Adhesively Bonded Joints with Non-Flat Interfaces

A THESIS PRESENTED

BY

Shih-Hung Chiu

TO

DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING

IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

NORTHEASTERN UNIVERSITY

BOSTON, MASSACHUSETTS

April 2011
Abstract

Adhesive bonding is used in many structural applications such as aircraft and aerospace industries due to its low-weight and fatigue-resistance and capability to attach dissimilar materials. One shortcoming of using adhesively bonded joints is that in most cases the bonded joint is the ‘weakest link’ of the structure and has inferior strength compared to other components, thus, limiting the overall load carrying capacity of the structural system. In this study, we examined the strength, energy absorption and failure of bonded joints with non-flat interfaces. Single lap bonded joints with different zig-zag shaped (dented) interfaces were fabricated and their response under uniaxial tension was compared with the response of a single lap joint with traditional flat interface. In the experiments, the yield stress, ultimate tensile stress, maximum elongation and energy absorption were obtained and compared in the different types of bonded joint. It was shown that these structural properties vary greatly by changing the topology of the adhesive-adherent interface, promising unique potential applications for each of the configurations studied. In the next step, we carried out a parametric finite element study to investigate the role of several geometrical parameters such as dent height, width, angle and also the adhesive Young’s modulus on the distribution of pealing and shearing stresses in the bonded joints. The results were linked to the experimental observations. Also in this study,
the crack shielding phenomena in the different types of joints was studied using finite element calculations and related to qualitative experimental observations.
Acknowledgement

First, I express my deep appreciation to Professor Ashkan Vaziri, my thesis advisor, for his kindness, guidance, and unlimited encouragement during this thesis. Throughout these two years, he taught me how to find hidden secrets in the nature and the methods to discover them. Moreover, he always shows me a very inspired way to approach the research problem and achieve those tasks. I am so glad to be a member in his team and accomplish this research project with him. I also want to thank Professor Hamid Nayeb-Hashemi for his advice and valuable suggestions for my research. I would not be able to complete this work without their help.

Beside of my advisor, I would like to give credit to Professor Vaziri’s lab members, Babak Haghpanah and Amin Ajdari. They helped me out a lot in my research and shared useful knowledge with me. I would like to express my sincere appreciation to Jonathan Doughty, a great machinist in NEU machine shop. During the time which I manufacture the specimens, he gave me so many advise for operating the machine tools. Truly thanks for the support from everyone in Northeastern University.

Also, I thank my family, my dad, mom, and little brother, for giving me a chance to pursue my master degree in the USA. They give me unconditional support
and encouragements through my life. I can’t find a word to say my appreciation. I love my family.
Table of Contents

Chapter 1 INTRODUCTION

1.1 Application in Adhesive Bonding Technology ............................................................ 10
1.2 Literature Review ....................................................................................................... 11
1.2.a Biomimetics of Nacre ................................................................................................. 11
1.2.b Adhesive Bonding Joints ............................................................................................ 13
1.3 Objective .................................................................................................................... 16
1.4 References ................................................................................................................. 19

Chapter 2 BRITTLE AND DUCTILE FRACTURE

2.1 Ductile Fracture ......................................................................................................... 26
2.2 Brittle Fracture ........................................................................................................... 30
2.3 Types of Brittle Fracture ............................................................................................ 31
2.4 Reference ................................................................................................................... 34

Chapter 3 EXPERIMENTAL INVESTIGATION

3.1 Specimen preparation ............................................................................................... 36
3.2 Procedure of Mechanical Testing .............................................................................. 38
3.3 Material test for ECCOBOND G 909 ........................................................................... 39
3.4 Discussion of Experimental Result ............................................................................. 42

Chapter 4 FINITE ELEMENT METHOD SIMULATION

4.1 ABAQUS Model Setup .............................................................................................. 47
4.2 The Effect of Geometry Factor $A/h$ to the Interface of Bonding ............................... 50
4.3 The Effect of Geometry Factor $B/L$ to the Interface of Bonding ............................... 52
4.4 The Effect of Dent’s Width and Height to the Maximum Shear and Peeling Stresses of Adhesive ........................................................................................................... 54
4.5 The Effect of Starting Angle $\theta$ to the Interface of Bonding ........................................ 55
4.6 The Effect of Normalized Crack Length $c/L$ ............................................................. 56
4.7 Result of Finite Element Analysis Simulation ............................................................. 57
List of Figures

Figure 1 (A) Structure of the nacre at nanoscale. (B) Transmission electron micrograph (TEM) of nacre from red abalone showing tablet waviness. TEM micrograph shows the thin interfaces between the tablets. Both asperities (upper) and direct connections (lower) were found across the interfaces. (C) Multi-material joint configuration developed by BAE systems for ship and aerospace structures...... 17

Figure 2 Schematic of the three different types of adhesive bonded joints .................. 17

Figure 3 Stress-strain curves for brittle and ductile materials.................................. 26

Figure 4 (A) Schematic of ductile fracture. (B) Schematic of moderately ductile fracture. (C) Schematic of brittle fracture................................................................. 28

Figure 5 (A) Transgranular fracture. (B) Intergranular fracture. (C) Schematic of fracture cracks pass through the grains (D) Schematic of fracture crack propagation along the grains. ......................................................................................... 33

Figure 6 (A) Adherents for model I. (B) Adherents for model II. (C) Adherents for model III. .................................................................................................................. 38

Figure 7 (A) Tensile test performed by INSTRON5582 (B) Zoom-in picture of specimen on the INSTRON. ......................................................................................... 39

Figure 8 (A) Setup for the uniaxial tensile test on the bar of pure cured adhesive material. (B) Specimen consisting of two metal bars aligned longitudinally and bonded by the adhesive material. (C) The fracture surface of the bar showing the flat fracture surface perpendicular to the axial direction........................................... 41

Figure 9 (A) Schematic of the adhesive bonded joint. (B) Specimens for different geometry ratio $A/h =0.5$, 0, -0.5. (C) Force versus elongation for different geometry ratio $A/h =0.5$, 0, -0.5. (D) Deformation process of the adhesive during experiment. The images of the adhesive’s deformation on stage (I), (II), (III), (IV) corespond with (C).................................................................. 44

Figure 10 Energy absorption versus elongation for different geometry ratio $A/h=0.5$, 0(flat), -0.5. ................................................................................................................ 45
Figure 11(A) V.Mises stress distribution over the adhesive bonded joint. (B) Peeling stress distribution through the adhesive bonding. (C) Share stress distribution through the adhesive bonding.

Figure 12 (A) Normalized maximum shear stress at adhesive versus normalized overlap length for geometry ratio $A/h = 0.5, 0, -0.5$ for two different ratio of Young’s modulus $E/E_s = 10^{-2}, 4 \times 10^{-3}$. (B) Normalized maximum peel stress at adhesive versus normalized overlap length for geometry ratio $A/h = 0.5, 0, -0.5$ for two different ratio of Young’s modulus $E/E_s = 10^{-2}, 4 \times 10^{-3}$. 

Figure 13 (A) Normalized maximum shear stress at adhesive versus geometry ratio $A/h$ for two different normalized Young’s modulus $E/E_s = 10^{-2}, 4 \times 10^{-3}$. (B) Normalized maximum peel stress at adhesive versus geometry ratio $A/h$ for two different normalized Young’s modulus $E/E_s = 10^{-2}, 4 \times 10^{-3}$. Solid line indicates that the maximum shear and peel stress was collected from the whole overlap length $L$. Dash line indicates that the maximum shear and peel stress was collected from region III.

Figure 14 (A) Normalized maximum shear stress at adhesive versus normalized overlap length for geometry ratio $B/L = 0, 0.25, 0.5, 0.75, 1$. (B) Normalized maximum peel stress at adhesive versus normalized overlap length for geometry ratio $B/L = 0, 0.25, 0.5, 0.75, 1$.

Figure 15 (A) Normalized maximum shear stress at adhesive versus geometry ratio $A/h$ for different geometry ratio $B/L = 0, 0.25, 0.5, 0.75, 1$. (B) Normalized maximum peel stress at adhesive versus geometry ratio $A/h$ for geometry ratio $B/L = 0, 0.25, 0.5, 0.75, 1$.

Figure 16 Normalized maximum shear and peel stress at adhesive versus the starting angle $\theta$ for different geometry ratio $B/L = 0, 0.25, 0.5, 0.75, 1$.

Figure 17 (A) Schematic of crack in the adhesive bonded joint. (B) Normalized maximum shear stress at adhesive versus normalized crack length $c/L$. (C) Normalized maximum peel stress at adhesive versus normalized crack length $c/L$. 
Chapter 1
Introduction
Chapter 1. Introduction

1.1 Application in Adhesive Bonding Technology

Adhesive bonding is widely used in structural applications. This technique provides several benefits such as low-weight, fatigue-resistance and it is extensively used in the bonding of dissimilar materials without being welded. The commonly used adhesive types are cyanoacrylate, two part epoxy, and polyvinyl acetate (PVA). Cyanoacrylates are used to assemble prototype electronics, flying model aircraft, and as retention dressings for nuts and bolts. Epoxy is used in electrical systems and electronics, consumer and marine applications, and aerospace applications. PVA are used as adhesives for porous materials, particularly for wood, paper, and cloth, and as a consolidation for porous building stone, in particular sandstone. Investigating the strength, fatigue life, and the cracks growth in adhesively bonded joints with different shapes and under various loading conditions is a common research issue.

The interfacial strength of multi-component materials and structures generally plays a key role in the overall behavior and function of the system. An interesting example is the hierarchical structure of the mother-of-pearl, also known as nacre, which is the iridescent material that forms the inner layer of seashells in gastropods and bivalves. The nacre structure is mostly made of microscopic ceramic tablets
densely packed and bonded together by a thin layer of biopolymer. The tablets are found to have wavy surfaces with the smallest features at the nanoscale: the surface of tablets is fashioned with nanoasperities, which are aragonite grains with crystallographic orientation normal to the plane of the tablets. Although mostly nacre was made of a brittle ceramic, its toughness is much higher than the original ceramic property because of its structure [1].

1.2 Literature Review

a) Biomimetics of Nacre

Nacre is a highly mineralized and stiff material, and it is 1000 times tougher than its original mineral constituent [2]. For that reason, it is valuable to study the mechanisms behind the remarkable performance of nacre to apply those secrets into artificial or biomimetic structures [3]. Many remarkable studies on the experimental determination of mechanical properties of nacre have been investigated.

Currey [4] in 1977 presented the first measurements based on precise experiments. Values of tensile strength, compressive strength, bending strength and modulus of elasticity were established for a number of species. The stress–strain
curve of nacre in tension was given by Currey[4]. In 1988, the mechanical properties
of nacre, Pintada umbricata, were obtained by Jackson [5]. The Young’s modulus of
nacre is about 70 GPa and a tensile strength of nacre is about 170 GPa. They also
reported a work of fracture of 350~1240 J/m$^2$.

The mechanisms of columnar nacre from red abalone have been well studied.
Song F et al. studied the structural and mechanical properties of the interfaces in nacre
to investigate a strengthening mechanism arising from the mineral bridges in the
organic matrix layers of nacre [6]. It was shown that the main mechanism governing
the strength of the organic matrix layers of nacre relies on the mineral bridges rather
than the organic matrix [6]. In 2007, Barthelat studied the wavy shaped tablets of
nacre that allowed sliding of the tablet and resulted in the strain hardening for nacre
[7]. The wavy tablets also postpone the localization and propagate the sliding
mechanism in the whole structure [7]. In 2007, Barthelat and Espinosa conducted
explicit uniaxial tension test and fracture experiments on nacre specimens. The full
crack resistance curve was also established for nacre. When the specimens were in
hydrated condition, they observed the large inelastic deformations explained by
sliding of the tablets on one another and progressive locking generated by their
micro-scale waviness [8].
b) Adhesive Bonding Joints

In the past few decades, many studies have focused on investigating the mode I and II crack propagation in order to estimate the life cycle of adhesive bonding joints. Fracture behavior of adhesive bonded joints under pure mode I has been profoundly studied by several authors [9~12]. In the case of mode II loading, there are several standard tests as the following: the End Notched Flexure (ENF), the End Loaded Split (ELS) and the Four-Point End Notched Flexure (4ENF). The ELS test involves a clamp which is a source of variability and increases the complexity of data reduction [13]. Moura [14] presented a deduction method for measuring the critical fracture energy of adhesive joints under pure mode II loading using the End Notched Flexure test.

Yang presented a general modeling approach to quantitatively predict the mode II fracture in adhesive joints [18]. Wahab [19] proposed a generalized numerical approach by using finite element (FE) analysis for the prediction of the fatigue lifetime in adhesively bonded joints. Kafkalidis [20] used both the numerical and experimental methods to investigate the relationship between the geometry and material fracture behavior on single lap-shear joints of adhesively bonded joints. Qin [21] developed a simple model for cracked adhesively bonded joints with arbitrary orthotropic laminated adherents. Erpolat [22] proposed an improved method incorporating a ‘cycle mix’ factor for predicting the fatigue life of bonded joints under the variable amplitude fatigue. Kaya [23] investigated the effects of various dynamic characteristics in the adhesively bonded joints under the dynamic forces by using the finite element method.

Keller [24] investigated the effect of changing the overlap length, adhesive layer thickness and adherent thickness on the stress-strain distribution and failure modes of adhesively bonded joints. This was done by experiments and numerical methods of pultruded GFRP flat sections under quasi-static axial tensile loading. Till Vallée [25] developed a method to predict the strength of adhesively bonded single and double
lap joints from pultruded GFRP composite adherents under the quasi-static axial
tensile loading based on a quadratic through-thickness shear–tensile interaction failure
criterion. Xie [26] presented a fracture criterion for kinking cracks in a tri-material
adhesively bonded joint under mixed mode loading. Cheng [27] analyzed adhesively
bonded single-strap joint integrated with shape memory alloy (SMA) reinforced
layers. Hogberg [28] investigated the different configurations of specimen under the
mixed mode loading.

Shenoy [29] experimentally measured the strength degradation of single lap
joints during fatigue cycling. Leffler [30] developed an experimental method based on
the end-notch flexure specimen to present the complete stress versus deformation
relationship for a thin adhesive layer under the shearing loading. Moura [31]
developed a numerical study based on the equivalent crack concept on the end
notched flexure wood specimen in order to avoid the most common difficulties in
monitoring crack propagation.

Pirondi [32] investigated the mixed mode I and mode II fatigue crack growth in
adhesive bonded joints by the fractographic analysis. Marannano [33] presented the
numerical, analytical, and experimental approaches to feature the energy release rate
in an aluminum–epoxy joint under mixed mode I/II. TerMaath [34] presented a
method based on superposition and dislocation theory for studying brittle fracture in an infinite plate containing interacting cracks of complex shape subjected to the general loading conditions. Nolting [35] investigated the influence of the variable amplitude loading on the fatigue life and failure mode of adhesively bonded double strap (DS) joints. In 1999, Kwon [36] investigated the correlation between the amount of artificial defects in bonded region and the acousto-ultrasonic parameters (AUPs). Wang presented a fracture model for fatigue crack propagation of a cracked metallic member reinforced with a composite patch based on the concept of material element fracture in front of a crack tip [37].

1.3 Objective

Inspired by the structure of nacre, we studied the role of surface topology on the behavior and strength of bonded joints. Bonded joints with different morphologies including zig-zag surfaces were fabricated and their uniaxial behavior was measured under uniaxial tension. Extensive finite element modeling was also carried out to study the distributions of stresses and strains and quantify the role of surface topology on the strength of the bonded joints.
Figure 1 (A) Structure of the nacre at nanoscale. (B) Transmission electron micrograph (TEM) of nacre from red abalone showing tablet waviness. TEM micrograph shows the thin interfaces between the tablets. Both asperities (upper) and direct connections (lower) were found across the interfaces. (C) Multi-material joint configuration developed by BAE systems for ship and aerospace structures.

In this study, we considered a pair of zig-zag shape adherents bonded with a thin layer of ECCOBOND G909 Epoxy Adhesive. By changing the geometry of the interface of adhesive, three types of specimen, schematically shown in the Figure 2, were produced and tensile tests were done to obtain the mechanical response of the each specimen.

![Schematic of the three different types of adhesive bonded joints.](image)

We verified our findings by modeling each specimen using finite element method and compared the data from FEA to our experimental results. In the next step,
by using the FEA software ABAQUS we investigated the role of several parameters such as the height of the dent, the width of the dent, the Young’s modulus and the area of adhesive on the distribution of shear and peal stresses in the adhesive which are important factors in predicting the adhesive failure in adhesively bonded joints.
1.4 References


Chapter 2
Brittle and Ductile Fracture
2.1 Ductile Fracture

Fracture can be denoted as a single body being divided into several pieces by an imposed stress at temperatures below the melting point. For solid materials there are two modes of fracture, ductile and brittle. In general, the major difference between ductile and brittle fracture can be attributed to the amount of plastic deformation that the material undergoes before fracture occurs. Ductile materials display large amounts of plastic deformation while brittle materials show little or no plastic deformation before fracture. A tensile stress-strain curve, shown in Figure 3, represents the degree of plastic deformation exhibited by both brittle and ductile materials before fracture.

![Stress-strain curves for brittle and ductile materials](Figure 3 Stress-strain curves for brittle and ductile materials)

Crack initiation and propagation are necessary to fracture. The manner
through which the crack propagates through the material gives great insight into the
mode of fracture. For ductile fracture, the crack spreads slowly and is accompanied by
a large amount of plastic deformation. The crack will usually not extend unless an
increased stress is applied. On the other hand, in dealing with brittle fracture, cracks
propagate very rapidly without or little plastic deformation. The cracks that propagate
in a brittle material won’t stop to grow and increase in magnitude once they are
initiated. Another important mannerism of crack propagation is the way in which the
advancing crack travels through the material. A crack that passes through the grains
within the material is undergoing transgranular fracture. However, a crack that
propagates along the grain boundaries is termed an intergranular fracture.

On both macroscopic and microscopic levels, ductile fracture surfaces have
distinct features. Macroscopically, ductile fracture surfaces have larger necking
regions and an overall rougher appearance than a brittle fracture surface. Figure 4
shows the macroscopic differences between two ductile specimens (A, B) and the
brittle specimen (C). On the microscopic level, ductile fracture surfaces also appear
rough and irregular. The surface consists of many microvoids and dimples.
The failure of many ductile materials can be attributed to cup and cone fracture. This form of ductile fracture occurs in stages that initiate after necking begins. First, small microvoids form in the interior of the material. Next, deformation continues and the microvoids enlarge to form a crack. The crack continues to grow and it spreads laterally towards the edges of the specimen. Finally, crack propagation is rapid along a surface that makes about a 45 degree angle with the tensile stress axis.
The new fracture surface has a very irregular appearance. The final shearing of the specimen produces a cup type shape on one fracture surface and a cone shape on the adjacent connecting fracture surface, hence the name, cup and cone fracture.

In most design situations a material that demonstrates ductile fracture is usually preferred for several reasons. First, brittle fracture occurs very rapidly without any warning. Ductile materials plastically deform, thereby slowing the process of fracture and giving people some time to fix the problem. Secondly, more strain energy is required to cause ductile fracture because of the plastic deformation. Next, ductile material’s toughness can allowed a mistake in the mechanical structure. In another way, the properties of a ductile material can be enhanced through the use of one of the strengthening mechanisms. Strain hardening is a very good demonstration, as the ductile material is deformed more and more its strength and hardness increase because of the generation of more and more dislocations. Therefore, in engineering applications, especially those that have safety concerns involved, ductile materials are the obvious choice. Safety and dependability are the main concerns in material design, but in order to attain these goals there has to be a thorough understanding of fracture, both brittle and ductile. Studying fracture and failure of materials will lead the mechanical engineers to develop safer and more reliable devices [1].
2.2 Brittle Fracture

Basically, brittle fracture is that a rapidly crack growth break through a stressed material. The growths of cracks usually expand so fast before sight noticing when the material is going to break. In another word, there is not so much plastic deformation before failure happens. In most of structures, this is the worst type of fracture because it is hard to repair visible damage in a part or structure before the break occurs. The cracks run close to perpendicular to the applied stress in brittle fracture. This perpendicular fracture leaves a comparatively flat surface at the break. Besides having a nearly flat fracture surface, brittle materials usually have a pattern on the fracture surfaces. Some brittle materials have lines and ridges beginning at the origin of the crack and spreading out across the crack surface. Other materials, like steels have back to back V-shaped markings pointing to the origin of the crack. These V-shaped markings are called chevrons. Very hard or fine grained materials have no special pattern on their fracture surface, and amorphous materials like ceramic glass have shiny smooth fracture surfaces.

A brittle material breaks without significant deformation (strain) when it subjected to stress. Brittle materials have relatively little energy absorption prior to
fracture, even those of high strength. You will hear a snapping sound when it breaks. Brittle materials include most ceramics, glasses (which do not deform plastically) and some polymers (such as PMMA and polystyrene). Many steels become brittle when it meets low working temperatures, depending on their composition and processing. When used in materials science, it is generally applied to materials that fail in tension rather than shear, or when there is little or no evidence of plastic deformation before failure. When a material has reached the limit of its strength, it usually has the option of either deformation or fracture.

2.3 Types of Brittle Fracture

The first category of fracture is transgranular, and this type of fracture travels through the grain of the material. The fracture changes direction from grain to grain due to the different lattice orientation of atoms in each grain. The crack have to find a new path or plane of atoms to travel on when it reaches a new grain because it is easier to change direction for the crack than it is to rip through. Cracks always choose the path of least resistance. It’s easier to see it when a crack has changed in direction through the material, because there is a slightly bumpy crack surface on the subject.
The second category of fracture is intergranular fracture. Intergranular fracture is the crack traveling along the grain boundaries, and not through the actual grains. Intergranular fracture usually happens when the phase in the grain boundary is weak and brittle. An intergranular fracture is a fracture that follows the grains of the material. If the material has multiple lattice organizations, when one lattice ends and another begins, the fracture changes direction to follow the new grain. This results in a fairly jagged looking fracture with bumpy edges. Intergranular fractures are cracks that take place along the grain boundary of a material. Straight edges of the grain and shiny surface may be seen. There are several processes that can lead to intergranular fracture. Figure 5 show the difference between the transgranular fracture and intergranular fracture [2].
Figure 5 (A) Transgranular fracture. (B) Intergranular fracture. (C) Schematic of fracture cracks pass through the grains (D) Schematic of fracture crack propagation along the grains.
2.4 Reference


Chapter 3
Experimental Investigation
3.1 Specimen Preparation

First, we transferred the geometry of the zig-zag interface into several parameters such as the height of dent over the total width of adherent ($A/h$), the total width of dent over the total overlap length of adhesive ($B/L$), the starting angle of interface between the adhesive and adherent ($\theta$). In the experiment, we chose the geometry ratios $A/h=0.5$, $A/h=0$ (flat), $A/h=-0.5$ to performed in the test. The geometry ratios $B/L=0.5$ were used for all specimens. Schematic of the adhesive bonded joint was shown in Figure 9A.

The adhesive in the experiments was using Emerson & Cuming TM ECCOBOND G 909 Very High Strength, One Component Epoxy Adhesive, designed for metal assemblies such as copper and aluminum. The ECCOBOND G909 adhesive is a one component adhesive (no mixture required), with high strength, non sag, isotropic, excellent peel strength, and high tensile shear strength over a broad temperature range. The working temperature range for this adhesive is $-40^\circ$C - $150^\circ$C. The thickness of adhesive layer was constant and equal to 1mm in all specimens.

The adherents in all specimens were manufactured from low carbon 1018 steel bars with the length, width and thickness of 120, 15 and 3 mm, respectively. The adherents
were joined together in a single lap configuration. The total length of the specimen was 200 mm and the overlap length of adhesive bonded joints was 40 mm. Adhesive was applied to all contact surfaces of the adherent components to obtain a good quality bonding. The contaminations on the contact surface of the components were removed by alcohol to obtain properly clean specimen during the curing process. The two adherent components were then bonded together using a small jig to create a better alignment. The jigs also provided proper contact pressure along the overlap during the curing process. The specimens were placed in oven for 20 minutes at 150°C to accelerate the curing process. They were then exposed to the room temperature for 2 to 4 hours as the post curing process. After the heat curing, the unwanted residual adhesive on the specimen was removed by grinding. Sample pictures of the obtained joints are shown in the Figure 9B four specimens of each category were tested in tension. The manufacturing time for specimens was around 5 working days per 10 bars.
3.2 Procedure of Mechanical Testing

The uniaxial tensile tests were performed by using INSTRON 5582. The force, F and the elongation were measured with a load cell located between the actuator grips. Unit of force is Newton (N), and unit of displacement is millimeter (mm). The applied displacement rate is 1mm per minute to simulate the static loading. In order to prevent the extra bending moment occur in the specimens, the specimens need to be place in the middle of the jig. The experimental setup was shown in Figure 7.
3.3 Material Test for ECCOBOND G 909

In general, engineering materials break by two main fracture mechanisms: ductile and brittle fracture. In ductile fracture, usually occurring in materials with relatively high toughness, large amounts of plastic deformation occurs before fracture while brittle materials show little or no plastic deformation before fracture.
In brittle materials, fracture can occur by cleavage as the result of tensile stress acting normal to crack plane. This perpendicular fracture leaves a relatively flat surface at the breakage. Besides having a nearly flat fracture surface, brittle materials typically contain a pattern (lines and ridges) of on their fracture surface beginning at the origin of the crack and spreading out across the crack surface.

To determine the fracture mechanism in the adhesive-metal joint, we first subjected a bar of pure cured adhesive material as shown in figure 8A. The cured adhesive bar was obtained by a 5-hour curing process at 80° C. And then, we also manufactured a specimen consisting of two metal bars aligned longitudinally and bonded by the adhesive material as shown in figure 8B. Both two types of specimens were tested under the uniaxial tension until the failure occurred in the specimen. This specimen was obtained by a 20 minutes curing process at 150° C. We use those two types of specimens to represent the material property of pure adhesive and the material property between the adhesive and adherent. The fracture surfaces of both bars are flat, showing the sudden crack growth at the cross section. There are no sign of microvoids, cup-cone shape, shear lips with no overall rough appearance associated with the ductile fracture surface,
demonstrating the brittle fracture characteristics of the cured adhesive material.

The fracture surfaces from both specimens were shown in figure 8C.

Figure 8 (A) Setup for the uniaxial tensile test on the bar of pure cured adhesive material. (B) Specimen consisting of two metal bars aligned longitudinally and bonded by the adhesive material. (C) The fracture surface of the bar showing the flat fracture surface perpendicular to the axial direction.
3.4 Discussion of Experimental Result

In Figure 9C, the applied force versus elongation of the specimens is shown. The three models completely differ in the mechanical response. For specimen type II, the first drop in the curve indicates the initial crack development at the interface between the adhesive and adherent. The crack was initiated from the region II, as shown in the Figure 9D. In stage (2), the crack is growing both in the forward and backward directions. At stage (3), the initial right and left crack reach and connect to each other followed by the total specimen breakage.

In specimen type III (i.e. the specimen with $A / h = -0.5$), at stage (2) of loading as shown on the loading curve the initial crack is developed in the region III of specimen. This causes the first drop in the associated force displacement curve. After the two cracks reach the dents tips, the growth of the cracks are halted and no crack growth is observed for a relatively large period of loading (i.e. between stages 2 and 3). The large end displacement observed at this period are associated with the opening of crack sides as seen in Figures 9D stages (3) and (4) accompanied by the necking of the fully plastic cross-section over the dent tips. At stage (4), after an elongation almost twice the maximum elongation of the specimen type II, the cracks from both right and left sides of the specimen III meet in the mid section of the
specimen followed by the specimen breakage in the stage (4).

We also calculate the energy absorption for three different specimens. In the Figure 10, this is the energy absorption versus elongation for different geometry ratio $\frac{A}{h}=0.5$, 0(flat), -0.5. Before the elongation reach to 1.4 mm, the specimens with $\frac{A}{h} = 0.5$ have better energy absorption compared to the specimens with $\frac{A}{h} = 0.5$ and 0. But in the end, the specimens $\frac{A}{h} = -0.5$ has the energy absorption almost 2 times larger than the other specimens.
Figure 9  (A) Schematic of the adhesive bonded joint. (B) Specimens for different geometry ratio $A / h = 0.5, 0, -0.5$. (C) Force versus elongation for different geometry ratio $A / h = 0.5, 0, -0.5$. (D) Deformation process of the adhesive during experiment. The images of the adhesive’s deformation on stage (I), (II), (III), (IV) co-respond with (C).
Figure 10 Energy absorption versus elongation for different geometry ratio $A/h=0.5$, 0(flat), -0.5.
Chapter 4
Finite Element Method Simulation
4.1 ABAQUS Model Setup

In this chapter, computational models of single lap adhesive bonding joints were developed by finite element analysis software ABAQUS. The effect of critical parameters in bonded joints such as height and width of dents and Young’s modulus of adhesive that affect the strength and behavior of the joint were investigated. In all simulations, total overlap length of the bonding $L$, total length and height of the specimen and the thickness of adhesive were kept constant. Adherents and adhesives were simulated as homogenous isotopic, linear elastic materials and no material or interface failure criterion were incorporated in the finite element analysis.

For the uniaxial tensile test simulation, the left end of modeled specimen were clamped and the right end of modeled specimens were subjected to the uniform load of $F = 10$ MPa. The adherents were modeled with the Young’s modulus and Poisson’s ratio of $E_s = 200$ GPa and $\nu_s = 0.3$, respectively, corresponding to elastic mechanical properties of steel. The adhesive was modeled with the Young’s modulus and Poisson’s ratio of $E = 2$ GPa and $\nu = 0.4$, respectively. The 4-node plane stress elements with reduced integration – and three degree of freedom at each node and quadratic shape functions – were used for meshing the computational models. Ten elements were created through the thickness of the adhesive. The mesh size of the adhesive
layer was 9 times smaller than the mesh for the adherent. The model of whole specimens was shown on the Fig 11 (A).

Approximations of stress distribution through the adhesive were obtained by finite element calculations when uniaxial tension test was performed on specimens. Specifically, the stresses along the interface between adhesive and adherent were only considered in this study. The models of adhesive were shown in Fig 11 (B).

The Stress $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{xy}$ in global coordinate (x, y) were collected through the interface of adhesives. In order to determine the share stress and peeling stress along the interface of the adhesive, the stress $\sigma_{xx}$, $\sigma_{yy}$ and $\sigma_{xy}$ in global coordinate (x, y) need to be convert to local coordinate (X, Y) at each element by the plane stress transformation theory. According to the theory of tensor of plane stress, the shear stress and peeling stress can be determined by the following equations (1~2). The $\theta_{local}$ was defined in Figure 11. All stress results were then normalized by the applied stress F = 10 MPa and presented in the non-dimensional form.

$$\sigma_{peeling} = \sigma_{xx}\sin^2\theta_{local} + \sigma_{yy}\cos^2\theta_{local} - 2\sigma_{xy}\sin\theta_{local}\cos\theta_{local}$$

(1)

$$\tau_{shear} = -(\sigma_{xx} - \sigma_{yy})\sin\theta_{local}\cos\theta_{local} + \sigma_{xy}(\cos^2\theta_{local} - \sin^2\theta_{local})$$

(2)
Figure 11(A) V.Mises stress distribution over the adhesive bonded joint. (B) Peeling stress distribution through the adhesive bonding. (C) Shear stress distribution through the adhesive bonding.
4.2 The Effect of Geometry Factor $A/h$ to the Interface of Bonding

First, we want to investigate how geometry ratios ($A/h$) affect the stress distribution on the interface of adhesive. So, we modeled the 3 different type of specimens with geometry ratios $A/h=0.5$, $A/h=0$ (flat), $A/h=-0.5$ which we used in experimental investigation. In the result, we can see the $A/h = 0.5$ has lower normalized maximum peeling stress and normalized maximum shear stress than $A/h = -0.5$. In the result of normalized maximum shear stress, the specimens with flat interface ($A/h=0$) produces the highest normalized maximum shear stress. We can see the same trend under different normalized Young’s modulus $E/E_s = 4 \times 10^{-3}$, $10^{-2}$. The results are plotted in Figure 12.

Next, we modeled the different specimens for $A/h = 0.9$, 0.7, 0.5, 0.2, 0 (flat), -0.2, -0.5, -0.7, -0.9 under the different normalized Young's modulus $E/E_s = 10^{-2}$, $4 \times 10^{-3}$. Then models of geometry ratios $A/h$ in positive zone have lower normalized maximum peeling stress than the models of geometry ratios $A/h$ in negative zone. The results of normalized maximum shear stress have the same pattern beside the $A/h = -0.2$, 0, 0.2. However, normalized maximum shear stress is very small compared to the normalized maximum peeling stress and the material property of adhesive is brittle. Therefore, we can know that the specimens are peeling stress...
dominated to the fracture. The effect of shear stress to the structure is small. We can see the same trend in different Young's modulus. The results are plotted in Figure 13.

Figure 12 (A) Normalized maximum shear stress at adhesive versus normalized overlap length for geometry ratio \( A / h = 0.5, 0, -0.5 \) for two different ratio of Young's modulus \( \frac{E}{E_s} = 10^{-2}, 4 \times 10^{-3} \). (B) Normalized maximum peel stress at adhesive versus normalized overlap length for geometry ratio \( A / h = 0.5, 0, -0.5 \) for two different ratio of Young's modulus \( \frac{E}{E_s} = 10^{-2}, 4 \times 10^{-3} \).
Figure 13 (A) Normalized maximum shear stress at adhesive versus geometry ratio $A/h$ for two different normalized Young's modulus $E/Es = 10^{-2}, 4 \times 10^{-3}$. (B) Normalized maximum peel stress at adhesive versus geometry ratio $A/h$ for two different normalized Young's modulus $E/Es = 10^{-2}, 4 \times 10^{-3}$. Solid line indicates that the maximum shear and peel stress was collected from the whole overlap length L. Dash line indicates that the maximum shear and peel stress was collected from region III.

4.3 The Effect of Geometry Factor $B/L$ to the Interface of Bonding

In this case, we are looking for the effect of geometry ratios ($B/L$) to the bond. Therefore, we compared the three different models ($A/h = 0.5, 0, -0.5$) under the different $B/L$. The Young’s modulus of the adhesive in this case is 2GPa. We can see that the normalized maximum shear stress and the normalized maximum peeling stress are always occurred in the region III when $A/h = -0.5$ (type III) and that the normalized maximum shear stress and the normalized maximum peeling stress are always occurred in the region II when $A/h = 0.5$ (type II). When $B/L$ is going to
smaller, that means that the dent is coming to be sharper and it will rise up the normalized maximum peeling stress. But the normalized maximum shear stress is in the opposite way and the flat specimens ($B / L = 0$) produce the highest normalized maximum shear stress. The specimens with $A / h = 0.5$ (type II) always has the lower normalized maximum shear stress and the lower normalized maximum peeling stress than the specimen with $A / h = -0.5$ (type III) even though the $B / L$ are different.

Figure 14 (A) Normalized maximum shear stress at adhesive versus normalized overlap length for geometry ratio $B / L = 0, 0.25, 0.5, 0.75, 1$. (B) Normalized maximum peel stress at adhesive versus normalized overlap length for geometry ratio $B / L = 0, 0.25, 0.5, 0.75, 1$. 
4.4 The Effect of Dent’s Width and Height to the Maximum Shear and Peeling Stresses of Adhesive

The geometry ratios $A / h$ and $B / L$ were both tested in this simulation by a series of models. In the result, the normalized maximum peeling stress increase when the geometry ratios $B / L$ decrease. The models which have positive $A / h$ always have the lower normalized maximum peeling stress than the models which have negative $A / h$. In the result of the normalized maximum shear stress, the stress goes up when $B / L$ increase. The result was shown in Figure 15.

Figure 15 (A) Normalized maximum shear stress at adhesive versus geometry ratio $A / h$ for different geometry ratio $B / L=0$, 0.25, 0.5, 0.75, 1. (B) Normalized maximum peel stress at adhesive versus geometry ratio $A / h$ for geometry ratio $B / L=0$, 0.25, 0.5, 0.75, 1.
4.5 The Effect of Starting Angle $\theta$ to the Interface of Bonding

In Figure 16, the maximum peeling and shear stresses versus the starting angle of specimen, $\theta$, for a series of specimens with different $B/L$ values are presented. As seen in this figure, the maximum peeling and shear stress developed in the joints with different geometry can be roughly expressed as a function of the single parameter $\theta$ as shown by the dashed lines. In this result, the models of the positive starting angle $\theta$ have the lower normalized maximum peeling stress than the models of the negative starting angle.
Figure 16 Normalized maximum shear and peel stress at adhesive versus the starting angle $\theta$ for different geometry ratio $B/L = 0, 0.25, 0.5, 0.75, 1$.

### 4.6 The Effect of Normalized Crack Length $c/L$

In the figure 10C, we can see that the crack in specimens $A/h = -0.5$ is locked from stage (2) to stage (3). This is very unusual phenomenal in fracture mechanics. In order to investigate the effect of crack shielding on the specimens, three different geometries with $A/h = -0.5, 0$ and $0.5$ were considered in a series of finite element
simulation. The effect cracks with the length $c/2$ growing along the adhesive-adherent interface in both ends of the joint was modeled by changing the adhesive-adherent contact properties of the cracked sections from tie to the frictionless contact condition in the finite element models.

Figure 17 (A) Schematic of crack in the adhesive bonded joint. (B) Normalized maximum shear stress at adhesive versus normalized crack length $c/L$. (C) Normalized maximum peel stress at adhesive versus normalized crack length $c/L$.

### 4.7 Result of Finite Element Analysis Simulation

To understand the significance of each of the aforementioned parameters on the distribution stresses inside the adhesive material, we carried out a parametric study by
systematically changing each of these parameters. At each simulation, the value of peeling stress normal to the adhesive-adherent interface and the value of shearing stress along the interface were obtained at each point. The effect of geometry ratio, $A/h$, on the shear and peeling stress distributions in the adhesive material, specimens with three different geometry factors $A/h = 0.5$, $A/h = 0$ (flat interface), and $A/h = -0.5$ were modeled using finite elements analysis. The average values of peeling and shear stresses along the thickness of adhesive material are shown in figure 13, respectively. Moreover, the contours of peeling and sheer stresses in the adhesive are shown in figure 11, respectively. According to results, the specimen with $A/h = 0.5$ demonstrates the lowest value of the maximum peeling stress along the adhesive-adherent interface and the most uniform peeling stress distribution along the interface compared to the other two geometries. The specimen with $A/h = -0.5$ corresponds to the highest value of maximum peeling stress along the interface. Considering the shear stress distribution, the specimen with $A/h$ ratio of 0, -0.5 and 0.5 correspond to the highest to lowest maximum shear stress value along the interface. According to observations that the adhesive material after curing process behaves brittle, it is rational to assume that the structure fails dominantly according to the excessive peeling stress rather than the shear stress. It is notable that the peeling stresses developed in specimen with $A/h = 0.5$ is compressive in region III
decreasing the likelihood of initiation micro-cracks at various directions in this region.

In the results presented in figure 13, we have shown the effect of the $A / h$ ratio on the maximum values of peeling stress and shear stress along the adhesive-adherent interface of joints with different ratios of Young modulus, $E / E_s$, and the total dent width, $B$, respectively. In figure 13B, we have considered both the maximum peeling stress over the entire overlap length $L$, marked by solid lines, and the maximum peeling stress in the region III, which is shown by dashed lines. The stresses in the latter region is particularly important since the stressing of the outer region of structures with the higher concentration of imperfections more likely results in the initiation of micro cracks/voids which eventually cause the failure of the joint structure. By gradually increasing the $A / h$ ratio from its initial negative value up to zero, the value of maximum peeling stress drops remarkably. In the positive range of $A / h$ values, By increasing the $A / h$ values from zero, the maximum peeling stress induced in the total of adhesive increases slightly while maximum peeling stress over region III nearly remains constant. According to the result presented in figure 16B, by increasing the geometry ratios $B / L$ the maximum peeling stress induced in the adhesive in the specimen with positive and negative $A / h$ ratio decreases.

In figure 17, the maximum peeling and shear stresses versus the starting angle of
specimen, $\theta$, for specimens with different $B/L$ values are presented. As seen in this figure, the maximum peeling and shear stress developed in the joints with different geometry can be roughly expressed as a function of the single parameter $\theta$ as shown by the dashed lines. Finally, we investigated the effect of crack growth on the maximum stresses induced in the adhesive. In this set of finite element simulation, three different geometries with $A/h = -0.5, 0$ and $0.5$ were considered. The effect cracks with the length $c/2$ growing along the adhesive-adherent interface in both ends of the joint was modeled by changing the adhesive-adherent contact properties of the cracked sections from tie to the frictionless contact condition in the finite element models. The results are shown in figures 17B and 17C for shear and peeling stresses, respectively. One evident trend in figure 17C is the huge drop in the maximum peeling stress induced in the joint with $A/h = -0.5$ after the crack size approaches the dent length (i.e. $c/B=0.5$ at $c/L = 0.25$). This explains the rapid crack growth at the initial stage (2) of specimen III that was observed in the experimental tensile test based on high developed stresses in region III while it also explains the sudden stop in the crack growth observed in this specimen after the crack reaches the tip dent.
Chapter 5
Conclusion
5.1 Conclusion

The effects of adherent-adhesive interface topology on the crack growth, energy adsorption and elongation of three geometrically different, single lap configuration, adhesively bonded joint were investigated. The joint under study consists of two zigzag shaped adherents stacked and bonded over the length of $L$ using adhesive material. The joints were subjected to uniaxial tensile loading. Three different zigzag geometries for the adherent-adhesive interface were considered and experimental and finite element analysis was performed on bonded joints.

From the experimental results, the first crack in the specimen II (i.e. the specimen with $A/h=0.5$) is developed at the nominal stress almost three time the corresponding stress in specimen type III (i.e. the specimen with $A/h=-0.5$). On the other hand, the ultimate strain and energy adsorption in the specimen III is nearly twice the elongation and energy absorption of the specimen II. The results from the finite element analysis were used for better comprehension of the experimental observations. It was shown that in type III specimen the peeling stress at region III is much higher that the corresponding stress in type I and type II specimen. The high peeling stress in region III of type III specimen leads to the premature crack initiation at this zone. However, our parametric finite element study shows that the crack size
does not increase beyond this region since the peeling stress drops as the size of crack reaches the value of $B / 4$. Finally, necking at the specimen accompanied by full plastic deformation of the cross section leads to a relatively large elongation of the specimen compared to specimen type I and II. The elevated normal stresses in the region III of specimen type III can be related to the orientation of the adherent-adhesive interface with the adhesive layer almost perpendicular to the imaginary lines of force that are being developed in the joint when it is subjected to tensile loading. The behavior of type II specimen under the uniaxial tensile loading is completely different. The crack initiation is first observed in region II of the specimen followed by the crack propagation to the entire adherent-adhesive interface. At this point the nominal stress of the specimen reaches its maximum, followed by the drop in the stress and the total failure of the structure. Moreover, it was shown in this study that the maximum peeling and shear stresses developed in the joints with different $A / h$ and $B / L$ ratios can be roughly expressed as a function of the single parameter $\theta$, starting angle of the adhesive-adherent interface of the specimen.

Two completely dissimilar and unique mechanical behaviors by mirroring the geometry pattern of the adhesive-adherent interface in two bonded joints are observed. Under the circumstances where the high strength of the structure is required,
the type II adhesive-adherent interface can be used to increase the load carrying capacity of the joint. On the other hand, the bonded joint can become more resistant to high strains before total fracture by applying the type III interface geometry. The two proposed geometries of the adhesively bonded joints are easy to manufacture due to the simple while efficient geometries.