1,034/4.6	31%
T-GRE-100-02-zzF-X	100% Grease Applic. (0.02mm thk.)	13	869/3.9	26%
T-GRE-100-05-zzF-X	100% Grease Applic. (0.05mm thk.)	13	357/1.6	11%
T-PWD-100-zzF-X	Baking powder 100% coverage	11	348/1.5	10%

Table 1: Summary of Ten-Specimen Weak Bond Set

While the most sensitive NDI methods were not able to completely quantify bond strength, they were able to accurately establish a strength threshold. Inspection data, most often color-coded C-scans, was able to indicate when the strength of the bond line falls below the 60-70% strength value. This is an important finding that provides the ability to more accurately and reliably establish accept-reject levels. Through-transmission ultrasonics was able to identify weak bonds. Figure 6 shows a series of amplitude plots along with the bond strength for each of the ten specimens in the weak bond set. These results show that the signal amplitude is affected by the physics of the changing bond. The resulting C-scan images are shown in Figure 7 where the general brightness of the C-scan darkens as the bond becomes weaker (amplitude decreases).

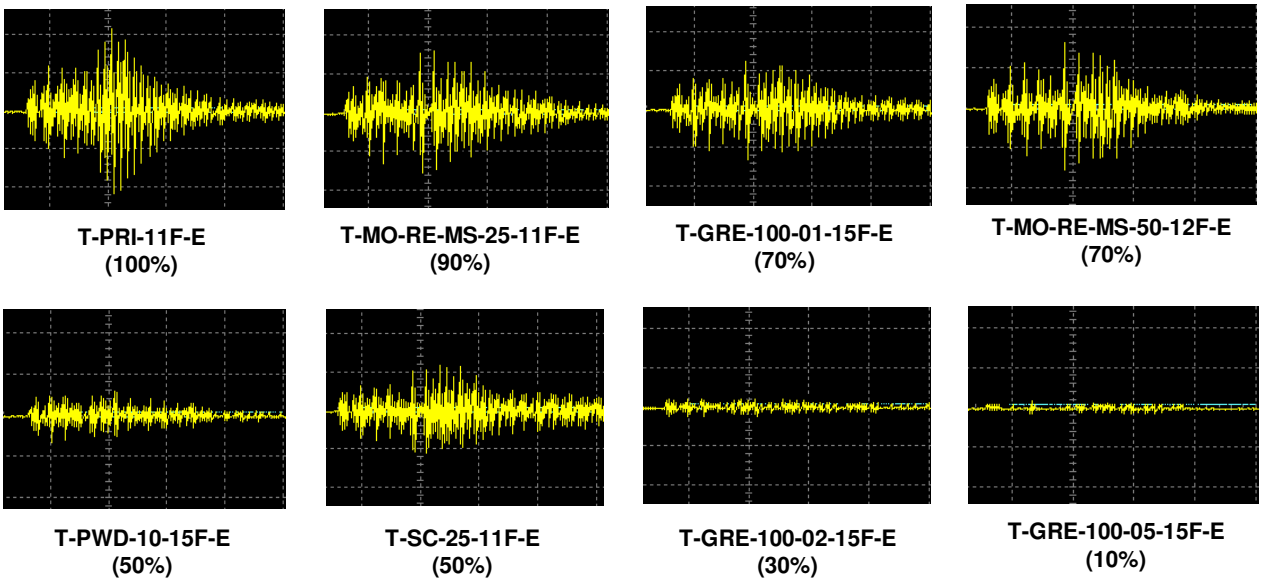

Figure 6: Through Transmission Ultrasonic A-Scans Showing Amplitude Reduction as Bond Strength Decreases (Bond Strength is Indicated by Percentage Numbers Below Each Graphic)

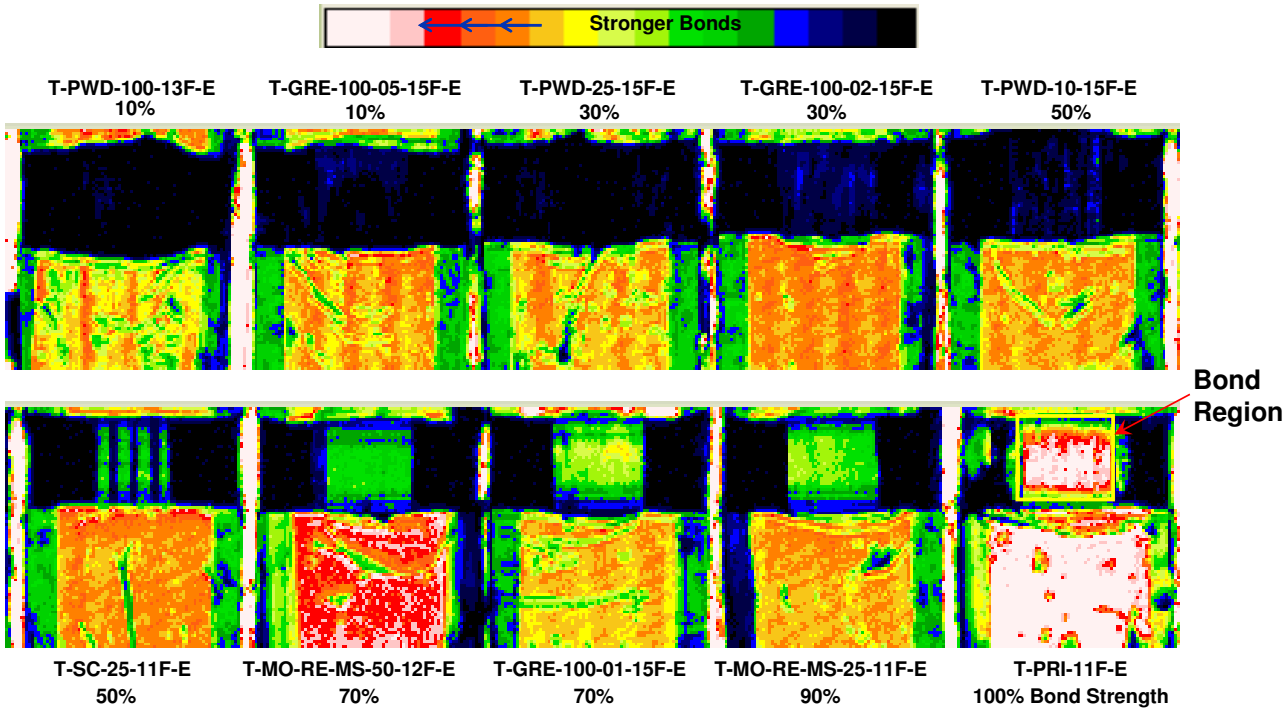

Figure 7: Tracing Bond Strength Using Through Transmission Ultrasonic Images

Field-deployable pulse-echo UT can also provide bond strength information using C-scan images produced after some custom signal analysis. Detailed analysis on pulse-echo ultrasonic signals was able to determine the portions of the signal that contained the primary bond strength information. These are highlighted as peaks 2, 3, and 5 in Figure 8. Echoes 1, 2, 4 and 7 are the multiple echoes in the upper plate, echoes 3 and 5 are the first and second echoes that pass through the upper interface of the bond and are reflected by the lower interface of the bond, and echo 6 is composed of three components, only one of which passes both the upper and lower interfaces of the bond. So, bond information can be ascertained from studying peaks 3, 5, and 6 while peak 2 provides baseline information on the initial bond line interface. Focused analyses on these A-scan peaks produced some success in identifying weak bonds. The C-scans in Figure 8 show the change in the ratio of peak 3 to peak 2 and clearly demonstrates the promise for use of pulse-echo UT to quantify bond strength. In both cases the C-scan colors change from warm, bright colors to darker, cool colors as the bond strength degrades.

The degree of variation in the C-scan images does not quite allow for exact bond strength values to be assigned based on the color codes. However, the images do significantly change when the bond strength drops to approximately the 60% (+/-) level. A-scan results from the weak bond specimen, such as the one depicted in Figure 8, show that the bond-related echoes 3, 5 and 6 are missing or reduced as the bond strength decreases. Thus, a measure of bond strength can be determined by calculating the ratios between the amplitudes of echo 2 (steel travel only) and echo 3 (bond line travel) for the array of specimens. Table 2 summarizes the results from this calculation and reveals that the UT peak signal measurements are close for 60-90% bond strength but can distinguish the bonds that are less than 50% (S/N levels are high enough to produce consistent results).

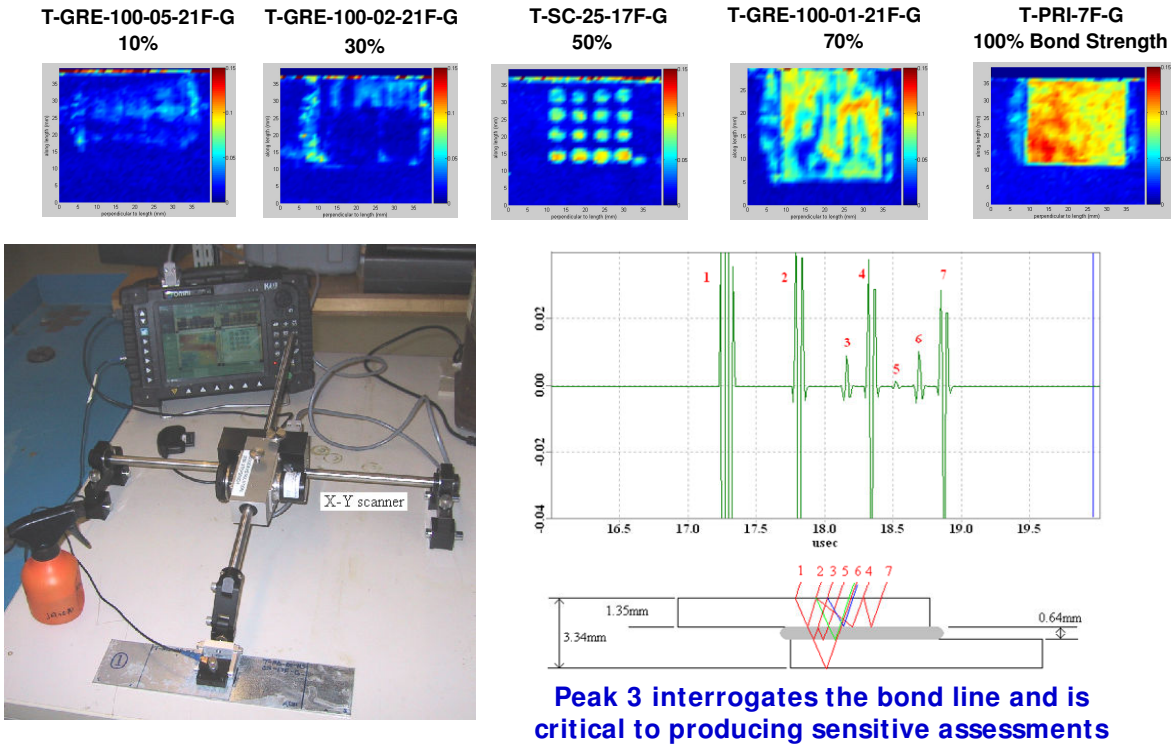

Figure 8: Pulse-Echo UT Inspections Show Promise for Assessing Bond Strength Using Ratio of Peak Amplitudes

Sample	Bond strength %	Amplitude E3/amplitude E2
T-PRI-7F-G	100	0.096
T-MO-RE-MS-25-17F	88	0.085
T-GRE-100-01-21F-G	62	0.087
T-MO-RE-MS-50-18F-G	58	0.097
T-PWD-10-21F	46	0.024
T-SC-25-17F-G	46	0.016
T-PWD-25-21F-G	31	0.042
T-GRE-100-02-21F-G	26	0.014
T-GRE-100-05-21F-G	11	0.006
T-PWD-100-19F-G	10	0.01

Table 2: Identification of Weak Bonds Using Ratio of UT Peak 2 and Peak 3 Amplitudes

Other NDI methods were applied to fully exploit all characteristic features in bond strength inspections. Swept-frequency narrow-band spectroscopy has shown promise for improving the UT signal and an ability to differentiate low from high bond strengths [8]. A dynamic modal testing method worked well when masses were added to the joints in order to uncouple the dynamic response

of the "plate slapping mode" from the other specimen resonances. The natural frequencies decrease and the damping increases as the bond gets weaker. Laser peening methods were able to properly characterize the bonds in order of strength but the high energy levels required for inspection may deteriorate the bond. Shear wave resonance testing and thermography were able to differentiate high strength from low strength bonds when noise reduction schemes were deployed.

Figure 9 shows a series of thermographic images of weak bond specimens obtained using the Thermal Wave Imaging pulsed thermography system. Data acquisition software enhancements were applied to filter the data and remove noise. In addition flash quenching hardware was deployed to optimize the heat pulse excitation. Thermography Signal Reconstruction (TSR) signal analysis was applied to improve the signal-to-noise levels [9]. The TSR filter removes temporal (local) noise but peak-to-valley levels (background contrast) are retained. Furthermore, the TSR derivative was calculated pixel-by-pixel and plotted to create a two-dimensional grayscale image where the signal-to-background contrast is improved considerably. The result is a much higher signal-to-noise ratio in the thermographic images and a greater sensitivity. This allows the bonds to be imaged differently, based on strength. The series of images in Figure 9 depict the ability of this thermography method to differentiate bond strength in the configuration shown in Figure 4.

Resonance-based inspections monitored changes in acoustic impedance and were able to image variations in the bond lines. Resonance testing utilizes narrow bandwidth transducers, which, when coupled to the item under test, produce a continuous sound field in the material. The test material, in turn, provides a mass loading on the transducer increasing the transducer bandwidth as well as changing the transducer's resonant frequency. Anomalies (such as disbonds) or changes in material stiffness result in changes to the transducer loading that cause changes in transducer resonance. Figure 10 shows the C-scan images from resonance testing (250KHz transducer) which essentially uses an acoustic wave to interrogate the structure for stiffness variations. If the steel adherend is thin enough, resonance testing can detect changes in the strength of the bonded joint because the bond line plays a bigger role in the overall stiffness of the assembly.

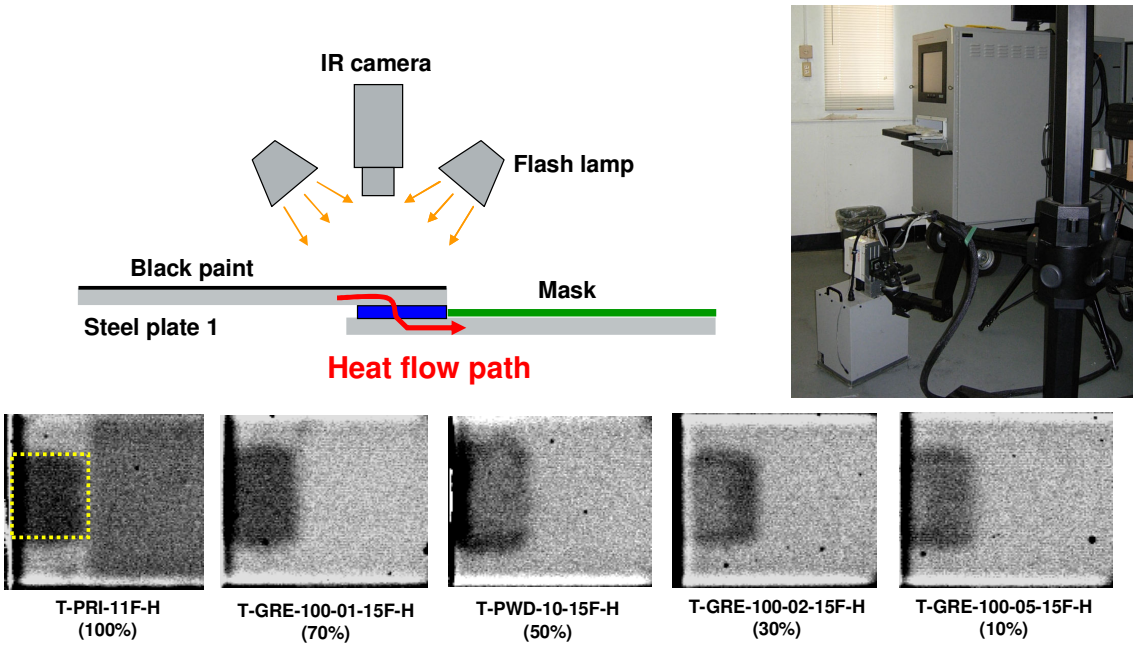

Figure 9: Thermography, Coupled with Signal Optimization Schemes, Can Differentiate Bond Strengths

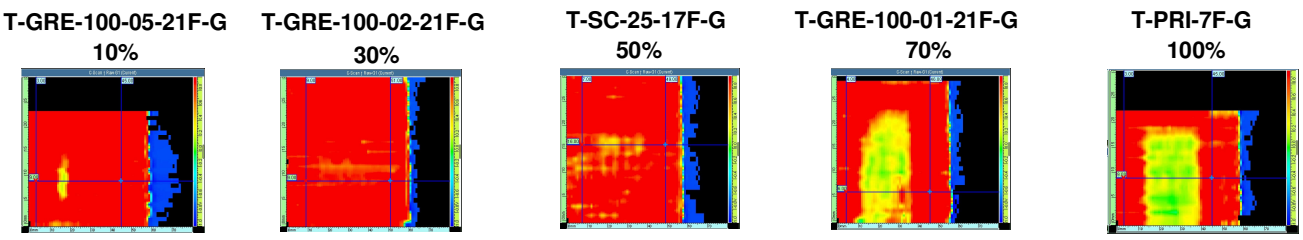

Figure 10: Resonance NDI Method Clearly Shows When Bond Strength Drops Below 70% Level (Bond Strength is Indicated by Percentage Numbers Above Each Graphic)

Most joints are designed to primarily carry shear loads so the application of shear stresses, rather than normal compression and tension forces, might more realistically be able to investigate the performance of the bond [10]. Oblique-incidence methods are more difficult to implement than the normal-incidence (longitudinal) wave methods, but they are able to apply a shear stress component to the interface and hence are potentially more sensitive to interfacial properties.

When examining the test specimens used in this work, the initial angle of incidence of the ultrasound beam was chosen to be slightly greater than the longitudinal wave critical angle in order to produce only shear waves with the shortest ultrasonic path length and prevent the production of any longitudinal waves in the adherends. Beyond the first critical angle, only the shear wave propagates as a bulk wave into the material. The initial angle of incidence of the ultrasound beam and the transducer separation were selected so that only the shear wave in the top plate was detected, which corresponds to a reflection from the near surface of the adhesive. Scans were obtained using transmit and receive angles, α of 15^{o} and a matched pair of 25 MHz transducers. Figure 11 shows a schematic of the set-up. Images of the bonded area were obtained by monitoring the amplitude changes of the shear-shear signal reflected from the rear of the top adherend (interface between the metal plate and the adhesive). Degradation of the adhesive joint is visible as lighter (yellow-white) colors in the scan, and well-bonded areas are darker in color as seen in Figure 12.

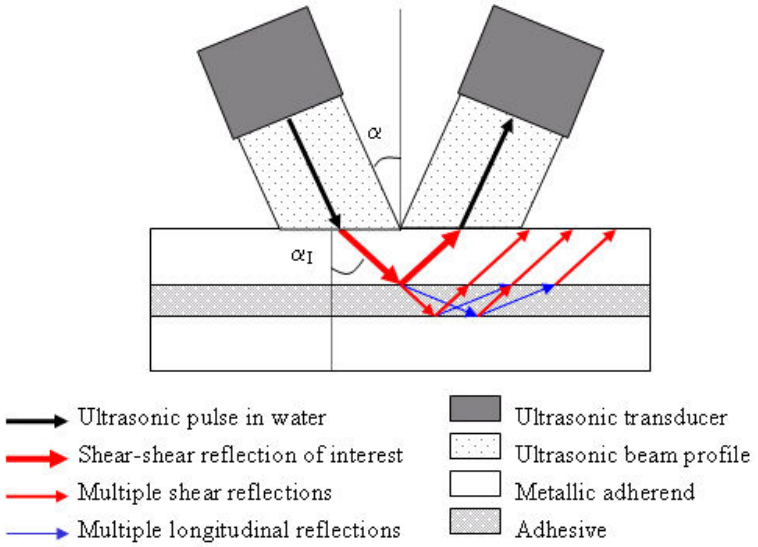

Figure 11: Schematic of the Oblique Incidence Set-up

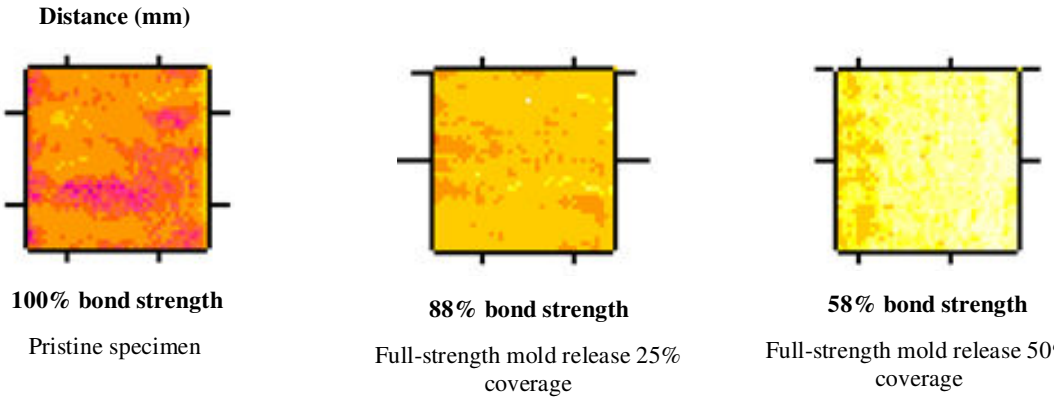

Figure 12: Oblique Incidence Scan for Steel Lap-Joint Bond Specimens with (left to right) 100%, 88% and 58% Bond Strengths.

Bond Strength and Durability Assessment

As an artifact of the weak bond study, it was also possible to evaluate the effects of various bond line thicknesses and environmental exposure levels on the strength of the bonded joint. A series of shear test specimens (see Figure 4) were produced to complete such a parametric study. In addition to the intentional weak bonds described above, the bond line thickness was studied in concert with the degrading exposure to hot-wet conditions (95% humidity at 140°F for 30 days). Both shear strength and fatigue (durability) tests were completed multiple coupons of each type and the results were averaged. Figure 13 shows that the thin and thick bond lines possessed approximately the same shear strength as the standard, 0.4 mm bond line. Hot-wet exposure reduced the bond strength and the thin bond line was least affected by environmental exposure. The fatigue test results shown in Figure 14 indicate that the thin bond (0.2 mm) exhibited the best durability results requiring almost 6 times as many fatigue cycles to produce failure as the standard bond line.

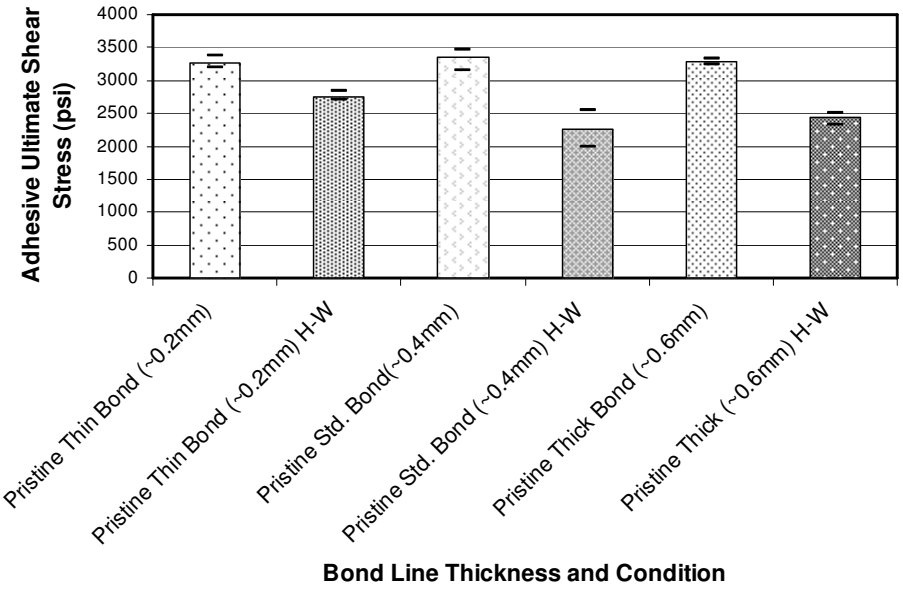

Figure 13: Strength Results for Varying Bond Line Thicknesses and Effect of Sustained Hot-Wet Exposure

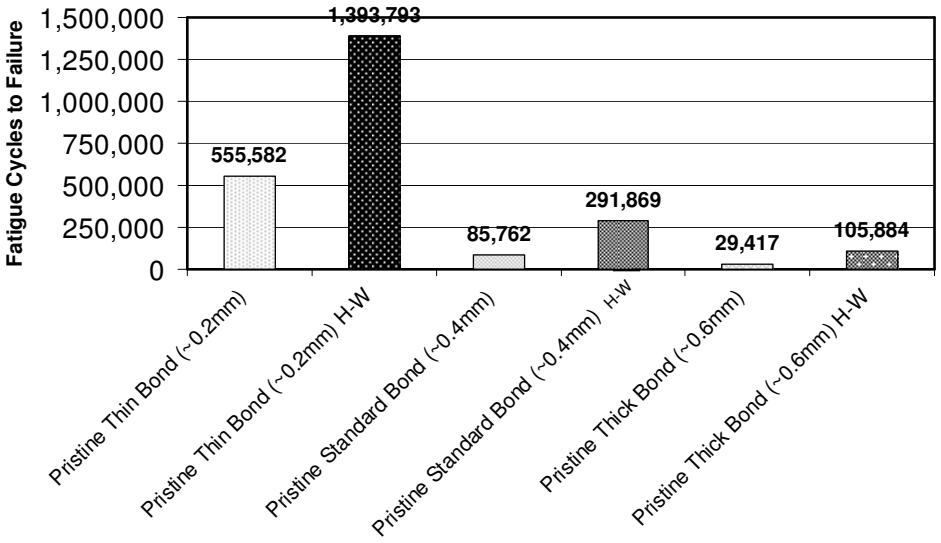

Figure 14: Durability/Fatigue Results for Varying Bond Line Thicknesses and Effect of Sustained Hot-Wet Exposure

Conclusions

Process control alone may not ensure satisfactory strength in bonded structures. Successful NDI must be sensitive to joint degradation stemming from a myriad of conditions including contamination, distributed micro-disbonds, stress, fatigue and the environmental effects of moisture, aging, and chemical exposure. As a result, one NDI method may not detect all types of weak bonds. Inspection methods must be highly sensitive in order to differentiate the subtle differences between optimum bonds and weak bonds. The use of noise reduction methods may be required to recognize these small changes in bonded joints. Significant progress was made in understanding the physics behind the weak bond both mechanically and from an NDI perspective. Fourteen different inspection methods were applied to sets of weak bond specimens. Several of the methods successfully identified and imaged the weak bonds when the hardware was optimized and the proper signal analysis was completed. Detailed analysis on pulse-echo ultrasonic signals was able to determine the portion of the signal that contained the primary bond strength information. While the ultrasonic-based NDI methods were not able to completely quantify bond strength, they were able to establish a strength threshold to ensure that a bond strength of least 60% has been obtained. Shear wave resonance testing and thermography were also able to differentiate high strength from low strength bonds. This weak bond study determined that inspection data, most often color-coded C-scans, is able to indicate when the strength of a bond line falls below the 60-70% strength value. This is an important finding that provides the ability to more accurately and reliably establish accept-reject levels.

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