Correlating Fracture Toughness and Surface Roughness for a Ductile Epoxy Adhered to Aluminum Substrates

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Stephanie TerMaath, Major Professor

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(Original signatures are on file with official student records.)
Correlating Fracture Toughness and Surface Roughness for a Ductile Epoxy Adhered to Aluminum Substrates

A Thesis Presented for the
Master of Science Degree
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ABSTRACT

Adhesively bonded joints are used across multiple disciplines as an efficient and cost effective method for reinforcing, repairing, or creating new structures. Sufficient understanding of the bond line characteristics of the adhesive is necessary to properly design a reliable bonded joint and ensure a long service life. It is well understood that surface preparation has a significant impact on these interface characteristics as a given level of surface roughness achieves mechanical interlocking between the resin and metal and is important to prevent premature interfacial failure [1]. The goal of this study is to characterize the fracture toughness values for an adhesive bonded to aluminum substrates of varying surface preparation quality. Foundational equations are developed for relating surface roughness measurements to experimentally determined fracture toughness.

Experimental tests are completed to determine the critical strain energy release rate, $G_c$, for mode I tension, $G_{Ic}$, mode II shear, $G_{IIc}$, and mixed-mode, $G_{I+II}$, loadings. The double cantilever beam (DCB), end-notched flexure (ENF), and single leg bend (SLB) tests are used for modes I, II, and I+II (mixed-mode) respectively with four types of surface preparations. Common data reduction methods are used for calculating $G_c$.

Characterization of the interface surface, including quantification of void, cohesion, and adhesion failure mechanisms at the bondline, is studied to quantify each sample’s failure modes and void properties as it relates to surface roughness and fracture energy. The characterization is used to develop an analytical model of the relationship between these three parameters and the resulting fracture energy. Fundamental equations are developed that relate the surface roughness parameters to the fracture energies. Numerical simulations in Abaqus finite element software use a potential-based cohesive zone model to predict adhesive failure and simulate crack propagation of a mixed-mode case. These simulations are validated against the SLB experimental results for accuracy. The surface roughness measurements, coupled with the mathematical equations relating fracture energy to surface roughness, provides an input to the numerical models. The simulations are used to predict bondline performance within specified confidence intervals of the roughness measurement distributions and provide a basis for determining load carrying characteristics of the metal to adhesive interface.
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CHAPTER 1: INTRODUCTION

The goal of this study is to characterize a ductile epoxy bonded to aluminum substrates using interface surfaces of varying preparation quality. The study will perform a series of experiments to determine interfacial fracture energies of an adhesive-aluminum interface and correspond the adhesive fracture surface characteristics and surface roughness to the experimentally determined values. The objectives for this study are to:

1. Characterize fracture toughness values for an adhesive bonded to aluminum substrates of varying surface preparation quality.
2. Develop foundational equations for relating surface roughness measurements to the experimentally determined fracture toughness.

It is desirable for engineers to have reliable material interface properties. Characterization of adhesive material, particularly related to its interface to a substrate, is critical to understanding how it will perform while in service. Critical strain energy release rate, $G_c$, or called fracture energy, is a property that quantifies a material’s resistance to fracture in the presence of a crack and is an important parameter when designing an adhesively bonded joint [2]. It is important to understand the failure under normal loadings, mode I, and shear loading, mode II, and it is just as important, if not more important, to study the behavior of a material under mixed-mode, I+II, loading. This is because materials are rarely ever loaded in the pure normal or shear directions, but more often a combination of both, creating a mixed-mode loading situation. It is noted that mode III shear is assumed to be equivalent to shear mode II.

Surface preparation of a substrate is a key component to any adhesive application where a material is bonded to another. Variations in surface preparation, including chemical pretreatment and surface roughness, can vary the performance of the adhesively bonded joint. Ensuring a given level of surface roughness to achieve mechanical interlocking between the resin and metal is important to prevent premature interfacial failure [1] as increasing the surface roughness provides increased contact area for adhesion [3]. These factors can enhance the mechanical bond at the interface of the adhesive and substrate.

This study will correlate the surface roughness and fracture energy for varying preparation methods. It will examine the implications of this surface roughness on the adhesive layer characteristics and how these characteristics affect the performance of the adhesive bondline. The tests used in this study have long been used by experimentalists and have been shown to
produce reasonably good results. Through data reductions methods, a value for $G_c$ will be calculated using the $P-\delta$ data extracted from the experiments. Numerical models completed using a finite element program will be validated against the experimental data and further used as a tool to understand the performance characteristics of the adhesive bondline as it relates to surface finish.
Background

Adhesive joints are more commonly being used as structural elements because of their many benefits, including, great strength to weight ratio, limited cost of fabrication, water/chemical resistance, and design flexibility [4]. Joining dissimilar materials to create hybrid structures enables lightweight, customized designs for complex shapes and specific design requirements that optimize the performance of each material in the structure resulting in faster vehicles, reduced fuel consumption, and increased payloads [5-7]. Benefits over traditional methods of joining (i.e. screws, rivets, welding, etc.) are present through the reduction of stress concentrations, weight savings, and the ability of the bonded surface to evenly distribute stresses across the entire interface surface. Field repairs of damaged metal structures, whether temporary or permanent, are made easier by co-curing fiberglass and epoxy in situ and does not require the heavy equipment and power of that needed for metal fabrication.

As with any method of joining, drawbacks of adhesive bonding do exist and will be discussed briefly. Structures that use adhesive bonding have had varied results. In some cases, the adhesive application provided exceptional service life while, on the other hand, other applications have demonstrated premature failure or heightened maintenance requirements in a relatively short period of time [4]. Environmental effects and multi-directional loading scenarios introduce potential problem areas, where complicated stress states mixed with unexpected climates could cause premature joint failure not originally considered in the design of the joint [8].

A major disadvantage is that bondline failure is a non-visible damage mechanism requiring non-destructive inspection. Small disbond areas that may be challenging to detect during inspection can create initiation sites for damage propagation and potential joint failure. Such interface disbond can occur under service loading such as bending, fatigue, or low velocity impact. No method of nondestructive evaluation (NDE) available has the capability to fully check the quality of the adhesion, giving no definitive evidence of proper bonding. Bondline structural reliability remains difficult to predict due to the many parameters influencing performance in addition to the complex physical behaviors observed experimentally but not explicitly accounted for in current analysis methods. Defects in adhesive bonds can manifest, for example, as delamination, voids, porosity, or cracks. Nondestructive (ND) quality assurance techniques for assessing joint integrity are limiting, with visual examination methods being mostly unusable because of hidden defects, and other conventional ND methods (ultrasonic, X-ray, etc.) only able to detect
delamination defects and not the quality of the adhesion. Thus, because of the fact that joint performance cannot be characterized, ND methods prove to be of limited utility [9].

**Experimental Tests**

A thin layer of adhesive can be assumed to perform as an interface. In other words, the interface properties are a function of the interface configuration and not just dependent on that of the material itself. Adhesion strength is reliant not only the adhesion material, but the substrate material and the type of surface preparation used. For this reason, $G_c$ is considered a property of the interface and is commonly referred to as interfacial fracture energy.[10] Many researchers have characterized $G_c$ using various combinations of adhesives, adherend material, and surface preparation methods. This study will focus on those where the adherend materials were metal and where experiments were characterizing failures in primarily normal, shear and mixed-mode directions.

Many researchers have published results of adhesive fracture energy using metal adherends. Banea, da Silva [11] and Banea, da Silva [12] studied the effects of temperature on the performance of adhesives and steel adherends for mode I and mode II. da Silva, Esteves [13] studied mixed mode fracture energy of steel/adhesive/steel joints using the single leg bend (SLB) test, which is a test first developed by S. H. Yoon [14] as a modified version of the end notched flexure (ENF) test. da Silva, de Magalhães [15] studied mode II fracture energy of a brittle and ductile adhesive as a function of adhesive thickness using steel adherends. Park and Dillard [16] characterized the fracture energy of an acrylic adhesive using an asymmetric DCB test and SLB. There are many tests available for obtaining the normal opening mode, or mode I, fracture energy, $G_I$. The DCB and the tapered double cantilever beam (TDCB) tests are the most common [17]. The DCB specimen consists of two uniform thickness rectangular shaped adherends, bonded together with a short delamination length towards the front. The TDCB specimen is the same as the DCB except it has tapered rectangular adherends that increases in thickness towards the unloaded side of the specimen. The tapered adherends have the benefit of linearly changing the compliance, $\delta/P$, which removes the need for monitoring crack length using the classical fracture energy formulation [18]. The DCB test is chosen for this study, though, because of the simple geometry, test setup and universal specimen geometry that can be used for further obtaining modes II and I+II results. More information on the DCB test can be found in [19].
Three dominant mode II shear tests are available: end loaded split (ELS), end notched flexure (ENF), and four-point notched flexure (4ENF). All methods present advantages and disadvantages. The ELS provides stable crack initiation, but unfortunately, inherent variability exists in the clamping fixture and large displacements are present. The 4ENF has several positives, including stable crack growth, straightforward data reduction methods, and simple test setup. However, it has been demonstrated that the results can be specimen dependent and estimate values higher than that of the ENF. Unstable crack initiation and difficulty monitoring crack propagation are issues with the ENF, but it has the benefits of having a simple test fixture and the same specimen geometry as that of the DCB. For these reasons, the ENF is chosen for this study. [20]

Many tests exist for determining the mixed mode fracture energy, these include the mixed mode bending (MMB), asymmetric DCB (ADCB) and single leg bend (SLB) [17]. Most of these tests require complex fixturing and unique specimen geometry. The single leg bend test requires no additional testing equipment beyond what is required for the ENF and uses a modified DCB specimen. Further, wide ranges of mixed-mode fracture energy can be calculated by varying the thickness ratios. For these reasons, this is the test used for determination of the mixed-mode fracture energy [14].

**Effects of Surface Topography on Adhesion**

Surface preparation may be the most important aspect to creating a strong and durable adhesively bonded joint [21]. Adhesion between two surfaces is achieved through two mechanisms: specific and mechanical adhesion. Specific adhesion, or also referred to as chemical adhesion, is the attraction of the atoms and molecules between the adhesive and adherend. Mechanical bonding, contributing to mostly all the bond strength, occurs as a result of the interlocking between the adhesive and the adherend surface. The interlocking effect predominantly rests with the coupling between the adhesive and the peaks and valleys of the roughness on the surface of the adherend. Surface roughness, though, not only allows for the beneficial mechanical bonding to occur, but also introduces opportunity for gas bubbles to become present in the adhesive [22]. Chester [23] found that surface treatment contributes to the presence of voids in the adhesive. They also found that previously absorbed water content in the metal adherends play a particular role in the development of voids, particularly in aluminum metal, during the curing process. Quantifying the effect of surface roughness on the interfacial fracture strength, with particular consideration
to mechanical adhesion and gas bubble effects, can provide valuable insight into the performance of bonded joints.
Many authors have published reports studying surface roughness and its relation to adhesion. W.S Kim [10] studied the effects adhesion strength by micro-morphological modification of metal adherends surface. The study found that by applying a micro-line patterned surface topography, the adhesion strength is superior to that of a surface that has been mechanically abraded and high fracture toughness was determined to be attributed to the mechanical interlock mechanism of the adhesive to the surface roughness of the substrate. Sinan [24] studied surface roughness effects on the joint strength of steel prismatic plug-in joints combined with adhesive. The study found that the shear strength of the joint was increased by increasing the surface roughness. Budhe, Ghumatkar [25] studied the surface roughness effect on the strength of aluminum single strap specimens. Results showed a strong correlation between surface roughness and bond strength, with optimum roughness values between 1.75–2.5 micrometers. Cordisco, Zavattieri [26] studied crack propagation along sinusoidal interfaces in DCB adhesively bonded joints. The study found that mode I strength and fracture toughness is directly correlated to the increasing aspect ratio of the surface finish. Guo, Carlson [27] studied the effects of laser ablated surface topography on the adhesive joint strength and toughness of high strength aluminum alloy and a commercial structural adhesive in DCB tests. The study found that fracture toughness can be increased by increasing adhesion area and the mechanical interlock between the substrate and adhesive. Xu, Ng [28] studied the effects of micro-surface texturing on the adhesion strength of single-lap-shear tests and found that the adhesive strength is significantly increased with the addition of surface texturing. The study also noted that the complex geometry of the texture may provide larger bond surface but may cause difficulty for the adhesive to fully flow into the micro channels.

**Interface Failure Behavior**

The two main fracture modes in an adhesive joint are adhesive and cohesive fracture [27]. The adhesive failure refers to the separation of the adhesive from the interface substrate. Cohesive fracture refers to the crack propagation through the adhesive material itself. The cohesive fracture mode is indicative of a soundly prepared joint. Cohesive fracture is associated to higher values of fracture toughness, as the adhesive material typically has higher fracture toughness than that of the interface toughness [29]. Many authors have studied the adhesive and cohesive
failure of bonded joints and have further worked to develop models to predict bondline behavior with the goal of creating a better performing adhesive joint.

Hirsch and Kästner [29] presented a method for modeling the failure behavior of bi-material interfaces. The study found that, by adjusting the adhesion properties through increased surface roughness, that strengthening of a joint can be achieved through the transition of the failure mechanism from adhesive to cohesive. Kim, Yun [1] found that the adhesion strength is increased by virtue of that fact that the increase in surface roughness causes the adhesive to transition from adhesive to cohesive failure. Yao and Qu [30] developed a model for determining the interfacial failure versus cohesive failure of polymer-metal interfaces. The model predicts the amount of cohesive failure near the adhesion interface and thus can be used to quantify adhesion enhancement of a given interface. van der Sluis [31] compared the adhesive and cohesive fracture and how the surface treatment changed the fracture locus.
CHAPTER 2: EXPERIMENTAL TESTING AND RESULTS

This chapter details the experimental testing and results of adhesively bonded aluminum samples. The materials were chosen according to their practical uses as a means of in-field vessel hull repair. The specimen geometry and experimental test plan was developed according to previously published work on similar problems. The surface preparation process corresponds to what might reasonably be used in the field for fabrication of an adhesively bonded joint. The prepared surfaces are examined both quantitatively and qualitatively, using a high-magnification optical camera and a surface roughness measurement device. Lastly, the fracture energies derived from the experimental results rely on well documented data reduction methods offered in literature.

Specimen Materials
The specimen adherends used in this study are composed of 5456 grade aluminum. This is a high strength, marine grade aluminum often used in saltwater environments. The yield strength of this material is 228 MPa and has a modulus of elasticity of 71 GPa. The adhesive is a 2-part ductile laminating epoxy from PRO-SET, M1002/237. This material has a Young’s modulus of 1,640 MPa and tensile strength of 69 MPa. The strength is taken from the manufacturer’s specifications and Young’s modulus from [32].

Specimen Geometry
The DCB geometry is chosen for this study because of the simple geometry, test setup, and universal configuration that can be used for further obtaining mode II via the ENF test [19]. The DCB specimen consists of two uniform thickness rectangular shaped adherends bonded together with an adhesive. An initial delamination length, located on the front section of the specimen, provides a location for crack initiation. The specimens used for the SLB tests are modified versions of the DCB. The SLB configuration is chosen for this study because of the simple geometry, it does not require additional test fixturing beyond that required for the ENF test, and the ability to change the mixed modity of the sample by modifying the thickness of one of the adherends [14]. The depictions of the geometries are presented in Figure 1.
Figure 1. DCB (a) ENF (b) SLB (c), (d) specimen and support dimensions
Figure 1 Continued
Specimen Preparation

Raw aluminum plates were cleaned with acetone and sanded to remove oxidation and other surface contaminants. 3M® AC-130-2 surface pre-treatment was applied to the sanded surfaces and allowed to dry for at least 60 minutes. 50-micron thick Teflon tape was applied to the interior surface of the specimens to reduce friction and provide an initial delamination span in this area. The resin and hardener were mixed according to the manufacturer’s recommendations. 100-micron glass beads introduced in the epoxy mixture maintained a constant adhesive layer thickness of .1 millimeters. The beads were introduced at less than 2 grams per 2.5 oz of epoxy. The beads are expected to have a negligible impact on the experimental results when compared to the value added when considering the consistency in the bond line thickness that is achieved. Vacuum bagging was used during the curing process to provide uniform pressure across the plates during the curing process. Curing was done in a drying oven at 60°C for 4 hours. Finally, specimens were precision cut to their final sizes using a waterjet machine. White spray paint was applied, where applicable, to the sides of each specimen to assist in visual detection of the crack during the experiment.

40-120-180 grit, respectively, and 40 grit, exclusively, were used during the oxidation and surface contaminate removal step of the DCB and ENF specimen preparation. These were applied using two methods: hand application and electric handheld DeWalt 5” random orbit sander. For purposes of brevity, the surface preparations will be referred to as 180 orbit, 40 orbit, 180 hand, and 40 hand. The SLB specimens were prepared using the 180 orbit method. The orbital sanding application was completed with moderate pressure in random zig zag patterns. The resulting finish was a visually consistent and uniform surface. Hand sanding used moderate to heavy pressure, applied with 4 fingers in a clockwise/counter-clockwise random circular motion. Circular patterns on the surface of the specimen are visible with this method of preparation, contrasting to the uniform and isotropic surface produced by the orbital sanding method. Sanding for both steps was complete when the oxidation layer was visually removed. The prepared surfaces are shown in Figure 2.
Figure 2. Surfaces for 180 orbit (a) 40 orbit (b) 180 hand (c) and 40 hand (d) surface preparations
Keyence Images
Four 4” X 4” aluminum samples, representing each type of surface preparation used for the specimens, were prepared in parallel effort during the specimen preparation process. A Keyence VHX-6000 digital microscope with a 2500X high magnification lens was used to examine three 1000 μm X 1000 μm square areas on each sample. The three areas examined were located on the sample approximately as shown in Figure 3. Stitched images of these areas on each sample are provided in Figure 4.

Surface Roughness Measurements
Ra and Rz surface roughness values were measured using an SPI Roughness Tester II surface profilometer. The surface profilometer is an instrument that is economical, small, easy to use, and relatively more affordable than other surface roughness measurement machines. The profilometer relies on physical measurements of the sample being measured, using a stylus moving laterally across the surface of interest to determine the roughness value.

The surface preparation samples were first cleaned with a lint-free cloth and acetone to remove contaminants and debris. Data was taken along five equally spaced lines across the width and height at 0deg, 45deg, and 90deg. Five measurements are taken along each line for a total of 75 measurements per sample. A depiction of these paths is provided in Figure 5. Figure 6 and Figure 7 summarizes the individual and combined Ra and Rz surface roughness for each sample in μm.

Testing
Testing was performed on a calibrated MTS universal testing machine using 10kN and 100kN load cells. Displacement, δ, was applied for all experiments at a rate of .50 mm/min and δ and load, P, were recorded versus time, t. High definition video, focusing on the adhesive layer of the specimen, was recorded when necessary to perform the subsequent fracture energy calculations. The video allows for the measurement of a versus t to be measured following the test and, further, the ability to combine the P-δ and a values into a convenient graph.

With exception of the DCB hinge block and plates, the test setups used the standard fixtures and supports supplied with the MTS machine. The fixtures are robust in design, having virtually no deflection under the loads applied during the experiments. Loading blocks were attached to the DCB test specimens using four #10-24 UNF screws, 2 on either side of the specimen. Hinge plates were attached to these loading blocks via pins and the hinge plates attached to the testing
Figure 3. Areas examined by Keyence microscope on surface preparation samples
Figure 4. Keyence images for 180 orbit (a), 40 orbit (b), 180 hand (c), 40 hand (d) specimen preparation samples.
Figure 4 Continued
Figure 4 Continued
Figure 4 Continued
Figure 5. Surface roughness measurement paths

Figure 6. Ra and Rz profilometer results for 180 orbit (a), 40 orbit (b), 180 hand (c), and 40 hand (d)
Figure 6 Continued

Figure 7. Ra and Rz profilometer results for combined Ra (a), and combined Rz (b)
Figure 7 Continued
machine using tensile grips. The ENF and SLB test setups used rollers for the specimen supports and load point applicator. Following the testing of the 180 hand DCB specimens, it was found that this batch of samples had a significant increase in the bondline thickness. Because the other samples did not have this issue and the fact that mode I fracture energy is affected by adhesive thickness, these samples were removed from this study [33]. The experimental setups are shown in Figure 8. The DCB tests required that the specimens be precracked prior to being tested. This procedure ensures the results do not become skewed from effects caused by a blunt crack [34]. This was completed by initially loading the specimens until a crack was formed and allowing the crack to briefly propagate. After this small propagation, specimen loading was stopped, and the testing machine brought back to its zero position. The location of the new $a_0$ was documented and the test began. This procedure was the same for all specimens used for the DCB tests. Crack length is documented for the DCB tests to provide indications of the new pre-crack following initial sample loading. The SLB samples were also visually monitored in order to provide data for the reduction methods that require measurement of the crack propagation. The crack is monitored in the video under 400% magnification with inverted colors. This inversion of the colors assists in the detection of the crack front by contrasting the crack with the sides of the adherend. White spray paint, applied to the sides of the specimen, contrasts the dark crack with the white adherends sides. Adhesive backed rulers attached to the sides of the specimens, having graduations .79 mm apart, were used as a reference in tracking the position of the crack length over time. Figure 9 shows an inverted image taken from one of the DCB test videos. The vertical pencil mark represents the end of the initial delamination length and provides a point of reference for computing total crack length.

**Data Reduction Methods**

Many data reduction methods exist for calculating the fracture toughness for mode I, II, and I+II. Beam theory is used as a basis for many of these methods. While reasonably accurate, these methods usually require precise measurements of the crack propagation during the experimental testing and do not capture the effects of the fracture process zone (FPZ) ahead of the crack tip. The effects from this FPZ have proven to be nonnegligible for ductile adhesives, such as the material used in this study. An equivalent crack method, developed by [34] and called the compliance-based beam method (CBBM), uses the load and displacement data from the test to
Figure 8. Experimental test setups for DCB (a) ENF (b) and SLB (c), (d).
Figure 8 Continued
Figure 9. Inverted picture of a specimen crack in a DCB specimen
compute a specimen compliance. This compliance is used to compute a corrected flexural modulus, based on the initial crack length. The fracture energy in mode I can be computed by the following equation

\[
G_{IC}^{DCB} = \frac{6P^2}{B^2 h} \left( \frac{2a_e^2}{h^2 E_f} + \frac{1}{5G_{13}} \right)
\]  

where \(P\) is load, \(B\) specimen width, \(h\) the adherend thickness, and \(G_{13}\) the shear modulus of the adherends. The corrected flexural modulus \(E_f\) is calculated using the following equation

\[
E_f = (C_0 - \frac{12(a_0 + |\Delta|)}{5BhG_{13}} - 1 \frac{8(a_0 + |\Delta|)^3}{Bh^3})
\]

where \(a_0\) is the initial crack length and \(\Delta\) is the root rotation correction on initial crack length. This parameter is found by numerically simulating three specimens of varying initial crack length and plotting according to the relation \(C^{1/3} = f(a)\). The equivalent crack length, \(a_e\), is calculated as a function of specimen compliance

\[
C = \frac{\partial}{P}
\]

where the subscript 0 in (2) denotes the initial compliance in the linear portion of the P-\(\delta\) curve. The equivalent crack is related using Castigliano’s Theorem

\[
\partial = \frac{8Pa^3}{E_1 Bh^3} + \frac{12Pa}{5BhG_{13}}
\]

More details on the formulation of this equation can be found at [34]. Much like mode I, the ability to measure crack propagation for the mode II ENF test is a difficult one. This is because, in addition to the FPZ issues, the compression of the adherends creates a scenario where the crack front becomes nearly impossible to detect. CBBM, developed by [20] using the ENF and ELS tests, has been shown to be an accurate scheme for calculating mode II fracture energy. \(G_{IIc}\) is found from the following equation

\[
G_{IIc}^{ENF} = \frac{9P^2 a_{eq}^2}{16B^2 E_f h^3}
\]

The corrected flexural modulus \(E_f\) is calculated using the following equation

\[
E_f = \frac{3a_0^3 + 2L^3}{8Bh^3 C_{0c}}
\]

where \(L\) is the half span of the ENF specimen. The equivalent crack length, \(a_e\), is calculated using the following relation
\[ a_e = \left[ \frac{C_C}{C_{0c}} a_0^3 + \left( \frac{C_C}{C_{0c}} - 1 \right) \frac{2L^3}{3} \right]^{1/3} \]  

where \[ C_C = C - \frac{3L}{10G_{13}Bh} \]  
\[ C_{0c} = C_0 - \frac{3L}{10G_{13}Bh} \]  
\[ C = \frac{\partial}{\partial P} \]  

where \( C \) is the specimen compliance (3) the subscript 0 in \( C \) denotes the initial compliance in the linear portion of the P-\( \delta \) curve. More information on the formulation can be found at [20].

For the SLB tests using the adherends with equal thickness, the CBBM approach is also used and does not require the crack length monitoring [35]. The fracture toughness components are calculated as

\[ G_i^{SLB} = \left( \frac{3P^2a_{eq}^2}{4B^2E_fh^3} \right)^{-1} + \frac{3P^2}{40G_{13}B^2h} \]  

and

\[ G_{II}^{SLB} = \frac{9P^2a_{eq}^2}{16E_fB^2h^3} \]  

where the flexural modulus is

\[ E_f = (C_o - \frac{3(a_o + 2L)}{20G_{13}Bh})^{-1} \frac{28a_0^3 + L^3}{32Bh^3} \]  

and the equivalent crack length, \( a_e \), is found using the Castigliano Theorem

\[ C = \frac{28a_0^3 + L^3}{32E_fBh^3} + \frac{3(a + L)}{20G_{13}Bh} \]  

The total mixed-mode I+II fracture toughness is found by

\[ G_T^{SLB} = G_i^{SLB} + G_{II}^{SLB} \]  

The SLB specimens with the different thickness adherends use another method of calculating fracture toughness. This method calculates the fracture energies based on beam theory and requires the load and crack length monitoring during the test:

\[ G_i^{SLB} = \frac{P^2a^2}{8b} \left( \frac{D_2^2}{(D_1 + D_2)^2} \left( \frac{1}{D_1} + \frac{1}{D_2} \right) \right) \]
\[ G_{II}^{SLB} = \frac{P^2 a^2}{8b} \left( \frac{1}{D_1 + D_2} - \frac{1}{D} \right) \]  

where \( a \) is the crack length measure during the test, and

\[ D_1 = E_1 I_1 \]  

for the upper beam

\[ D_2 = E_2 I_2 \]  

for the lower beam, and

\[ D = (EI)_{eff} \]

for the bonded beam section. More information on this calculation can be found at [10].

**Results**

Experimental P-\( \delta \) curves of the DCB, ENF, and SLB tests are presented in the following sections. R-curves, comparing the crack propagation to the calculated \( G \), are subsequently shown. The P-\( \delta \) curves show approximately linear behavior in the beginning of the experiment then drop off when adhesive failure begins and the crack starts to grow. A plateau region in the R-curves is indicative of stable crack growth, and thus, provides a value for fracture energy. It is noted that the initial slopes vary from test to test. This discrepancy can be explained by the fact that the new \( a_0 \), measured after the precracking procedure, varied from specimen to specimen. The new \( a_0 \) dimensions P-\( \delta \) curves, with approximate \( a_0 \) values, for the DCB experiments is provided in Figure 10. The experimental R-curves for the DCB experiments are provided in Figure 11. Flat regions in these plots represent regions of stable crack growth during the experimental test. Only experiments that provided satisfactory regions of stable growth are presented. P-\( \delta \) curves of the ENF tests are presented in Figure 12. Experimental R-curves for the ENF experiments are provided in Figure 13. The SLB specimens were required to be precracked in the same manner as that of the DCB described previously. The resulting P-\( \delta \) curves for the SLB experiments are provided in Figure 14. The experimental R-curves for the SLB experiments are provided in Figure 15.

**Discussion of Results**

The tests results for the DCB samples demonstrate significant variability. The experimental R-curves vary from test to test and specimen preparation type. The resulting fracture energies for mode I range from about 0.4 - .75 N/mm. Considering the percent difference compared to the DCB, ENF samples are very consistent for the 180 orbit group, with acceptable stable crack
growth for each test. ENF tests deviate from this consistency as the surface finish changes with unstable crack growth becoming present in the other test groups. Considering the tests with stable crack growth, the ENF mode II 180 orbit tests yielded a fracture energy ranging about 4.70-5.50 N/mm, the 40 orbit 3.10-4.88 N/mm, 180 hand 4.00-5.63 N/mm, and 40 hand 3.96-5.81 N/mm. The same thickness adherend SLB experiments yielded results of .17-.25 N/mm and .13-.19 N/mm for the mode I and mode II components, respectively. The last SLB test yielded .6-.8 N/mm and .05-.07 N/mm for the mode I and mode II components, respectively.
Figure 10. DCB experimental $P$-$\delta$ curves for 180 orbit (a), 40 orbit (b), and 40 hand (c).
Figure 11. DCB experimental R-curves for 180 orbit (a), 40 orbit (b), and 40 hand (c).
Figure 12. ENF experimental P-δ curves for 180 orbit (a), 40 orbit (b), 180 hand (c), and 40 hand (d).
Figure 13. ENF experimental R-curves for 180 orbit (a), 40 orbit (b), 180 hand (c), and 40 hand (d).
Figure 14. SLB experimental P-\(\delta\) curves for specimens with same thickness (a) and different thickness (b) adherends
Figure 15. SLB $G_I$ and $G_{II}$ Experimental R-curves for specimens with same thickness (a, b) and different thickness (c, d) adherends.
CHAPTER 3: SURFACE CHARACTERIZATION

Understanding the failure modes of the fracture surfaces is important when considering how these modes effect the overall fracture toughness. Kim, Yun [1] discussed that the presence of cohesive failure is associated with higher joint strength. The transitioning of the adhesive from interfacial to cohesive failure is associated with higher strength and toughness because the adhesive material generally has a higher strength and toughness value. The goal of this section is to provide a quantitative evaluation of the samples fracture surfaces and how the cohesive and interfacial failures, and the air voids, impact the respective mode I and II fracture energies.

The fracture surfaces of the tested samples were studied following the completion of the experimental testing. Pictures of the interface fracture surfaces were taken of each sample side. An accompanying ruler in the image provides scaling. Lighting was arranged such that it maximized visual contrast between the metal and adhesive regions on the samples. The software ImageJ was used to crop an approximately 15mm wide X 25.4mm tall rectangular image from the upper and lower sides of each sample. The rectangular box starts at the initial delamination length line and extends into the sample 15mm.

The ImageJ software was used to threshold each 15mm X 25.4mm image to separate the metal and adhesive regions. The thresholding process allows the image to be filtered by color, brightness, and saturation level. Prior to thresholding the image, tuning the brightness and contrast provides an image where the differences in the adhesive and metal are maximized. A tool in ImageJ called “Particle Analysis” is then used to quantify the resulting area of the threshold image. The result is a black and white, or red and white, image. These black and red shaded regions in the images represent the area of the adhesive remaining on the metal. ImageJ is then used to calculate the approximate area of these shaded regions.

The individual images are combined to create an overlay of the upper and lower adhesive regions. The purpose of this study is to reconstruct the metal/adhesive regions and ascertain the failure mechanism (adhesive or cohesive) at the interface and determine void quantity and respective area(s). By using the thresholding and particle analysis methods again, the overlay images provide the total area, area where cohesive failure occurred, and area where adhesive failure occurred. These terms, along with void area, will be referred to in this study as the interface parameters. The overlay image white areas are void, grey and light red, adhesive, and dark red cohesive regions. Figure 18-Figure 24 provides the overlay images for the DCB and
Figure 16. DCB 15 upper and lower fracture surfaces

Figure 17. DCB 15 Upper (a) and Lower (b) Threshold Images
Figure 18. DCB Overlay Images for 180 Orbit
Figure 19. DCB Overlay Images for 40 Orbit
Figure 19 Continued

Figure 20. DCB Overlay Images for 40 Hand
Figure 20 Continued
ENF test samples according to individual specimen identification. Table 1 and Table 2 details the interface parameters for the DCB and ENF overlay images, respectively. Figure 25 plots the adhesive and cohesive values for each surface preparation group. The voids are discussed in detail in the following Section.

**Void Quantification**

The void content in the adhesive clearly varies. Chester [23] found that a contributing factor to the presence of voids, and the degree to which they exist, can be due to bonding area, surface treatment, assembly pressure, adhesive flow, and entrapped air. Another contribution, found when comparing steel to aluminum adherends, is that the presence of moisture proves to be of consequence during the curing process in the particular case of aluminum metals. The moisture is naturally absorbed from the atmosphere into the aluminum during material storage. The voids are created when the water vapor is expelled from the material during the curing process and disturbs the adhesive bond line. This, along with the factors described above, contribute to the overall void content in the adhesive.

Table 1 and Table 2 presents the total void area in each overlay image. To have a better understanding of how voids manifest at the interface according to surface preparation method, this section details work to determine total number, average area, and maximum void size according to surface preparation method.

By using the thresholding and particle analysis process in ImageJ described in the previous section for each overlay image, an image is generated representing the void area along with a table detailing the total number and area of the particles in the threshold image. An example void area image is presented in Figure 26.

The total number of voids (x-axis), average area of voids (y-axis), and largest void size (circle diameter), for DCB, ENF, and the combined voids, organized by preparation method, is plotted in Figure 27 and Figure 28. The total void area, organized by preparation method, for DCB, ENF, and combined is provided in Figure 29 and Figure 30. The horizontal bars in Figure 29 and Figure 30 is the average for the respective group.
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Figure 21. ENF Overlay Images for Group 180 orbit
Figure 22. ENF Overlay Images for 40 orbit
Figure 22 Continued
Figure 23. ENF Overlay Images for 180 hand
Figure 23 Continued
Figure 24. ENF Overlay Images for 40 hand
Table 2. ENF Fracture Surface Characterization

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Figure 25. Total adhesive and cohesive failures for DCB, (a) and (b), and ENF, (c) and (d) with horizontal bars for the mean.
Figure 25 Continued
Figure 26. DCB02 void area image (right) created from the overlay image (left)

Figure 27. The total number of voids (x-axis), average area of voids (y-axis), and largest void size (circle diameter), for DCB (a) and ENF (b) samples
Figure 27 Continued

Figure 28. The total number of voids (x-axis), average area of voids (y-axis), and largest void size (circle diameter), for combined ENF and DCB samples.
Figure 29. The total void area for DCB (a) and ENF (b) samples with horizontal bars for the mean.
Figure 30. The total void area for combined ENF and DCB samples with horizontal bars for the mean.
Void, Cohesion, and Adhesion for Overlay Partitions

The surface characterization described above provides a complete overview of the condition of the fracture surfaces of the ENF and DCB specimens with regard to the interface parameters. It is clear that a correlation between the voids, adhesive zones, cohesive zones, and the fracture energy values is needed. This is especially true of the DCB tests, where scattered experimental data was observed.

The R-curves generated from the experimental data are compared to the DCB and ENF overlay pictures. Partitions of the images are extracted that correspond to regions of the R-curve where stable crack growth is present. Stable crack growth is indicated at plateau regions of the R-curve. Multiple partitions are taken along the R-curves who have varying values of fracture energy with stable crack growth. Figure 31 depicts the methodology for extracting the partitions from the overlay images. ImageJ is used to extract the interface parameter information. Table 3 and Table 4 provide the numerical results of the interface parameters and corresponding fracture energy for each of the DCB and ENF partition images, respectively.

Correlating $G$ to Interface Parameters

XLSTAT is used to perform nonlinear regression analysis on the interface parameters gathered from the partition images provided in Table 3 and Table 4 and the respective fracture energy from the R-curves. Equations 22-24 describe the relationship between the mode I fracture energy and interface parameters for 180 orbit, 40 orbit, and 40 hand, respectively. Equation 21 describes the mathematical relationship between adhesive, cohesive, and void areas. Cohesive area is substituted for Equation 21 in Equations 22-24. Figure 32 shows the predicted (calculated) $G_I$ value from Equations 22-24 plotted against the actual measured $G$ from the experimental R-curves.

\[ \text{Coh} \% = 100\% - \text{Ad} \% - \text{Void} \% \]  \hfill (21)

\[ G_{I,1} = \quad .001971594 \times \text{Ad}(\%)^2 + .00476506 \times \text{Ad}(\%) \times \text{Void}(\%) + .380906 \times \text{Ad}(\%) + .00340289 \times \text{Void}(\%)^2 + .481006 \times \text{Void}(\%) + 19.0053 \]  \hfill (22)

\[ G_{I,2} = .002798715 \times \text{Ad}(\%)^2 - .00050985 \times \text{Ad}(\%) \times \text{Void}(\%) + .3346265 \times \text{Ad}(\%) + .000675802 \times \text{Void}(\%)^2 + .001244 \times \text{Void}(\%) + 10.60705 \]  \hfill (23)

\[ G_{I,4} = -.0008589313 \times \text{Ad}(\%)^2 - .001620344 \times \text{Ad}(\%) \times \text{Void}(\%) + .1330344 \times \text{Ad}(\%) - .000676162 \times \text{Void}(\%)^2 + .1160344 \times \text{Void}(\%) - 4.40172 \]  \hfill (24)
Figure 31. Corresponding overlay pictures with the R-curve

Table 3. Summary of DCB partitions

<table>
<thead>
<tr>
<th>Preparation</th>
<th>DCB #</th>
<th>Adhesive (%)</th>
<th>Cohesive (%)</th>
<th>Void (%)</th>
<th>G (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 Orbit</td>
<td>4_1</td>
<td>57.82</td>
<td>15.81</td>
<td>27.09</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>4-2</td>
<td>46.73</td>
<td>19.09</td>
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<tr>
<td></td>
<td>4-3</td>
<td>49.53</td>
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<td>35.51</td>
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<tr>
<td></td>
<td>5_1</td>
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<td>10.26</td>
<td>21.37</td>
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<tr>
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<td>62.77</td>
<td>9.24</td>
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<td>15.21</td>
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<td>ENF #</td>
<td>Adhesive (%)</td>
<td>Cohesive (%)</td>
<td>Void (%)</td>
<td>G (N/mm)</td>
</tr>
<tr>
<td>-------------</td>
<td>-------</td>
<td>--------------</td>
<td>--------------</td>
<td>----------</td>
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<td>68.20</td>
<td>19.79</td>
<td>12.81</td>
<td>5.13</td>
</tr>
</tbody>
</table>
Figure 32. Actual values of $G_1$ plotted against predicted $G_1$ for Equations 22 (a), 23 (b), and 24 (c).
Equations 25-28 describe the relationship between the mode II fracture energy and interface parameters for 180 orbit, 40 orbit, 180 hand, and 40 hand, respectively with Equation 21 being substituted for the cohesive percentage. Figure 33 provides the predicted (calculated) value plotted against the actual measured $G_{II}$ from the experimental R-curves.

$$G_{II,1} = 0.01 \times \text{Adhesive} \% - 0.047 \times \text{Void} \% + 4.6$$  \hspace{1cm} (25)

$$G_{II,2} = 0.00791468 \times \text{Adhesive} \%^2 + 0.0048665 \times \text{Adhesive} \% \times \text{Void} \%$$

$$- 1.12665 \times \text{Adhesive} \% + 0.002113219 \times \text{Void} \%^2 - 0.42665 \times \text{Void} \% + 44.3325$$  \hspace{1cm} (26)

$$G_{II,3} = -0.076 \times \text{Adhesive} \% - 0.301 \times \text{Void} \% + 12.8$$  \hspace{1cm} (27)

$$G_{II,4} = -0.0217 \times \text{Adhesive} \% - 0.0891 \times \text{Void} \% + 7.85$$  \hspace{1cm} (28)

Figure 34 and Figure 35 plots Equations 22-28 in 2-dimensional space. The void percentage is shown on the x-axis, adhesive percentage on the y-axis, and the contour color represents the respective fracture energies. The diagonal dashed lines represent the cohesive percentages. Only the ranges observed in the experimental tests are included in the graphs. Ranges represent the limitations on the validity of Equations 22-28 and are constrained by the ranges of the analyzed sample data from which the equations were generated from.

**Correlating G to Surface Roughness**

The amount of surface area is an influential parameter when considering the mode I fracture energy [29]. Given that a change in surface roughness equates to an overall change in available area for the adhesive to be bonded to, a relationship between roughness and surface area is needed. If the surface roughness profile is idealized as a series of simple right triangles, it becomes straightforward to relate the surface roughness values, Ra and Rz, to the triangles. The height of the triangle is defined by Rz, the width by Ra, and the length of the hypotenuse represents the bonding surface of the adhesive/adherend interface.

The average values of the surface roughness measurements are provided in Table 5. The resulting hypotenuse length for the 180 orbit case is calculated to be 9.60. The hypotenuse value for the 40 orbit is 19.12. If leaving the Ra value the same as the 180 orbit case (1.16), the resulting hypotenuse length for 40 orbit is calculated to be 18.99. The resulting .7% shows the Ra has little effect on the hypotenuse length. As a result, the Ra surface roughness parameter is left out of consideration. The average mode I fracture energy values are compared to the
Figure 33. Actual values of $G_{II}$ plotted against predicted $G_{II}$ for Equations 25 (a), 26 (b), 27 (c), and 28 (d)
Figure 34. Equations 22 (a), 23 (b), and 24 (c) plotted in 2D space with void percent on the x-axis, adhesive % on the y-axis, cohesive % on the diagonal, and fracture energy shown in contour band.
Figure 35. Equations 25 (a), 26 (b), 27 (c), and 28 (d) plotted in 2D space with void percent on the x-axis, adhesive % on the y-axis, cohesive % on the diagonal, and mode II fracture energy shown in contour band
Table 5. Average Ra, Rz, and G by preparation group

<table>
<thead>
<tr>
<th>Group</th>
<th>Ra (μm), Average</th>
<th>Rz (μm), Average</th>
<th>G_{1} (N/mm), Average</th>
<th>G_{u} (N/mm), Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 Orbit</td>
<td>1.16</td>
<td>9.53</td>
<td>.48</td>
<td>4.88</td>
</tr>
<tr>
<td>40 Orbit</td>
<td>2.52</td>
<td>18.95</td>
<td>.53</td>
<td>3.64</td>
</tr>
<tr>
<td>180 Hand</td>
<td>.99</td>
<td>7.82</td>
<td>---</td>
<td>4.98</td>
</tr>
<tr>
<td>40 Hand</td>
<td>1.59</td>
<td>13.11</td>
<td>.52</td>
<td>5.15</td>
</tr>
</tbody>
</table>
respective average Rz values in Figure 36. The data indicates that as Rz roughness increases, $G_I$ increases. The equation for the curve fit is

$$G_I = 0.530393 - \frac{(0.0697192)}{1 + \left(\frac{Rz}{10.80232}\right)^{7.575512}}$$  \hspace{1cm} (29)$$

The mode II fracture toughness is compared to the Ra and Rz values. The compressive nature of the ENF experimental test introduces consideration of the surface interaction between the top and bottom adherends. The interaction between the top and bottom adherends creates mechanical interlocking between the peaks and valleys of the adherends [29]. The contributions of the mechanical interlocking on the overall mode II fracture energy are driven by the angle of the hypotenuse of the right triangle described previously. The steeper the slope, Rz/Ra, of the hypotenuse the more interlocking effect this will have. Figure 37 provides the relationship between the slope and average fracture energy for mode II. The equation for the curve fit is

$$G_{II} = 3.718673 \left(\frac{Rz}{Ra}\right)^3 - 92.36668 \left(\frac{Rz}{Ra}\right)^2 + 764.5017 \left(\frac{Rz}{Ra}\right) - 2103.435$$  \hspace{1cm} (30)$$
Figure 36. Average Rz roughness compared to average mode I fracture toughness

Figure 37. Slope (Rz/Ra) of roughness compared to average mode II fracture toughness
CHAPTER 4: NUMERICAL STUDY

Having the ability to predict adhesive performance via numerical simulation is a powerful tool for engineers to assess joint loading and limitations. The ability to predict maximum force that may be carried by a bondline is helpful information to proper design of an adhesive joint. This chapter will present a representative numerical model of the single leg bend test. The equations developed, relating surface finish and fracture energy, are used to calculate the respective energy values with respect to the measured surface finished. The numerical P-δ results will be plotted with the experimental results.

A numerical model of the SLB test is created in Abaqus® finite element software. Implementation of the adhesive layers were simulated using a potential-based cohesive zone model (PPR model) developed based on fracture mechanics. The PPR model provides the ability to control the softening shape of the traction-separation curves and receives as input, in part, the mode I and II fracture energies individually. This model has been shown to accurately simulate mixed-mode fracture failure and represents an alternative approach compared to the standard cohesive element in the Abaqus® library. This PPR model was implemented as a user-defined element (UEL) in Abaqus®. More information on this PPR UEL can be found at [36]. The finite element model used 2D 8-node, reduced integration plane stress elements for the adherends and the previously discussed UEL for the adhesive layer. The finite element model is shown in Figure 38.

Comparison of Experimental and Numerical Results

Load magnitude and load point displacement are measured during the numerical simulation. These are plotted in Figure 39, in addition to the experimental results. Values of .48 and 4.88 N/mm are used for Mode I and II, respectively. These values represent the averages of the 180 orbit mode I and mode II, respectively, calculated from the partitioning analysis described in a previous Section.

The equations developed relating the surface roughness to the fracture energies are used to study how these parameters impact the force-displacement results of the numerical model. As a basis for input, a normal distribution of 3 standard deviations is established for each set of Ra and Rz measurements provided in a previous Section. Confidence intervals of 97% and 50% are chosen that bound the roughness values. These values, along with the mean, are used to perform numerical simulations on each surface preparation group. An example of the normal distributions
Figure 38. Finite element model of the SLB

Figure 39. Comparison of experimental and finite element model for the SLB test
for the 180 orbit preparation is provided in Figure 40. The resulting roughness values, used as the input to the numerical simulations, are provided in Table 6. The results of the numerical simulations are provided in Figure 41. The results are broken up according to the initial slope of the curve, corresponding to the difference in the initial delamination length of the samples. Overall, the simulations do a good job of bounding the observed experimental results, although the simulation results in Figure 41 (a) provide a lesser conservative prediction of the force. This is observed by the fact that the maximum force measured during the test corresponds to the lower end of the predicted force in the simulation. The maximum and minimum values predicted from the simulation are 447 N and 413 N, respectively. The experimental test peaked at a maximum of 415 N. Because of the ranges of surface roughness values possible, as is shown in the measured data and the respective normal distributions, it is unknown where the experimental sample in this case falls in that regard. On the other hand, (b) provides a reasonable approximation of the as-measured peak forces. The experimentally determined values are 467 N and 440 N and the simulated results 472 N and 447 N. These simulations provide an approach for calculating the maximum and minimum expected forces in a mixed-mode adhesively bonded sample. This information is crucial for engineers to properly design a bonded joint using the surface preparation techniques to inform the numerical simulations.
Figure 40. Normal distributions of surface roughness Ra (a) and Rz (b) for 180 orbit

Table 6. Surface Roughness and Resulting Fracture Energies for Specified Confidence Intervals

<table>
<thead>
<tr>
<th>Preparation</th>
<th>Conf. Int.</th>
<th>Ra (μm)</th>
<th>Rz (μm)</th>
<th>G\textsubscript{i} (N/mm)</th>
<th>G\textsubscript{II} (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 Orbit</td>
<td>Mean</td>
<td>1.16</td>
<td>9.53</td>
<td>.480</td>
<td>5.098</td>
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<td>99.7 (-)</td>
<td>0.61</td>
<td>2.90</td>
<td>0.461</td>
<td>3.000</td>
</tr>
<tr>
<td></td>
<td>99.7 (+)</td>
<td>1.71</td>
<td>16.16</td>
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<td>5.100</td>
</tr>
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</tr>
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</tr>
<tr>
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<td>9.62</td>
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<td>5.067</td>
</tr>
</tbody>
</table>
Figure 41. Load-displacement results of the numerical simulations
CHAPTER 5: CONCLUSION

The goal of this study was to characterize a ductile epoxy bonded to aluminum substrates using interface surfaces of varying preparation quality. Experimental tests were used to determine the interfacial mode I, II, and mixed-mode (I+II) fracture energies of the aluminum and epoxy. The surfaces of these samples were prepared in a way that provided four unique interface surfaces, both by machine and manual methods. The surface roughness values were measured using a roughness instrument and provided in this report.

Following the experimental tests, the interface parameters, cohesive and adhesive failure, and void, were calculated from the fracture surface of the samples. From this information, fundamental equations were developed relating these interface parameters to the fracture energy of the tests. Further, the surface roughness values measured were compared to the average fracture energies measured from the experimental tests. Trends were observed between the fracture energy and resulting roughness and equations were developed to represent these trends.

Using Abaqus finite element software, a representative numerical model of the single leg bend test was developed. Using the average mode I and II fracture energies from the experimental tests, the mixed mode model showed excellent agreement with the observed load-displacement data. This numerical model was used to study the influence of the surface roughness values on the overall adhesive performance. By using normal distributions of 3 standard deviations, the surface roughness values used in the simulation represented the mean, 50% and 99.7% confidence for the overall roughness values measured in this report. The results of the numerical simulation provided reasonable approximations compared to the results of the experimental tests.
REFERENCES


VITA

Kurt Smith grew up in Knoxville, Tennessee. He attended Tennessee Technological University in Cookeville, TN, where he obtained a Bachelor of Science in Mechanical Engineering in 2012. Since graduating with his bachelor’s degree, Kurt worked for 5 years at the National Aeronautics and Space Administration in Cape Canaveral, FL as a ground systems design engineer. Currently, he is employed full-time by the Oak Ridge National Laboratory as an irradiation design engineer, where he began completing his master’s degree part-time. He plans to graduate from the University of Tennessee with a Master of Science in Mechanical Engineering in May of 2021.