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The Sensitivity of Composite Scarf Joints to the Height of the Blunt Tip

by

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Abstract

As advanced composites see increased use in military and commercial aircraft, there is a growing need to understand the structural behavior of these composite structures after repair. In this work, a numerical and experimental investigation was conducted to characterize the sensitivity of the behavior of the composite scarf joint, particularly with regard to failure, to changes in the height of the blunt tip, the adherend thickness, and the ratio of the two parameters, defined as the "blunt height ratio". All specimens manufactured for the experimental testing and modeled via finite element analysis were constructed from the same adherend material and adhesive material: Toray Industries T800/3900 pre-impregnated carbon fiber/epoxy composite material, and 3M™ Scotch-Weld™ Structural Adhesive Film AF 555M, respectively. In the numerical work, linear elastic plane strain analyses were performed via finite element modeling to determine the stress and strain fields for a homogeneously orthotropic configuration with moduli equivalent to a \([\pm 15]_{ns}\) configuration and for cases of \(n\) equal to 1, 3, and 5; blunt tip heights of 0, 0.6\(t_{ply}\), and \(t_{ply}\); and blunt height ratios of 0%, 5%, 8.3%, and 25%. In the experimental work, all configurations considered were tested in uniaxial tension to failure, and have adherends of a \([\pm 15]_{3S}\) laminate, which are bonded via a single layer of film adhesive with different scarf angles of 3°, 5°, and 10°, and have blunt tip heights of 1, 2, 3, and 4 plies. The results from the numerical investigation indicate that the strain fields of the scarf joint depend on the blunt height ratio, and not any individual lengthscale as the finite thickness of the joint affects the load traveling through the joint. At the corner of the blunt tip, there are large gradients of longitudinal and shear strain that dissipate along the length of the bondline and away from the blunt tip and this magnified strain at the corner is not due to any specific lengthscale, but is simply due to the existence of the corner. As the blunt height ratio increases, the size and magnitude of this gradient increases and approaches the center of the joint due to the effects of the finite thickness. The general response of the scarf joint with a blunt tip can be modeled as a hybrid of an "ideal" scarf joint, dominated by shear, and a butt joint, dominated by longitudinal strain, acting in parallel. In the experimental work, the load-displacement responses of all specimens exhibit the same general characteristics, with an initial linear region that transitions to increasingly nonlinear behavior to the point of maximum load. The maximum load-carrying capability of all test cases indicate that decreasing the blunt height ratio or the scarf angle increases the load-carrying capability of the scarf joint. In addition, variations of
the maximum load amongst specimens of the same test case and differences in the type of failure throughout the joint region are shown to relate to the cured film adhesive thickness. Recommendations for future work are presented, particularly the need to perform additional numerical and experimental work using thicker laminates with a constant blunt height ratio on the order of 1%, and with varying heights of the blunt tip in order to determine any sensitivity of the response of the scarf joint to the height of the blunt tip.

Thesis Supervisor: Professor Paul A. Lagacé
Title: Professor of Aeronautics and Astronautics and Engineering Systems
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100, hblunt

B.6

Load versus extensional strain for Specimen 3 (a

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100, hblunt

B.7

Load versus extensional strain for Specimen 1 (a

B.8

Load versus extensional strain for Specimen 2 (a = 100, hblunt

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Nomenclature

\( BH \) blunt height ratio: ratio of the height of the blunt tip to the adherend thickness

\( E_{eff} \) effective longitudinal stiffness of scarf joint in joint region

\( E_{ii} \) extensional modulus of ply in the \( i \)-direction (\( i = 1, 2, 3 \))

\( E_{L,\text{base}} \) longitudinal modulus of the “base” adherend

\( E_{L,\text{patch}} \) longitudinal modulus of the “patch” adherend

\( G_{ij} \) shear modulus of ply in the \( i-j \) plane (\( i, j = 1, 2, 3 \))

\( h_{\text{blunt}} \) height of the blunt tip of the adherend

\( L \) actual total length of specimen

\( L_{\text{adherend}} \) actual total length of an adherend in the \( x \)-direction, from the beginning of the grip tab to the blunt tip of the adherend

\( L_{\text{nominal, adherend}} \) nominal total length of an adherend in the \( x \)-direction, from the beginning of the grip tab to the blunt tip of the adherend

\( L_{\text{nominal, free}} \) nominal free length of the specimen in the \( x \)-direction, from the beginning of the grip tab to the beginning of the joint region

\( L_{\text{free}} \) actual free length of the specimen in the \( x \)-direction from the end of the grip tab to the beginning of the joint region

\( L_{\text{joint}} \) total length of the joint region in the \( x \)-direction

\( L_{\text{jointline}} \) length along the jointline between the two blunt tips
\( L_{\text{scarf}} \): length of the scarfed region of an adherend in the x-direction, from the point of the obtuse angle to the blunt tip

\( L_{\text{tab}} \): length of the grip tabs in the x-direction

\( P_{\text{linear}}^{[N]} \): value of load for intersection of load-displacement data with line offset from linear fit by N \( \mu \text{strain} \)

\( P_{\text{max}} \): maximum load value of load-displacement response of a specimen

\( R^2 \): coefficient of variation of a least-squares linear fit

\( t_{\text{nominal}} \): designed nominal thickness of the grip tabs in the z-direction

\( t_{\text{adherend}} \): thickness of adherend in the z-direction

\( t_{\text{adhesive}} \): thickness of the cured film adhesive layer of the joint

\( t_{\text{base}} \): thickness of "base" adherend in the z-direction

\( t_{\text{patch}} \): thickness of "patch" adherend in the z-direction

\( t_{\text{ply}} \): ply thickness in the z-direction

\( t_{\text{tab}} \): actual thickness of the grip tabs in the z-direction

\( u_{\text{app}} \): extensional displacement on boundary edge of model

\( w \): width of the specimen in the y-direction

\( x \): direction aligned with the 0° fiber direction along the length of the adherends and joint

\( x^m \): direction aligned with the longitudinal direction of the vertical milling machine used for scarfing

\( y \): direction along the width of the adherends and joint

\( y^m \): direction aligned with the transverse direction of the vertical milling machine used for scarfing

\( z \): direction through the thickness of the laminated adherends and the joint
$z^m$ direction aligned with the vertical direction and the rotation axis of the cutting bit of the vertical milling machine used for scarfing

$\alpha_{\text{nominal}}$ nominal scarf angle

$\alpha_{\text{scarf}}$ actual scarf angle

$\delta^{[N]}_{\text{linear}}$ value of displacement that corresponds to $P^{[N]}_{\text{linear}}$

$\delta_{\text{final}}$ value of final displacement at which a specimen is unable to continue to carry load

$\delta_{\text{max}}$ value of displacement that corresponds to $P_{\text{max}}$

$\epsilon_{ij}$ tensorial strain component ($i, j = 1, 2, 3$)

$\epsilon_{11}^{\text{avg}}$ average far-field longitudinal strain at model edge ($x$ equal to 0)

$\gamma_{13}$ engineering shear strain in 1-3 plane

$\nu_{ij}$ Poisson’s ratio of ply in the i-j plane ($i, j = 1, 2, 3$)

$\theta$ fiber direction of ply as measured positive counterclockwise from x-axis about z-axis
Chapter 1

Introduction

Advanced polymer matrix composites are seeing increased use in primary structures for military and commercial aircraft. These materials offer advantages in weight savings without sacrificing strength and mechanical performance. Consisting of fibers with high strength and high stiffness within a polymer matrix material that is less stiff and less strong, the high strength-to-weight ratio combined with high fatigue and corrosion resistance make these materials ideal in the aerospace industry [1]. One such composite is carbon fiber reinforced polymer (CFRP). This material has found prominence in the aerospace industry not only because of its strength and mechanical performance, but the relative ease that it provides to assemble complex components [1, 2].

The military has been using carbon fiber composites rather than conventional metallic materials such as aluminum and titanium alloys since the late 1960s. Bell Helicopter began using composites in the 1980s following their Advanced Composite Airframe Program (ACAP) when they were able to achieve 20% reduction in weight on metallic airframe. The V22 Osprey tilt-rotor developed by Bell utilizes an all-composite wing to meet its critical stiffness, which could only be met using composites without sacrificing weight [3]. More recently, composites are being applied in commercial aircraft as a significant portion of the structure. Composites are providing a solution to ever-increasing fuel costs and environmental lobbying to improve aircraft performance. The high strength-to-weight ratio of composites allows
companies to save weight without sacrificing mechanical performance. This translates to better fuel efficiency. The Boeing Company developed the Boeing 787 Dreamliner where 50% of the weight of the structure is fabricated from carbon fiber composite. The aircraft has a take-off weight of about 550,000 pounds carrying 290 passengers and a fully loaded range of over 8,000 miles [2]. However, despite all of the benefits, composite structures will see damage in use and repairs will thus be necessary. As the use of composite material increases, it is important that the structural behavior of composite structures after repair is well understood.

In response to damage in composite structures, the current solution is a structural joint, which can be produced in any number of ways. The typical methodology is the removal of a damaged portion and then applying new material over the region that was damaged, thus forming a structural joint. A joint can be adhesively bonded, mechanically fastened, or a hybrid of the two [4,5]. A mechanical joint, typically used in the repair of metal structures, involves the drilling and bolting of new material onto the parent surface. These joints offer the advantage of being easy to implement, inspect, and require no special surface preparation [4]. And while the stress concentrations at a bolt or bearing make the behavior predictable in alloy structures, this can cause complications in composite structures.

Drilling holes into composite structures requires special care to avoid causing significant degradation of the laminate. If performed poorly, not only do issues such as delamination or cracking arise from drilling, but also the poor bearing properties of composites can lead to fatigue vulnerabilities at stress concentrations in the joint [4]. An alternative is the adhesive joint. Unlike mechanical joints, the adhesive joint offers the advantage of uniformly distributing stress in the joint and provides relatively low stress concentrations in the adherends. However, in order to ensure a strong and reliable bond, high quality control and surface preparation is required when manufacturing adhesive joints. Additionally, the nature of the joint makes it very difficult to inspect, as it cannot be disassembled [4].

There are several different types of adhesive joints: lap joints, strap joints, stepped-lap joints, and scarf joints [5]. The single version of these joints is illustrated in Figure 1.1. The
two main types of adhesive joint configurations in use for composites applications are the lap joint and the scarf joint. The single lap joint is the simplest adhesive joint. However, while simple to create, the joint leads to significant stress concentrations in the adhesive layers at the ends of the joint region. These stress concentrations can be alleviated by a scarf joint configuration [6–8].

The scarf joint offers the advantage of maintaining the original surface profile after repair. This can be an important consideration for aerodynamic structures. Put simply, the adhesive scarf joint is manufactured by bonding two scarfed surfaces together with adhesive. The geometry of the scarf joint is therefore of particular interest. The scarfed surfaces allow the structure to maintain its original surface profile after bonding. However, this requires that parent material be removed for scarfing. The geometry of the joint is a large factor in determining the amount of material to be removed [9]. This large removal of material can be a disadvantage as it sets limitations on the structure and effects where a scarf joint can be implemented.

Aside from the amount of material to be removed, there are a number of geometric and material parameters that drive the overall geometry of the adhesive scarf joint and its structural behavior. Several key properties are the angle at which the adherends are scarfed before bonding, the laminate layup, and type of adhesive material. Another important factor is the tip of the scarfed region. An ideal scarf joint consists of a “feather edge” with a thickness of zero. However, this is a mathematical idealization that cannot be physically manufactured and controlled. In reality, any manufactured joint will have some degree of tip bluntness. The effects of such parameters and others have been studied previously using finite element modeling techniques and limited experimental work in order to assess sensitivities of the structural response in two-dimensional (2D) scarf joints. This previous work is discussed in Chapter 2.

The current work builds upon the results of such work in investigating influences on the structural response of scarf joints via experimental and further numerical analysis. The emphasis is on examining the influence of the height of the blunt tip on the structural
response of the scarf joint. A summary of past work studying scarf joints is presented in Chapter 2. The objective of the current work and the approach used to examine the response of the adhesive scarf joint to geometric parameters is presented in Chapter 3. Details of the development of the finite element models used to study the scarf joint response are given in Chapter 4. The results of the finite element study are given in Chapter 5. The experimental procedure is described in Chapter 6. Also, included in Chapter 6 is the specimen geometry, the experimental setup in manufacturing the specimen, and the means by which the tensile tests were accomplished. The experimental test results are presented in Chapter 7. A discussion of all the results, both the experimental and the finite element analysis, is given in Chapter 8. Conclusions and recommendations are given in Chapter 9.
Figure 1.1  Illustration of four types of adhesive joints: (a) a single-lap joint; (b) a single-strap joint; (c) a stepped-lap joint; and (d) a scarf joint.
Chapter 2

Previous Work

A review of existing literature regarding research on scarf joints is presented in this chapter. The background and context for this work is first set by examining research associated with the general characteristics and behavior of composite scarf joints. Numerical and analytical techniques as well as experimental investigations are examined. Research that establishes the general characteristics and behavior of scarf joints is considered and discussed. Lastly, the limitations in that current knowledge base is identified.

In order to isolate scarf joints for characterization, a two-dimensional or "effective" two-dimensional joint is often used. A reference two-dimensional scarf joint region is shown in Figure 2.1 with key geometric variables identified. These include the thickness of the adherends, $t_{\text{adherend}}$, the thickness of the adhesive layer, $t_{\text{adhesive}}$, the scarf angle of the adherends, $\alpha_{\text{scarf}}$, and the height of the blunt adherend tip, $h_{\text{blunt}}$. A numerical analysis performed by Gunnion and Herszberg showed that the two-dimensional scarf joint exhibits adhesive stress distributions that are identical in form to those found in a “slice” or cross-section of a corresponding section in-line with the loading direction of a three-dimensional joint [9]. However, the magnitudes of the strains between the two cases differed due to load by-pass considerations. It has been shown numerically and experimentally that the two-dimensional joint underpredicts the strength performance compared to the three-dimensional joint by 20% to 40% due to these effects [9, 10]. In a numerical study, a two-dimensional
joint configuration is straightforward to develop. Alternatively, experimental studies can approximate a two-dimensional joint by utilizing a constant cross-section across a specimen of finite width, ensuring the width is large enough that edge effects do not constitute a significant portion of the response. It is assumed that there are no gradients in response across the width of the specimen [11].

There have been several investigations, via several different models, of the sensitivities of scarf joint response, under tensile loading, to scarf joint parameters. Numerical and analytical models have shown that the stresses and strains are nonuniform throughout the joint, with magnitudes of the strain in the adhesive region being higher than in the adherends due to the lower modulus of the adhesive [9,12–15]. The through-thickness stiffness distribution of the adherend depends on the laminate configuration. Specifically, plies with the fiber direction in the loading direction have a higher stiffness. This stiffness in the loading direction determines the amount of load carried by the individual plies and transferred locally to the adhesive which is of lower stiffness [16]. Thus, the adhesive region close to stiffer plies experiences a higher load transfer causing a nonuniform strain distribution in the adhesive layer [9,12–14]. Consequently, stress concentrations arise in the adhesive at points adjacent to ply interfaces due to ply-by-ply stiffness mismatches in the adherend [17,18]. However, by reducing the ply-by-ply stiffness mismatch in the adherends, the magnitude of the stress concentrations in the adhesive region can be reduced.

In some previous work, finite element models used averaged, or “smeared”, properties to model adherends with no ply-by-ply stiffness mismatch. In these models, the stiffness properties of the individual plies were averaged, resulting in a “smeared”; longitudinal and transverse modulus, effectively creating a homogenized adherend. For scarf joint adherends with homogenized stiffness properties through the thickness of the material, previous work shows local stress concentrations near the acute tips of both adherends in the joint [10, 13, 15, 16]. Alternatively, the strains in the adhesive layer approach zero near the obtuse angle of each adherend in the joint, indicating little load transfer through the joint at these locations. [13,15]. These stress concentrations near the acute adherend tips cause the overall
Figure 2.1 Illustration of the joint region of a two-dimensional scarf joint specimen with key geometry identified.
joint response to be very sensitive to small changes in the geometry of the acute adherend tips [12, 15].

Overall, the strain fields in a two-dimensional scarf joint configuration, as described by Adil, is influenced by a combination of global/macroscopic features and local features [15]. The global/macroscopic effects are illustrated via the effective through-thickness stiffness of the configuration in the joint region, $E_{eff}$, and equilibrium along the bondline. Joint features such as the scarf angle, adhesive thickness, and laminate configuration have been seen to have a global effect on the response of the scarf joint. The local effects are seen at the ends of the joint region at the tips of the adherend, and through ply-by-ply stiffness mismatch within the adherend [15].

Various studies have examined the structural response of the scarf joint to perturbations in these global and local features. One of these is a parametric study of composite scarf joints performed by Gunnion and Herszberg where the stress distribution along the adhesive bondline is investigated [9]. This study shows the dependence of peak values to perturbations in scarf angle, adhesive thickness, ply thickness, laminate thickness, laminate configuration, and “over-laminates”. These “over-laminates” are formed from bonding additional plies, so-called “overlay-plies”, over the scarf joint at the acute tips of the adherend and extending onto both the base adherend and patch adherend. The overlay plies support load transfer at the acute tips by providing an additional path for load travel, thus causing a reduction in peak stresses near the acute tip. Results from this study indicate a strong sensitivity to the scarf angle. In an ideal scarf joint with a blunt tip height of zero, the scarf angle and laminate thickness determine the overall length of a scarf joint bondline since this length is equal to the laminate thickness, divided by the sine of the scarf angle. A decrease in scarf angle, while the laminate thickness remains constant, causes an increase in the length of the bondline of the scarf joint. Consequently, the “effective” length over which the load can be transferred from the adherend to the adhesive is increased. This causes a decrease in the average stresses. Studies investigating scarf angles ranging from 2° to 15° found that an increase in the scarf angle results in an increase in both the peel stress, the stress normal to
the plane of the bond, and the shear stresses within the joint [9,12,15,18]. After mapping the strain fields in the joint, Adil found that the magnitudes of strains increase with increasing scarf angle due to equilibrium considerations during load transfer. This variation in strain is described as a macroscopic effect due to the varying scarf angle, which is a global feature [15].

Compared to the relation to the scarf angle, the stress and strain distributions in the scarf joint is less sensitive to changes in the film adhesive thickness [9,15,17]. Overall findings from the parametric study performed by Gunnion and Herszberg indicate little sensitivity to the average stresses along the bondline due to the stacking sequence, laminate thickness, adhesive thickness, and mismatched stiffness of the adherends [9]. Similarly, Adil shows that the magnitudes of strains show relatively little sensitivity to variations in the value of adhesive thickness. He concludes that changes in the magnitudes of strains are comparable to the variation in the “effective” cross-sectional stiffness of the joint region [15]. This stiffness of the joint, which Adil describes as a macroscopic feature, depends on the thickness ratio of the adhesive to the adherends. Thus, Adil did find that as the adhesive thickness increases, the magnitudes of strains at the midline of the adhesive in the joint are reduced compared to those at the bondline [15].

After establishing the general characteristics and behavior of the “ideal” scarf joint, research continued to explore the effects of a nonideal joint. As described in Chapter 1, the “ideal” scarf joint consisting of acute tips with infinitely sharp “feather edge” geometry is a mathematical idealization that cannot be physically manufactured and controlled. In reality, the microstructure of long-fiber composite materials causes fiber breakage to occur during machining. This results in some finite degree of tip bluntness. Numerical and experimental work has examined the effects of these acute adherend tips with a finite blunt tip [12, 13, 19]. The parametric finite element study performed by Jeffrey concluded that the tip bluntness has a significant impact on the response of the joint locally near the blunt tip region. Away from the blunt tip region, the response is unaffected and is the same as the “ideal” configuration. But, the region that is affected by the blunt tip increases with increasing the height of the blunt tip [13].
In an early analytical and experimental study on the ultimate strength of scarf joints, Adkins tested scarf joints with different scarf angles under tensile loading [12]. It was found that cases with lower angles had the highest total strength values although only 64% of the original adherend strength could be restored without the use of overlay plies. Later confirmed in other studies (e.g. [20,21]), Adkins found that increasing the scarf angle beyond 2° to 3° showed a monotonic decrease in ultimate strength of the joint. During this work, Adkins found that the ultimate strength predicted from the stresses calculated in the analytical model did not align with the experimental results. Closer investigation of this discrepancy revealed that the acute tips of the scarfed adherends that Adkins had attempted to manufacture as feather edges with no bluntness at the tip, exhibited a blunt tip. The tips of the adherends broke off at a thickness of five fibers during machining, resulting in a blunt tip height of 0.0016 inches. The blunt tips with a small scarf angle resulted in an observed experimental ultimate strength of the joint that is 20% to 50% less than those predicted using results from the analytical model. A modified analytical model accounting for the geometry of the blunt tip height was then developed. The stress concentrations calculated in this model could then be used to predict the strength of scarf joints. These predicted strengths aligned with the experimental strength data well for all scarf angles examined. Adkins concluded that the blunt tip was the primary cause in the reduction of ultimate strength for the experimental specimens. A failure analysis was conducted for a set of specimens with a blunt tip, from which Adkins noted that the specimens consistently failed first on one side of the joint, where the adherend tip was blunted [12].

A number of experimental studies have observed the mode of failure of scarf joints. They each agree that under tensile loading, joints with smaller scarf angles show a different failure mode than joints with larger scarf angles [12,20,21]. For scarf angles of 2° to 3° and less, the failure mode occurred in both the adherend and the adhesive, representing a mixed cohesive and interlaminar/intralaminar failure. Failure began at the adherend tips and traveled through the thickness of the joint, traveling through the adhesive and adherend. The fracture surface in the adherend showed fiber pull-out and fiber fracture, as well as
delamination. Fracture in the adhesive mainly showed the adhesive separating from itself. Alternatively, for scarf joints having scarf angles greater than 2° to 3°, the failure mode was mainly only in the adhesive. Failure initiated at the edges of the joint and propagated towards the center of the joint through the adhesive with the adhesive separating from itself.

Following these experimental studies, numerical models were developed in an effort to predict failure in scarf joints [19–21]. A study performed by Kumar et al., following experimental testing, used the results of finite element analysis as a method of determining joint failure. In this work, ABAQUS finite element analysis (FEA) was carried out by modeling the composite laminate as a homogenous orthotropic continuum with linear elastic behavior. The uniaxial tensile stress-strain response of the adhesive used was that of an elastic-plastic solid perfectly bonded to the laminate [20]. A three-dimensional failure criterion proposed by Hashin [22] and Lee [23] was used as a subroutine in ABAQUS to account for the onset of damage in the composite laminate. The simulated stress-strain response for scarf joints with angles ranging from 0.5° to 5.0° showed that the failure load decreased with increasing scarf angle. This involved a progressive failure model that focused on the adhesive via an increment in overall displacement. Engineering strain and associated stress was found using the applied displacement for each increment over the original gauge length with the elastic-plastic behavior of the adhesive layer applied.

An experimental and numerical study performed by Camphil et al examined the behavior of adhesively-bonded carbon-epoxy scarf repairs, using scarf angles ranging from 2° to 45°. The objective of this work was to propose a suitable numerical model to simulate the tensile behavior of CFRP scarf joints. In order to account for the ductile behavior of the adhesive used, a cohesive mixed-mode damage model was implemented between interfacing finite elements. In order to replicate numerically the experimental failure paths, the cohesive laws of the adhesive layer, composite interlaminar and composite intralaminar (i.e., in the transverse and fibre direction) in pure modes I and II, were determined using double cantilever beam and end notched flexure tests, using an inverse method. This method consisted of using these two tests to obtain the fracture toughness of the adhesive in pure mode I.
and II and then estimating the remaining parameters of the pure mode laws by a fitting iterative procedure between the numerical and experimental load-displacement curves. An elastic stress analysis was performed to identify critical regions of damage onset and the model performance was evaluated comparing numerical and experimental results, in terms of repair initial stiffness, maximum load and corresponding displacement, and failure mode. Generally, this comparison showed a good agreement between numerical and experimental results [21]. It should be noted that neither of these studies considered effects due to a finite blunt tip in the experimental or numerical analysis (i.e. [20,21]).

Studies have noted the reduction in ultimate strength of the joint resulting from the blunt tips is more significant for joints with smaller scarf angles [12,19]. Adkins and Pipes show that scarf joints with small scarf angles are especially sensitive to stiffness mismatch between the adherends and to adherend tip bluntness. They attribute this effect to the increased stress concentrations at the ends of the joints for decreasing scarf angle. These stress concentrations are associated with boundary layers in the solutions to the equations modeling the adhesive stresses. Analysis performed by Adkins and Pipes modeled the adhesive using shear/tension spring equations and the adherends as laminates of elastic orthotropic layers. Large adhesive stresses occur in the boundary layers and they become larger as the scarf angles are reduced [19].

In summary, a significant number of studies performed have advanced the general understanding of scarf joint behavior and loading response. Parametric studies using numerical modeling techniques generally investigate the stress and strain distributions around the joint region. They further show that the typical scarf joint configuration results in higher strains within the adhesive region compared to the adherend due to the lower stiffness of the adhesive. These studies also found that peak and average peel and shear stress and strain values are more sensitive to variations in the scarf angle and height of the blunt tip. Experimental studies have focused on the ultimate strength and postmortem failure characteristics of the scarf joint. These studies examined the relation between the scarf angle and blunt tip height to the ultimate strength and failure mode of the joint. Current models developed
for comparison to experimental work show a correlation between the scarf angle and the structural response. Specifically, increasing the scarf angle causes a decrease in the ultimate strength of the joint [12,19-21]. These models further showed that variations in the blunt tip influence the structural response of the scarf joint, particularly for small values of scarf angle (i.e. scarf angles less than 3°) with stress concentrations increasing around the acute blunt tips of the adherend. However, most of the existing experimental work often fails to document the achieved blunt tip height and less work has attempted to control the height of the blunt tip to examine the sensitivity of the response to variations in the blunt tip. Thus, there is a need to fully characterize the development of this feature and its effect on the overall response of a scarf joint.
Chapter 3

Objectives and Approach

The primary objective of this work is to investigate the influence of the height of the blunt tip on the response of a scarf joint. This builds on previous work to investigate the response due to the specific joint parameters associated with the blunt tip in order to understand the influences of various factors on the mechanical response of composite scarf joints. In order to achieve the primary objective of this work, a number of items must be addressed. This includes the design of a scarf joint test specimen and establishing controlled manufacturing and characterization techniques in order to ensure consistency and repeatability throughout the manufacturing process. A discussion of the approach pursued, including the specifics considered during this investigation in order to achieve this primary objective and associated items, is presented.

3.1 Approach Details and Parameters Considered

The approach of this work involves two different methods. The first method is an experimental study using tensile tests to failure in order to examine the influence of the height of the blunt tip on the overall response, and particularly the ultimate tensile strength, of the scarf joint configuration. The second is a numerical study using the finite element method to examine the stress and strain response of a scarf joint as geometric parameters
are varied.

Previous finite element work modeled two-dimensional specimens to investigate the mechanical response and load transfer mechanisms of composite scarf joints in relation to various geometric and material parameters [13, 15]. The mechanical response is defined to be the stress and strain fields occurring in the joint when subjected to a uniform extensional displacement. The primary objective of this work, investigating the influence of the height of the blunt tip on the response of the scarf joint, can be achieved by investigating a two-dimensional idealization of the scarf joint. This will provide a fundamental understanding of the influence of various parameters on the joint response that can then be extended to study three-dimensional configurations. The two-dimensional composite scarf joint geometry considered in this study is presented in Section 3.2.

In this work, finite element analysis and experimental tests are used to examine the effects of the height of the blunt tip on the response of a scarf joint. In order to examine the influence of the blunt tip, three parameters are varied in this work: the scarf angle, \( \alpha \), the adherend thickness, \( t_{\text{adherend}} \), and the blunt tip height, \( h_{\text{blunt}} \). These parameters are identified in the joint geometry illustrated in Figure 2.1.

For ease of comparison of results among test cases, all specimens manufactured for the experimental testing and modeled via finite element analysis are constructed from the same adherend and adhesive materials. The material for the adherends is Toray Industries T800/3900 pre-impregnated carbon fiber/epoxy composite material. The nominal ply properties of this material are listed in Table 3.1. The nominal properties of a composite used to model adherends in previous studies are also shown in this table, T700/2510. The adhesive material for bonding the scarfed adherends is 3M™ Scotch-Weld™ Structural Adhesive Film AF 555M. The idealized shear stress versus engineering shear strain behavior of this material is shown in Figure 3.1. The data is also shown in this figure for a common film adhesive used in previous studies, the Cytec FM300-2K film adhesive [13, 15]. Both adhesive materials have an initial linear region up to a specific point called the “linear limit”. This is followed for both adhesives by a second linear region with a reduced tangent shear modulus.
At the end of this second region, there is a defined “knee point” at a shear stress between 6000 psi and 7000 psi for both adhesives. Beyond this, there is a third linear region for both adhesives with a significantly reduced tangent shear modulus. This continues to the ultimate shear stress of each adhesive. Specific values for the shear stress and engineering shear strains according to the data sheet for each material as well as the tangent moduli for each region are presented in Table 3.2 [24,25].

The scarf joint parameters varied in the experimental part of this study are the blunt tip height and the scarf angle. The adherend thickness and laminate configuration remain constant for all cases. All adherends are a \([\pm 15]_{3S}\) laminate of T800/3900 plies, bonded via a single layer of AF 555M film adhesive. This laminate configuration is used because it exhibits no ply-to-ply variation in longitudinal stiffness, and therefore more closely approximates the behavior of the “homogenized” adherends used in previous numerical work [13]. In this previous work, the adherend is modeled as an orthotropic material with the averaged, or “smeared”, properties of a laminate in order to decouple some of the microscopic and macroscopic effects within the joint as discussed in Chapter 2. This simplification removes the stress-strain variations associated with changes in stiffness properties through the adherend thickness on a ply-to-ply level [13].

In order to relate results from this experimental work to results from previous finite element work, the basic joint response is initially established using a baseline case. The baseline joint geometry consists of a scarf angle of 10°, a blunt tip height equal to 0.0074 inches, which is equivalent to one cured nominal ply thickness, and a cured adhesive thickness of 0.0035 inches (nominal for this material) for the experimental work. All test cases examined in this study are compared with this reference baseline specimen.

Each parameter is varied individually in order to examine their individual effects on overall behavior and ultimate strength. For the experimental work, variations from the baseline case were chosen in order to be large enough to cause sufficient change in the response while also considering manufacturing tolerances. Three different scarf angles are chosen in order to study a first order sensitivity. The baseline value of 10°, as well as values of 3° and
Table 3.1  Ply properties of T800/3900 Carbon/Epoxy and T700/2510 Carbon/Epoxy

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T800/3900</td>
</tr>
<tr>
<td>$E_{11}$</td>
<td>20.6 Msi</td>
</tr>
<tr>
<td>$E_{22}$</td>
<td>1.13 Msi</td>
</tr>
<tr>
<td>$E_{33}$</td>
<td>1.13 Msi</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>0.580 Msi</td>
</tr>
<tr>
<td>$G_{13}$</td>
<td>0.580 Msi</td>
</tr>
<tr>
<td>$G_{23}$</td>
<td>0.370 Msi</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.340</td>
</tr>
<tr>
<td>$\nu_{13}$</td>
<td>0.340</td>
</tr>
<tr>
<td>$\nu_{23}$</td>
<td>0.530</td>
</tr>
<tr>
<td>Longitudinal Tensile Strength</td>
<td>379 ksi</td>
</tr>
<tr>
<td>Longitudinal Compressive Strength</td>
<td>229 ksi</td>
</tr>
<tr>
<td>Transverse Tensile Strength</td>
<td>8.29 ksi</td>
</tr>
<tr>
<td>Longitudinal Shear Strength</td>
<td>13.1 ksi</td>
</tr>
<tr>
<td>$t_{ply}$</td>
<td>0.0074 in</td>
</tr>
</tbody>
</table>
Figure 3.1  Shear Stress vs. Shear Strain for 3M™ Scotch-Weld™ Structural Adhesive Film AF 555M and Cytec FM300-2K film adhesives
Table 3.2  Key values in shear stress vs. shear strain behavior of 3M™ Scotch-Weld™ AF 555M and Cytec FM300-2K film adhesives

<table>
<thead>
<tr>
<th>Property</th>
<th>AF 555M</th>
<th>FM-3002K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Modulus – Region 1</td>
<td>63 ksi</td>
<td>122 ksi</td>
</tr>
<tr>
<td>Linear Limit – Shear Stress</td>
<td>4350 psi</td>
<td>1255 psi</td>
</tr>
<tr>
<td>Linear Limit – Shear Strain</td>
<td>0.069 in/in</td>
<td>0.0103 in/in</td>
</tr>
<tr>
<td>Shear Modulus – Region 2</td>
<td>24 ksi</td>
<td>70 ksi</td>
</tr>
<tr>
<td>Knee Point – Shear Stress</td>
<td>6660 psi</td>
<td>6114 psi</td>
</tr>
<tr>
<td>Knee Point – Shear Strain</td>
<td>0.166 in/in</td>
<td>0.0795 in/in</td>
</tr>
<tr>
<td>Shear Modulus – Region 3</td>
<td>2.4 ksi</td>
<td>2.6 ksi</td>
</tr>
<tr>
<td>Ultimate Failure – Shear Stress</td>
<td>7610 psi</td>
<td>8000 psi</td>
</tr>
<tr>
<td>Ultimate Failure – Shear Strain</td>
<td>0.556 in/in</td>
<td>0.8 in/in</td>
</tr>
</tbody>
</table>
5°, are examined. This range is set based on work in previous literature which has shown that the strain fields in scarf joints with scarf angles less than 3° to 5° are highly sensitive to variations in the blunt tip height [12]. Other works have also shown that specimens with scarf angles in, or slightly below, this range demonstrate an ultimate strength that is closest to the original undamaged laminate strength [12, 20, 21]. Increasing the scarf angle beyond 5° showed a monotonic decrease in ultimate strength of the specimen [20, 21]. Scarf angles less than 3° were not considered due to the large specimen lengths needed for such small angles. The blunt tip height is varied in increments of one cured nominal ply thickness. This increment was selected due to manufacturing realities. A brief manufacturing investigation performed prior to the work in this study showed that a blunt tip height equivalent to an integer multiple of the ply thickness results in blunt tips with consistently good quality in terms of minimizing fiber pull-out and breakage at the sharp corners of the blunt tip. Therefore, besides the baseline case of one nominal ply thickness, blunt tip heights of two, three, and four nominal plies are examined. These blunt tip heights are equivalent to 0.0074, 0.0148, 0.0222, and 0.0296 inches. The range of blunt tip heights examined was stopped at a maximum of four nominal plies due to laminate thickness considerations in order to avoid the blunt tip from approaching the center line of the adherend. Due to the geometry of the scarf joint and the adhesive used to join the adherends, the majority of the load is transferred in shear through the joint. An “effective length” can therefore be defined as the length of the jointline, $L_{jointline}$, between the two blunt tips where the majority of the load is transferred through shear. As seen in equation 3.1 and Figure 3.2, this “effective length” is affected by the height of the blunt tips:

$$L_{jointline} = \frac{t_{adherend} - 2h_{blunt}}{\sin(\alpha)}$$

(3.1)

The test matrix resulting from these variations in the two parameters is shown in Table 3.3. Three specimens are tested for each scarf joint configuration as this is an important minimum in experimental work.

The part of this work using the finite element analysis specifically considers the effects of the height of the blunt tip, the adherend thickness, and the ratio of these two parameters.
Figure 3.2 Illustration of the "effective length" of the jointline of a two-dimensional scarf joint specimen with key geometry identified.
Table 3.3  Experimental Test Matrix

<table>
<thead>
<tr>
<th>Height of Blunt Tip [Nominal Plies]</th>
<th>Scarf Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3°</td>
</tr>
<tr>
<td>1</td>
<td>3\textsuperscript{a}</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Number of test specimens

\textsuperscript{b}Baseline case
These two geometric properties can be independently varied while also considering various values of their ratio as another key metric as defined in equation 3.2.

\[ BH = \frac{h_{\text{blunt}}}{t_{\text{adherend}}} \times 100\% \]  

(3.2)

This is defined as the blunt height ratio, BH.

The basic joint response is initially considered via the finite element analysis by investigating an initial case similar to the baseline case for the experimental work. The specifications of this initial case were chosen based on relevance to typical practical applications, to the experimental work performed in this study, and to previous work. With regard to the parameters associated with the blunt height ratio, this initial case has an adherend thickness of 0.089 inches, or equivalently the properties of a “smeared” [±15]_{3S} laminate, as per the experimental work, and the height of the blunt tip is equal to the nominal thickness of one ply of cured composite (0.0074 in). This yields a value of BH of 8.3%.

The thickness of the adherend is then varied with three different adherend thicknesses chosen. In addition to the baseline thickness of 0.089 inches, the two thicknesses examined are 0.029 inches and 0.148 inches, or equivalently the thickness of a [±15]_{S} and [±15]_{5S} laminate, using the same “smeared” laminate properties. This results in cases with values of BH equal to 25%, and 5%, respectively. These ratios were selected to simulate realistic laminate configurations, and to study the differing stress and strain fields associated with a blunt tip of this same height for a laminate of various thicknesses. An additional model was studied using the same adherend thickness and material properties of a “smeared” [±15]_{3S} laminate, but with the height of the blunt tip decreased to 0.0044 in (three-fifths nominal ply). This results in a blunt height ratio of 5%, which matches the ratio of the case studied having a thicker adherend thickness and blunt tip height equal to one nominal ply. These two cases were chosen in order to compare the effects when the individual geometric parameters differ (blunt tip height and adherend thickness), while their ratio is equal.

The two materials used to model the adherend and adhesive in this work were selected in order to match materials used in this experimental work and to allow this work to be related to previous finite element work [13,15]. The adherend material is Toray Compos-
ites T800/3900 carbon fiber/epoxy composite material, and the adhesive material is 3M™ Scotch-Weld™ Structural Adhesive Film AF 555M. The physical value of the adhesive thickness is 0.003 in, which is the nominal cured thickness of the film adhesive used in this experimental work. Although these two materials are not the same used in the works by Arsalan or by Jeffrey, which are Toray Composites T700/2510 and Cytec FM300-2K for the adherend and adhesive respectively, the results can be related to those from these previous finite element work via the following considerations. First, the values of the longitudinal modulus of the composite materials used for each work are within 3%. Second, the ultimate longitudinal tensile strength of the composite materials differ only by 2.5%. And finally, both film adhesives have similar nonlinear shear stress-strain behavior. Characterization of these pertinent items for the two adhesives and adherends is shown in Table 3.1, Figure 3.1, and Table 3.2.

In this work, exploration was limited to the mechanical response of two-dimensional scarf joints in the linear stress-strain regime of the adhesive and the adherends. While typical adhesives used in scarf joints possess extensive load-bearing capability when deforming in their nonlinear stress-strain regime, this work focused on the linear regime as previous finite element work has indicated that nonlinear results show a sensitivity to variables in a similar manner as linear results [13]. Thus, sensitivity to parameters can be assessed via analysis in the linear regime.

All models developed model the adherend as an orthotropic material with the averaged, or “smeared”, properties of a laminate made from Toray Composites T800/3900. This simplification has been examined in previous finite element studies to study the sensitivity to specific geometry by removing the stress-strain variations associated with changes in stiffness properties through the adherend thickness on a ply-by-ply level [13, 15].

The scarf angle was selected and held constant for all models considered in order to relate results to a more practical situation in industry. As discussed in Chapter 2, scarf angles of 3° or less have been found to restore the largest amount of original strength. Additionally, previous work has shown that scarf joints with small scarf angles are more
sensitive to variations in the height of the blunt tip.

These parameters selected in the finite element analysis allow the results to be related to and build upon those of previous studies. A final case having a feathered edge and an adherend thickness of 0.089 inches, or equivalently the properties of a “smeared” \([±15]_{3s}\) laminate, was included in this work in order to establish an initial response of the scarf joint without the effects of a blunt tip. This initial response allowed this work to relate back to previous studies that have examined the sensitivities of the scarf joint to various geometric and material properties both with and without a finite blunt tip height. In relation to this work, Adil examined the sensitivity of the scarf joint with a feathered edge to individual variations in the scarf angle, adhesive thickness, and laminate configuration [15]. Additionally, in the work by Jeffrey, the response of the scarf joint with and without a finite blunt tip was examined [13]. The chosen scarf angle equal to 3° further allows this work to relate back to studies performed by Adkins and Pipes, who modeled the response of the scarf joint with and without a finite blunt tip at similar scarf angles [19].

3.2 Two-dimensional Scarf Joint Configuration

Based on the philosophy of the building block approach [26], “effective” two-dimensional coupon testing is necessary before more complex three-dimensional specimens can be examined. Thus, in this work, a two-dimensional representation of a fully three-dimensional scarf repair was chosen, as the behavior of the constituent materials is well understood, but their interactions when combined in varying geometries is yet to be explored. This requires an “effective” two-dimensional test specimen for this experimental work that can be consistently manufactured. An “effective” two-dimensional test specimen is one such that the partials of the stress and strain with respect to the width \((y)\) direction are basically zero. This allows a three-dimensional specimen to effectively be modeled as a two-dimensional scarf joint specimen. In this work, the test specimen is composed of two anti-symmetrically scarfed laminated “adherends” bonded together via a layer of film adhesive. The geometric configuration of the “effective” two-dimensional test specimen used in the experimental study is
Figure 3.3: "Effective" two-dimensional scarf joint configuration.
shown in Figure 3.3.

The total specimen length, $L_{\text{total}}$, consists of the joint region, $L_{\text{joint}}$, two grip tab regions to hold the specimen in the testing machine, each $L_{\text{tab}}$, and two free sections, each $L_{\text{free}}$, separating the joint and tab regions. This free section is sufficiently long such that the stress-strain fields created by the boundary conditions at the ends of the specimen do not interfere with the fields created by the joint region of interest. This relation between the total length and individual regions of the specimen is

$$L_{\text{total}} = L_{\text{joint}} + 2L_{\text{free}} + 2L_{\text{tab}}$$  \hspace{1cm} (3.3)

As discussed in Chapter 2, several studies have been performed for various scarf joint geometries, but experimental work is not as well documented in literature. The lack of a standard, common joint geometry combined with the lack of documentation of manufacturing procedures, makes it difficult to replicate and compare future work. In order to ensure validity and repeatability, it is important to have consistency in specimen geometry and associated manufacturing and inspection processes. These manufacturing processes and specific values chosen for these key lengths are documented in Chapter 6.

The geometric configuration of the two-dimensional specimen modeled in the finite element analysis is similar to that of the experimental specimen. However, the lack of grip tabs and the two-dimensional assumption allows the free length to equal the joint length for this case. The details behind the specific configuration and reasoning for such is discussed in Chapter 4.
Chapter 4

Finite Element Modeling

The primary objective of this work is to investigate the influence of the height of the blunt tip on the response of the scarf joint. This requires an understanding of the effects of both the height of the blunt tip and the adherend thickness on the response, as well as the relation between the two parameters on the response. In order to understand the effects of the height of the blunt tip, the adherend thickness, and the ratio of the two parameters, as defined in Section 3.1, finite element modeling is used to simulate the overall load-deflection response of a scarf joint as well as the resulting stress and strain fields. The details of the finite element modeling performed in this work is presented in this chapter. This includes a discussion of the approaches, assumptions, and considerations involved in assembling the finite element models. The typical finite element model geometry is presented in Section 4.1 including the details of the boundary conditions applied on all finite element models. The material properties and considerations used to model the composite plies and adhesive are discussed in Section 4.2. The discretization aspects of the finite element models, including the element type and mesh density is described in Section 4.3. Abaqus version 6.16 is used throughout this work to define the model and complete the analysis.
4.1 Model Geometry and Conditions

For this work, a two-dimensional geometry with plane strain assumptions is used. This two-dimensional model represents an infinitesimally thin slice of a scarf joint that does not vary in the y-direction, or equivalently a slice of the “effective” two-dimensional joint designed for the experimental work as described in Chapter 6. An illustration of a two-dimensional model is shown in Figure 4.1, with the key geometry identified. As shown in Figure 4.1, the model is in the xz-plane of the joint, and as the joint would in reality be much wider in the y-direction than the thickness of the modeled joint, plane strain assumptions are used.

Most of the geometric dimensions for all finite models developed were determined from the total length of the joint along the x-axis, $L_{\text{joint}}$. This includes the scarfed area of the adherend and the adhesive. The parameters that determine this feature are defined in Equation 4.1:

$$L_{\text{joint}} = \frac{t_{\text{adherend}} \cdot \cos(\alpha) + t_{\text{adhesive}}}{\sin(\alpha)}$$  (4.1)

This length is set by the adherend thickness, $t_{\text{adherend}}$, the scarf angle, $\alpha$, and the adhesive thickness, $t_{\text{adhesive}}$. As discussed in Chapter 3, the scarf angle of 30° and the adhesive thickness of 0.003 inches were used for all the cases studied. The adherend thickness was varied among the cases. Thus, the joint length changes for different cases.

In this work, the distance between the vertical edges of the configuration and the joint region was chosen to equal the joint length, $L_{\text{joint}}$, for each model considered. This implies that each model has a total length, $L$, equal to three times the joint length. Each model has a center joint region of interest and a region of undamaged adherend on either side with a length equal to the joint length. This is done in order to ensure that the distance between the joint region and the boundary conditions is sufficiently large in order to allow the strain state outside the joint region to lose the effects introduced by the joint region and return to far-field values being sufficiently uniform across the thickness of the configuration at the location where the uniform displacements are applied. Previous work has shown that the stress-strain fields in a two-dimensional scarf joint return to far-field within a distance of a
Figure 4.1 Illustration of a two-dimensional model with key geometry identified.
joint length away from the end of the scarf joint region [13,15]. The resulting values of $L_{\text{joint}}$ and $L$ are given in Table 4.1 for all finite element models.

The two-dimensional finite element models investigated in this work were subjected to a uniform extensional displacement. This is applied via a boundary condition in Abaqus. All finite element models were arranged in Abaqus such that they began at $x = 0$ with a vertical line to the left of the joint and ended at $x = L$, with a vertical line to the right of the joint. The orientation of each model inside Abaqus, with pertinent geometry shown, is illustrated in Figure 4.1.

At the vertical line to the left of the joint, or equivalently at $x = 0$, an "encastre", or clamped boundary condition, is applied for all models. This results in no displacement or rotation at the vertical edge of the model. Additionally, in this work, a uniform extensional displacement, $u_{\text{app}}$, is applied as a boundary condition at the vertical edge of the model at $x = L$. All models had a displacement of 0.001 inches applied in the positive x-direction. All models utilize a geometric linearity in the strain-displacement relation, and material linearity in the stress-strain relation. Thus, the structural response of the models for a specific displacement can be scaled to any other applied displacement corresponding to a different loading condition as long as conditions remain in the linear regime. This is discussed further in Chapter 5.

4.2 Material Properties

The adherend and adhesive materials selected for use in this work are presented in Chapter 3. The adherend and adhesive are modeled after Toray Composites T800/3900 carbon fiber/epoxy composite material and 3M Scotch-Weld Structural Adhesive Film AF 555M. In this work, exploration was limited to the mechanical response of two-dimensional scarf joints in the linear stress-strain regime of the adhesive and the adherends. Therefore, the adhesive was modeled as being linearly isotropic with a Young’s Modulus of 0.176 Msi and a Poisson’s ratio of 0.400. The material properties for the adherends also remained linear for all cases. In Chapter 3, a simplification was presented based on previous work performed.
Table 4.1  Geometric length dimensions, $L_{joint}$ and $L$, of each finite element model

<table>
<thead>
<tr>
<th>Height of Blunt Tip [in]</th>
<th>Laminate Configuration</th>
<th>$L_{joint}$ [in]</th>
<th>$L$ [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$[\pm 15]_{3S}$</td>
<td>1.75</td>
<td>5.25</td>
</tr>
<tr>
<td>0.0074</td>
<td>$[\pm 15]_{3S}$</td>
<td>1.75</td>
<td>5.25</td>
</tr>
<tr>
<td>0.0074</td>
<td>$[\pm 15]_{S}$</td>
<td>0.62</td>
<td>1.86</td>
</tr>
<tr>
<td>0.0074</td>
<td>$[\pm 15]_{5S}$</td>
<td>2.88</td>
<td>8.64</td>
</tr>
<tr>
<td>0.0044</td>
<td>$[\pm 15]_{3S}$</td>
<td>1.75</td>
<td>5.25</td>
</tr>
</tbody>
</table>
In order to eliminate variation of material properties from ply to ply, all adherends were modeled as a homogeneously orthotropic linear elastic plate having the equivalent stiffness properties of the averaged, or “smeared”, $[\pm 15]_n$ laminate made from Toray Composites T800/3900.

The adherend material was defined in Abaqus using the orthotropic linear elastic material option. The specific material properties were found using Classical Laminated Plate Theory to average the material properties of each ply orientation in the associated laminate under consideration. The stiffness properties for a T800/3900 unidirectional ply given in Table 3.1 are used as inputs into CLPT.

These “smeared”, or averaged, properties, shown in Table 4.2, were input directly into Abaqus as a material definition of the adherends. This implies that since all of the laminates under consideration use the same ply orientations, of $+15^\circ$ and $-15^\circ$, in a balanced and symmetric configuration, that all of the models define the adherend material using the same inputs. After defining the material properties, the model was categorized into three different sections: the “base adherend” to the left of the joint, the “patch adherend” to the right of the joint, and the adhesive region. Each section of the model was assigned specific material properties and the overall model was defined as solid and homogeneous in Abaqus. The two designations, “Base Adherend” and “Patch Adherend”, are strictly for discussion and reference purposes as there are no geometry or material differences between the two adherends.

4.3 Model Discretization

All two-dimensional scarf joint models in this work are discretized using three-noded (linear), plane strain, displacement-based elements, defined as CPE3 in the Abaqus standard element library. Linear triangular elements are used in order to improve efficiency while still ensuring adequate resolution of the resulting stress and strain fields around the areas of interest.

To properly mesh each model, all edges in the model are assigned “mesh seeds”. Once
Table 4.2 Adherend stiffness properties of "Smeared" [±15]ns laminate

<table>
<thead>
<tr>
<th>Stiffness Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_L$</td>
<td>16.3 Msi</td>
</tr>
<tr>
<td>$E_T$</td>
<td>1.17 Msi</td>
</tr>
<tr>
<td>$E_Z$</td>
<td>1.14 Msi</td>
</tr>
<tr>
<td>$G_{LT}$</td>
<td>0.57 Msi</td>
</tr>
<tr>
<td>$G_{LZ}$</td>
<td>1.75 Msi</td>
</tr>
<tr>
<td>$G_{TZ}$</td>
<td>0.38 Msi</td>
</tr>
<tr>
<td>$\nu_{LT}$</td>
<td>0.13</td>
</tr>
<tr>
<td>$\nu_{LZ}$</td>
<td>1.22</td>
</tr>
<tr>
<td>$\nu_{TZ}$</td>
<td>0.51</td>
</tr>
</tbody>
</table>
the mesh seeds are assigned, mesh controls are applied that are used to determine the
manner by which the automatic mesh generator sets the mesh between the edges. Each
model is separated into three geometric sections: the “base” adherend, “patch” adherend,
and adhesive region labeled “A”, “C”, and “B”, respectively, in Figure 4.2. These geometric
sections are related to the material properties and geometric features that influence the mesh
density.

The adhesive region is discretized to ensure sufficient elements through the thickness
of the adhesive. All of the edges around the adhesive region, labeled “1” in Figure 4.2,
are seeded using an element size set to 0.001 inches. This element size was selected to
ensure a higher mesh density where there will be large gradients in stress and strain due
to the geometry of the scarf joint. This size allows three elements to be placed across the
adhesive thickness, which has been presented in previous work to sufficiently capture the
large gradients expected in the adhesive region [13,15].

The “base” adherend and “patch” adherend are discretized in a similar manner. The
vertical edges, labeled “2” in Figure 4.2, of each section at x equal to 0 and x equal to L
are seeded by element size using 0.0074 inches. This size is selected based on the thickness
of ply from which the adherends would be manufactured in a real repair. This allows for a
consistent mesh in future work that uses ply geometry as the key reference for the element
size thereby allowing one element per ply through the thickness of the region unaffected
by geometric effects of the scarf joint. The remaining four edges in the “base” adherend
section and “patch” adherend section, labeled “3” and “4” in Figure 4.2, that connect the
end vertical edges to the adhesive region are seeded using the biased mesh seeding technique
in Abaqus. The minimum seed size was set to 0.001 inches, the same as the adhesive region,
and the maximum seed size was set to 0.0074 inches to match the end sections. The bias was
set so the smaller elements were near the adhesive allowing the mesh density to be higher
near the adhesive region compared to the rest of the adherend.

After seeding, mesh controls are applied to the model to determine the means by which
the automatic mesh generator creates the mesh. After defining the element shape to be
Figure 4.2 Illustration of a two-dimensional model with geometric sections indicated and edges labeled for mesh seeding.
triangular, the control technique was set to the free meshing method using the advancing front algorithm. This generates a mesh in an unstructured manner from the mesh seeds, and is good for complex shapes and geometries. The advancing front method creates elements at the edges of the region and then fills in the region starting from the outside and working towards the interior. The method follows the seeding exactly. The mesh is defined using the same controls, bias, and seed sizes for each configuration in this work.

The mesh for the model with a $[\pm 15]_S$ laminate configuration and blunt tip with a height of 0.0074 inches is illustrated in Figure 4.3. This model has 28,758 elements. The mesh for each configuration looks similar as the one shown, but the geometry for the different parameters studied affects the total number of elements in each configuration. For example, the $[\pm 15]_{3S}$ laminate configuration with a blunt tip height equal to a zero nominal ply, one nominal ply, and three-fifths nominal ply have a total element count equal to 188,728 elements, 198,004 elements, and 193,625 elements. Finally, the model consisting of a $[\pm 15]_{5S}$ laminate configuration has a total of 520,621 elements.

In addition to all models using the same material properties, boundary conditions, and meshing, each model is also symmetric. Specifically, the geometry of each model is anti-symmetric across the adhesive region. This results in a model similar to what would be developed in a real situation, as an actual scarf joint in practice would have a blunt tip on both the “base” and “patch” adherend.
Figure 4.3 View of mesh in the scarf joint region.
Chapter 5

Finite Element Results

The results of the two-dimensional composite scarf joint investigation using the finite element method is presented in this chapter, and discussed in Chapter 8. Overall, five different joint configurations are examined in this work. In Section 5.1, the results of the three models with a laminate configuration of $[\pm15]_3s$ and blunt tip heights of zero, $0.6t_{ply}$, and $t_{ply}$ are presented. The results of the three configurations with a blunt tip height of $t_{ply}$, but with laminate configurations with different laminate thicknesses, $[\pm15]_s$, $[\pm15]_3s$, and $[\pm15]_{55}$, are presented in Section 5.2.

These results are presented as strain distributions from the various models along defined coordinate axes in the scarf joint region. Several different axes are considered which do not align with the global x-z coordinate system, or which align with the global coordinate system but have a different origin than used to define the geometry of the model. These local coordinate systems, of which there are two types, are shown in Figure 5.1.

The first type of axes is a $x'-z'$ coordinate system related to the scarf angle, $\alpha_{scarf}$, in the configuration. This system is obtained by rotating the x-z system by the scarf angle, which is equal to $3^\circ$ in all configurations. The axis of $x'$ resulting from this is used along the bondlines and along the midline of the adhesive. Specifically, the axis of $x'$ at the midline, $x'_{midline}$, runs along the midline of the adhesive along the scarf length and begins at the bottom of the configuration ($z = 0$). The interface between the adhesive and the “patch”
Figure 5.1  Illustration of scarf joint with coordinate axes used for plots of strain.
adherend is defined as the patch bondline. In previous works, the term “bondline” has been used to indicate any location within the adhesive [9]. However, in this work, as in the work preceding it (e.g. [13, 15]), the term “bondline” is defined as the location of the interface between the adhesive and the adherend. This means that for the scarf joint modeled in this work, there are two bondlines: one at the “base” adherend, and one at the “patch” adherend. The interface between the adhesive and the “patch” adherend is defined as the “patch” bondline. The direction of the axis of $x'$ at the bondline is along the bondline due to the rotation of the axis of $x$ by the scarf angle. In section 5.1, the axis of $x'$ along the “patch” bondline, $x'_{bondline}$, has its origin at point A in Figure 5.1, which is the corner created by the sharp feathered tip or where the sharp feathered tip would be if the blunt tip did not exist. However, in section 5.2, the origin of the axis of $x'$ along the “patch” bondline, $x'_{bondline}$, is at point B in Figure 5.1, which is the corner created by the blunt tip in the “patch” adherend. The former is referred to as the “nominal” bondline and the latter as the “bondline from the corner”. In both sections, the axes end at the wide angle of the “patch” adherend. In addition, these axes run within two materials: one in the adhesive, and one in the adherend. Results along the “base” bondline are not presented in this work as they are similar to the results along the “patch” bondline due to the asymmetry of all models considered.

The second type of axes is aligned with the global x-z coordinate system, but has different origins. Two different axis systems of this type are defined. The first runs parallel to the axis of $x$ with the origin at the “base” bondline and is denoted as $x_a$, as shown in Figure 5.1. This origin location is selected as the location of the “base” bondline because this location is independent of the geometry at the “patch” blunt tip under consideration and is therefore at the same position for all three cases of height of blunt tip. These axes are used at specific through-thickness locations, and are thus at a constant value of z. Due to the origin of the axis of $x_a$ at the “base” bondline, this implies that strain results in the “base” adherend along this axis are plotted at values of $x_a$ less than zero. A second axis system runs parallel to the axis of $z$ with the origin at $z$ equal to 0. This is used at specific locations along the length (x-direction) of the specimen. These axes are defined as $z_a$. Thus,
Figure 5.2  Distribution of normalized longitudinal strain and through-thickness strain at the midline of the adhesive for the feathered edge configuration.
each axis runs in the $z$-direction at a constant value of $x$ as shown in Figure 5.1.

The strain plots presented in this chapter are the distributions of the longitudinal strain, $\varepsilon_{11}$, and the engineering shear strain, $\gamma_{13}$. The finite element results from Abaqus are given as engineering shear strain and are thus presented as such. The results from the through-thickness strain, $\varepsilon_{33}$, are related to the longitudinal strain via Poisson’s effects as the distribution of the through-thickness normal strains, $\varepsilon_{33}$, generally exhibits a similar trend, but negative in magnitude, as the longitudinal strain, $\varepsilon_{11}$. This is shown in the distribution of the normalized strains, $\varepsilon_{11}$ and $\varepsilon_{33}$, along the adhesive midline for the case of the feathered edge in Figure 5.2. Thus, results of the through-thickness strain are not presented in this work as they would add no new observations. In order to capture the behavior of each material at the bondline, where both the adherend and the adhesive materials interface, results for each material are taken separately at points starting one element length, 0.001 inches, into each material in the $x$-direction. Within this distance, the strain results are representative of the behavior of each material at the bondline.

Each strain plot is normalized by $\varepsilon_{11}^{avg}$, the average value of the far-field longitudinal strain. This value is the average of the longitudinal strain, $\varepsilon_{11}$, occurring at the end of each model. The average strain in the “patch” adherend at $x$ equal to $L$ is used for consistency across all models as there is less than 1% of variation in $\varepsilon_{11}$ through-the-thickness of the specimen at this location. The average values of the far-field longitudinal strain, $\varepsilon_{11}^{avg}$, for each case are presented in Table 5.1.

In Sections 5.1 and 5.2, the strain distributions in each plot are presented and labeled in a similar manner for consistency and ease of comparison. In order to compare pertinent geometry, the labeling of each strain distribution is given in the following format capturing the three pertinent aspects of the geometry of the configurations: $A$, $B$, ($C\%$). The first parameter, $A$, gives the height of the blunt tip and takes on three possible values: 0 ply, $0.6t_{ply}$, and $t_{ply}$. The second parameter, $B$, captures the laminate thickness in the following manner. All laminates are of the configurations, $[\pm15]_{NS}$, and $B$ is set to NS such that there are three possible values: S, 3S, and 5S. Finally, the parameter, $C$, is the blunt height ratio.
Table 5.1  Average far-field strain, $\epsilon_{11}^{avg}$ for each finite element model

<table>
<thead>
<tr>
<th>Height of Blunt Tip [in]</th>
<th>Laminate Configuration</th>
<th>BH</th>
<th>$\epsilon_{11}^{avg}$ [µstrain]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$[\pm 15]_{3S}$</td>
<td>0%</td>
<td>186</td>
</tr>
<tr>
<td>0.0044</td>
<td>$[\pm 15]_{3S}$</td>
<td>5%</td>
<td>186</td>
</tr>
<tr>
<td>0.0074</td>
<td>$[\pm 15]_{3S}$</td>
<td>8.3%</td>
<td>185</td>
</tr>
<tr>
<td>0.0074</td>
<td>$[\pm 15]_{S}$</td>
<td>25%</td>
<td>436</td>
</tr>
<tr>
<td>0.0074</td>
<td>$[\pm 15]_{5S}$</td>
<td>5%</td>
<td>114</td>
</tr>
</tbody>
</table>
parameter, as defined in Equation 3.2, and is a percentage with four possible values: 0, 5, 8.3, and 25.

5.1 Effects of Blunt Tip Height

In order to relate this work to the results of previous work, a scarf joint configuration having a feathered edge, an adherend thickness of 0.089 inches, and the properties of a “smeared” [±15]₃s laminate, is included in this work. This model establishes an initial response of the scarf joint without the effects of a blunt tip. Plots of the longitudinal strain, $\epsilon_{11}$, and the engineering shear strain, $\gamma_{13}$, along the coordinate axes previously defined, establish the mechanical response of the scarf joint without a blunt tip. These are very similar to the results shown in preceding work (e.g. [13,15]).

In order to examine the effects of the height of the blunt tip, this feathered edge case is compared to the two other models that have the adherend thickness and properties of a “smeared” [±15]₃s laminate with a thickness of 0.089 inches. Specifically, this feathered edge case is compared to the cases having a blunt tip height equal to the nominal thickness of one ply of cured composite (0.0074 inches) and a blunt tip height equal to 60% of the height of one ply of cured composite, resulting in a height of 0.0044 inches. This yields a blunt height ratio, BH, of 8.3% and 5%, respectively.

Three sets of results are presented along the direction of $x'$ previously described. These are along the “nominal” bondline in the “patch” adherend, along the “nominal” bondline in the adhesive, and along the midline of the adhesive. Note that for the first of these, values are only given from the corner of the blunt tip since no adherend exists before this point. The strains are also presented along four different axes of $x_a$ as shown in Figure 5.3. These axes are located at the bottom of the adherend (z equal to 0), at the corner created by the blunt tip (z equal to $h_{blunt}$), at a distance of one ply from the bottom of the adherend, and at the centerline of the adherend (z equal to $t_{adherend}/2$). Note that the axis of $x_a$ at a distance of one ply from the bottom of the adherend is not shown in the figure due to the variations in the geometry of the cases under consideration. In the case with a blunt tip height of $t_{ply}$
Figure 5.3  Illustration of scarf joint with detailed coordinate axes locations used for plots of strain.
this axis is at the height of the blunt tip. However, in the other two cases, the case with a feathered edge and a blunt tip height of 0.6$t_{ply}$, this axis is at a distance above these tips. Strains are also presented along several different axes of $z_a$ as shown in Figure 5.3. These axes are located at the location in x of the feathered tip for the “patch” adherend, at the location in x where a blunt tip height of one ply occurs in the “patch” adherend, and at the location in x of the end of the joint in the “patch” adherend (at the wide angle). Note that the axis of $z_a$ at the location in x where a blunt tip height of one ply occurs is such that for the case with a blunt tip height of $t_{ply}$, this axis is at the blunt tip, but starts in the “patch” adherend just beyond the blunt tip. However, in the other two cases, this axis is at some distance beyond the tip in the “patch” adherend. In order to compare these three models that have varying geometry in the joint region, the strain distributions are plotted against true location values along the axes.

The distributions of the normalized longitudinal strain and shear strain in the adherend along the “patch” nominal bondline are presented in Figures 5.4 and 5.5. Results are shown along the axis of $x'_{bondline}$ with the origin of the axis at the feather tip and at a point that is one element length into the “patch” adherend. In the distribution of longitudinal strain presented in Figure 5.4, all configurations have an initial peak magnitude followed by a similar value along the center of the bondline, and then a second peak located towards the end of the bondline near the wide angle. In the feathered edge case, a maximum strain concentration of 3.7 occurs in the adherend at the sharp adherend tip and a second peak strain value of 1.4 is located 0.057 inches from the end of the bondline near the wide angle of the “patch” adherend. The middle 80% of the bondline has a region of approximately constant longitudinal strain. This constant region begins 10% along the bondline from either end and has a strain value of 1.035 at the center of the bondline. The configurations with blunt tips show similar characteristics except that the initial peak has a lower value than the middle region. The configurations with a blunt tip height of 0.6$t_{ply}$ and of $t_{ply}$ have an initial minimum value of 0.6 and 0.7, respectively, at the corner created by the blunt tip. A second local maximum in the case of 0.6$t_{ply}$ occurs equal to 1.9 at a location of 0.14 inches from
Figure 5.4  Distribution of normalized longitudinal strain in the adherend at the “patch” nominal bondline for the configurations with different heights of blunt tip.
Figure 5.5 Distribution of normalized shear strain in the adherend at the “patch” nominal bondline for the configurations with different heights of blunt tip.
the wide angle. Similarly, in the case of $t_{\text{ply}}$, a second local maximum equal to 2.2 occurs at a location of 0.20 inches from the end of the bondline. In the center region of both these cases, the longitudinal strain is approximately constant and equal to the strain distribution in the feathered edge case. The constant strain value of 1.034 and 1.036 occurs, respectively, for the cases of blunt tip heights of $0.6t_{\text{ply}}$ and of $t_{\text{ply}}$. After the secondary peaks described, each configuration has similar values equal to 0.67, 0.64, and 0.63, respectively, for the cases having a blunt tip height equal to 0, $0.6t_{\text{ply}}$, and $t_{\text{ply}}$, at the top of the laminate along the bondline.

The distributions of the normalized shear strain in the adherend along the “patch” nominal bondline is shown in Figure 5.5 and shows similar characteristics as the longitudinal strain. In the feathered edge case, a maximum normalized shear strain of 2.7 occurs at the sharp adherend tip and a second local maximum of 2.4 occurs 0.49 inches from the end of the bondline near the wide angle before decreasing to a final value of 0.75 at the end of the bondline. In the configurations of a blunt tip height of $0.6t_{\text{ply}}$ and $t_{\text{ply}}$, an initial negative shear strain equal to -4.6 and -6.2, respectively, occurs at the corner of the blunt tip in each case. A jump from a local minimum and maximum then occurs near the end of the bondline near the wide angle where the shear strain jumps from a negative to a positive value. In the configuration with a blunt tip height of $0.6t_{\text{ply}}$, the normalized shear strain jumps from -0.92 to 2.9 at a location 0.14 inches from the wide angle of the “patch” adherend before decreasing to a final value of 0.72 at the end of the bondline. Similarly, in the configuration with a blunt tip height of $t_{\text{ply}}$, the shear strain jumps from a value of -1.4 to 3.3 at a location 0.20 inches from the end of the bondline near the wide angle before decreasing to a final value of 0.71 at the end of the bondline. In all three cases, the normalized shear strains approach a constant value along the center region of the bondline. This value is equal to 0.12 in the case of the feathered edge and the case of the blunt tip height of $t_{\text{ply}}$, and 0.11 in the case of the blunt tip height of $0.6t_{\text{ply}}$.

The distributions of normalized longitudinal strain in the adhesive at the “patch” nominal bondline of the joint are presented in Figures 5.6 and 5.7. The distribution of the
Figure 5.6  Distribution of normalized longitudinal strain in the adhesive at the “patch” nominal bondline for the configurations with different heights of blunt tip.
Figure 5.7 Distribution of normalized shear strain in the adhesive at the “patch” nominal bondline for the configurations with different heights of blunt tip.
normalized longitudinal strain in the adhesive, shown in Figure 5.6, has the same basic shape as the normalized longitudinal strain distribution in the adherend. However, the magnitudes increase. The maximum in the adhesive of the feathered tip case still occurs at the sharp adherend tip, but has a value of 10.2, compared to the maximum value of 3.7 in the adherend. A second local maximum of 2.7 occurs at a point that is 0.057 inches from the wide angle of the “patch” adherend, which is the same location as in the adherend. In the cases with a blunt tip height of 0.6t_{ply} and t_{ply}, a maximum normalized longitudinal strain value of 14.1 and 15.1, respectively, occurs at the corner created by the blunt tip. This maximum value is followed by a second local maximum in each case equal to 4.1 at a point 0.14 inches from the wide angle in the configuration of 0.6t_{ply}, and 7.8 at a point 0.20 inches from the wide angle in the configuration of t_{ply}. These are the same locations as in the adherend. Following these second peaks, at the end of the bondline, the three configurations having a blunt tip height of 0, 0.6t_{ply}, and t_{ply}, decrease to final values equal to 0.69, 0.65, and 0.64, respectively. All three configurations have a constant value of 1.8 at the center region of the bondlines with approximately 1% variation between the three configurations.

The distributions of normalized shear strain in the adhesive at the “patch” nominal bondline are shown in Figure 5.7. Similar to the distribution of the longitudinal strain, each configuration shows a peak at the locations near the feathered edge or blunt tip. In the case of the feather edge configuration, the peak shear strain occurs near the sharp adherend tip, but not exactly at the sharp tip as for the longitudinal strain. This is shown in the plot as a peak of -18.0 just beyond x' equal to zero. Towards the end of the bondline, as the distribution approaches the wide angle of the “patch” adherend, the shear strain has a second peak of -16.6 at a point 0.074 inches from the end of the bondline before rapidly decreasing in magnitude to zero shear strain. The configurations with a blunt tip height of 0.6t_{ply} and t_{ply} have an initial peak magnitude at the corner of the blunt tip equal to 39.4 and 45.6, respectively. The configuration of 0.6t_{ply} has a secondary peak magnitude of 31.8 located at a point 0.14 inches from the wide angle. Similarly, the configuration of t_{ply} has a secondary peak strain magnitude of 38.6 located at a point 0.21 inches from the wide angle.
of the "patch" adherend. These are the same locations as the peak longitudinal strains. All three configurations have approximately a constant value along the center region of the bondline with basically the same value. The actual values are 14.66, 14.64, and 14.69 for the feathered edge case, the $0.6t_{\text{ply}}$ case, and the $t_{\text{ply}}$ case, respectively.

The distributions of the normalized longitudinal strain and normalized shear strain at the midline of the adhesive are shown in Figures 5.8 and 5.9. For all three configurations, the results for the distributions are symmetric. The distributions of normalized longitudinal strain consist of a peak at either end and approximately the same value between the peaks. The cases of a feathered edge, $0.6t_{\text{ply}}$, and $t_{\text{ply}}$ have peak values of 5.5, 7.6, and 8.5 at a point located at 0.03 inches, 0.11 inches, and 0.17 inches, respectively. The normalized shear strain distributions show a similar trend. After decreasing from zero at the outer edges of the joint along the midline, the feathered edge case, case of $0.6t_{\text{ply}}$, and the case of $t_{\text{ply}}$ have peak magnitudes of 16.6, 34.5, and 40.1, at a point located at 0.04 inches, 0.11 inches, and 0.17 inches, respectively. Between these peaks, the distributions of longitudinal strain for all three cases approach the same value of 1.81 with less than 1% variation between the three cases. Similarly, the distributions of shear strain approach a magnitude of 14.67 with less than 1% of variation amongst the three cases. Note that the through-thickness location (along the z-axis) for the corner of the blunt tip on the midline is located at a distance equal to 0.08 inches along the midline for the case with a blunt tip of $0.6t_{\text{ply}}$ and 0.14 inches from the origin along the midline for the case with a blunt tip of $t_{\text{ply}}$. Thus, the peak values of these distributions occur approximately 0.03 to 0.04 inches from this location.

The results along the various axes of $x_a$ are subsequently presented. First, the normalized longitudinal strain along the axis of $x_a$ at the bottom of the adherend is presented in Figures 5.10, 5.11, and 5.12, for the three different model sections: "base" adherend, adhesive, and "patch" adherend. Note that due to symmetry, the distributions at the top of the model, a value of $z$ equal to the thickness of the adherend, is basically the same as the strain distributions across the bottom of the model, a value of $z$ of 0, except that the distribution is from the "patch" bondline with the positive direction towards the "base" due
Figure 5.8  Distribution of normalized longitudinal strain in the adhesive at the midline for the configurations with different heights of blunt tip.
Figure 5.9 Distribution of normalized shear strain in the adhesive at the midline for the configurations with different heights of blunt tip.
Figure 5.10  Distribution of normalized longitudinal strain in the “base” adherend at a constant value of $z$ equal to 0 for the configurations with different heights of blunt tip.
Figure 5.11  Distribution of normalized longitudinal strain in the adhesive at a constant value of $z$ equal to 0 for the configurations with different heights of blunt tip.
Figure 5.12 Distribution of normalized longitudinal strain in the “patch” adherend at a constant value of $z$ equal to 0 for the configurations with different heights of blunt tip.
to the symmetry of the geometry.

The distributions of the normalized longitudinal strain in the “base” adherend along the axis of $x_a$ for a value of $z$ of 0 are presented in Figure 5.10. The results have been cropped to present the distributions less than a distance of 1.5 inches from the “base” bondline. Any results beyond this point would give no additional information as all configurations have come within 1% of their far-field values at this point. All three cases under consideration show a similar shape as the strain distributions start at the far-field value and decrease in value in nearing the “base” bondline in front of the blunt tip of the “patch” adherend. The case of a blunt tip height of $0.6t_{ply}$ reaches within 1% of the far-field value at a distance of -0.88 inches from the “base” bondline, which is the greatest distance from the “base” bondline amongst the three configurations. The case of a blunt tip height of $t_{ply}$ and of a feathered edge reach a similar value at a point -0.86 inches and -0.73 inches from the “base” bondline, respectively. The distributions of longitudinal strain in the feathered edge case, case of $0.6t_{ply}$, and the case of $t_{ply}$ decrease to a minimum value at the “base” bondline equal to 0.68, 0.65, and 0.64, respectively.

The distributions of the normalized longitudinal strain in the adhesive along the axis of $x_a$ for a value of $z$ of 0 are shown in Figure 5.11. The strain values in the adhesive, at the “base” bondline, are the same values as the minimum values in the “base” adherend at the bondline. This indicates stress equilibrium across the bondline from the adherend to the adhesive at the wide angle of the “base” adherend. The case of a blunt tip height of $t_{ply}$ increases to a maximum strain value of 11.4 at the blunt tip interface. Similarly, the feathered edge case, and case of a blunt tip of $0.6t_{ply}$ both increase to a maximum strain value of 10.2 at the feathered tip and blunt tip interface.

The distributions of the normalized longitudinal strain in the “patch” adherend along the axis of $x_a$ for a value of $z$ of 0 are shown in Figure 5.12. The results from the three configurations have been cropped to present the distributions less than a distance of 2.0 inches along the axis of $x_a$ from the “base” bondline. Any results beyond this point would give no additional information as all configurations have come within 1% of the far-field.
value. The three cases have initial peak values located at the tip of the “patch” adherend in each case, and follow similar trends with a small variation near the end of the joint region below the wide angle of the “patch” adherend, which is located 1.75 inches from the “base” bondline. The case of a feather edge has an initial peak value of 3.7 at the feathered tip of the “patch” adherend and a minimum strain value of 0.94 in the variation at a distance of 1.68 inches from the “base” bondline. This case then reaches a strain value equal to 1% of the far-field value at a point that is 1.82 inches from the “base” bondline or 1.77 inches from the feathered tip of the “patch” adherend. The case of a blunt tip height of 0.6$t_{ply}$ has an initial strain of 0.30 at the blunt tip region, which is located 0.13 inches from the “base” bondline. This distribution shows a local minimum in the variation equal to 0.86 at a point that is 1.61 inches from the “base” bondline, and reaches 1% of the far-field value at a location that is 1.84 inches from the “base” bondline or 1.71 inches from the blunt tip of the “patch” adherend. The configuration of a blunt tip of $t_{ply}$ has an initial strain value of 0.28 at the blunt tip of the “patch” adherend, which is located 0.20 inches from the “base” bondline. Similar to the other two cases, this configuration has a local minimum of 0.77 in the variation at a point that is 1.57 inches from the “base” bondline, and reaches within 1% of the far-field value at a point that is 1.9 inches from the “base” bondline, or 1.70 inches from the blunt tip of the “patch” adherend.

The distributions of the normalized shear strain along the axis of $x_a$ at a value of $z$ of 0 are presented in Figures 5.13, 5.14, and 5.15 for the three different model sections: “base” adherend, adhesive, and “patch” adherend. For each figure, the axis of $x_a$ has been cropped in a similar manner as in the figures of the longitudinal strain plots previously described.

The normalized shear strain at the bottom of the “base” adherend along the axis of $x_a$ for a value of $z$ equal to 0 is presented in Figure 5.13. The results for each configuration are very similar in shape with shear strain of zero occurring in the majority of the “base” adherend, but the value of the shear strain increasing when very near the wide angle of the “base” adherend. The feathered edge case, case of blunt tip height of 0.6$t_{ply}$, and case of blunt tip height of $t_{ply}$ have similar peak shear strain values of 0.75, 0.72, and 0.71, respectively.
Figure 5.13  Distribution of normalized shear strain in the "base" adherend at a constant value of z equal to 0 for the configurations with different heights of blunt tip.
Figure 5.14  Distribution of normalized shear strain in the adhesive at a constant value of $z$ equal to 0 for the configurations with different heights of blunt tip.
Figure 5.15 Distribution of normalized shear strain in the “patch” adherend at a constant value of z equal to 0 for the configurations with different heights of blunt tip.
The shear strain quickly jumps back to zero in the adhesive at the wide angle of the “base” adherend as seen in Figure 5.14. All three configurations show shear strain of zero through the adhesive until very near the interface with the “patch” adherend where all three cases go to a negative value with a large magnitude. In the case of the feathered edge, the shear strain increases to a magnitude of 10.6 in the adhesive at the feathered tip of the “patch” adherend. However, the cases with a blunt tip height of $0.6t_{ply}$ and $t_{ply}$ show a local minimum/maximum near the blunt tip region before the large jump to a magnitude of 10.6 and 13.3, respectively, at the blunt tip.

The distributions of the normalized shear strain in the “patch” adherend along the axis of $x_a$ at a value of $z$ equal to 0 are shown in Figure 5.15. The case of a feathered edge in this plot shows an initial peak of 2.7 in the adherend at the feathered edge of the “patch” adherend, which quickly decreases to 0.01 at point that is 0.15 inches from the “base” bondline, or 0.099 inches from the feathered edge, and then stays equal to 0 until nearing the region below the wide angle of the “patch” adherend. In the cases with a blunt tip height of $0.6t_{ply}$ and $t_{ply}$, the initial strain distribution jumps from a negative strain to a positive peak strain over the course of two data points. Both cases then show distributions that are followed by a local minimum before approaching a strain value of zero, which remains constant until the region below the wide angle of the “patch” adherend. In the case with a blunt tip height of $0.6t_{ply}$, the shear strain jumps from a value of -0.86 to 0.14 and then reaches -0.01 and eventually zero at a point that is 0.31 inches from the “base” bondline or 0.18 inches from the blunt tip of the “patch” adherend. Similarly, in the case with a blunt tip height of $t_{ply}$, the first two data points jump from -1.4 to 0.35 and then the strain settles to a value of -0.01 and eventually zero at a point that is 0.43 inches from the “base” bondline or 0.23 inches from the blunt tip of the “patch” adherend. All three configurations then experience a local minimum/maximum where the shear strain changes sign from positive to negative with small magnitudes of less than 0.13 before returning to a value of zero at the region below the wide angle of the “patch” adherend. In each configuration, the point where the change of sign occurs is at the same location from the “base” bondline as where the local
Figure 5.16 Distribution of normalized longitudinal strain in the “base” adherend at a constant value of z equal to $h_{\text{blunt}}$ for the configurations with different heights of blunt tip.
Figure 5.17  Distribution of normalized longitudinal strain in the adhesive at a constant value of $z$ equal to $h_{blunt}$ for the configurations with different heights of blunt tip.
Figure 5.18  Distribution of normalized longitudinal strain in the “patch” adherend at a constant value of $z$ equal to $h_{blunt}$ for the configurations with different heights of blunt tip.
minimum values in the normalized longitudinal strain occur.

The distributions of the normalized longitudinal strain along the axis of $x_a$ at a constant value of $z$ equal to $h_{blunt}$ are shown in Figures 5.16, 5.17, and 5.18 for the “base” adherend, adhesive, and “patch” adherend, respectively. In these figures, due to the selection of the axis at the blunt tip height in each case, the distribution of the feathered edge case is not shown in these figures. This also implies that the axis of $x_a$ in each case shown is at a different height in $z$ of $0.6t_{ply}$ and $t_{ply}$, respectively. In all three regions, the two cases have almost identical shapes, but a difference in magnitude. In the “base” adherend, the case with a blunt tip height of $0.6t_{ply}$ reaches within 1% of the far-field value at a point that is -1.14 inches from the “base” bondline, or -1.19 inches from the corner of the blunt tip of the “patch” adherend. As this distribution nears the “base” bondline, the distribution decreases slightly to a value of 0.90 at a point that is -0.53 inches from the “base” bondline before increasing to a maximum value of 1.17 at the “base” bondline. Similarly, the case with a blunt tip height of $t_{ply}$ reaches within 1% of the far-field value at a point that is -1.27 inches from the “base” bondline or -1.32 inches from the blunt tip of the “patch” adherend. The distribution of this case then decreases slightly as it nears the “base” bondline to a minimum value of 0.94 at a point that is -0.86 inches from the “base” bondline before increasing to a maximum value of 1.38 at the “base” bondline.

The distributions of the normalized longitudinal strain in the adhesive along the axis of $x_a$ at a constant value of $z$ equal to $h_{blunt}$ are shown in Figure 5.17. Both cases show the same trend. The case with a blunt tip height of $0.6t_{ply}$ has an initial value of 1.38 at the “base” bondline before increasing to a maximum of 13.7 at the corner of the blunt tip of the “patch” adherend. Similarly, the case with a blunt tip height of $t_{ply}$ has an initial value of 1.60 at the “base” bondline and increases to a maximum value of 15.06 at the corner of the blunt tip of the “patch” adherend.

The distributions of the normalized longitudinal strain in the “patch” adherend along the axis of $x_a$ at a constant value of $z$ equal to $h_{blunt}$ are shown in Figure 5.18. The cases with a blunt tip height of $0.6t_{ply}$ and $t_{ply}$ have initial values equal to 0.55 and 0.65, respectively,
at the corner of the blunt tip of the “patch” adherend. The two case follow the same trend increasing as the distribution moves away from the blunt tip to a maximum value of 1.07 at a point that is 0.31 inches from the “base” bondline for the 0.6\(t_{\text{ply}}\) case, and a maximum value of 1.06 at a point that is 0.37 inches from the “base” bondline for the case of \(t_{\text{ply}}\). The case with a blunt tip of 0.6\(t_{\text{ply}}\) subsequently decreases to a local minimum of 0.89 at a point that is 1.53 inches from the “base” adherend, and then increases to within 1% of the far-field value at a point that is 1.76 inches from the “base” bondline. Similarly, the case with a blunt tip of \(t_{\text{ply}}\) decreases to a local minimum of 0.86 at a point that is 1.43 inches from the “base” adherend, and then increases to within 1% of the far-field value at a point that is 1.75 inches from the “base” bondline.

The distributions of the normalized shear strain along the axis of \(x_a\) at a constant value of \(z\) equal to \(h_{\text{blunt}}\) are shown in Figures 5.19, 5.20, and 5.21 for the “base” adherend, adhesive, and “patch” adherend, respectively. Similar to the distribution of the longitudinal strain, the two cases shown have almost identical shapes, but a difference in magnitude. In the “base” adherend, the cases with a blunt tip height of 0.6\(t_{\text{ply}}\) and \(t_{\text{ply}}\) have a value of strain of zero along a majority of the length of the axis of \(x_a\), except near the “base” bondline where the strain values increase with a positive magnitude to 2.71 and 3.18, respectively. In the distributions of shear strain in the adhesive shown in Figure 5.20, for the cases with a blunt tip of 0.6\(t_{\text{ply}}\) and of \(t_{\text{ply}}\), the distributions start with a value of -0.17 and -0.43 and decrease to -22.7 and -26.7, respectively, at the corner of the blunt tip of the “patch” adherend. The distribution of the shear strain in the “patch” adherend, shown in Figure 5.21, is similar as the two cases follow the same shape. The cases with a blunt tip height of 0.6\(t_{\text{ply}}\) and of \(t_{\text{ply}}\) have initial negative values of maximum magnitude of 4.82 and 6.13, respectively, at the corner of the blunt tip of the “patch” adherend. The two distributions then quickly approach zero along this axis of \(x_a\) until the end of the joint region where both cases have a local minimum/maximum before returning to zero strain along the remainder of the axis.

In comparison to the distributions shown along the axis of \(x_a\) at a constant value of \(z\) of \(h_{\text{blunt}}\), the distributions of the normalized longitudinal strain along the axis of \(x_a\) at a
Figure 5.19 Distribution of normalized shear strain in the “base” adherend at a constant value of $z$ equal to $h_{blunt}$ for the configurations with different heights of blunt tip.
Figure 5.20  Distribution of normalized shear strain in the adhesive at a constant value of $z$ equal to $h_{blunt}$ for the configurations with different heights of blunt tip.
Figure 5.21  Distribution of normalized shear strain in the “patch” adherend at a constant value of \( z \) equal to \( h_{\text{blunt}} \) for the configurations with different heights of blunt tip.
Figure 5.22  Distribution of normalized longitudinal strain in the “base” adherend at a constant value of $z$ equal to the height of one cured ply for the configurations with different heights of blunt tip.
Figure 5.23  Distribution of normalized longitudinal strain in the adhesive at a constant value of $z$ equal to the height of one cured ply for the configurations with different heights of blunt tip.
Figure 5.24  Distribution of normalized longitudinal strain in the “patch” adherend at a constant value of \( z \) equal to the height of one cured ply for the configurations with different heights of blunt tip.
constant value of z equal to the height of one cured ply (0.0074 inches) are shown in Figures 5.22, 5.23, and 5.24 for the “base” adherend, adhesive, and “patch” adherend, respectively. In the “base” adherend, the feathered edge case reaches within 1% of the far-field value at a point that is -1.16 inches from the “base” bondline and then increases to a maximum value of 1.17 before slightly decreasing to a strain value of 1.14 at the “base” bondline. The case of a blunt tip height of $0.6t_{ply}$ and the case of $t_{ply}$ both reach 1% of far-field at the same distance from the “base” bondline, at a location of -1.27 inches. The case of blunt tip height of $0.6t_{ply}$ then increases to a peak value of 1.85 at a point that is -0.02 inches from the “base” bondline before decreasing to a value of 1.81 at the bondline. The case of a blunt tip height of $t_{ply}$ only increases and to a maximum value of 1.38 at the “base” bondline.

The distributions of the normalized longitudinal strain in the adhesive along the axis of $x_a$ at a constant value of z equal to the height of one cured ply (0.0074 inches) are shown in Figure 5.23. The strain distribution in the feathered edge case is basically constant across the adhesive with a value equal to 1.999 in the adhesive at the “base” bondline and a value of 1.957 at the “patch” bondline. The case of a blunt tip height of $0.6t_{ply}$ shows a similar trend, but is not constant across the adhesive. The strain distribution in the adhesive for this case starts at a value of 2.98 at the “base” bondline and decreases to a value of 2.08 at the “patch” bondline. Alternatively, in the distribution of strain for the case of a blunt tip height of $t_{ply}$, there is an initial strain value equal to 1.60 at the “base” bondline and the strain increases to a value of 15.06 in the adhesive at the blunt tip of the “patch” adherend.

The distributions of the normalized longitudinal strain in the “patch” adherend along the axis of $x_a$ at a constant value of z equal to the height of one cured ply (0.0074 inches) are shown in Figure 5.24. The feathered edge case, case of a blunt tip height of $0.6t_{ply}$, and case of a blunt tip height of $t_{ply}$ each have initial values equal to 1.11, 0.96, and 0.64, respectively. The strain in the two cases with a blunt tip then increase while the strain in the feathered edge case decreases. All three configurations then converge and show the same distribution of strain through the “patch” adherend until the end of the joint region beneath the wide angle of the “patch” adherend. The feathered edge case decreases to a minimum value of
0.96 at a point that is 1.46 inches from the “patch” bondline. This case then reaches within 1% of the far-field value at a distance of 1.62 inches from the “patch” bondline. The case of a blunt tip height of 0.6tply decreases to a minimum value of 0.92 at a point located 1.42 inches from the “patch” bondline before increasing to within 1% of the far-field value at a point that is 1.66 inches from the “patch” bondline. Similarly, the case of blunt tip height of tply decreases to a value of 0.86 at a point located 1.37 inches from the “patch” bondline before increasing to within 1% of the far-field value at a point that is 1.69 inches from the “patch” bondline.

The distributions of the normalized shear strain along the axis of $x_a$ at a constant value of $z$ equal to the height of one cured ply (0.0074 inches) are shown in Figures 5.25, 5.26, and 5.27 for the “base” adherend, adhesive, and “patch” adherend, respectively. In the “base” adherend, there is shear strain equal to zero through most of the adherend until near the “base” bondline. In the feathered edge case, the strain distribution increases to a maximum value of 0.81 located at -0.64 inches from the “base” bondline then begins to decrease. As the strain distribution nears the bondline, the strain jumps back up to a peak value of 0.94 at a point located -0.48 inches from the “base” bondline before decreasing back to a final value of 0.13 at the bondline. Alternatively, the distribution for the case of a blunt tip height of 0.6tply in the “base” adherend increases to a value of 2.3 at a point that is -0.17 inches from the “base” bondline before decreasing to a value of 0.31 at a point that is -0.02 inches from the bondline. This case then has a final value of 0.66 at the “base” bondline. The strain distribution in the case of a blunt tip height of tply is different from the other two configurations in that the shear strain does not change directions, but increases to a value of 3.2 at the “base” bondline.

The distributions of the normalized shear strain in the adhesive along the axis of $x_a$ at a constant value of $z$ equal to the height of one cured ply (0.0074 inches) are shown in Figure 5.26. Similar to the longitudinal strain distribution shown in the adhesive, the distribution of the feathered edge case is roughly constant with a variation of -16.3 at the “base” bondline and -16.1 at the “patch” bondline. The case with a blunt tip height of 0.6tply increases
Figure 5.25  Distribution of normalized shear strain in the “base” adherend at a constant value of \( z \) equal to the height of one cured ply for the configurations with different heights of blunt tip.
Figure 5.26  Distribution of normalized shear strain in the adhesive at a constant value of $z$ equal to the height of one cured ply for the configurations with different heights of blunt tip.
Figure 5.27  Distribution of normalized shear strain in the “patch” adherend at a constant value of $z$ equal to the height of one cured ply for the configurations with different heights of blunt tip.
from a value of -31.4 at the “base” bondline to a value of -22.2 at the “patch” bondline. Alternatively, the case with a blunt tip height of $t_{ply}$ shows an opposite trend in that the distribution decreases from a value of -0.43 at the “base” bondline to a value of -26.7 at the corner of the blunt tip of the “patch” adherend.

The distributions of the normalized shear strain in the “patch” adherend along the axis of $x_a$ at a constant value of $z$ equal to the height of one cured ply (0.0074 inches) are shown in Figure 5.27. The feathered edge case, case of a blunt tip height of 0.6$t_{ply}$, and case of a blunt tip height of $t_{ply}$ have initial values at the “patch” bondline equal to 0.07, -1.24, and -6.13, respectively. After these initial values, the three different strain distributions converge and follow the same trend. Near the end of the joint at the region below the wide angle of the “patch” adherend, the strain distribution of each changes sign from a peak positive value to a peak negative value. The point at which this sign change occurs is the same point as the minimum values identified in Figure 5.24.

The distributions of the normalized longitudinal strain along the axis of $x_a$ at a constant value of $z$ equal to $t_{adherend}/2$ (the middle of the laminate) are shown in Figures 5.28 and 5.29 for the adhesive and the “patch” adherend, respectively. The distributions of strain in the “base” adherend for each specimen is not shown as it would be a mirrored reflection of the distribution in the “patch” adherend due to symmetry. In the adhesive, all three configurations are constant with similar values. The feathered edge case has a constant value of 1.81 through the adhesive while the cases of blunt tip heights of 0.6$t_{ply}$ and $t_{ply}$ have constant values of 1.81 and 1.80 respectively. Thus, these values are within 1% for the three configurations.

The distributions of the normalized longitudinal strain in the “patch” adherend along the axis of $x_a$ at a constant value of $z$ equal to $t_{adherend}/2$ (the middle of the laminate) are shown in Figure 5.29. At this location at the center of the adherend, the three cases have approximately the same initial value at the “patch” bondline equal to 1.03. From this initial value, the three cases have the same shape, but differences in magnitude towards the end of the joint region before converging to the far-field value. Towards the end of the joint region,
Figure 5.28  Distribution of normalized longitudinal strain in the adhesive at a constant value of $z$ equal to $t_{adherend}/2$ for the configurations with different heights of blunt tip.
Figure 5.29 Distribution of normalized longitudinal strain in the “patch” adherend at a constant value of $z$ equal to $\frac{t_{\text{adherend}}}{2}$ for the configurations with different heights of blunt tip.
each case has two separate peaks. Comparing the local minimum between the two peaks where the strain drops slightly, the case of the feathered edge has a value of 1.02 located 0.85 inches from the “base” bondline, and reaches within 1% of the far-field value at a point that is 0.98 inches from the “base” bondline. The case with a blunt tip height of 0.6\(t_{\text{ply}}\) has a local minimum value of 1.04 located 0.76 inches from the “base” bondline, and reaches within 1% of the far-field value at a point that is 1.04 inches from the “base” bondline. For the case of a blunt tip height of \(t_{\text{ply}}\), the local minimum has a value of 1.08 at a point that is 0.71 inches from the “base” bondline, and reaches within 1% of the far-field value at a point that is 1.07 inches from the “base” bondline.

The distributions of the normalized shear strain along the axis of \(x_a\) at a constant value of \(z\) equal to \(t_{\text{adherend}}/2\) (the middle of the laminate) are shown in Figures 5.30 and 5.31 for the adhesive and the “patch” adherend, respectively. The distributions of the three cases in the adhesive and the “patch” adherend are very similar to the longitudinal strain. In the adhesive, the three cases all show a constant strain of basically the same value. This value is approximately 14.66 with less than 1% variation between the three cases. In the “patch” adherend, similar to the longitudinal strain, the three cases have approximately the same initial strain at the bondline. The case of a feathered edge, of 0.6\(t_{\text{ply}}\), and of \(t_{\text{ply}}\) have initial values equal to 0.12, 0.11, and 0.12, respectively. Near the end of the joint region, the three cases all show a jump from a positive value to a negative value before returning to a value of zero along the remainder of the axis. The location where each case crosses zero is the same location as the local minimum described in the distribution of the longitudinal strain.

In the case of the feathered edge, the distribution drops from its initial value to a negative value of -0.23 at a point located 0.87 inches from the “base” bondline. The case with a blunt tip height of 0.6\(t_{\text{ply}}\) shows a change in sign as the distribution jumps from a peak positive to a peak negative value. These values are equal to 0.37 and -0.38. Similarly, the case with a blunt tip height of \(t_{\text{ply}}\) shows a jump from a peak positive to a peak negative value with values equal to 0.66 and -0.49.

The results along the various axes of \(z_a\) are subsequently presented. First, the distribu-
Figure 5.30 Distribution of normalized shear strain in the adhesive at a constant value of $z$ equal to $t_{adherend}/2$ for the configurations with different heights of blunt tip.
Figure 5.31  Distribution of normalized shear strain in the “patch” adherend at a constant value of $z$ equal to $t_{adherend}/2$ for the configurations with different heights of blunt tip.
tions of the normalized longitudinal strain are presented along the axis of \( z_a \) at the location of the sharp feathered tip, or, in the cases that have a blunt tip, this is the location where the feathered tip would be if the blunt tip did not exist. These distributions are shown in Figure 5.32. In the case of the feathered edge, there is a large initial strain value of 10.2 at the corner of the feathered edge. This strain value drops quickly through the adhesive thickness until the interface of the “base” bondline, which is located 0.003 inches from the feathered edge along the axis of \( z_a \). In this case, the strain distribution at this interface jumps from 2.49 in the adhesive to 1.38 in the “base” adherend. After this jump, the strain value begins to level to a more constant value until a final value of 0.94 is reached at the top of the “base” adherend. In the case of a blunt tip height of \( 0.6t_{py} \), the strain is relatively constant through the adhesive with an initial value of 1.19 at the bottom of the specimen and a final value of 1.18 in the adhesive at the “base” bondline. The strain for this case then jumps to a value of 1.05 and slowly increases to a maximum value of 1.136 at a point that is 0.012 inches along the axis before settling back to a final value of 0.92 at the top of the “base” adherend. Similar to the other blunt tip case, in the case of the blunt tip height of \( t_{py} \), the strain is relatively constant through the adhesive with an initial value of 1.13 at the bottom of the specimen and a final value of 1.12 in the adhesive at the “base” bondline. The strain for this case then jumps to a value of 1.0 and slowly increases to a maximum value of 1.129 at a point that is 0.020 inches along the axis before settling back to a final value of 0.91 at the top of the “base” adherend.

The distributions of the normalized shear strain along the axis of \( z_a \) at this same location in \( x \) of the location of the “nominal” feathered edge are presented in Figure 5.33. In the case of the feathered edge, there is an initial strain value of -10.5 in the adhesive at the corner of the feathered edge. Following the axis through the adhesive, the strain decreases to a value of -11.0 at a point that is 0.0018 along the axis of \( z_a \) before increasing to a final value of -10.07 in the adhesive at the “base” bondline interface. In this case, the strain jumps to a value of 1.59 in the adherend across the bondline and then begins to decrease. The distribution crosses a value of strain of zero at a point that is 0.029 inches along the axis, and continues
Figure 5.32  Distribution of normalized longitudinal strain through the thickness in z at a constant value of x equal to the location of the “nominal” feathered edge for the configurations with different heights of blunt tip.
to decrease before curving back to a final value of -0.027. Similar to the longitudinal strain, the two cases with a blunt tip are very similar to one another. In the case of the blunt tip height of 0.6\(t_{ply}\), the configuration has an initial value of approximately zero at the bottom of the specimen in the adhesive. This decreases slightly through the adhesive to a value of -0.05 in the adhesive at the “base” bondline. In this case, the strain jumps to a peak value of 2.47 in the adherend, and then decreases until it cross a value of zero at a point that is 0.024 inches along the axis before ending with a final value of -0.08 at the top of the adherend.

In the case with a blunt tip height of \(t_{ply}\), similar to the other blunt tip case, the strain is approximately zero at the bottom and decreases to a value of -0.04 in the adhesive at the “base” bondline before jumping to a value of 2.37 in the adherend. In this case, a value of zero is reached at a point that is 0.028 inches along the axis. The distribution of strain then continues to curve until reaching a value of -0.09 at the top of the adherend.

The results along the axis of \(z_a\) at a constant value of \(x\) where the blunt tip occurs for the case of a blunt tip height of \(t_{ply}\) in the “patch” adherend are subsequently presented. The distributions of the normalized longitudinal strain through the joint thickness are first presented in Figure 5.34. In the case of the feathered edge, the distribution is roughly constant through the thickness with values only changing at the bondlines. Through the “patch” adherend at this distance beyond the feathered edge, there is an initial value of 1.13 at the bottom of the adherend and a value of 1.11 in the adherend at the “patch” bondline. Along this axis, the shear strain then jumps to a constant value in the adhesive of 1.96 and then jumps back at the “base” bondline to a value of 1.11 in the “base” adherend and slowly decreases to a final value of 0.95 at the top of the “base” adherend. In the case of a blunt tip height of 0.6\(t_{ply}\), the distribution is not as consistent as in the feathered case. In this blunt tip case, the initial value at the bottom of the “patch” adherend equals 0.89 and increases to a value of 0.98 in the adherend at the “patch” bondline before jumping to a value of 2.06 in the adhesive at the “patch” bondline. The distribution along this axis increases through the adhesive to a value of 2.22 in the adhesive at the “base” bondline before jumping down to a value of 1.17 in the adherend at the “base” bondline. The strain then slightly decreases
Figure 5.33  Distribution of normalized shear strain through the thickness in z at a constant value of x equal to the location of the “nominal” feathered edge for the configurations with different heights of blunt tip.
to a final value of 0.92 at the top of the “base” adherend. In the case of the blunt tip height of $t_{ply}$, this is considered initially within the “patch” adherend. The distribution is much different in magnitude compared to the other two cases as the axis is located at the location of the blunt tip for this configuration. This case has an initial strain value of 0.28 followed by a minimum value of 0.19 at a point that is 0.003 inches from the bottom of the adherend, and then a value of 0.71 in the “patch” adherend at the corner of the blunt tip. At the “patch” bondline, the strain jumps in value to a peak of 5.5 in the adhesive above the “patch” blunt tip. The strain distribution decreases in value along the axis through the adhesive to a value of 4.5 at the “base” bondline before jumping to a value of 2.07 in the “base” adherend. In this case, the distribution continues to slowly decrease in value along the axis through the “base” adherend to a final value of 0.78 at the top of the adherend.

The distributions of the normalized shear strain along the axis of $z_a$ at a constant value of $x$ equal to the location where the blunt tip occurs for the case of a blunt tip height of $t_{ply}$ are presented in Figure 5.35. The distributions for the three cases are very similar in shape and trend as the longitudinal strain, but negative in magnitude. The feathered edge case has an initial value of 0.01 and increases to a value of 0.07 in the adherend at the “patch” bondline before jumping to a value of -16.0 in the adhesive. In this case, the strain in the adhesive region stays approximately constant followed by a jump back to a value of 0.09 in the “base” adherend at the bondline, and reaching a final value of 0.01 at the top of the “base” adherend. In the case with a blunt tip height of 0.6$t_{ply}$, the strain decreases from an initial value of -0.09 at the bottom of the “patch” adherend to a value of -1.05 in the “patch” adherend at the bondline. At the bondline, the strain jumps to a value of -21.1 in the adhesive and remains relatively constant before jumping back to a value of -0.56 in the “base” adherend at the bondline, and reaching a final value of 0.04 at the top of the “base” adherend. In the “patch” adherend of the case with a blunt tip height of $t_{ply}$, the strain increases in magnitude from an initial value of -1.38 at the bottom of the “patch” adherend to a value of -4.84 at the bondline. The strain jumps to a magnitude of -48.8 in the adhesive at the “patch” bondline and -34.9 in the adhesive at the “base” bondline. The magnitude
Figure 5.34  Distribution of normalized longitudinal strain through the thickness in $z$ at a constant value of $x$ equal to the location where the blunt tip occurs for the case of a blunt tip height of $t_{\text{ply}}$ for the configurations with different heights of blunt tip.
Figure 5.35  Distribution of normalized shear strain through the thickness in z at a constant value of x equal to the location where the blunt tip occurs for the case of a blunt tip height of $t_{\text{ply}}$ for the configurations with different heights of blunt tip.
then jumps in the “base” adherend to a value of 0.64 at the “base” bondline and slowly decreases in magnitude along the axis to a value of 0.09 at the top of the “base” adherend.

The distributions of the normalized longitudinal strain and normalized shear strain along the axis of $z_a$ at the wide angle are presented in Figure 5.36 and 5.37, respectively. In both figures, the three cases considered show very similar trends. In the distribution of the normalized longitudinal strain, the case with a feathered edge, case of a blunt tip height of 0.6$t_{ply}$, and case of a blunt tip height of $t_{ply}$, have initial values equal to 0.974, 0.966, and 0.956, respectively. The feathered edge case increases to a maximum value of 1.04 at a point that is 0.069 inches through the thickness and a final value of 0.68 at the top of the “patch” adherend at the wide angle. Similarly, the case with a blunt tip height of 0.6$t_{ply}$ has a maximum value of 1.06 at a point that is 0.063 inches through the thickness, and a final value of 0.65 at the wide angle of the “patch” adherend. Finally, the case with a blunt tip height of $t_{ply}$ has a maximum value of 1.07 at a point that is 0.059 inches through the thickness, and this is followed by a final value of 0.64 at the wide angle of the “patch” adherend.

The distributions of the normalized shear strain along the axis of $z_a$ at the wide angle are presented in Figure 5.37. The feathered edge, 0.6$t_{ply}$, and $t_{ply}$ cases have values of -0.044, -0.049, and -0.055, respectively, at the bottom of the “patch” adherend. The case with the feathered edge has a minimum value of -0.22 at a point that is 0.029 inches through the thickness, a maximum value of 0.93 at a point that is 0.087 inches through the thickness and a value of 0.75 at the wide angle of the “patch” adherend. Similarly, in the case of a blunt tip height of 0.6$t_{ply}$, there is a minimum value of -0.34 at a point that is 0.029 inches through the thickness, a maximum value of 0.97 at a point that is 0.085 inches through the thickness, and a value of 0.72 at the wide angle of the “patch” adherend. Finally, in the case with a blunt tip height of $t_{ply}$, there is a minimum value of -0.42 at a point that is 0.029 inches through the thickness, a maximum value of 0.98 at a point that is 0.085 inches through the thickness, and a value of 0.71 at the wide angle of the “patch” adherend.
Figure 5.36  Distribution of normalized longitudinal strain through the thickness in z at a constant value of x equal to the location of the wide angle for the configurations with different heights of blunt tip.
Distribution of normalized shear strain through the thickness in $z$ at a constant value of $x$ equal to the location of the wide angle for the configurations with different heights of blunt tip.
5.2 Effects of the Laminate Thickness

In this section, the results of three configurations with the same height of the blunt tip equal to the nominal thickness of one ply of cured composite (0.0074 in), but with different laminate thicknesses of $[\pm 15]_s$, $[\pm 15]_{3s}$, and $[\pm 15]_{5s}$, are presented. These yield blunt height ratios, BH, equal to 25%, 8.3%, and 5%, respectively.

For each of these configurations, results are presented in a similar manner as in Section 5.1 via the distribution of the normalized longitudinal strain, $\epsilon_{11}$, and the normalized engineering shear strain, $\gamma_{13}$. The same sets of axes as previously described are used. These are along the directions of $x'$, $x_a$, and $z_a$ as shown in Figure 5.1. These are along the bondline from the corner in the adherend and at the midline of the joint. Due to the fact that the feathered edge case is not being considered in this section, the origin for all results along the bondline is at the corner created by the blunt tip. This is for simplicity and ease of comparison since all configurations under consideration have the same blunt tip height in the joint region. This implies that since the origin remains at the corner created by the blunt tip, the location in the adhesive between the point where the sharp feathered edge would be and the blunt tip is negative in value for $x'$. The strains are also presented along three different axes of $x_a$ as shown in Figure 5.3. These axes are located at the bottom of the adherend (z equal to 0), at the corner created by the blunt tip (z equal to $h_{blunt}$), and at the centerline of the adherend (z equal to $t_{adherend}/2$). Strains are also presented along several different axes of $z_a$. These axes are located at the location in x where there would be a feathered tip for the “patch” adherend, at the location in x of the “patch” blunt tip, and at the location in x of the end of the joint in the “patch” adherend (at the wide angle). Note that for the axis of $z_a$ at the location in x of the “patch” blunt tip, two sets of plots are presented to show the distributions in the adhesive directly in front of the blunt and the adherend directly behind the blunt tip. Also, in order to compare these three models that have varying geometry in the joint region, the strain distributions are plotted against true location values along the axes.

The distributions of the normalized longitudinal strain in the adherend along the “patch”
Figure 5.38  Distribution of normalized longitudinal strain in the “patch” adherend at the bondline from the corner for the configurations with different laminate thicknesses.
Figure 5.39  Distribution of normalized longitudinal strain in the “patch” adherend at the bondline flipped with origin at the wide angle for the configurations with different laminate thicknesses.
Figure 5.40 Distribution of normalized shear strain in the “patch” adherend at the bondline from the corner for the configurations with different laminate thicknesses.
bondline are shown in Figure 5.38. Results are shown along \( x_{\text{bondline}} \) at a starting point that is one element length into the "patch" adherend and at the corner created by the blunt tip of the "patch" adherend. All of the configurations shown have a minimum near the corner created by the blunt tip, and a maximum peak located towards the end of the bondline near the wide angle of the "patch" adherend. The configuration with a BH equal to 25% has a shorter bondline due to the thinner laminate thickness. This thinner configuration has a strain of about 1.0 at the corner created by the blunt tip before decreasing to a minimum of 0.89 at a point that is 0.01 inches along the bondline from that corner. The two configurations with a BH value of 8.3% and 5% have normalized longitudinal strain values equal to 0.69 and 0.64, respectively, near the corner created by the blunt tip. Approximately 0.1 inches away from the corner created by the blunt tip, a change in slope occurs in each configuration. In the configuration having a BH of 25% the slope increases towards a maximum value of the strain of 3.8 at a point that is 0.19 inches from the end of the bondline near the wide angle of the "patch" adherend. The other two configurations level out to approximately a constant value along the bondline away from the blunt tip. This value has a 1% variation between the center region of the bondline for the cases of BH of 8.3% and 5% where minimum values of 1.02 and 1.03 occur, respectively. Near the end of the bondline, a peak strain value of 2.2 occurs for the case of a BH of 8.3% at a location that is 0.19 inches away from the end of the bondline. Similarly, the case of a BH of 5% has a peak value equal to 2.0 at a location that is also 0.19 inches away from the wide angle of the patch adherend. The three configurations, with a BH of 25%, 8.3%, and 5%, have values of 0.73, 0.64, and 0.61, respectively, at the end of the bondline at the wide angle of the "patch" adherend.

In order to show that these peaks in Figure 5.38 occur at a similar distance from the wide angle of the patch adherend, the distribution of the normalized longitudinal strain is plotted from the opposite direction. This distribution of the longitudinal strain in the adherend of the "patch" bondline is shown in Figure 5.39, with the origin at the corner of the wide angle in the patch adherend and ending at the corner created by the blunt tip. The three configurations, which all have a blunt tip height of 0.0074 inches, have a maximum
peak located 0.19 inches along the bondline from the wide angle. This can be related to a distance in the z-direction using the scarf angle to 0.0099 inches from the top of the adherend. Note that this is a representative case as this portrayal of the results flipped along the axis of x' can be shown in all results along the other axis of x' that are presented.

The distributions of the normalized shear strain in the adherend along the “patch” bondline are shown in Figure 5.40. These three cases have similar shapes with an initial negative shear strain of large magnitude near the corner of the blunt tip before rapidly approaching zero. Then, near the wide angle of the “patch” adherend at the end of the bondline, there is a local minimum followed by a maximum peak. After the initial negative shear strain value of -9.3 at the corner of the blunt tip, the case of a BH of 25% increases to an initial local maximum of 0.24 that is located 0.15 inches from the corner of the blunt tip. In this case, the strain then drops back to a local minimum of 0 before climbing to a maximum value of 5.8 located 0.16 inches from the end of the bondline. Similar to the longitudinal strain, the cases of a BH of 8.3% and 5% look similar in shape. Starting from negative values near the corner of the blunt tip, the distribution of shear strain in both configurations approach zero as the distance from the blunt tip increases and remain constant along the bondline. These cases each have an initial value of -6.2 and -5.8, respectively. As the case of BH of 8.3% approaches the end of the bondline, near the wide angle, the normalized shear strain decreases to a local minimum of -1.5 located 0.22 inches from the end of the bondline followed by a maximum of 3.3 located 0.16 inches from the end of the bondline. Similarly, the case of BH of 5% has a local minimum equal to -1.5 at a distance of 0.22 inches from the end of the bondline followed by a maximum shear strain value of 3.0 located 0.16 inches from the end of the bondline. At the end of the bondline, at the wide angle of the “patch” adherend, the three cases of BH of 25%, 8.3%, and 5% have a final value of 0.78, 0.71, and 0.69, respectively.

The distributions of the normalized longitudinal strain in the adhesive along the “patch” bondline are shown in Figure 5.41. All three configurations demonstrate similar results with a maximum peak located in the adhesive at the corner created by the blunt tip before returning
Figure 5.41  Distribution of normalized longitudinal strain in the adhesive at the “patch” bondline from the corner for the configurations with different laminate thicknesses.
Figure 5.42  Distribution of normalized shear strain in the adhesive at the "patch" bondline from the corner for the configurations with different laminate thicknesses.
to a minimum value and then a second peak located towards the end of the bondline near the wide angle of the “patch” adherend. The cases with a BH of 25%, 8.3%, and 5% have a maximum strain value at the corner of the “patch” blunt tip equal to 24.9, 15.3, and 14.5, respectively. The three configurations, follow a similar trend of decreasing strain until a distance of 0.24 inches along the bondline where the case of BH of 25% has a local minimum value of 2.2 after which the strain increases along the length of the bondline until a second peak is reached with a strain value equal to 7.8 located 0.19 inches from the end of the bondline. Alternatively, the other two configurations level out to a constant strain value equal to 1.81 for most of the bondline. The variation at the middle region for the two cases varies by roughly 1% with minimum values of 1.81 and 1.80. Towards the end of the bondline, the case with a BH of 8.3% has a second peak strain equal to 4.9 located 0.19 inches from the end of the bondline. Similarly, the case with a BH of 5% has a second peak strain equal to 4.4 located 0.19 inches from the end of the bondline.

The distributions of the normalized shear strain in the adhesive along the “patch” bondline are shown in Figure 5.42. All three configurations have a maximum magnitude of the normalized shear in the adhesive at the corner of the blunt tip. The cases with a BH of 25%, 8.3%, and 5% have maximum magnitudes of normalized shear strain at the corner equal to 66.9, 46.3, and 42.9, respectively. The normalized shear strain in the configuration with a BH of 25% then decreases in magnitude along the bondline moving away from the blunt tip in the “patch” adherend. At a distance equal to 0.31 inches from the end of the bondline, at the wide angle of the “patch” adherend, a local minimum occurs in the magnitude of the normalized shear strain equal to 19.3. The shear strain then increases in magnitude as it moves towards the end of the bondline. A local maximum in the magnitude equal to 53.7 occurs at a distance of 0.20 inches from the end of the bondline. In the cases with a BH of 8.3% and 5%, after the maximum at the corner of the blunt tip, the normalized shear strain increases to a similar minimum magnitude equal to approximately 15 and remains constant along the center region of the bondline. In each configuration, near the wide angle of the patch adherend, there is a local maximum in the magnitude of the normalized shear strain.
The configuration with a BH of 8.3% has a local maximum in the magnitude equal to 39.0 at a distance of 0.20 inches from the end of the bondline. Similarly, the configuration with a BH of 5% has a local maximum in the magnitude equal to 36.5 at a distance of 0.20 inches from the end of the bondline.

The distributions of the normalized longitudinal strain along the midline in the adhesive are shown in Figure 5.43. The results from all three configurations are symmetric along the midline with peaks located at either end near the regions closest to the blunt tips and a minimum value between the two peaks. The configuration with a BH of 25% has a maximum at the peaks equal to 12.9 located 0.167 inches from the origin followed by a center minimum of 2.25. The configuration with a BH of 8.3% has a peak value of 8.5 located 0.167 inches from the origin and a minimum value of 1.81. Similarly, the configuration with a BH of 5% has a maximum value of 7.7 located 0.167 inches from the origin and a minimum value of 1.80. Note that the through-thickness location (along the z-axis) for the corner of the blunt tip on the midline is located at a distance equal to 0.1414 inches from the origin along the midline for a blunt tip height equal to 0.0074 inches.

The distributions of the normalized shear strain along the midline in the adhesive are shown in Figure 5.44. The results for all three configurations are similar to those for the longitudinal strain along the midline in such that the results are symmetric, but negative in magnitude. The configuration with a BH of 25% has a maximum magnitude at the peaks equal to 57.8 located 0.17 inches from the origin followed by a center minimum of 19.1. The configuration with a BH of 8.3% has a peak magnitude of 40.4 located 0.17 inches from the origin and a minimum value of 14.6. Similarly, the configuration with a BH of 5% has a maximum magnitude of 37.3 located 0.17 inches from the origin and a minimum of 14.7.

The results along the various axes of $x_a$ are subsequently presented. First, the normalized longitudinal strain along the axis of $x_a$ at a height in z of 0 is presented in Figures 5.45, 5.46, and 5.47, for the three different model sections: “base” adherend, adhesive, and “patch” adherend. As in Section 5.1, due to symmetry, the distributions at the top of the model, a value of z equal to the thickness of the adherend, are similar to the strain distribu-
Figure 5.43  Distribution of normalized longitudinal strain in the adhesive at the midline for the configurations with different laminate thicknesses.
Figure 5.44  Distribution of normalized shear strain in the adhesive at the midline for the configurations with different laminate thicknesses.
tions across the bottom of the model, a value of \( z \) of 0, except that the distributions are from the “patch” bondline with the positive direction towards the “base” due to the symmetry of the geometry.

The distributions of the normalized longitudinal strain in the “base” adherend along the axis of \( x_a \) for a \( z \) value of 0 are presented in Figure 5.45. The results have been cropped to present the distributions less than a distance of 2.0 inches from the “base” bondline. Any results beyond this point would give no additional information as all configurations have come within 1\% of their far-field values at this point. All three cases under consideration show a similar shape as the strain distributions start at the far-field value and decrease in value in nearing the “base” bondline. The configuration with a BH of 25\% reaches within 1\% of the far-field value a distance of -0.31 inches from the “base” bondline and has a minimum strain value of 0.73 at the “base” bondline. The case with a BH of 8.3\% reaches within 1\% of the far-field value at a distance of -0.86 inches from the “base” bondline and then decreases to a minimum value of 0.64 at the “base” bondline. The configuration with a BH of 5\% reaches within 1\% of the far-field value at the greatest distance from the “base” bondline, -1.32 inches, and has a minimum value of 0.61 at the “base” bondline.

The distributions of the normalized longitudinal strain in the adhesive along the axis of \( x_a \) for a z value of 0 is shown in Figure 5.46. The strain values in the adhesive, at the “base” bondline, are the same values as the minimum values in the “base” adherend at the bondline. This indicates stress equilibrium across the bondline from the adherend to the adhesive at the wide angle of the “base” adherend. In the three cases, the distributions then increases in magnitude. The cases with a BH of 25\%, 8.3\%, and 5\% increase to a maximum value of 21.3, 11.4, and 10.4, respectively, at the blunt tip region of the “patch” adherend. Note that in all three cases, a “blip” occurs where the distributions of strain level out briefly before continuing to a peak magnitude. This “blip” occurs approximately 0.005 inches from the blunt tip in each configuration and is shown in the distributions of both the normalized longitudinal strain and normalized shear strain.

The distributions of the normalized longitudinal strain in the “patch” adherend along
Figure 5.45  Distribution of normalized longitudinal strain in the "base" adherend at a constant value of z equal to 0 for the configurations with different laminate thicknesses.
Figure 5.46  Distribution of normalized longitudinal strain in the adhesive at a constant value of $z$ equal to 0 for the configurations with different laminate thicknesses.
Figure 5.47  Distribution of normalized longitudinal strain in the “patch” adherend at a constant value of z equal to 0 for the configurations with different laminate thicknesses.
the axis of $x_a$ for a $z$ value of 0 are shown in Figure 5.47. The results from the three configurations have been cropped to only present the distributions less than a distance of 3.5 inches along the axis of $x_a$ from the “base” bondline. Any results beyond this point would give no additional information as all configurations have come within 1% of the fair-field value. The configuration with a BH of 25% is similar in shape to the other two cases, but with greater extremes in magnitude. Starting with an initial strain of 0.51, the distribution increases to a strain of 1.09 at a location of 0.28 inches from the “base” bondline or 0.08 inches from the blunt tip of the “patch” adherend. After this peak, the strain in this case quickly decreases to a value of -0.32 at a location of 0.43 inches from the “base” bondline or 0.23 inches from the blunt tip. This location can be compared to the location of the wide angle of the “patch” adherend, which is at a point 0.62 inches from the “base” bondline or 0.43 inches from the blunt tip of the “patch” adherend. The configuration with a BH of 8.3% has an initial strain value of 0.28 at the blunt tip region. This increases to a local maximum of 1.06 at a distance of 0.53 inches from the “base” bondline or 0.32 inches from the blunt tip of the “patch” adherend. The distribution then continues with a negative slope to a local minimum of 0.78 at a distance of 1.58 inches from the “base” bondline or 1.37 inches from the blunt tip of the “patch” adherend. This local minimum is just before the end of the joint region, or the location of the wide angle of the “patch” adherend, which is a distance of 1.55 inches from the blunt tip of the “patch” adherend. A very similar distribution is seen in the case of BH of 5%. This case has an initial strain value of 0.26 at the blunt tip region followed by a maximum value of 1.05 at a location 0.68 inches from the “base” bondline or 0.49 inches from the blunt tip of the “patch” adherend. The distribution then decreases to a local minimum of 0.89 at a location of 2.69 inches from the “base” bondline or 2.49 inches from the blunt tip of the “patch” adherend. The location of this minimum strain value can be compared to the location of the wide angle of the “patch” adherend, which is at a location of 2.68 inches from the blunt tip. The three cases with a BH of 25%, 8.3%, and 5%, then reach within 1% of the far-field value at a location that is 0.68 inches, 1.90 inches, and 3.04 inches from the “base” bondline, respectively.
The normalized shear strain distributions along the axis of $x_a$ at a value of $z$ equal to 0 are presented in Figures 5.48, 5.49, and 5.50, for the three different model sections: "base" adherend, adhesive, and "patch" adherend. For each figure, the axis of $x_a$ has been cropped in a similar manner as in the longitudinal strain plots previously described.

The distributions of the normalized shear strain in the "base" adherend along the axis of $x_a$ for a value of $z$ equal to 0 are presented in Figure 5.48. The results for each configuration are very similar in shape. Each configuration experiences a shear strain of zero in a majority of the "base" adherend, but the value of shear strain increases when very near the wide angle of the "base" adherend. The cases of a BH of 25%, 8.3%, and 5% have a peak value of 0.78, 0.71, and 0.69, respectively.

The distributions of the normalized shear strain in the adhesive along the axis of $x_a$ for a value of $z$ equal to 0 are presented in Figure 5.49. In all three cases, the strain jumps back to zero in the adhesive at the wide angle of the "base" adherend until very near the blunt tip region where there is a local minimum and maximum before a large drop in value. The cases with a BH of 25%, 8.3%, and 5% drop to a shear strain value of -24.3, -13.3, and -12.2, respectively, at the blunt tip of the "patch" adherend.

The distributions of the normalized shear strain in the "patch" adherend along the axis of $x_a$ at a $z$ value of 0 are shown in Figure 5.50. In the figure, it appears that all of the configurations start at an initial negative value of shear strain before increasing to zero. This initial negative strain value is the result of one or two data points in each case. In the case of BH of 25%, the value of strain jumps from -2.59 to 0.7 at the blunt tip of the "patch" adherend. From the initial jump at the blunt tip region, the three cases all decrease to a local minimum at approximately the same distance from the blunt tip. In the case of a BH of 25%, this value is equal to -0.35 at a point 0.21 inches from the "base" bondline or 0.01 inches from the blunt tip of the "patch" adherend. In the case of a BH of 8.3% and 5%, this value is equal to -0.23 and -0.20, respectively, at the same distance of 0.22 inches from the "base" bondline or 0.02 inches from the blunt tip of the "patch" adherend. Following these initial trends, which are similar for all three configurations close to the blunt tip, all three
Figure 5.48  Distribution of normalized shear strain in the “base” adherend at a constant value of z equal to 0 for the configurations with different laminate thicknesses.
Figure 5.49 Distribution of normalized shear strain in the adhesive at a constant value of $z$ equal to 0 for the configurations with different laminate thicknesses.
Figure 5.50  Distribution of normalized shear strain in the “patch” adherend at a constant value of z equal to 0 for the configurations with different laminate thicknesses.
configurations experience a local maximum and minimum where the shear strain changes from a positive value to a negative value before returning to zero. The location where this change of sign occurs for each configuration is at the same location of \( x_a \) as the local minimum values in the distributions of the normalized longitudinal strain. Each configuration changes sign at a location of 0.19 inches from the end of the joint region or the location of the wide angle of the “patch” adherend.

The distributions of the normalized longitudinal strain along the axis of \( x_a \) for a constant value of \( z \) equal to \( h_{\text{blunt}} \) are shown in Figures 5.51, 5.52, and 5.53 for the “base” adherend, adhesive, and “patch” adherend, respectively. The distributions in the “base” adherend are first presented in Figure 5.51. In the “base” adherend, the case with a BH of 25% reaches within 1% of the far-field value at a location of -0.59 inches from the “base” bondline or -0.65 inches from the blunt tip of the “patch” adherend. Unlike the other two cases, there is no negative slope to the strain distribution in this case. Instead, the strain distribution increases to a value of 2.4 at the “base” bondline in front of the blunt tip of the “patch” adherend. Comparatively, the case with a BH of 8.3% reaches within 1% of the far-field value at a location of -1.27 inches from the “base” bondline or -1.32 inches from the corner created by the “patch” blunt tip. The strain distribution then descends to a minimum value of 0.94 at a location -0.86 inches from the “base” bondline or -0.92 inches from the blunt tip. In this case, the distribution then increases to a maximum value of 1.4 at the bondline of the “base” adherend. Note that the case with a BH of 5% is very similar to the case with a BH of 8.3%. This case reaches within 1% of the far-field value at a location equal to -1.80 inches from the “base” bondline or -1.86 inches from the corner of the blunt tip of the “patch” adherend. This distribution of strain then decreases to a minimum of 0.91 at a distance of -0.91 inches from the “base” bondline or -0.96 inches from the “patch” blunt tip, and then a maximum value of 1.26 at the “base” bondline.

The distributions of the normalized longitudinal strain in the adhesive along the axis of \( x_a \) for a constant value of \( z \) equal to \( h_{\text{blunt}} \) are presented in Figure 5.52. The case with a BH of 25% is similar in shape to the other two configurations, but has greater magnitudes of
Figure 5.51  Distribution of normalized longitudinal strain in the “base” adherend at a constant value of z equal to $h_{blunt}$ for the configurations with different laminate thicknesses.
Figure 5.52  Distribution of normalized longitudinal strain in the adhesive at a constant value of $z$ equal to $h_{\text{blunt}}$ for the configurations with different laminate thicknesses.
Figure 5.53  Distribution of normalized longitudinal strain in the “patch” adherend at a constant value of $z$ equal to $h_{blunt}$ for the configurations with different laminate thicknesses.
strain with a strain value of 2.87 at the “base” bondline and a maximum strain value of 24.5 at the corner created by the blunt tip of the “patch” adherend. Alternatively, the case with a BH of 8.3% has an initial strain of 1.6 at the “base” adherend bondline and then increases to a maximum value of 15.06 at the corner created by the blunt tip of the “patch” adherend. Similarly, the case with a BH of 5% has an initial strain value of 1.46 and increases to a maximum value of 14.0.

The distributions of the normalized longitudinal strain in the “patch” adherend along the axis of $x_a$ for a constant value of $z$ equal to $h_{\text{blunt}}$ are shown in Figure 5.53. The cases with a BH of 25%, 8.3%, and 5% have initial values of 0.99, 0.69, and 0.66, respectively. The three cases then drop to a local minimum 0.84, 0.64, and 0.59, respectively. These local minima occur at a distance of 0.066 inches from the “base” bondline in the case of a BH of 25% and at a distance of 0.063 inches from the “base” bondline in the cases of a BH of both 8.3% and 5%. These three cases then increase to maximum values of 1.12 at a point 0.19 inches from the “base” bondline, of 1.06 at a point 0.38 inches from the “base” bondline, and of 1.04 at a point 0.53 inches from the “base” bondline for the cases of BH of 25%, 8.3%, and 5%, respectively. All three configurations then have a minimum value at the same location, located 0.19 inches from the wide angle of the “patch” adherend. At these locations, the cases with BH of 25%, 8.3%, and 5% have local minimum strain values equal to 0.91, 0.86, and 0.92, respectively. These three configurations then approach to within 1% of the far-field value at locations 0.43 inches, 1.69 inches, and 2.85 inches, respectively, from the corner created by the blunt tip of the “patch” adherend.

The distributions of the normalized shear strain along the axis of $x_a$ at a constant value of $z$ equal to $h_{\text{blunt}}$ are presented in Figures 5.54, 5.55, and 5.56 for the “base” adherend, adhesive, and “patch” adherend, respectively. In the “base” adherend, there is a shear strain of zero through most of the adherend until near the joint region. In the three cases with a BH of 25%, 8.3%, and 5%, the strain increases to values of 5.2, 3.2, and 2.9, respectively, at the “base” bondline.

The distributions of the normalized shear strain in the adhesive along the axis of $x_a$ at
Figure 5.54 Distribution of normalized shear strain in the “base” adherend at a constant value of z equal to $h_{blunt}$ for the configurations with different laminate thicknesses.
Figure 5.55  Distribution of normalized shear strain in the adhesive at a constant value of $z$ equal to $h_{blunt}$ for the configurations with different laminate thicknesses.
Figure 5.56  Distribution of normalized shear strain in the “patch” adherend at a constant value of $z$ equal to $h_{blunt}$ for the configurations with different laminate thicknesses.
a constant value of $z$ equal to $h_{blunt}$ are presented in Figure 5.55. Similar to the longitudinal strain distributions in the adhesive, the distributions start with a low magnitude at the “base” adherend and increase in magnitude at the blunt tip of the “patch” adherend. However, for these distributions the magnitudes are negative. The three cases with BH of 25%, 8.3%, and 5%, have initial values of -1.17, -0.43, and -0.38, respectively, in the adhesive at the “base” bondline, and then increase in magnitude to values of -42.2, -26.7, and -24.9, respectively, at the corner of the blunt tip of the “patch” adherend.

The distributions of the normalized shear strain in the “patch” adherend along the axis of $x_a$ at a constant value of $z$ equal to $h_{blunt}$ are presented in Figure 5.56. The three cases with BH of 25%, 8.3%, and 5%, have initial values of -9.2, -6.1, and -5.7, respectively, in the “patch” adherend at the corner of the blunt tip. The case with a BH of 25% then continuously increases to a value of 3.9 at a point 0.27 inches from the “base” bondline or 0.22 inches from the “patch” blunt tip. In this case, following this peak, the strain decreases to a value of -1.6 at a point 0.34 inches from the “base” bondline or 0.29 inches from the blunt tip of the “patch” adherend. The location where the distribution of strain in this case changes sign is at the same location as the minimum value described in the longitudinal strain near the end of the joint region. Alternatively, in the cases of BH of 8.3% and 5%, after the initial negative value, the strain distribution levels out to a strain of zero until near the end of the joint region where a local minimum and maximum occurs. Similar to the 25% case, the point where the strain changes sign is the same distance from the end of the joint region in all three cases, which is 0.19 inches from the wide angle of the “patch” adherend.

The distributions of the normalized longitudinal strain along the axis of $x_a$ at a constant value of $z$ equal to $t_{adherend}/2$ are shown in Figures 5.57 and 5.58 for the adhesive and “patch” adherend, respectively. The distributions of strain in the “base” adherend for each specimen is not shown as it is a mirrored reflection of the distribution in the “patch” adherend due to symmetry. In the adhesive, the case with a BH of 25% is not constant, but has a value of 2.47 at either bondline and a minimum value of 2.25 at the center of the adhesive region. However, the cases with a BH of 8.3% and 5% are constant with values of 1.81 and 1.80,
Figure 5.57 Distribution of normalized longitudinal strain in the adhesive at a constant value of \( z \) equal to \( t_{\text{adherend}}/2 \) for the configurations with different laminate thicknesses.
Figure 5.58 Distribution of normalized longitudinal strain in the “patch” adherend at a constant value of $z$ equal to $t_{\text{adherend}}/2$ for the configurations with different laminate thicknesses.
respectively.

The distributions of the normalized longitudinal strain in the “patch” adherend along the axis of $x_a$ at a constant value of $z$ equal to $t_{adherend}/2$ are shown in 5.58. At this location at the center of the adherend, the case with a BH of 25% has an initial value of 1.42 at the “patch” bondline while the other two cases with a BH of 8.3% and 5% have similar initial values at the “patch” bondline equal to 1.04 and 1.02, respectively. The case with a BH of 25% then increases to a maximum value of approximately 2.2 at a point 0.14 inches from the “base” bondline, and then decreases and levels out to reach within 1% of the far-field value at a point 0.40 inches from the “base” bondline. Alternatively, the case with a BH of 8.3% increases to a maximum of 1.09 at a point 0.66 inches from the “base” bondline, and then reaches within 1% of the far-field value at a point 1.07 inches from the “base” bondline. Finally, the case with a BH of 5% has a maximum value of 1.04 at a point 1.15 inches from the “base” bondline and reaches within 1% of far-field value at a point 1.66 inches from the “base” bondline.

The distributions of the normalized shear strain along the axis of $x_a$ at a constant value of $z$ equal to $t_{adherend}/2$ are shown in Figures 5.59 and 5.60 for the adhesive and “patch” adherend, respectively. The distributions of strain in the “base” adherend for each specimen is not shown as it is a mirrored reflection of the distribution in the “patch” adherend due to symmetry. Similar to the longitudinal strain in the adhesive, the case with a BH of 25% is not constant, but has a value of -20.7 at either bondline and a value of -19.1 at the center of the adhesive region. Alternatively, the cases with a BH of 8.3% and 5% are constant with values of -14.7 and -14.8, respectively.

The distributions of the normalized shear strain in the “patch” adherend along the axis of $x_a$ at a constant value of $z$ equal to $t_{adherend}/2$ are shown in Figure 5.60. The case with a BH of 25% has an initial value of 0.23 at the “patch” bondline while the other two cases with a BH of 8.3% and 5% have similar initial values at the “patch” bondline equal to 0.12 and 0.07, respectively. The case with a BH of 25% then increases to a maximum value of 3.97 at a point 0.14 inches from the “base” bondline, and then decreases to a value of
Figure 5.59  Distribution of normalized shear strain in the adhesive at a constant value of $z$ equal to $t_{adherend}/2$ for the configurations with different laminate thicknesses.
Figure 5.60  Distribution of normalized shear strain in the “patch” adherend at a constant value of $z$ equal to $t_{\text{adherend}}/2$ for the configurations with different laminate thicknesses.
-0.51 at a point 0.28 inches from the “base” bondline before converging on a strain of zero. Alternatively, the case with a BH of 8.3% increases to a maximum of 0.66 at a point 0.69 inches from the “base” bondline, and then decreases to a minimum of -0.49 at a point 0.81 inches from the “base” bondline before returning to a value of zero. Finally, the case with a BH of 5% has a maximum value of 0.32 at a point 1.23 inches from the “base” bondline followed by a minimum value of -0.33 at a point 1.39 inches from the “base” bondline before returning to a value of zero.

The results along the various axes of $z_a$ are subsequently presented. First, the distributions of the normalized longitudinal strain along the axis of $z_a$ at the location in $x$ where the sharp feathered tip would be if the blunt tip did not exist are shown are shown in Figure 5.61. In the case with a BH of 25%, there is an initial value of 1.57 at the origin and the strain decreases in value through the adhesive to a value of 1.50 in the adhesive at the “base” bondline. The interface of the “base” bondline, between the adherend and the adhesive, is located 0.003 inches from the origin along the axis of $z_a$. In this case, the strain jumps from a value of 1.50 in the adhesive to 1.32 in the “base” adherend at the bondline. Along the axis, the strain then slowly increases to a maximum at a distance of 0.007 inches from the bottom of the model before decreasing to a final value of 0.72 at the top of the “base” adherend. In the case with a BH of 8.3%, the strain is relatively constant through the adhesive with an initial value of 1.13 at the bottom of the specimen in the adhesive and a final value of 1.12 in the adhesive at the “base” bondline. The strain for this case then jumps to a value of 1.0 and slowly increases to a maximum value of 1.129 at a point 0.020 inches along the axis before settling back to a final value of 0.91 at the top of the “base” adherend. The case with a BH of 5% follows a very similar trend as the other two cases. The strain is relatively constant through the adhesive region with an initial value of 1.07 and a final value of 1.06 in the adhesive at the “base” bondline. The strain for this case then jumps to a value of 0.94 and increases to a maximum value of 1.09 at a point 0.026 inches from the bottom of the model before decreasing to a final value of 0.94 at the top of the “base” adherend.

The distributions of the normalized shear strain along the axis of $z_a$ at the location
Figure 5.61  Distribution of normalized longitudinal strain through the thickness in $z$ at a constant value of $x$ equal to the location of the feathered edge for the configurations with different laminate thicknesses.
in x where the sharp feathered tip would be if the blunt tip did not exist are presented in Figure 5.62. In each case, the general trend is very similar to that of the longitudinal strain distribution. In the case with a BH of 25%, it has an initial value of strain equal to -0.02, which decreases through the adhesive region to a value of -0.11 in the adhesive at the “base” bondline. In the case with a BH of 8.3%, the initial strain is approximately zero with a value of -0.007 and decreases through the adhesive region to a value of -0.04 at the “base” bondline. Similarly, the case with a BH of 5% has a strain of approximately zero at the bottom of the model with a value of -0.007 and decreases to a value of -0.04 in the adhesive at the “base” bondline. At the “base” bondline, these three cases with a BH of 25%, 8.3%, and 5%, then jump to a value of 3.02, 2.4, and 2.2, respectively, in the “base” adherend at the bondline. The three cases with a BH of 25%, 8.3%, and 5% then decrease to values of -1.11 at a point of 0.02 inches from the bottom, -0.58 at a point 0.06 inches from the bottom, and -0.36 at a point 0.09 inches from the bottom, respectively. The distributions of strain for these three cases then curve back to final values of -0.36, -0.09, and -0.04 at the top of the “base” adherend for each case, respectively.

The results along the axes of $z_a$ at the location in x of the blunt tip of the “patch” adherend are subsequently presented. In order to capture the results in the adhesive and adherend at this location, two different axes of $z_a$ are presented. One is at a distance in x of 0.001 inches just before the blunt tip, and the other is at the same distance of 0.001 inches, but just beyond the blunt tip. First, the distributions of the normalized longitudinal strain along the axis of $z_a$ just before the blunt tip are presented in Figure 5.63. In the adhesive for the case with a BH of 25%, the case has an initial value of 21.31 at the bottom of the model and decreases to a local minimum value of 15.9 at a point 0.004 inches from the bottom in front of the blunt tip of the “patch” adherend. The strain in this case then increases to a peak magnitude of 24.6 in the adhesive at the corner of the blunt tip of the “patch” adherend before decreasing along the axis through the adhesive to a value of 6.5 in the adhesive at the “base” bondline above the blunt tip of the “patch” adherend. The other two cases show a very similar trend as this case, and these cases with a BH of 8.3% and
Figure 5.62  Distribution of normalized shear strain through the thickness in $z$ at a constant value of $x$ equal to the location of the feathered edge for the configurations with different laminate thicknesses.
5% are also very similar in value to each other. The case with a BH of 8.3% has an initial value of 11.4 and decreases to a minimum value of 9.3 at a point of 0.0027 inches from the bottom before increasing to a peak of 16.9 in the adhesive at the corner of the blunt tip of the "patch" adherend. The strain then decreases through the adhesive region to a value of 4.1 in the adhesive at the "base" bondline. Similarly, the case with a BH of 5% has an initial value of 10.4 and decreases to a minimum value of 8.6 at a point of 0.0026 inches from the bottom before increasing to a peak of 14.8 in the adhesive at the corner of the "patch" blunt tip. In this case, the strain drops in the adhesive region to a value of 3.8 at the "base" bondline. The three cases, with BH values of 25%, 8.3%, and 5%, all drop in value at the "base" bondline to values of 3.6, 2.1, and 1.9, respectively, in the "base" adherend, before reaching final values of -0.25, 0.78, and 0.89 at the top of the "base" adherend.

The distributions of the normalized shear strain along the axis of $z_a$ just beyond the blunt tip are presented in Figure 5.64. The cases with a BH of 8.3% and 5% appear almost identical in values as they follow the same pattern while the case with a BH of 25% shows a difference in magnitude. In the adhesive in front of the "patch" blunt tip, the distributions shows a "wavy" pattern with an increase and decrease in magnitude until jumping to a peak magnitude at the corner of the blunt tip. In each case, the strain then decreases in magnitude through the adhesive region before jumping in value at the "base" bondline. These three cases, with a BH of 25%, 8.3%, and 5%, have initial values equal to -24.3, -13.4, and -12.2, respectively, and increase to peak values of -55.9, -36.4, and -35.2, respectively, at the corner of the blunt tip. These three cases then have values of -48.8, -33.7, and -31.3, respectively, in the adhesive at the "base" bondline and then jump to values of 2.5, 0.52, and 0.38, respectively, in the adherend at the "base" bondline. Finally, the three cases eventually have values of 0.93, 0.08, and 0.02 at the top of the "base" adherend for the three cases.

The distributions of the normalized longitudinal strain along the axis of $z_a$ just beyond the blunt tip of the "patch" adherend are presented in Figure 5.65. To ease comparison and reduce repeating results, the distributions have been cropped to show results less than the height of the blunt tip, a height of 0.0074 inches, as any further results would basically be
Figure 5.63  Distribution of normalized longitudinal strain through the thickness in z at a constant value of x equal to the location of $h_{blunt}$ (just before the blunt tip) for the configurations with different laminate thicknesses.
Figure 5.64  Distribution of normalized shear strain through the thickness in z at a constant value of x equal to the location of $h_{blunt}$ (just before the blunt tip) for the configurations with different laminate thicknesses.
identical to those presented in the axis of $z_a$ in front of the blunt tip. Thus, the distributions in the “patch” adherend just beyond the blunt tip are subsequently presented. All three cases have the same shape, but with differences in magnitude. The three cases with a BH of 25%, 8.3%, and 5% have an initial value of 0.51, 0.28, and 0.26, respectively. This is followed by a minimum in each case equal to 0.32, 0.19, and 0.17. This minimum value is at the same location in $z$ of 0.0026 inches for all three cases. These three cases then have a peak in the adherend at the corner of the blunt tip equal to 0.99, 0.71, and 0.66, respectively.

The distributions of the normalized shear strain along the axis of $z_a$ in the “patch” adherend just beyond the blunt tip are presented in Figure 5.66. The three cases, with a BH of 25%, 8.3%, and 5%, have initial values of -2.6, -1.4, and -1.3, respectively. In each case, the strain increases in a similar “wavy” pattern to a final increased magnitude of 7.2, 4.8, and 4.5, respectively, all being negative.

The distributions of the normalized longitudinal strain and normalized shear strain along the axis of $z_a$ at the end of the joint region are presented in Figure 5.67 and 5.68, respectively. In both figures, the three cases considered show very similar trends. In the distribution of the normalized longitudinal strain, the cases with a BH of 25%, 8.3%, and 5%, have initial values equal to 0.939, 0.955, and 0.969, respectively. The case of BH of 25% increases to a maximum value of 1.08 at a point 0.019 inches through the thickness and a final value of 0.72 at the top of the “patch” adherend at the wide angle. Similarly, the case with a BH of 8.3% has a maximum value of 1.07 at a point 0.059 inches through the thickness followed by a final value of 0.64 at the wide angle of the “patch” adherend. The case with a BH of 5% has a maximum value of 1.05 at a point 0.11 inches through the thickness followed by a final value of 0.61 at the wide angle of the “patch” adherend.

In the distributions of the normalized shear strain at the end of the joint region, presented in Figure 5.68, the cases with a BH of 25%, 8.3%, and 5%, have similar trends with initial values equal to -0.17, -0.05, and -0.03, respectively, at the bottom of the “patch” adherend. The case with the BH of 25% has a minimum value of -0.49 at a point 0.009 inches through the thickness, a maximum value of 0.94 at a point 0.028 inches through the
thickness and a value of 0.78 at the wide angle of the “patch” adherend. Similarly, in the case with a BH of 8.3%, there is a minimum value of -0.42 at a point 0.029 inches through the thickness, a maximum value of 0.98 at a point 0.085 inches through the thickness, and a value of 0.71 at the wide angle of the “patch” adherend. Finally, the case with a BH of 5%, has a minimum value of -0.29 at a point 0.05 inches through the thickness, a maximum value of 0.98 at a point 0.14 inches through the thickness, and a value of 0.69 at the wide angle of the “patch” adherend.
Figure 5.65  Distribution of normalized longitudinal strain through the thickness in $z$ at a constant value of $x$ equal to location of $h_{\text{blunt}}$ (just beyond the blunt tip) for the configurations with different laminate thicknesses.
Figure 5.66 Distribution of normalized shear strain through the thickness in z at a constant value of x equal to location of $h_{\text{blunt}}$ (just beyond the blunt tip) for the configurations with different laminate thicknesses.
Figure 5.67  Distribution of normalized longitudinal strain through the thickness in z at the end of the joint region for the configurations with different laminate thicknesses.
Figure 5.68 Distribution of normalized shear strain through the thickness in z at the end of the joint region for the configurations with different laminate thicknesses.
Chapter 6

Experimental Procedure

The details of the experimental procedures utilized in this work are presented in this chapter. The procedures described largely follow those established in previous work by Elizabeth Jones during an experimental study on the effects of imperfections on the behavior of composite scarf joints [27]. Thus, many of the details are taken from that reference directly. The specific details of and reasoning for the chosen test specimen geometry is first presented. This is followed by a detailed description of the manufacturing process used for all test specimens. The methods and necessary tools used to measure and inspect the specimens throughout the manufacturing process are described with the results provided for all specimens used in this work. Finally, the testing procedure is described, followed by a description of the post-mortem techniques used for damage characterization of the specimens.

6.1 Specimen Geometry

The specimen geometry chosen for this study is based on ASTM D3039/D3039M, the standard for testing tensile properties of CFRP and similar materials [11]. The standard has been adapted for a specimen containing an adhesive joint. The general configuration for all specimens consists of two laminates with a constant rectangular cross-section joined together at the center of the specimen length. To allow for loads to be transferred into
the specimen during testing, the nominal specimen includes grip tabs that are of similar thickness and width to those of the laminate, and are beveled at a 30° angle. The grip tabs are 1.5 times as long as the specimen is wide as per ASTM D3039/D3039M [11]. All adherends are manufactured from a 12-ply laminate of Toray T800/3900 CFRP material in a [±15]_3s laminate configuration as described in Chapter 3, and resulting in a nominal adherend thickness of 0.089 inches. From this adherend thickness, the specimen width is chosen to be about 10 times larger than the specimen thickness so that edge effects are insignificant overall. This results in a specimen width set to 1.0 in. As briefly described in Chapter 3, the adherend length is chosen such that the strain fields created by the joint region and boundary conditions at the grip tabs do not interfere with each other. The strain field created by the joint region is assumed to return to far-field strain within one joint length, \( L_{joint} \), away from the end of the joint region. This assumption has been confirmed in numerical studies performed by Adil and Jeffrey [13, 15]. The length over which the strain field created by the boundary condition at the grip tabs returns to far-field strain is determined by ASTM D3039/D3039M and set to be equivalent to the specimen width [11]. Therefore, the nominal adherend length between the end of the joint region and the grip tabs, referred to as the “nominal free length” \( L_{nominal}^{free} \), is the sum of the specimen width and the joint length. The nominal lengths and thicknesses are illustrated in Figure 6.1.

Due to limitations imposed by the testing machine used for this experimental work, changes were made to the desired nominal geometry of the specimen. The nominal specimen features grip tabs having at least the same thickness as the thickness of the adherend. This implies that for a specimen with an adherend thickness of 0.089 inches, the total thickness at the end of the specimen with two grip tabs would equal 0.27 inches, not accounting for any additional thickness due to the adhesive used to bond the grip tabs to the adherend. However, the grip jaws installed in the pneumatic testing grips used in this work to grip the specimen during testing can accommodate a maximum thickness of 0.25 inches. Therefore, the grip tab thickness was reduced to allow the tabbed specimens to fit inside the grip jaws. The grip tab material used in this work has a thickness of 0.060 ± 0.008 inches, which is
Figure 6.1 Nominal adherend key lengths and thicknesses for baseline specimen.

\[ L_{\text{tab}} = 1.5w \]

\[ L_{\text{adherend}} = L_{\text{tab}} + L_{\text{free}} + L_{\text{scarf}} \]

**Legend**
- Grip tabs
- Film adhesive

**NOT TO SCALE**
Figure 6.2
Actual adherend key lengths and thicknesses used for experimental specimens.
67\% of the laminate thickness and results in a maximum thickness of about 0.209 inches at the ends of the specimen. This reduction in the grip tab thickness reduces the ability of the grip tabs to effectively transfer load from the grip jaws to the specimen. It was thus necessary to increase the free adherend length to allow the strain field at the grip tabs to return to far-field value. This required length, which was previously described to be equal to the width of the specimen, was doubled to allow the strain field from the grip jaws to return to far-field values. The actual lengths and thicknesses used in this work are illustrated in Figure 6.2.

A non-damaged test specimen with no joint was designed and tested in order to confirm that the strain field due to the thinner grip tabs returns to far-field value within twice the specimen width from the grip tabs. To accomplish this, strain gauges were used to measure the longitudinal strain across the width of the specimen at a distance of twice the specimen width from the grip tabs. At this distance, gages were positioned at three evenly spaced locations. The first gage had its centerline aligned along the centerline of the specimen, and the other two gages had their centerlines located 0.15 inches and 0.30 inches from the centerline of the specimen. A schematic of the strain gauge placement is shown in Figure 6.3. Results from this test showed that the longitudinal strain across the width of the specimen at this distance from the end of the grip tabs varied by less than 7\%, confirming a uniform far-field strain distribution had been reached as predicted via classical laminated plate theory (CLPT). The longitudinal modulus as measured at each of the three gages is 16.1 Msi at the y-centerline, 16.2 Msi at 0.15 inches from the centerline, and 15.4 Msi at 0.30 inches. The nominal value calculated using CLPT is 16.3 Msi. The least-squares linear fits used to calculate each of these moduli all had the same coefficient of variation of R² equal to 0.9997.

The total length of the joint along the x-axis is \( L_{\text{joint}} \). This feature was first introduced in Chapter 3 and further defined in Chapter 4 to include the scarfed area of the adherend and the adhesive. This length is set by the adherend thickness, \( t_{\text{adherend}} \), the scarf angle, \( \alpha \), and the adhesive thickness, \( t_{\text{adhesive}} \), as shown in Equation 4.1.

As previously described, \( L_{\text{free}} \) is determined from the specimen width and the joint
Figure 6.3  Illustration of placement of strain gages on validation specimen for thin grip tab configuration.
length. Thus, the specific joint geometry of the joint region varies among test cases. Specifically, the scarf angle is varied amongst test cases. This causes variation in the joint length, \( L_{\text{joint}} \), among specimens. Using Equation 4.1 with the three scarf angles considered in this work, 3°, 5°, and 10°, results in nominal joint lengths equal to 1.8 inches, 1.1 inches, and 0.50 inches respectively. Therefore, according to the described method for setting the adherend length, the adherend length will differ amongst cases of differing scarf angle. To reduce manufacturing effort, all cases having similar scarf angles were manufactured with the same adherend length regardless of the height of the blunt tip. Thus, cases having a scarf angle equal to 3°, 5°, and 10° were manufactured using adherends with nominal lengths, \( L_{\text{adherend}} \), equal to 6.8 inches, 5.5 inches, and 4.5 inches respectively. However, it was found that this resulted in slight variations between the total lengths of specimens that had the same scarf angle, but different blunt tip heights. Due to the scarfing process described in Section 6.2.2, it was found that variations in the blunt tip caused slight variations in the overall length of the specimen. This is due to the decision to keep the overall adherend lengths constant. For example, the largest difference in the total length between between two different specimens, one manufactured with a 3° scarf angle and a blunt tip height equal to one ply and another specimen with a 3° scarf angle and a blunt tip height equal to four plies, is 0.42 inches. Such changes have no effect on the behavior of the configuration. In reality, for the total length, \( L \), to remain constant, the adherend length would need to change for different blunt tip heights. This is illustrated in Figure 6.4.

### 6.2 Specimen Manufacturing Procedures

The specimen manufacturing procedures allow laminate panels to be scarfed and bonded together and then cut into multiple specimens for increased efficiency. The steps of the overall manufacturing procedures are outlined in Figure 6.5. Uncured, unidirectional pre-impregnated CFRP material is cut into plies that are laid up and cured into the desired laminate configuration, a \([\pm 15]_{3S}\) laminate. These laminates are cut into four “adherend panels”, then scarfed and trimmed in preparation for scarf joint bonding. Two scarfed ad-
Figure 6.4  Illustration of the dependence of the specimen length on the height of the blunt tip for a constant adherend length.
herend panels are joined via a layer of film adhesive and cured to form a “bonded panel”. This panel is then cut into two test specimens of final dimensions as specified. Grip tabs and strain gauges are then applied to each specimen in preparation for final testing. The processes, tools, and procedures implemented to accomplish this overall procedure are detailed in this section.

Throughout the manufacturing process, repeatability and consistency among specimens is a prime focus. In order for this to occur, a key concept known as a “reference corner” is implemented throughout the process. All operations are aligned and referenced to this reference corner, which propagates through each step of the manufacturing process. The establishment and propagation of this reference corner throughout the manufacturing process is discussed in the following subsections. Additionally, for tracking and discussion purposes, the two adherends that are bonded together to form a scarf joint are referred to as the “base adherend” and “patch adherend”. This designation is only for reference purposes as there is no geometry or material differences between the two adherends. The only difference between the two adherends is the location of the reference corner of each adherend in the final specimen configuration. This is discussed in Section 6.2.3.

6.2.1 Bulk Laminate Manufacturing

As stated in Chapter 3, all adherends are manufactured using a Toray Composites T800/3900 unidirectional pre-impregnated carbon fiber/epoxy composite material. The material is intended as a net resin or “no-bleed” system, which comes on a 12-inch wide roll with a waxed backing paper on one side of the material to prevent self-adhesion. Individual plies are cut from a roll of unidirectional material. These plies are 14 inches long in the longitudinal (0° ply) direction and 12 inches wide in the transverse direction. To vary the fiber orientation, a single-edge razor blade is used to cut the unidirectional roll at an angle into two halves. The two halves are then laid up against each other along the fiber direction with no gap or overlap. For consistency among plies, metal cutting templates, or guides, are used in cutting the appropriate shapes from the unidirectional roll to form the
Figure 6.5  Schematic illustration of steps in specimen manufacturing.
appropriate fiber angles. An illustration of the templates used in cutting the angled plies is shown in Figure 6.6. Each side of the templates is covered in “guaranteed” non-porous Teflon®-coated (“GNPT”) adhesive-backed fabric to prevent the templates from sticking to the composite material. The templates are wiped with a methanol solvent before each use to prevent contamination of the composite material.

After the appropriate angled plies are cut from the unidirectional roll, they are laid up individually to create laminates having a $[\pm 15]_{3s}$ configuration. Each layup is performed on a flat metal tool with two perpendicular vertical dams affixed to it. The first ply is set into the $90^\circ$ corner created by the vertical dams with the waxed backing paper towards the bottom side and against the metal surface. The remaining plies are also aligned with this $90^\circ$ corner and placed directly on top of the bottom ply with the backing paper on top to form the reference corner at the corner created by the vertical dams. After adding each ply, the backing paper is left on and a hard rubber roller is used to press each ply to the laminate and remove air bubbles between plies. The backing paper is then removed before adding the next ply. After the final ply is laid up, the backing paper is left on the final ply, resulting in a laminate having the desired configuration with protective waxed paper on the top and bottom. Each laminate has one dedicated orthogonal, aligned corner created by alignment to the two vertical dams. This reference corner is marked on the backing paper and tracked throughout the manufacturing process. The laminate configuration is also labeled on the backing paper.

Following the layup, the laminate is prepared for cure. A cutting template is used to trim the two edges of the laminate opposite the reference corner to a final size of 11-7/8 inches wide by 13-7/8 inches long. The backing paper is then removed from the laminate and two 13-inch by 16-inch sheets of peel-ply fabric are placed squared to the reference corner on both the top and bottom sides of the laminate. Careful consideration is taken to mark the correct corner of the peel-ply as the reference corner. The peel-ply used is a nylon woven fabric with a cross-linked polymer finish to aid in release from the laminate after the cure. A hard rubber roller is used to press the peel-ply onto both sides of the laminate. Both sheets
Figure 6.6 Illustration of procedure for cutting angled plies from unidirectional tape: (a) first template, for cutting ply out of unidirectional tape; (b) second template, for splitting ply into two halves; and (c) two halves of the angled ply assembled in the final configuration.
of peel-ply are then trimmed along all edges to be flush with the laminate, except for the short edge opposite the reference corner. A 1/2-inch long tab of each piece of peel-ply is left to overhang this short edge of the laminate in order to provide a location to peel the material from the laminate after the cure. The laminate then has two pieces of GNPT placed on its top and bottom surface, one being the same size as the laminate panel, and the other being 1 inch wider and 1 inch longer than the panel. This allows the larger sheet to overlap by 1/2 inch around all four edges. The larger sheet of GNPT is wrapped evenly around all four edges and secured tightly and thoroughly to the smaller sheet of GNPT using flash tape, an inelastic, non-porous polyester tape with silicone adhesive. Consideration is taken to ensure there are no wrinkles in the GNPT that could adversely affect the laminate surface during cure. Additionally, no gaps are left in the flash tape during wrapping. This is to ensure that the laminate matrix material does not escape, which would cause thickness variations between laminates. The flash tape is also confined to as near the edges of the laminate as possible in order to ensure that most of the cured laminate is pristine and as flat as possible.

An aluminum caul plate is then prepped for the cure. The plate used during this cure process is a 33 inch wide by 57 inch long caul plate that has been ground flat to within 0.005 inches across the entire plate, and was made using a casting process to minimize warping as it undergoes temperature changes. In preparation for the cure, this plate is first sprayed with two coats of aerosol mold release and allowed to dry for at least two minutes. The plate is then covered by a sheet of GNPT. The sheet of GNPT is secured on all four edges with flash tape to prevent any escaped matrix material from sticking to the caul plate. A 2 inch wide border around the perimeter of the caul plate is left free of mold release spray and GNPT to allow room for vacuum tape to be applied for use during the cure. The aerosol mold release spray used throughout the manufacturing process is Mold Wiz® F-57 NC release agent.

For each laminate, aluminum dams and plates are used in order to preserve the orthogonality of the laminate reference corner. All aluminum dams and plates that will be in contact with a laminate during the cure are sprayed with two coats of mold release spray and allowed to dry for at least two minutes prior to setting up the following cure assembly.
There are vertical dams that have been formed from two 1/2-inch thick square aluminum bars that have been welded together and then machined to form a T-shape in order to provide a space for the reference corner of two different laminates. Each T-dam is firmly taped to the caul plate using flash tape. The GNPT-wrapped laminate is then placed in the T-shape with the reference corner butted against the orthogonal corner. Two additional aluminum dams are then placed against the remaining two edges of the laminate to keep the laminate firmly pressed against the T-shape to preserve orthogonality. These additional dams are 3/8-inch square aluminum bars of equal length to the two remaining edges and are held in place using a combination of vacuum tape and flash tape in order to provide a flexible support that allows for thermal expansion of the laminate during cure. This flexible support is approximately half an inch in length and is placed at two different locations as seen in Figure 6.7. Finally, a 3/8-inch thick aluminum plate, or “top plate”, having the same length and width as the laminate, is set on top of each laminate to provide uniform pressure across a flat surface during the cure. Each top plate is wrapped in a sheet of GNPT that is secured in place with flash tape on the top side of the plate that is not in direct contact with the laminate. The top plates are manufactured from the same cast aluminum as the caul plate, and likewise ground to a flatness of ±0.0005 inches.

The caul plate is sized such that it can accommodate three T-dams allowing a total of six laminates to be cured at once. A top-down schematic view of a cure assembly with six laminates is shown in Figure 6.7. After the laminates to be cured have been setup on the caul plate as described, three layers of porous Teflon®-coated fabric are laid over the entire assembly. This is the same material as the GNPT but with a lower content of Teflon®. Three layers of fiberglass breather fabric are then laid over the entire assembly. These additional layers of porous Teflon® and breather fabric prevent escaped matrix material from adhering the cure assembly components to the breather material, while also allowing air to quickly escape the assembly. The three layers of a plain-woven fiberglass cloth with an areal weight of 0.038 pounds per square foot, as determined through trial-and-error, provides an acceptable rate of vacuum pull. The entire assembly is finally covered in a nylon vacuum bagging film.
Figure 6.7  Top-down illustration of a cure setup for six laminates.
This is sealed around the edges of the caul plate with flexible vacuum tape. A cross-sectional schematic of the laminate cure stackup described is shown in Figure 6.8.

After preparations are complete, vacuum is pulled to a minimum of 28 inches Hg via connected ports at each end of the caul plat and the bag is examined for leaks. The vacuum seal is considered satisfactory if, when the vacuum bag is isolated from the vacuum source line via a shutoff valve, the vacuum pressure drops by less than 0.1 inch Hg in 20 seconds. The vacuum is then released and the caul plate is rolled into the autoclave. A vacuum of at least 28 inches Hg is then pulled and the cure is performed per the manufacturer's recommended cure cycle. The autoclave door is shut and locked, and the cure cycle begins. First, a vacuum is pulled in the bag to a minimum of 28 inches Hg. After vacuum is obtained, the autoclave pressure chamber is set to a pressure of 85 psi. When the autoclave pressure reaches 20 psi during ramp-up, the vacuum in the bag is vented to the atmosphere for the remainder of the cure. After 85 psi is reached, the autoclave temperature is ramped up to 355° at a rate of 3°F to 5°F per minute. The temperature is then held at 355° ±10°F for 120 minutes. After the hold is complete, the temperature is ramped down at a rate not exceeding 5°F per minute. Once the temperature drops to 100°F, the autoclave pressure is released. When the autoclave pressure equalizes with the ambient pressure, the door is opened and the cure setup is disassembled.

During this disassembling process, the reference corner and laminate layup is marked directly on the laminate surface once the peel-ply is removed. An opaque white paint marker is used to label the correct corner as the reference corner.

6.2.2 Adherend Trimming and Scarfing Procedure

Following the cure, the bulk laminate panels are cut into 4-inch wide “adherend panels”. Depending on the intended scarf angle, each adherend panel is cut to a specific length as described in Section 6.1. Panels intended to have a scarf angle equal to 3°, 5°, or 10° were cut to a nominal length equal to 6.8 inches, 5.5 inches, or 4.5 inches, respectively. A single bulk laminate panel can be cut to obtain four adherend panels with a length equal to 5.5
Figure 6.8  Cross-sectional illustration of the cure material stackup for a laminate cure.
inches or 4.5 inches. Due to the increased length, only two adherend panels having a length equal to 6.8 inches can be obtained from a single bulk laminate. The longitudinal and transverse cuts that divide a bulk laminate into these adherend panels are aligned parallel to the two reference edges. Therefore, all four edges of each panel are parallel to their respective reference edge, and as mutually orthogonal as the original reference corner, to within the cutting tolerance of the horizontal milling machine (±0.1°). Despite this parallelism and orthogonality, a derived reference corner is marked on each adherend panel at the corner that was closest to the original reference corner. Additionally, during this cutting process, the adherend panels are grouped into pairs and are referenced as “base adherends” or “patch adherends”. These pairs are bonded together to produce a final specimen. The width of each panel is such that two specimens, which are 1 inch in width, can be obtained from a set of panels with 2 inches of extra material necessary for subsequent manufacturing procedures. There is no difference between the paired adherends except that the reference corners are on opposite sides. This is to ensure a consistent laminate configuration through the joint.

The adherend panels produced from each bulk laminate are cut from the center of the laminate panel to avoid the edges of the laminate panel that have variations in thickness due to the flash tape and GNPT wrapping used during the cure. The adherend panels are cut from the bulk laminate on a horizontal milling machine with a 120-grit diamond-coated abrasive cutting wheel with a diameter of 11 inches and thickness of 0.06 inches. The milling table is fed automatically in its longitudinal direction at a constant rate of 11.1 inches per minute, with a spindle speed of 1100 revolutions per minute, and a resulting blade edge velocity of 6050 inches per minute. The spin direction of the cutting wheel is selected such that the cutting forces on the laminate press down onto the milling table in order to reduce vibration, prevent delamination, and result in a cleaner cut. This described cutting direction can be seen in Figure 6.9(b). Water cooling is used during all cuts made on the horizontal milling machine. Each cut is aligned to the reference edge of the laminate using an alignment dam affixed to the milling table. A narrow groove down the length of the milling table in its longitudinal direction allows the blade to cut through the thickness of the laminate
material without interfering with the milling table. However, this groove prevents the cutting wheel from being adjustable in the transverse direction with respect to the alignment dam. Therefore, it is necessary to use custom fiberglass shims to achieve the designed lengths and widths. These fiberglass shims are made using a pre-cured, commercially-available fiberglass mat composite panel of 1/8-inch thickness. A shim is manufactured for every cut necessary by setting one straight edge of the shim a measured distance away from the alignment dam that is equal to the desired cut length, then cutting across the opposite edge of the shim. During every cut, an aluminum bar spanning the length of the material being cut is bolted to the milling table with a layer of foam rubber between the bar and the material in order to press the material firmly to the table and hold it in place while cutting. Finally, in order to cut the laminate material to the desired length and width, several cuts are made using various shims. For each cut, a fiberglass shim is butted against the alignment dam, and the reference edge of the laminate is butted against the edge of the fiberglass shim opposite the alignment dam. The aluminum bar with a foam rubber pad is bolted to the table to hold the laminate firmly in place during each cut. This horizontal milling setup is depicted in Figure 6.9(a).

After the adherend panels are cut from the bulk laminates, they are scarfed to the appropriate scarf angle corresponding to the specific length of each adherend. The blunt tip height is also machined during this process. Scarfing is performed on a two-axis CNC vertical milling machine using a 120-grit diamond-coated rotary grinding burr with a cylindrical diameter of 0.73 inches. The cutting is performed at a spindle speed of 2800 revolutions per minute and a horizontal feed rate of 4.0 inches per minute. Water cooling is used throughout. The adherend panel is clamped to a stainless steel mounting plate via two aluminum bars. The mounting plate is 1/2-inch thick and has been ground flat and parallel to within ±0.001 inches. Two through-holes in each aluminum clamp allow for two set screws to tighten the clamps to the adherend panel via threaded holes in the mounting plate. Each aluminum clamp covers 1/4-inch of the adherend panel width, leaving 3.5 inches of the width exposed for the scarfing operation. During clamping, the reference edge along the width direction
Figure 6.9 Illustration of: (a) milling table setup; and (b) standard cutting directions for all laminate cutting operations performed on the horizontal milling machine with diamond cutting wheel.
of the adherend is aligned flush with the edge of the mounting plate using a steel precision machinist’s block. This block is held flat against the edge of the mounting plate and the reference edge is held flush with the block while the set screws of the clamps are tightened. Careful consideration was taken as to which surface of the adherend was facing up towards the cutting bit. The “base” adherend and “patch” adherend pairs that are to be bonded had to be scarfed such that the laminate configuration stayed constant across the joint since a 180° rotation about the x-axis changes the ply configuration from \( +\theta \) to \( -\theta \). For consistency, “base” adherends were scarfed on the side such that the reference corner was on the left of the sine plate, and “patch” adherends were positioned with the reference corner to the right as seen in Figure 6.11. The use of this sine plate is subsequently described.

To achieve the desired scarf angle, the mounting plate is affixed to the top of a precision single-axis-rotation sine plate. The mounting plate is aligned to the edge of the sine plate with a vertical dam and threaded holes on the sine plate are used to screw the mounting plate in place. The angle of the sine plate, which is equivalent to the desired scarf angle, is set by placing precision thickness gage blocks between the base of the sine plate and the free end opposite the pivot point of the sine plate. A schematic of the described setup is shown in Figure 6.10. The distance between the centerlines of the pivot point and the cylindrical contact point at the free end of the sine plate is 10 ±0.0002 inches. Therefore, the gage block combined thicknesses required to create an angle equal to 3°, 5°, or 10° on the working surface for scarfing are 0.5234, 0.8716, or 1.7365 inches, respectively. The gage block stack is inserted and the cylindrical contact roll is held against the gage block stack while the side clamp on the sine plate is firmly tightened.

The scarfing operation on each laminate begins by zeroing the cutting bit in all three milling axes of \( x^m \), \( y^m \), and \( z^m \), as shown in Figures 6.10 and 6.11. With respect to the milling coordinate axes, the zero location in \( x^m \) is set with the edge of the cutting bit 1/8 ±1/16 inches away from the aluminum side clamp, the zero location in \( y^m \) is set with the edge of the cutting bit overhanging the adherend panel edge to be scarfed by 1/8 ±1/16 inches, and the zero location in \( z^m \) is set with the bottom (cutting) surface of the bit in
Figure 6.10 Schematic of sine plate setup for scarfing of adherend panels on milling machine. (Note: Side clamps are not pictured.)
Figure 6.11  Schematic of $x$-$y$ milling pattern of center point of cutting bit.
contact with the uppermost edge of the adherend panel. The finding of the precise edge in $x^m$ and $y^m$ is unnecessary, since the milling operation is designed to scarf away a sufficiently wide area of the adherend panel such that the $\pm 1/8$ inch tolerance of the zeros will cause no issues. The two-axis CNC capability of the milling machine is utilized to create an automatic milling program in order to guarantee a consistent and repeatable feed rate and milling pattern among all specimens. The scarfing operation is set up such that the milling operations only occur in the $x^m$-$y^m$ plane with a manual step in the $z^m$-direction between each milling operation.

Each $x^m$-$y^m$ milling operation has the same milling pattern, feed rate, and spindle speed. A schematic of the $x^m$-$y^m$ milling pattern is shown in Figure 6.11. The spindle speed is set to 2800 revolutions per minute, the highest speed capable for the specific milling machine used, and a constant feed rate of 4.0 inches per minute was chosen in order to produce a smooth and consistent surface finish. The milling operation begins by moving the bit to the starting position in $x^m$ and $y^m$, which is at an $x^m$-location of zero and a $y^m$-location of -2.500 inches, so that the bit will begin every $x^m$-$y^m$ milling operation out of contact with the part irrespective of the desired scarf angle. The bit is then manually lowered to the appropriate depth in $z^m$ for the current pass and locked in place to hold the $z^m$-depth constant. The number of necessary passes on the milling machine varies for the desired scarf angle and blunt tip height. As presented in Table 3.3, three different scarf angles are considered: 3\(^\circ\), 5\(^\circ\), and 10\(^\circ\). At each scarf angle, four different blunt tip heights are studied ranging from one nominal ply thickness to a blunt tip height of four nominal plies. Initial passes on the milling machine are performed with a change in depth in $z^m$ of -0.020 inches between each pass. After each pass, the number of exposed scarfed plies are counted by the operator. When 2 to 3 plies remain yet to be exposed before the desired blunt tip height is reached, the total depth in $z^m$ is divided by the number of exposed plies to determine the average thickness of the plies with respect to the milling $z^m$-axis. This average ply thickness is then used to calculate the $z^m$-depth necessary for the final few passes based on the desired blunt tip height, $h_{blunt}$. The final few passes are made with changes in $z^m$-depth no greater than -0.010 inches until
the desired blunt tip height is achieved. This is done in order to allow for greater accuracy and a cleaner surface finish. The desired blunt tip height is achieved when the number of visible plies in the scarfed region equals 12 (total number of plies in the laminate) minus the nominal blunt tip height desired. These operations are repeated until the desired final height of the blunt tip is achieved. Each operation is performed automatically and without pause at the prescribed feed rate of 4.0 inches per minute. The bit travels 2.400 inches in the \( y'^m \)-direction, resulting in a total scarfed area width of 3.13 inches.

After scarfing the adherend panels, the unscarfed sides are trimmed away using the previously described horizontal milling machine method. A section of width of 3/4 inches is trimmed off each side of the panel using the long reference edge of the panel for alignment resulting in a scarfed adherend panel that is 2.5 inches wide.

### 6.2.3 Scarf Joint Bonding Procedure

The scarfed adherend panels resulting from the procedures detailed in Section 6.2.2 are bonded primarily via a single layer of 3M\textsuperscript{TM} Scotch-Weld\textsuperscript{TM} structural adhesive film AF 555M. This comes on a roll sandwiched between a layer of waxed backing paper and a thin plastic backing film. Prior to placing the film adhesive on the scarfed panels for curing, the scarfed surface of each panel is wiped with acetone to remove any debris and residue and allowed to dry for at least 15 minutes. For each pair of scarfed panels, one rectangular section of film adhesive that is at least as large as the final desired area is cut using a single-edge razor blade from the bulk material. The waxed backing paper is removed, and the rectangular section is laid onto the scarfed surface of the “patch” adherend. The film adhesive is placed such that approximately 1/8 inch of the film adhesive overlaps both ends of the joint region in the \( x \)-direction, and full coverage is achieved in the width (\( y \)-direction). A hard rubber roller is used to press the film adhesive onto the scarfed panel with the plastic backing film still in place. Any overhanging film adhesive in the \( y \)-direction is then trimmed using a single-edge razor blade before removing the plastic film.

The “patch” adherend with the film adhesive applied is then placed with its side against
a vertical alignment dam of 1/2-inch thickness. The “base” adherend scarfed panel is positioned with its long reference edge against the dam with some separation between the panels. Due to the choice to scarf the short reference edge of each adherend panel, the long reference edge of the “patch” adherend is opposite the reference edge of the “base” adherend as shown in Figure 6.12. However, since the long edges of the adherend are parallel within ±0.1° due to the horizontal milling machine cutting tolerance as previously stated, this is not an issue for alignment of the two adherend panels in the longitudinal direction. When joining the two panels, the “patch” adherend with the film adhesive is held in place while the “base” adherend panel is moved in the x-direction along the alignment dam until it makes firm contact with the “patch” adherend. The z-motion of the panels during mating is restricted by pressing them against a flat glass working surface so that the top and bottom surfaces are flush with each other. This procedure is illustrated in Figure 6.12. However, due to the blunt tip feature of the joint, additional film adhesive is required to fill the empty space created in front of the blunt tip during the mating process. As shown in Table 3.3, blunt tip heights ranging from one nominal ply thickness to a thickness of four nominal plies are examined. After trial and error, it was concluded that adding an additional piece of film adhesive in front of the blunt tips of each joint for each nominal ply thickness of the blunt tip was sufficient in aiding the prevention of voids in front of the blunt tips due to adhesive starvation. This implies that for a laminate having a blunt tip height equal to one nominal ply, a single strip of film adhesive is placed in the region in front of the blunt tip. Similarly, a joint having a blunt tip height equivalent to four nominal plies requires adding four additional thin strips of film adhesive to the area in front of the blunt tips. This process is performed in front of both blunt tips of the joint (i.e. on the top and bottom surface). When multiple strips are necessary, they are sized such that the strips decrease in length in the x-direction with each additional strip. These lengths are dependent on the scarf angle and the height of the blunt tip in each configuration. The first and longest ply of adhesive added to each configuration was equal to the visible length between the blunt tip and the end of the joint. Subsequent plies were shorter in length and measured to fill the opening when positioned directly on top.
of the previous ply of film adhesive. These subsequent plies started from the blunt tip and ended at the top surface of the specimen as seen in Figure 6.13. Each layer spans the full width of the scarfed panel in the y-direction and is butted directly against the blunt tip edge of each scarfed panel. Each strip was originally cut longer than necessary in the x-direction and then trimmed to the required length once positioned against the blunt tip. Trimming was performed using a single-edge razor blade and an aluminum ruler against the specimen for a cutting surface. This process allows the entire empty area in front of the blunt tip region to be filled with film adhesive. An example of the placement of extra strips of film adhesive is illustrated in Figure 6.13 for a specimen having a blunt tip height equivalent to four nominal plies.

The setup for the scarf joint bond cure is similar to the setup described for the laminate cure in Section 6.2.1. All aluminum plates and alignment tools that will come in contact with the specimens are sprayed with two coats of mold release spray and allowed to dry for at least two minutes. The caul plate is covered in GNPT which is secured using flash tape in a similar manner as for the laminate cure. The vertical alignment dams used to align the specimens during this bond cure are machined from aluminum of 1/2 inch thickness in a “cross” shape, as shown in the planar view in Figure 6.14. This cross shape provides four spaces for bonded panels to be placed for curing, and multiple cross-shaped dams can be used simultaneously to bond numerous specimens in a single cure. Each cross-shaped dam is firmly taped to the top of the GNPT-covered caul plate using flash tape. Each set of joined panels are aligned on the caul plate with the long side of the specimen against the long leg of the taped dam and the short edge of the “base” adherend against the orthogonal short leg of the taped dam. An additional vertical dam, an aluminum bar with a 3/8-inch square cross-section, is then placed against the long side of the joined panels opposite the aligned side. This additional dam is held in place with flexible tape to allow for thermal expansion during the cure. However, no additional vertical dam is placed against the remaining short side of the joined panels in order to allow the panel to freely move in the longitudinal direction as the film adhesive layer changes thickness during cure. A GNPT-covered top plate that is 3/8
Illustration of placement of film adhesive and alignment of adherend panels for joining.

- Reference corner
- Glass working surface
- Alignment dam
- Film adhesive layer
- Fixed "patch panel" adherend
- "Base adherend" panel
- "Base adherend" is moved to join panels
- Indicating direction
- NOT TO SCALE
Figure 6.13  Illustration of placement of extra strips of film adhesive to reduce voids in front of blunt adherend tip.
inches thick and of similar width and length as the joined panels is then placed on top of the specimen. Similar to the laminate cure, the entire setup is covered in three layers of porous Teflon® fabric, three layers of fiberglass breather fabric, and a layer of vacuum bagging film sealed with vacuum tape. A schematic of the bond cure material stackup is shown in Figure 6.15. The aligned long edge of the joined panels becomes the reference edge of the bonded panels for the final cutting operations following the bond cure.

The cure process begins with the vacuum bag being checked for leaks, as described in Section 6.2.1, by pulling full vacuum of at least 28 inches Hg, isolating the vacuum bag from the source, and confirming that the vacuum pressure drops by less than 0.1 inch Hg in 20 seconds. The vacuum is then released and the caul plate is rolled into the autoclave. A vacuum of at least 28 inches Hg is then pulled and the cure cycle is performed per the instructions in the Technical Data Sheet for the material from the manufacturer [24]. Pressure is ramped up to 20 psi. When the pressure reaches 15 psi, the vacuum bag is vented to the atmosphere. The temperature is then ramped up at a rate of 3°F to 5°F per minute to 355°F. The temperature is held at 355 ±5°F for 120 minutes ±5 minutes. The temperature is then ramped down at a maximum rate of 5°F per minute to 100°F. At this point, the positive pressure is released, the cure assembly is removed from the autoclave, and the bonded panels are removed from the cure assembly.

6.2.4 Final Cutting and Specimen Tabbing

After bonding the scarf joint, the 2.5-inch wide bonded panel is trimmed into two 1-inch wide test specimens using the cutting process on the horizontal milling machine described in Section 6.2.2. The cuts are aligned from the long reference edge resulting from the scarf joint bond cure. The same process is then used to cut grip tabs to size on the horizontal milling machine from a pre-cured, commercially-available fiberglass mat material. Each grip tab is 1.5 inches long by 1-inch wide and is placed into a machined jig that can hold up to four grip tabs at once, and is used to press the tabs against a belt sander to bevel the 1-inch wide end to a 30° angle with as close to a feather edge as achievable. The quality of the
Figure 6.14 Planar illustration of the scarpt joint bond cure setup for four bonded panels.
Figure 6.15  Cross-sectional illustration of the cure material stackup for a sweet joint bond of two adherend panels.

- Vacuum port
- Flexible tape
- Fixed vertical dam
- Joined adherend panels
- GNPT
- Top plate
- Porous Teflon
- Fiberglass breather
- Vacuum bagging film
acute tips of the grip tabs is not a concern for this application, provided the 1.5-inch length of the tab is preserved, as the 30° bevel serves only to transfer gripping loads gradually into the specimen during testing.

Once the specimens and tabs are cut to their final size, each grip tab is laid directly onto a roll of film adhesive and pressed down with a hard rubber roller. The film adhesive used is Cytec® FM® 73M film adhesive with a nominal area weight of 0.060 pounds per square foot, and a lower temperature cure cycle than the film adhesive used for the scarf joint bond in order to prevent potential issues such as re-softening of the scarf joint adhesive. A razor blade is used to cut the film adhesive such that all edges are flush with the edges of the grip tab. The backing paper is then peeled from the film adhesive, and the grip tab is visually aligned and applied to the end of the specimen. Visual alignment is sufficient to initially place the grip tabs as the alignment dams used during the cure correct any small misalignment.

The grip tab cure setup is similar to the setup described for the laminate cure in Section 6.2.1 and the scarf joint bond cure in Section 6.2.3. All aluminum plates and alignment tools that will come in contact with the specimens are sprayed with two coats of mold release spray and allowed to dry for at least two minutes. The cross shape vertical dams used for the scarf joint bonding cure are also used for this grip tab cure. These machined dams are firmly taped to the top of the GNPT-covered caul plate with flash tape and each specimen, with all four grip tabs in place, is placed against an orthogonal corner of a firmly taped dam, with the longitudinal direction of the specimen adjacent to the longer leg of the dam. Two additional vertical dams are then applied to the remaining side and end of the specimen. These dams are 3/8-inch square aluminum bars held in place using flexible tape to allow for thermal expansion during cure. Finally, an aluminum top plate, which is of the same length and width of the specimen and 1/2-inch thick is laid on top of the specimen. This top plate spans the two grip tabs on the top of the specimen, and the specimen rests on the caul plate via the two bottom grip tabs, allowing the total free length of the specimen to be suspended between the grip tab pairs without applied pressure. As in previous cures, the entire cure
setup is covered in three layers of porous Teflon® cloth, three layers of fiberglass breather cloth, and a vacuum bagging film sealed to the caul plate. A planar illustration of the cure assembly is shown in Figure 6.16, and the cure stackup is shown in Figure 6.17.

The bag is checked for leaks using the same method described in Section 6.2.1. A full vacuum of at least 28 inches Hg is pulled, then the vacuum bag is isolated from the source, and it is confirmed that the vacuum pressure drops by less than 0.1 inch Hg in 20 seconds. The vacuum is then released, the cure assembly is rolled into the autoclave, and the cure for the grip tab film adhesive begins by pulling full vacuum on the vacuum bag. Application of vacuum is not specified in the manufacturer's recommended cure procedure, but is incorporated to remove any air bubbles in the film adhesive layer in an attempt to minimize voids. The autoclave pressure is then ramped up to 40 psi ±5 psi. When the pressure reaches 20 psi, the vacuum bag is vented to the atmosphere. When the target pressure is reached, the temperature is ramped up at a rate of 4°F to 5°F per minute to 250°F. The temperature is held at 250°F ±5°F for 60 minutes. The temperature is then ramped down at a maximum rate of 5°F per minute to 100°F. The pressure is then released and the specimens are removed from the autoclave.

### 6.2.5 Specimen Strain Gaging

Each completed specimen is instrumented with four strain gages in preparation for testing. The strain gages used are Micro-Measurements EA-06-125AD-120 gages with a 0.125-inch linear gage pattern, 120-ohm resistance, and a gage factor of 2.085. Two gages are placed at the same (x,y) position on opposite sides of each adherend of the specimen. These co-located pairs allow for both bending and extensional strain to be calculated from the measured strains. All four gages are centered on the y-centerline of the specimen so that no edge effects are captured in the measured response, and are positioned in the x-direction such that they are within the far-field strain regions of the adherends. For simplicity, all strain gages were placed in the x-direction a distance equal to the joint length away from the edge of the joint, or equivalently two inches away from the the nearest grip tab. This
Figure 6.16  Planar illustration of the cure assembly for a grip tab bond cue of a specimen.

Caul plate  □ GNPT  ■■■■ Tabbed specimens  ○ Vacuum ports
□ Firmly taped dams  ■ Flexibly taped dams  □ Flexible vacuum tape
Figure 6.17  Cross-sectional illustration of the cure material stackup for a grip tab bond.
position, found as described in Section 6.1 via the testing of a non-damaged test specimen, is such that the strain fields induced by the grip tabs return to far-field. Additionally, previous numerical work has already shown that the strain fields due to the joint region return to far-field within a distance equal to a joint length away from the edge of the joint. Therefore, for simplicity and consistency, each strain gage was placed on the y-centerline and two inches in the x-direction from the grip tabs or equivalently 3.5 inches from the end of the specimen as the grip tabs are 1.5 inches in length. The placement of the four strain gages on each specimen is illustrated in Figure 6.18.

6.3 Specimen Quality Inspection

The methods used to measure and characterize the produced geometry of each specimen at several steps throughout the manufacturing process are described in this section. The process for characterizing the thickness of the adherends, the variation within one adherend, and the variability across all adherends is described in Section 6.3.1. The process for characterizing the angle and flatness of the x-y scarf plane of each adherend is detailed in Section 6.3.2. The process by which the achieved height of the blunt adherend tips and thickness of the film adhesive layer is described in Section 6.3.3. Finally, the measurements and key results obtained from all of these processes are presented in Section 6.3.4.

6.3.1 Thickness Measurements of Adherends

After the bulk laminate is cut into adherend panels of 4-inch widths, the reference corner is marked on each panel, and the thickness of the adherend panel is measured using a dial drop gage mounted on a measurement stand as shown in Figure 6.19. The adherend panel sits between two contact points on the measurement stand that consists of a steel rod with hemispherical-shaped tips of 1/4-inch diameter. The steel rod of the drop gage is spring loaded so that when no material is present in the system, the two contact points are touching and aligned in the x and y directions. The drop gage is mounted to the measurement stand
Figure 6.18 Placement of the four strain gages on each specimen.
Figure 6.19 Illustration of drop gage measurement stand used for adherend panel thickness measurements.

Cantilevered rod

Drop gage

Spring-loaded steel rod, 1/4 inch diameter

Vertical post

Fixed steel rod, 1/4 inch diameter

Adherend panel

Measurement stand base

6 in

NOT TO SCALE
via a cantilevered rod and vertical post. The contact point where measurements are taken is located 6 inches away from the vertical rod, which causes some amount of error due to the increase in drop gage spring force normal to the end of the cantilevered rod when material is inserted for measurement. This error was determined using a precision ground block of 0.10000 inches in thickness into the measurement stand. This error was determined to be negligible within the measurement precision of the drop gage dial readout of 0.001 inches.

The thickness of the adherend is measured at 18 locations throughout the center region of the panel, which will become the two specimen adherends. This results in nine measurements being recorded per specimen adherend. A grid of nine measurements per specimen is set up across the width and length of the specimen as shown in Figure 6.20. In the width (y) direction, measurements are taken at 10%, 50%, and 90% of the final width of 1 inch or equivalently 0.1 inches, 0.5 inches, and 0.9 inches from the long edge of the specimen. Similarly, in the length (x) direction, measurements are taken at 10%, 50%, and 90% of the adherend length. However, depending on the desired scarf angle, the total adherend length varies amongst cases due to the dependence of the joint length on the scarf angle. In order to take these measurements consistently at the correct locations for all specimens, three different paper templates were created. Each template is four inches in width and has lengths equal to the necessary adherend lengths for the three scarf angles studied. A 1/8-inch diameter hole was created at each measurement point. The appropriate template for each adherend length is aligned with the reference corner of the panel and temporarily taped in place using masking tape. Measurements were then recorded within each hole in the paper template resulting in a possible measurement deviation in the x and y direction up to ±1/16-inch.

6.3.2 Profile Measurements of Scarfed Surface

Prior to the scarf joint bonding cure, the scarfed surface of each adherend is characterized using a non-contact laser depth measurement system. The scarfed surface depth is measured at evenly spaced locations across the width and length of the scarfed area. The number of
Figure 6.20 Dimensions of template used to locate thickness measurements of adherend panels.

- Adherend panel
- Specimen adherend regions
- Measurement location

NOT TO SCALE
All dimensions in [inches]
measurement points varies between test cases due to the variations in the exposed scarfed area being influenced by the three different scarf angles examined, and the four different blunt tip heights considered. The minimum scarfed area measured is for specimens consisting of a \(10^\circ\) nominal scarf angle and a blunt tip height equal to four nominal plies. This entails 44 measurement points. The largest scarfed area examined is for specimens having a \(3^\circ\) nominal scarf angle and a blunt tip height equal to one nominal ply. This entails 88 measurement points. The setup used to take these measurements was custom-made for this application, and an illustration of the overall setup is shown in Figure 6.21. The laser displacement sensing system used is a Keyence LK-G32 sensor head with a LK-GD500 controller and CA-U4 24VDC power supply. The LK-G32 sensor head has a measuring range of \(\pm 0.2\) inches at 1.18 inches from the sensor head and a maximum laser spot diameter of 0.005 inches at the extremes of the measuring range. The measurement output by the laser is the average measurement over the area of the laser spot on the surface being measured. The system is capable of measurement repeatability of 2 microinches.

The laser is suspended over the scarfed panel via a rigid truss frame composed of square aluminum extrusions. The scarfed panel is mounted on a two-axis cross-slide table beneath the laser that allows precise positioning of the specimen in the x- and y-directions. The driving ball screws translate the table 0.100 inches in the x- or y-direction per full rotation of the control handle, with a maximum vertical deviation of the working surface of \(\pm 0.0005\) inches per rotation. Linear displacement sensors of the magnetic slide type were added to both axes of the cross-slide table to track the precise position of the table via a digital readout. The sensors have an accuracy of 0.0002 inches. A custom mount was designed to hold each specimen on the cross-slide table. The custom mount includes three spherical contact points upon which to rest the adherend, and three vertical alignment posts to fix the panel in the x-y plane.

In order to position the scarfed panel on the mount, the panel is placed on the three mounting balls with the scarfed region facing up towards the laser sensor. The scarfed edge of the panel, which is the short reference edge, is butted up against two alignment rods.
Figure 6.21: Illustration of overall layout of setup used to take profile measurements of the scarred surface of adhered panels.
that are positioned outside the scarfed region to prevent damage to the acute edge. These
two alignment rods prevent motion in the x-direction and rotation in the x-y plane. When
measuring a “base” adherend, the long reference edge of the adherend is then pressed against
a third alignment rod to prevent motion in the y-direction. Alternatively, when measuring
a “patch” adherend, the long edge opposite the reference edge is in contact with the third
alignment rod due to the choice to scarf each panel along the short reference edge. This
placement and zero location of the scarfed panel is illustrated in Figure 6.22.

The alignment corner formed by these three alignment rods is the set zero (x,y) location
for measurements taken of the scarfed surface. The plane that the scarfed panel sits on is
characterized using the three spherical contact points. The position of these three contact
points with respect to the alignment corner is known from machining the mount, and the
relative heights of each point is measured using the laser system. The laser measurement
output display is set to zero when the laser is centered on the mounting ball nearest the
scarfed edge of the panel. The heights of the other two mounting points can then be measured
relative to this zero height to define the mounting plane. This mounting plane is subtracted
from any measurement taken of the scarfed surface to remove any errors associated with a
mounting angle.

Before taking any surface profile measurements, the laser is zeroed in the z-direction
at the location of the spherical mount closest to the scarfed edge to account for ambient
temperature variations that can affect measurements. The x- and y- position readout is next
zeroed at the corner to which the adherend panel is aligned, which is nominally the same
for all panels. However, cutting tolerances of the horizontal milling machine as described
in Section 6.2.2 cause slight variations. This process is performed for each scarfed panel by
first positioning the laser spot approximately 1/16 inches away from the aligned edge in x
and aligned edge in y of the panel. The table is then moved in the negative x-direction until
the displayed laser measurement changes from a positive to a negative number, indicating
the majority of the laser spot is no longer on the panel. The position in the x-direction
just before the measurement becomes negative is set as a temporary zero point in x. The
Figure 6.22 Illustration of details of scarfed panel placement, zero location, and x, y locations for laser depth measurements.
table is then moved in the positive x-direction by 0.005 inches, or equivalently the maximum
diameter of the laser spot, and the final zero in x is set. This process ensures that the entire
area of the laser is fully over the specimen. This process can then be repeated to set the
zero in the y-direction.

After zeroing, the measurements of the surface profile of the scarf region are taken.
Measurements are taken using a grid of equally spaced locations across the width and length
of the entire scarfed area. The exact grid sizing and therefore the number of measurement
points taken varies between test cases due to the dependence of the scarfed area on the scarf
angle and blunt tip height. While all panels have a scarfed region with similar widths due
to the scarfing process described in Section 6.2.2, the length of the scarfed regions vary with
different scarf angles and blunt tip heights. Therefore, for all specimens, independent of the
scarf angle and blunt tip height, the measurement location in the width (y) direction begins
at y equal to 1.0000 inches, and are taken at increments of 0.2000 inches up to a value of
y equal to 3.0000 inches. For measurement locations in the length (x) direction, all panels
begin at x equal to 0.0000 inches, but the increment and maximum distance vary per test
case. Measurements taken in the x-direction for all specimens that have a nominal scarf
angle equal to 10° are at increments of 0.1000 inches. Measurements taken in the x-direction
for specimens that have a nominal scarf angle equal to 3° or 5° are at increments of 0.2000
inches. This change in increment is meant to prevent excessive measuring of larger scarfed
regions to improve efficiency. The maximum x-location varies amongst cases due to the
varying scarf lengths. However, all cases began at an x equal to 0.0000 and moved at the
necessary increment described until visually measurements were no longer being taken in the
scarfed region. A sample measurement grid is shown in Figure 6.23.

6.3.3 Microscopic Visual Inspection

The tools and procedures used to quantify the height of the blunt tips resulting from
the scarfing procedure and the thickness of the film adhesive following the scarf joint bond
cure are given in this section. An optical microscope and associated analysis equipment are
Figure 6.23 Illustration of grid of points on the scarfed adherend panel at which laser surface depth measurements are taken relative to specimen adherend placement within the panel.
used in these procedures.

The microscope used is a Zeiss high-power microscope with a 10X zoom objective lens and provides direct lighting on the surface of the specimen through the objective lens. This microscope can be used in “analog mode” by viewing the specimen directly though the provided eyepieces, or in “digital mode” via a camera mounted on the microscope that outputs a live view to a computer as a black and white digital image using the proprietary software from the microscope manufacturer. Using this program, a photograph can be snapped of the current view, and features can be measured digitally using tools in the program. This works by relating a certain number of pixels in the photo to a certain length. Therefore, the program is calibrated by the manufacturer so that when the digital camera lens and objective lens are identified, which are 0.63X and 10X respectively in this case, a conversion factor relates a certain number of pixels to a length. For this work, a line is drawn on a snapped photograph between two points of interest and the program displays the length in micrometers to three decimal places (4 × 10⁻⁸ inches), although the actual precision achievable using this “click-and-drag” measurement method is lower. The actual precision of this method was determined by comparing repeated measurements of a precision thickness gage block. Measurements using this “click-and-drag” method were found to be repeatable within ±0.0002 inches (±5.08 micrometers).

Each specimen to be viewed is placed on the adjustable three-axis table of the microscope, with the surface of the specimens edge to be viewed facing upwards toward the objective lens. A 1/2-inch thick aluminum bar is placed on each side of the specimen to hold it upright on its edge. The specimen is positioned such that the x-axis of the specimen aligns with the x-direction of motion of the table. A drop of water is applied using a finger to the area of the specimen to be viewed, and a thin glass cover slide is added over the wetted area of the specimen. The glass slide is placed by first setting one corner of the glass down, then slowly lowering the other side to rest on top of the wetted area, in order to allow air bubbles to squeeze out from beneath the glass. This process allows for a more clear and accurate view of the specimen under the microscope. The index of refraction of the water
droplet allows the details of the materials viewed under the microscope with direct lighting to appear with much more contrast, color, and clarity. The glass slide flattens the rounded surface of the water droplet so that the surface viewed through the water does not appear distorted. After prepping the specimen to be viewed on the table, the area of interest is brought into focus beneath the objective lens.

Prior to taking any measurements, the alignment of the specimen in the x-z plane with respect to the motion of the microscope table is adjusted in a more precise manner. After setting the microscope to digital mode, a live image from the digital camera is displayed on a computer using the required software with crosshairs superimposed over the center of the image. These superimposed crosshairs allow a more precise alignment to be performed. The table is moved in the directions of x and z until the crosshairs are positioned in the center of an interply layer of the “base” adherend. The table is then moved in the x-direction while observing the alignment of the crosshair within the interply layer. If the interply layer goes out of alignment with the crosshair, the angle of the specimen is adjusted as necessary until the table can be moved at least 1/4 inch in the x-direction without misalignment. An interply layer is used for this alignment process instead of the upper or lower surfaces of the specimen because these edges often show fiber distortion or fraying due to the horizontal milling process. This cutting damage is isolated to the upper and lower surfaces. However, no such damage appears within the cut surface away from the edges, which is the reason that an interply layer is used for this alignment because the relatively thin, dark lines of the interply layer are visually easy to distinguish. A photograph of a typical digital view of a specimen under the microscope is shown in Figure 6.24, with the interply layer identified and measurements included.

After alignment, the specimen measurements are taken. All measurements are taken in the z-direction, including the film adhesive thickness measurement, which is then multiplied by the cosine of the nominal scarf angle of the specimen under examination to get the actual film adhesive thickness perpendicular to the scarf plane. The microscope software allows a measurement line to be drawn as exactly vertical lines. This provides more consistency than
Figure 6.24 Photograph of the digital microscopic view of a typical specimen, with key features identified and measurements overlaid as they appear in the software program.
visually estimating the correct angles of the measurement lines as they are drawn.

The blunt tip height of the acute tips are measured at four locations on each specimen, two per adherend, simply because the blunt tip is only visible at the ends of the width of the joint, along the two cut x-z surfaces of the specimen. Each measurement is performed by taking a picture of the blunt tip region and then drawing a vertical (z) measurement line coincident with the blunt tip and visually aligning the endpoints of the line with the top and bottom of the blunt tip. This method is subject to some variability based on the choice of the location of the top and bottom points that define the blunt tip height. This is especially apparent in some cases where the visible corner of the blunt tip has been frayed or damaged from the cutting process on the horizontal milling machine.

The film adhesive thickness measurements are taken at six locations per specimen. Specifically, four measurements are taken within one ply thickness (in the z-direction) of each visible blunt tip region. The precise location of this measurement within this region is determined on a case-by-case basis to be the location where the bondlines between the film adhesive layer and the adherends appear to be the most well-defined. In some cases, fiber distortion and fraying from the adherend into the film adhesive layer occurs from the cutting process on the horizontal milling machine. At each suitable location, a vertical line is drawn from the bondline on the “patch” adherend through the adhesive layer to the opposite bondline on the base “adherend”. This measurement is then multiplied by the cosine of the nominal scarf angle of the specimen under consideration to determine the film adhesive thickness at each location. Two additional adhesive thickness measurements are also taken along the centerline of the joint at the two visible cut surfaces. For a 12-ply laminate, the centerline in the z-direction corresponds to the interply layer between the sixth and seventh ply in the laminate. This centerline point is found using the superimposed crosshairs on the specimen. While observing the crosshairs, the table is moved to find the top surface of the specimen. The number of plies is then counted while also moving the table in the negative z-direction until the sixth ply is found. The crosshairs are then aligned with the interply layer between the sixth and seventh ply, which corresponds to the centerline of
the specimen in the z-direction. The table is then moved in the x-direction, causing the
crosshairs to travel along this interply layer, until the adhesive layer is found. The crosshairs
are visually centered at this point in the adhesive layer, and a measurement can be taken.
Similar to previous adhesive measurements, a vertical line is drawn and this measurement is
then multiplied by the cosine of the nominal scarf angle of the specimen under examination.

6.3.4 Results of Specimen Quality Inspection

The results of the specimen quality inspection procedures are summarized in this sec-
tion. A summary of the averages of the nine thickness measurements of each adherend are
presented for all specimens in Tables 6.1, 6.2, and 6.3. The average value of the measured
adherend thicknesses across all specimens is 0.0923 inches, which equates to an average ply
thickness of 0.0077 inches. This is 0.0003 inches thicker than the nominal ply thickness of
the laminate material of 0.0074 inches. The coefficient of variation (C.V.), which is defined
as the standard deviation of a set of values divided by the average of the set of values, of
the average adherend thicknesses is 0.012.

The width of each adherend as measured, using dial calipers with 0.001-inch increments,
at the same x-location as each pair of strain gauges is reported in Tables 6.4, 6.5, and 6.6.
The average width across all specimens is 0.991 inches, which is about 1% less than the
nominal width of one inch. The coefficient of variation across all adherends is 0.006. These
widths are used along with the adherend thickness averages to calculate the applied stress
on each adherend to perform the modulus calculations in Chapter 7.

A summary of key values of the scarfed profile measurements are provided in Tables 6.7,
6.8, and 6.9. These values characterizing the scarfed profile were calculated in the following
manner from the laser measurements. First, five best-fit lines are calculated via the least-
squares method to fit the data points at each of the five measurement locations across the
y-direction of the specimen. The average value at these five lines is then calculated and
reported in the table as the average scarf angle, $\alpha_{\text{scarf}}$. The average plane created by this
average scarf angle is subtracted from the measured data plane to determine the error of
each point in the z-direction. This error in the z-direction is also reported in the table as the absolute error in z, $|z| - \text{error}$, which is a metric of the flatness of the scarf plane. The average scarf angle for all specimens having a nominal scarf angle equal to 3°, 5°, and 10° are 3.0°, 5.0°, and 9.6° respectively.

The measured heights of all manufactured blunt tips are presented in Tables 6.10, 6.11, and 6.12. The nominal blunt tip heights examined range from one nominal ply thickness to four nominal plies. For a nominal cured ply thickness of 0.0074 inches, this equates to nominal heights of 0.0074 in, 0.0148 in, 0.0222 in, and 0.0296 in. The average value for all specimens with a manufactured nominal blunt tip height equal to one nominal ply thickness, regardless of scarf angle, is 0.0086 inches with a coefficient of variation equal to 0.102. The average value for all specimens with a manufactured nominal blunt tip height of two, three, and four nominal plies is 0.0157 in, 0.0225 in, and 0.0303 in with coefficients of variation equal to 0.099, 0.045, and 0.053 respectively. In comparison to the nominal values, these averages range in accuracy from a 1% to 15% error.

The results of all measured adhesive thicknesses are presented in Tables 6.13, 6.14, and 6.15. These results include the four adhesive measurements taken locally near each visible blunt tip and the two measurements recorded along the centerline. The average adhesive thickness for each specimen is also provided. The average adhesive thickness measured for all specimens examined is equal to 0.0058 inches with a coefficient of variation equal to 0.545. This differs from the nominal cured value of the film adhesive used in this work, which equals 0.0035 in, by about 60%. Variations in the measured film adhesive ranged from a minimum measured thickness of 0.0012 inches to a maximum measured thickness of 0.0132 inches.

6.4 Testing and Characterization

All specimens in this study were tested in quasi-static, uniaxial tension to failure. As described in Chapter 3, the main objective of this experimental work is to characterize the overall behavior of the scarf joint for various test cases. The response of the specimens to uniaxial tensile loading to failure is recorded during testing, and the damage characteristics
Table 6.1  Average of adherend thicknesses for specimens with a nominal scarf angle of 3° (all values in [inches])

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Specimen Number</th>
<th>Adherend</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{nominal}$</td>
<td>$h_{blunt}$</td>
<td>Base</td>
</tr>
<tr>
<td>3°</td>
<td>1</td>
<td>0.095</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.093</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.093</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
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<td>0.091</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td>0.093</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.095</td>
</tr>
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</table>
Table 6.2  Average of adherend thicknesses for specimens with a nominal scarf angle of $5^\circ$ (all values in [inches])

| Specimen Type | Specimen Number | Adherend |  \
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<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>$\alpha_{\text{nominal}}$</td>
<td>$h_{\text{blunt}}$</td>
<td>Base</td>
<td>Patch</td>
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<td>0.091</td>
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<tr>
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<td>3</td>
<td>0.093</td>
<td>0.092</td>
</tr>
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Table 6.3  Average of adherend thicknesses for specimens with a nominal scarf angle of 10° (all values in [inches])

<table>
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<th>Specimen Type</th>
<th>Specimen Number</th>
<th>Adherend Base</th>
<th>Adherend Patch</th>
</tr>
</thead>
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<tr>
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<td>2</td>
<td>0.095</td>
<td>0.094</td>
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<td>0.095</td>
<td>0.093</td>
</tr>
<tr>
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<td>3</td>
<td>0.093</td>
<td>0.092</td>
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Table 6.4  Adherend widths for specimens with a nominal scarf angle of 3°  
(all values in [inches])

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<th>Specimen Type</th>
<th>Specimen Number</th>
<th>Adherend Widths</th>
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<td>$h_{\text{blunt}}$</td>
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<td></td>
<td>3</td>
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<td>0.993</td>
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Table 6.5  Adherend widths for specimens with a nominal scarf angle of $5^\circ$
(all values in [inches])

<table>
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<th>$\alpha_{\text{nominal}}$</th>
<th>$h_{\text{blunt}}$</th>
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<td>0.995</td>
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Table 6.6  Adherend widths for specimens with a nominal scarf angle of 10°
(all values in [inches])

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Table 6.7  Scarf plane angle and flatness for specimens with a nominal scarf angle of $3^\circ$
($\alpha_{scarf}$ in [degrees], $|z|$-error in [inches])

<table>
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<th>Base Adherend</th>
<th>Patch Adherend</th>
</tr>
</thead>
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<td>$h_{blunt}$</td>
<td>$\alpha_{scarf}$</td>
<td>$</td>
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<td></td>
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<td>3.1</td>
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<td></td>
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<td>2.9</td>
</tr>
<tr>
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<td>2.9</td>
</tr>
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<td></td>
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<td>3.0</td>
</tr>
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<td></td>
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<td>3.0</td>
</tr>
<tr>
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<td>3.0</td>
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<tr>
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</tr>
</tbody>
</table>
Table 6.8  Scarf plane angle and flatness for specimens with a nominal scarf angle of 5°
($\alpha_{\text{scarf}}$ in [degrees], $|z|$-error in [inches])

| Specimen Type $\alpha_{\text{nominal}}$ | Specimen Number $h_{\text{blunt}}$ | Base Adherend $\alpha_{\text{scarf}}$ | $|z|$-error | Patch Adherend $\alpha_{\text{scarf}}$ | $|z|$-error |
|----------------------------------------|-----------------------------------|-------------------------------------|------------|-------------------------------------|------------|
| 5°                                     | 1                                 | 4.9                                 | 0.0002     | 5.0                                 | 0.0002     |
|                                        | 2                                 | 5.0                                 | 0.0002     | 5.0                                 | 0.0002     |
|                                        | 3                                 | 5.0                                 | 0.0001     | 5.1                                 | 0.0002     |
| 5°                                     | 2                                 | 4.9                                 | 0.0005     | 5.0                                 | 0.0006     |
|                                        | 2                                 | 4.9                                 | 0.0005     | 5.0                                 | 0.0008     |
|                                        | 3                                 | 4.9                                 | 0.0004     | 5.0                                 | 0.0002     |
| 5°                                     | 3                                 | 5.1                                 | 0.0002     | 5.0                                 | 0.0003     |
|                                        | 2                                 | 5.2                                 | 0.0004     | 5.1                                 | 0.0001     |
|                                        | 3                                 | 5.0                                 | 0.0002     | 5.0                                 | 0.0001     |
| 5°                                     | 4                                 | 5.1                                 | 0.0002     | 5.1                                 | 0.0004     |
|                                        | 2                                 | 5.1                                 | 0.0001     | 5.1                                 | 0.0003     |
|                                        | 3                                 | 5.0                                 | 0.0002     | 5.0                                 | 0.0002     |

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Table 6.9  Scarf plane angle and flatness for specimens with a nominal scarf angle of 10°  
\(\alpha_{scarf}\) in [degrees], \(|z|\)-error in [inches])

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Specimen Number</th>
<th>Base Adherend</th>
<th>Patch Adherend</th>
</tr>
</thead>
<tbody>
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<td>(h_{blunt})</td>
<td>(\alpha_{scarf})</td>
<td>(</td>
</tr>
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<td>0.0029</td>
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<tr>
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<td>0.0029</td>
</tr>
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<td>9.2</td>
<td>0.0017</td>
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Table 6.10  Blunt tip height, $h_{blunt}$, measurements for all specimens with a nominal scarf angle of 3° (all values in [inches])

<table>
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<th>Specimen Type</th>
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<th>Patch Adherend</th>
</tr>
</thead>
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Table 6.11  Blunt tip height, $h_{\text{blunt}}$, measurements for all specimens with a nominal scarf angle of 5° (all values in [inches])

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<th>Patch Adherend</th>
</tr>
</thead>
<tbody>
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<td>$y = 1 \text{ in}$</td>
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Table 6.12  Blunt tip height, $h_{blunt}$, measurements for all specimens with a nominal scarf angle of 10° (all values in [inches])

<table>
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<th>Patch Adherend</th>
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Table 6.13  Adhesive thickness measurements for all specimens with a nominal scarf angle of 3° (all values in [inches])

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<th>Patch</th>
<th>Average</th>
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</thead>
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<td>y=0</td>
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Table 6.14  Adhesive thickness measurements for all specimens with a nominal scarf angle of 5° (all values in [inches])

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<th>Specimen Number</th>
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<th>Patch</th>
<th>Average</th>
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<td>y=0</td>
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</table>
Table 6.15  Adhesive thickness measurements for all specimens with a nominal scarf angle of 10° (all values in [inches])

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Specimen Number</th>
<th>Base</th>
<th>Midline</th>
<th>Patch</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α</td>
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<td>y=0</td>
<td>y=1</td>
<td>y=0</td>
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of the specimen are characterized following testing. The test setup used to achieve this objective is described in Section 6.4.1. The parameters chosen for the testing procedure and data acquisition are detailed in Section 6.4.2. The test procedure is described in Section 6.4.3. Finally, the methods used to characterize the post-failure damage of the specimens are detailed in Section 6.4.4.

6.4.1 Test Setup

All specimens were tested on an Instron 8501 load frame with variable pressure hydraulic wedge grips and an Instron controller. The upper grip is attached via a 50 kN load cell to a crossbar that is hydraulically clamped to the two columns of the testing machine frame. The lower grip is attached to a hydraulic piston that serves as the movable crosshead. The “patch” adherend of the specimen is aligned and clamped in the upper grip jaws of the testing machine, and the “base” adherend is then clamped in the lower grip jaws. In order to apply a uniaxial tensile load to the specimens at a constant displacement rate, the upper grip remains fixed while the lower grip displaces downward, in the positive x-direction of the testing machine.

Prior to testing, the upper grip jaws are aligned with the lower grip jaws in rotation about the loading axis of the testing machine. This is performed by first loosening the upper grip head from the testing frame crossbar so that it is free to rotate about the loading axis. A machined straight steel bar of a thickness of 1/4 inch is clamped between the upper and lower grip jaws to lock the relative rotations of the two grip heads. The upper grip head is then tightened firmly to the testing frame crossbar with the steel bar still in place. Once tightened, the steel bar is removed from the system and the upper grip head is again checked that it is firmly tightened to the crossbar and unable to rotate.

During testing, three different parameters are examined and recorded. These are the displacement via the testing machine crosshead position measured at the crosshead piston, the applied load measured via the load cell, and the adherend strains measured via the four strain gages at the locations indicated in Section 6.2.5. The crosshead position and applied
load are output from the testing machine control tower as a DC voltage with an output range of -10 volts to +10 volts. The conversion factors from voltage to length and force are input by the user into the control tower thereby regulating the output voltage. These two voltages being output from the control tower are read as inputs into a data acquisition (DAQ) box that interfaces with a data acquisition computer via a USB connection. The DAQ box used for this work is a National Instruments USB-6218 DAQ box, providing 16-bit analog inputs from -10 volts to +10 volts.

Measurements from the four strain gages are acquired using Vishay Micro-Measurements strain gage signal conditioner boxes, which convert the strain gage resistance to a DC voltage output. The gain of the voltage output for each conditioner box is set by the user before each test. These voltage outputs from the four strain gages are input into different channels of the same DAQ box used to read the testing machine position and load voltages. All six analog voltage inputs are recorded by the data acquisition computer via a data recording routine written in National Instruments LabVIEW software that interfaces with the DAQ box. The raw voltages from the six different inputs are recorded for the duration of each test, and the set conversion factors and gains to convert the voltages to position, load, and strain are noted for post-processing of the raw data.

6.4.2 Testing and Data Acquisition Parameters

The grip jaw hydraulic pressure used for all testing is 3000 psi. This was determined during the test of the non-damaged specimen used for the grip tab validation discussed in Section 6.1. This proved to be a sufficient clamping pressure to hold the specimen in the grip tabs without slippage and without crushing the adherends. All testing was performed at a constant displacement rate of 0.002 mm/s (0.0047 ipm). This rate resulted in failure of the baseline specimen occurring within 2 minutes to 5 minutes, which is within the recommended range for quasi-static tensile testing as described in ASTM D3039/3039M [11]. The conversion factors used for the testing machine position and load outputs varied based on scarf angle. As discussed, in Chapter 2, the response of a scarf joint is highly sensitive to the
scarf angle. Therefore, to increase precision among test cases, while also ensuring that the maximum position and maximum load did not exceed the upper limit of the DAQ box (+10 volts), the conversion factors were varied. The conversion factor used for the testing machine position and load outputs for all specimens having a nominal scarf angle equal to 10° were 0.2 mm/V and 2.0 kN/V. All specimens with a nominal scarf angle equal to 5° utilized conversion factors equal to 0.25 mm/V and 3.0 kN/V. And all specimens with a nominal scarf angle equal to 3° used conversion factors equal to 0.3 mm/V and 3.5 kN/V. The gain set for the voltage outputs from the strain gage conditioner boxes is 10,000 μstrain/V. Following testing, these conversion factors are used in the post-process of the data to convert the raw voltages to their respective measurements.

The continuous analog voltage outputs for all six measurements acquired are sampled and recorded simultaneously by the data acquisition system at a rate of 4 Hz. This is set by the limitations of the control tower. The data acquisition is initiated after the specimen is clamped in the upper and lower grip jaws, and one to three seconds before the testing routine is initiated. Similarly, the data acquisition system is terminated one to three seconds after ultimate failure of the specimen occurs.

6.4.3 Test Procedure

The test procedure begins by gripping the “patch” adherend of the test specimen into the upper grip jaws of the testing machine. The specimen is inserted from the side into the machine from the open side of the grip head. A precision ground machine square is held flush against the flat bottom face of the upper grip head, and one of the thin x-z edges of the specimen is held flush against the orthogonal surface of the square. The specimen is visually centered within the grip jaws in the y-direction, and inserted in the x-direction such that the serrated surfaces of the grip jaws fully enclose the grip tabs of the “patch” adherend. While the specimen is held in this position, the upper grip jaws are clamped to the set pressure. If positioned and aligned correctly, the “base” adherend should be sitting in the center of the lower grip jaws. The lower grip jaws should not be coming into contact with the grip tabs of
the “base” adherend. In this position, with the “patch” adherend clamped in the upper grip jaws and the “base” adherend hanging freely without interference from the lower grip jaws, the testing machine load cell and all four strain gages are zeroed. The lower grip jaw can then be clamped onto the “base” adherend while ensuring that the serrated surfaces of the grip jaws fully enclose the grip tabs of the “base” adherend. After clamping the specimen in the upper and lower jaws, the specimen is forced to align with the loading direction of the testing machine, and any non-flatness of the overall specimen will result in initial bending strain relative to the “relaxed” configuration or when the specimen is hanging freely and the strain gages are zeroed. The existence or magnitude of this non-flatness of the specimens does not correlate with the parameters considered in this study.

Once the specimen is clamped in the lower grip jaws, the data acquisition is initiated via the LabVIEW program on the data acquisition computer. One to three seconds following, the predetermined testing routine with the testing parameters discussed in Section 6.4.2 is initiated on the testing machine controller. Any initial load and strain introduced during clamping is thus recorded in these first few seconds before the testing routine is initiated. Within one second after ultimate failure of the test specimen, the testing routine is stopped via the testing machine controller, which stops the movement of the crosshead. Ultimate failure of the specimen was identified as the point at which the specimen is no longer able to carry any load. This point is characterized for all specimens by a drop in force by at least 90% at the testing machine load cell over the span of less than two seconds, or eight data samples. In these cases, failure was also accompanied by an audible “pop” from the specimen itself. Within one to three seconds after stopping the test routine, the data acquisition is terminated via the labVIEW program. After, everything has been stopped, the “base” adherend is held while the lower grip clamping pressure is released, then the “base” adherend is removed from the testing machine while avoiding contact with the “patch” adherend. This process is repeated for the “patch” adherend in the upper grip. Both adherends are then stored in such a way that the failure surfaces are not disturbed, to preserve them for later inspection and characterization. Some specimens did not fully separate upon
ultimate failure, with some intact bits of film adhesive bridging from the scarfed surface of the "base" adherend to the scarfed surface of the "patch" adherend, thereby holding the two adherends together after removal from the testing machine. These specimens were stored in this attached configuration, and the two adherends were later separated while the film adhesive layer was observed under a microscope.

6.4.4 Damage Characterization

After concluding with all experimental testing, the post-mortem characteristics of each specimen were visually examined. This characterization of the failed specimens began with identification of the general characteristics of the failure surfaces. The three specimens in each test case were first compared within that group in an attempt to define the general failed behavior exhibited. Subsequently, the specimens within a group were compared with other specimens that had either a similar scarf angle or a similar blunt tip height. Finally, the failed surfaces of all specimens were compared regardless of individual geometric features. In the process, the types of failure of the joint, classified as adherend, adhesive, or cohesive, were first identified by observation of the scarf planes of the two adherends of each specimen. These observations were made at a magnification ranging from 1X to 5X using a Zeiss low-power optical microscope with two individually adjustable sources of light.

Photographs were taken of the failure surface on the scarf planes of all specimens from an x-y plane orientation of the microscope at a magnification of 1.8X in order to capture the entire surface. Due to the angle of the scarfed surface under examination, it was not possible to focus on the entire surface at one time from the x-y plane. Therefore, all photographs were taken with the center of the visible area in focus. Several photographs were also taken at 5X to capture details of the failure surfaces and the features within the film adhesive layer. Such features included regions of delamination and voids in the adhesive layer. Again, these were taken from the x-y plane and focus was done on the center of the visible area.

In order to understand the behavior around the blunt tip region, the two blunt tips in every specimen were examined. Each blunt tip was examined alongside the region on
the adjacent adherend from where the blunt tip failed. This examination was performed at various magnifications ranging from 1.8X to 5X with photographs taken of the blunt tip region in the y-z plane and the x-z plane of various specimens.

During characterization of the type of failure, several features stood out that required further investigation. Similar to the previous experimental work, from which this work builds upon, the failed surface of each adherend consisted mainly of black and red regions caused by either the absence or abundance of cured adhesive material. In this previous work, the color helped indicate the path of failure as well as the quality of the adhesive cure [27]. These regions of black scarfed adherend, that have no red film adhesive remaining, were classified based on the reflectivity of the surface. Regions consisted of either a matte surface with low reflectivity or a highly reflective, glossy surface. In order to determine the source of these differences in reflectivity, the failure surfaces on the scarf planes of the two adherends of a specimen are examined side-by-side and the features of the two surfaces compared at corresponding (x,y) positions.

Another feature that required further investigation is delamination. In some specimens, small regions of laminate delamination were found along the edges of the scarfed surface in the y-direction. In specimens where this occurred, these (x,y) locations on both adherends were examined and photographed under the 5X magnification. Due to the location of the delamination, it was also feasible to examine the feature in the x-z plane to measure the z-location of the delamination in each adherend. These regions were examined under a 10X magnification using a Zeiss high-power microscope with direct lighting to examine the microscopic details of the failure and quantify the location and extent of the delamination.
Chapter 7

Experimental Results

The results of the experimental work in this study are presented in this chapter. The data acquired during each test, including the load, displacement, and adherend strains, are presented in Section 7.1 and 7.2. The characteristics of the load applied to each specimen plotted against the displacement are presented in Section 7.1. This is followed by the far-field extensional strain and bending strain measured on each specimen versus the load in Section 7.2. The results of the failure surface characterization are presented in Section 7.3.

7.1 Load-Displacement

The measured results of the load carried by each specimen at the testing machine load cell plotted against the displacement of the testing machine crosshead are presented in this section. The individual plot of load versus displacement for each specimen is given in Appendix A. In this section, the plot of specimen 2 from the baseline configuration, which has a scarf angle of 10° and a blunt tip height of 1 ply, is presented in Figure 7.1. Since the results of most configurations all exhibit similar overall characteristics, Figure 7.1 is a representative plot of the general characteristics in the response of load verses displacement.

It is noted that specimen 1 of the baseline case is not representative of the general characteristics of the other configurations due to noise in data sampling that occurred during
data acquisition. The displacement data recorded for specimen 1 in the baseline case included an abundance of noise. Therefore, the measured displacement data was not used in analysis. Instead, the measured load data for specimen 1 of the baseline data is plotted against a displacement calculated from the constant crosshead displacement rate used during testing and the sampling frequency of the data acquisition system discussed in Chapter 6. This is the only test case where this event occurred.

As described in Chapter 6, testing is performed in uniaxial, quasi-static tension using a constant crosshead displacement rate of 0.002 millimeters per second (0.0047 inches per minute) and a sampling frequency of 4 Hz. In all test cases, there was an initial compressive load applied on the specimen resulting from the gripping of the specimen in the testing machine jaws. In all load-displacement plots, this initial region of compression is not shown as it is not pertinent to the tensile behavior of the specimens. In order to isolate the tensile load response of each specimen, the load data was cropped to begin at the point immediately following the last negative value of the measured load. The absolute position of the crosshead at this point is then subtracted from the entire displacement data set resulting in a plot starting from zero and representing the total crosshead displacement from the position of initial tensile load.

The load-displacement plot for each specimen spans from the initial loading condition of zero to the point at which the specimen is no longer able to carry additional load. This point is characterized for all specimens by a drop in force by at least 90% at the testing machine load cell. For most cases, this occurred over the span of two successive data points. However, in some specimens, this point occurred less suddenly over the span of less than two seconds, or less than eight data samples. In each case, the load data was manually examined and the final point at which the specimen could no longer carry additional load was selected and the data was cropped at that point.

As described in Chapter 6, an initial region of constant load was recorded at the beginning of data collection before the testing routine was initiated. This region is not shown in the load-displacement plots, but was evaluated for each case to determine the typical
Figure 7.1  Load versus displacement for Baseline Specimen 2 ($\alpha = 10^\circ$, $h_{blunt} = 1$ ply).
“noise”, or error, in the load readings. These calculations resulted in a standard deviation of 1.3 lbf. Thus, three times the standard deviation, or ±4 lbf, is considered the tolerance of the load measured in this work.

As seen in Figure 7.1, the load-displacement plot for specimen 2 of the baseline configuration shows an initial linear region that transitions to nonlinear over the course of the test as the load increases. Near the maximum load, this nonlinear region becomes more apparent as the tangent to the plot decreases to zero at the point of maximum load. After this point of maximum load, the load decreases as the displacement increases until the specimen eventually fails. The overall characteristics of the load versus displacement plots for each specimen show very similar trends and characteristics.

There are only slight variations in the general behavior of the different configurations. These occur between the point of maximum load and the point of specimen failure, such as the time between the two points. However, specimen 2 of the configuration having a scarf angle of 10° and a blunt tip height of 3 plies exhibited unique behavior in the load-displacement plot as seen in Figure A.8 in the Appendix. After the point of maximum load, the specimen experienced load dropoff, but rather than suddenly failing, the plot shows a relatively constant load, equal to approximately 94% of the maximum load value, as the displacement continues to increase until eventual failure of the specimen. This is the only specimen that exhibits this particular behavior.

In the load-displacement plots of some specimens, another unique feature was a “blip” in the data that appeared as a spike in the measured load or the measured displacement. In two cases where a noticeable spike occurred, the data was manually examined and the spike was found to be the result of one or two data points. In one case, the spike represented a sudden jump back to a zero load condition. This improbable scenario combined with the fact that the spike consisted of only one data point leads to the conclusion that this spike may be attributed to excessive noise in the data reading at this point. In another case, a “blip” occurred after failure during the drop in load. The displacement data showed a spike where the displacement suddenly decreased. Upon examination of the data, this highly improbable
scenario was the result of two data samples and it was concluded that the spike was due to excessive noise in the data at these points.

After examination of each individual load-displacement plot, several values of interest for each specimen were calculated. These are presented in Tables 7.1 to 7.12. During this analysis, a line was fit to the initial linear region of each specimen to gather information such as the linear slope and the point of transition to the nonlinear region. This line was fit to the region between the point of initial loading, where the displacement equals zero, and the point where the load equals 150 lbf. This final point was selected after examining all results and concluding that this point was within the linear region for all specimens. The least-squares method was used to calculate the best-fit line in the linear region for each specimen. The slope and the coefficient of determination, $R^2$, of each best-fit line are provided in the tables for each specimen.

In order to characterize the transition from linear to nonlinear behavior, this work used a method similar to that of previous work that used a combined load and strain offset approach [27]. First, the linear fit is shifted down by the data acquisition tolerance of 4 lbf to prevent the offset fit from intersecting the data prematurely due to noise. Offset values of constant overall specimen strain are then introduced to the linear fit with offset load. These values of strain are multiplied by the nominal length of the test section of each specimen (length between the grip tabs) to calculate the equivalent displacement offset in inches. Three offset strain values of 10 $\mu$strain, 20 $\mu$strain, and 30 $\mu$strain were chosen as these values are approximately 10%, 20%, and 30% of the strain at 150 lbf for the baseline cases. The intersection of the load data with each of the offset linear fits is determined to be the point at which the load value drops below the offset line. The values of the load and displacement at this point are presented for each offset value in the tables for each specimen. These parameters are referred to as $P_{\text{linear}}^{[N]}$ for the load, and $\delta_{\text{linear}}^{[N]}$ for displacement, where the superscript, $N$, is the value of the offset strain in $\mu$strain.

In addition to the linear fit, offset lines, and the key values associated with these, the maximum load obtained for each test case is provided, $P_{\text{max}}$, along with the displacement
value associated with the maximum load, $\delta_{\text{max}}$. The displacement value at which the specimen is determined to have failed, $\delta_{\text{final}}$, is also presented in the tables. Finally, the average value of the film adhesive thickness and height of the blunt tip for each specimen is provided for comparison to other key values.

7.2 Extensional and Bending Strains

The load carried by the specimen measured at the testing machine load cell versus the far-field strains measured on the surface of the adherends is presented in this section. As described in Chapter 6, each specimen is instrumented with four strain gages, with one on each side of the two adherends. These gages are positioned at a location where the strain is expected to have reached far-field value, between the strain fields created by the joint region and the tabbed region where the specimen is gripped. These four strain gages allow for both the extensional strain and through-thickness bending strain of each adherend to be measured. The extensional strain is the average of the strain gage readings on each adherend, whereas the bending strain is calculated as half the total difference between the strain gages on each adherend. Each calculation is performed point-by-point for all recorded strain data for each specimen. The two calculated strains, extensional and bending, are plotted separately for each specimen against the corresponding load values.

The load versus extensional strain plots of each specimen show the calculated strain in both the “patch” adherend and the “base” adherend. The general shape of the load-extensional plot for each specimen is very similar as all are linear in shape and the results from both adherends overlap almost exactly in most cases. Thus, a representative example of the general shape of the load versus extensional plot is shown in Figure 7.2 for the second specimen of the baseline case. The remaining load versus extensional strain plots are all shown in Appendix B. For each adherend in each specimen, a best-fit line is calculated for the load versus extensional strain data using the least-squares method to determine the slope and coefficient of determination. The slope of each line is then divided by the cross-sectional area using the average measured adherend thickness and measured width of each adherend.
Table 7.1  Summary of key values from load versus displacement data for specimens with $\alpha = 10^\circ$, $h_{blunt} = 1$ ply (baseline case)

<table>
<thead>
<tr>
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<th>Specimen 1*</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
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<tbody>
<tr>
<td>Slope of linear fit</td>
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<td>147</td>
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<td>0.999</td>
<td>0.994</td>
<td>0.992</td>
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<td>0.0016</td>
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<td>0.0022</td>
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<tr>
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<tr>
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* Other information used in determination of displacement due to noise in data.
Table 7.2  Summary of key values from load versus displacement data for specimens with $\alpha = 10^\circ$, $h_{blunt} = 2$ ply

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<td>146</td>
<td>148</td>
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<tr>
<td>$R^2$</td>
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<td>0.993</td>
<td>0.991</td>
</tr>
<tr>
<td>$P_{linear}^{[10]}$ [lbf]</td>
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<td>0.0036</td>
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<td>511</td>
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<td>0.0022</td>
<td>0.0036</td>
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<td>0.0154</td>
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<td>$\delta_{final}$ [in]</td>
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<tr>
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Table 7.3  Summary of key values from load versus displacement data
for specimens with $\alpha = 10^\circ$, $h_{blunt} = 3$ ply

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<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
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<tbody>
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<td>Slope of linear fit</td>
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<td>128</td>
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<tr>
<td>$R^2$</td>
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<td>0.996</td>
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<tr>
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<td>296</td>
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<tr>
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<td>0.0021</td>
<td>0.0024</td>
</tr>
<tr>
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<td>0.0039</td>
<td>0.0038</td>
</tr>
<tr>
<td>$P_{max}$ [lbf]</td>
<td>1187</td>
<td>1231</td>
<td>1165</td>
</tr>
<tr>
<td>$\delta_{max}$ [in]</td>
<td>0.0126</td>
<td>0.0117</td>
<td>0.0130</td>
</tr>
<tr>
<td>$\delta_{final}$ [in]</td>
<td>0.0126</td>
<td>0.0141</td>
<td>0.0131</td>
</tr>
<tr>
<td>$t_{adhesive}$ [in]</td>
<td>0.0086</td>
<td>0.0078</td>
<td>0.0126</td>
</tr>
<tr>
<td>$h_{blunt}$ [in]</td>
<td>0.0228</td>
<td>0.0224</td>
<td>0.0234</td>
</tr>
</tbody>
</table>
Table 7.4 Summary of key values from load versus displacement data for specimens with $\alpha = 10^5$, $h_{blunt} = 4$ ply

<table>
<thead>
<tr>
<th></th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit [lbf/in $\times 10^3$]</td>
<td>128</td>
<td>128</td>
<td>129</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.994</td>
<td>0.990</td>
<td>0.994</td>
</tr>
<tr>
<td>$P_{linear}^{[10]}$ [lbf]</td>
<td>350</td>
<td>310</td>
<td>420</td>
</tr>
<tr>
<td>$\delta_{linear}^{[10]}$ [in]</td>
<td>0.0028</td>
<td>0.0024</td>
<td>0.0033</td>
</tr>
<tr>
<td>$P_{linear}^{[20]}$ [lbf]</td>
<td>426</td>
<td>310</td>
<td>421</td>
</tr>
<tr>
<td>$\delta_{linear}^{[20]}$ [in]</td>
<td>0.0034</td>
<td>0.0024</td>
<td>0.0034</td>
</tr>
<tr>
<td>$P_{linear}^{[30]}$ [lbf]</td>
<td>430</td>
<td>382</td>
<td>422</td>
</tr>
<tr>
<td>$\delta_{linear}^{[30]}$ [in]</td>
<td>0.0034</td>
<td>0.0030</td>
<td>0.0034</td>
</tr>
<tr>
<td>$P_{max}$ [lbf]</td>
<td>960</td>
<td>1001</td>
<td>933</td>
</tr>
<tr>
<td>$\delta_{max}$ [in]</td>
<td>0.0105</td>
<td>0.0113</td>
<td>0.0096</td>
</tr>
<tr>
<td>$\delta_{final}$ [in]</td>
<td>0.0106</td>
<td>0.0113</td>
<td>0.0096</td>
</tr>
<tr>
<td>$t_{adhesive}$ [in]</td>
<td>0.0063</td>
<td>0.0075</td>
<td>0.0120</td>
</tr>
<tr>
<td>$h_{blunt}$ [in]</td>
<td>0.0309</td>
<td>0.0288</td>
<td>0.0312</td>
</tr>
</tbody>
</table>
Table 7.5  Summary of key values from load versus displacement data for specimens with \( \alpha = 5^\circ \), \( h_{blunt} = 1 \) ply

<table>
<thead>
<tr>
<th></th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit ([\text{lbf/in} \times 10^3])</td>
<td>124</td>
<td>124</td>
<td>123</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.994</td>
<td>0.994</td>
<td>0.995</td>
</tr>
<tr>
<td>( P_{linear}^{[10]} ) [\text{lbf}]</td>
<td>352</td>
<td>424</td>
<td>262</td>
</tr>
<tr>
<td>( \delta_{linear}^{[10]} ) [\text{in}]</td>
<td>0.0029</td>
<td>0.0035</td>
<td>0.0022</td>
</tr>
<tr>
<td>( P_{linear}^{[20]} ) [\text{lbf}]</td>
<td>497</td>
<td>548</td>
<td>384</td>
</tr>
<tr>
<td>( \delta_{linear}^{[20]} ) [\text{in}]</td>
<td>0.0041</td>
<td>0.0046</td>
<td>0.0032</td>
</tr>
<tr>
<td>( P_{linear}^{[30]} ) [\text{lbf}]</td>
<td>511</td>
<td>569</td>
<td>523</td>
</tr>
<tr>
<td>( \delta_{linear}^{[30]} ) [\text{in}]</td>
<td>0.0043</td>
<td>0.0049</td>
<td>0.0045</td>
</tr>
<tr>
<td>( P_{max} ) [\text{lbf}]</td>
<td>3232</td>
<td>4653</td>
<td>4806</td>
</tr>
<tr>
<td>( \delta_{max} ) [\text{in}]</td>
<td>0.0333</td>
<td>0.0473</td>
<td>0.0487</td>
</tr>
<tr>
<td>( \delta_{final} ) [\text{in}]</td>
<td>0.0334</td>
<td>0.0473</td>
<td>0.0487</td>
</tr>
<tr>
<td>( t_{adhesive} ) [\text{in}]</td>
<td>0.0029</td>
<td>0.0060</td>
<td>0.0053</td>
</tr>
<tr>
<td>( h_{blunt} ) [\text{in}]</td>
<td>0.0089</td>
<td>0.0089</td>
<td>0.0091</td>
</tr>
</tbody>
</table>
Table 7.6 Summary of key values from load versus displacement data for specimens with $\alpha = 5^\circ$, $h_{blunt} = 2$ ply

<table>
<thead>
<tr>
<th></th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit [lbf/in $\times 10^3$]</td>
<td>122</td>
<td>116</td>
<td>119</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.993</td>
<td>0.994</td>
<td>0.995</td>
</tr>
<tr>
<td>$P_{linear}^{[10]}$ [lbf]</td>
<td>262</td>
<td>446</td>
<td>308</td>
</tr>
<tr>
<td>$\delta_{linear}^{[10]}$ [in]</td>
<td>0.0021</td>
<td>0.0039</td>
<td>0.0027</td>
</tr>
<tr>
<td>$P_{linear}^{[20]}$ [lbf]</td>
<td>515</td>
<td>447</td>
<td>365</td>
</tr>
<tr>
<td>$\delta_{linear}^{[20]}$ [in]</td>
<td>0.0044</td>
<td>0.0039</td>
<td>0.0032</td>
</tr>
<tr>
<td>$P_{linear}^{[30]}$ [lbf]</td>
<td>517</td>
<td>516</td>
<td>365</td>
</tr>
<tr>
<td>$\delta_{linear}^{[30]}$ [in]</td>
<td>0.0044</td>
<td>0.0045</td>
<td>0.0032</td>
</tr>
<tr>
<td>$P_{max}$ [lbf]</td>
<td>2931</td>
<td>3145</td>
<td>3662</td>
</tr>
<tr>
<td>$\delta_{max}$ [in]</td>
<td>0.0320</td>
<td>0.0337</td>
<td>0.0379</td>
</tr>
<tr>
<td>$\delta_{final}$ [in]</td>
<td>0.0321</td>
<td>0.0339</td>
<td>0.0379</td>
</tr>
<tr>
<td>$t_{adhesive}$ [in]</td>
<td>0.0035</td>
<td>0.0033</td>
<td>0.0058</td>
</tr>
<tr>
<td>$h_{blunt}$ [in]</td>
<td>0.0141</td>
<td>0.0145</td>
<td>0.0159</td>
</tr>
</tbody>
</table>
Table 7.7  Summary of key values from load versus displacement data for specimens with $\alpha = 5^\circ$, $h_{blunt} = 3$ ply

<table>
<thead>
<tr>
<th></th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit [lbf/in x $10^3$]</td>
<td>116</td>
<td>114</td>
<td>115</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.993</td>
<td>0.995</td>
<td>0.994</td>
</tr>
<tr>
<td>$P_{linear}^{[10]}$ [lbf]</td>
<td>256</td>
<td>340</td>
<td>297</td>
</tr>
<tr>
<td>$\delta_{linear}^{[10]}$ [in]</td>
<td>0.0022</td>
<td>0.0030</td>
<td>0.0027</td>
</tr>
<tr>
<td>$P_{linear}^{[20]}$ [lbf]</td>
<td>513</td>
<td>476</td>
<td>434</td>
</tr>
<tr>
<td>$\delta_{linear}^{[20]}$ [in]</td>
<td>0.0046</td>
<td>0.0043</td>
<td>0.0039</td>
</tr>
<tr>
<td>$P_{linear}^{[30]}$ [lbf]</td>
<td>513</td>
<td>533</td>
<td>497</td>
</tr>
<tr>
<td>$\delta_{linear}^{[30]}$ [in]</td>
<td>0.0046</td>
<td>0.0049</td>
<td>0.0045</td>
</tr>
<tr>
<td>$P_{max}$ [lbf]</td>
<td>1814</td>
<td>1952</td>
<td>2568</td>
</tr>
<tr>
<td>$\delta_{max}$ [in]</td>
<td>0.0219</td>
<td>0.0228</td>
<td>0.0288</td>
</tr>
<tr>
<td>$\delta_{final}$ [in]</td>
<td>0.0221</td>
<td>0.0229</td>
<td>0.0288</td>
</tr>
<tr>
<td>$t_{adhesive}$ [in]</td>
<td>0.0046</td>
<td>0.0430</td>
<td>0.0062</td>
</tr>
<tr>
<td>$h_{blunt}$ [in]</td>
<td>0.0216</td>
<td>0.0218</td>
<td>0.0235</td>
</tr>
</tbody>
</table>
Table 7.8  Summary of key values from load versus displacement data for specimens with $\alpha = 5^\circ$, $h_{blunt} = 4$ ply

<table>
<thead>
<tr>
<th></th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit [lbf/in $\times 10^3$]</td>
<td>109</td>
<td>110</td>
<td>108</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.996</td>
<td>0.995</td>
<td>0.996</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[10]}$ [lbf]</td>
<td>248</td>
<td>328</td>
<td>312</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[10]}$ [in]</td>
<td>0.0023</td>
<td>0.0030</td>
<td>0.0029</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[20]}$ [lbf]</td>
<td>319</td>
<td>467</td>
<td>505</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[20]}$ [in]</td>
<td>0.0030</td>
<td>0.0044</td>
<td>0.0048</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[30]}$ [lbf]</td>
<td>499</td>
<td>467</td>
<td>548</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[30]}$ [in]</td>
<td>0.0047</td>
<td>0.0044</td>
<td>0.0054</td>
</tr>
<tr>
<td>$P_{\max}$ [lbf]</td>
<td>1398</td>
<td>1400</td>
<td>1868</td>
</tr>
<tr>
<td>$\delta_{\max}$ [in]</td>
<td>0.0170</td>
<td>0.0171</td>
<td>0.0217</td>
</tr>
<tr>
<td>$\delta_{\text{final}}$ [in]</td>
<td>0.0173</td>
<td>0.0172</td>
<td>0.0219</td>
</tr>
<tr>
<td>$t_{\text{adhesive}}$ [in]</td>
<td>0.0030</td>
<td>0.0025</td>
<td>0.0067</td>
</tr>
<tr>
<td>$h_{\text{blunt}}$ [in]</td>
<td>0.0298</td>
<td>0.0305</td>
<td>0.0308</td>
</tr>
</tbody>
</table>

260
Table 7.9  Summary of key values from load versus displacement data for specimens with $\alpha = 3^\circ$, $h_{\text{blunt}} = 1$ ply

<table>
<thead>
<tr>
<th></th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit [lbf/in $\times 10^3$]</td>
<td>105</td>
<td>98</td>
<td>99</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.994</td>
<td>0.996</td>
<td>0.995</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[10]}$ [lbf]</td>
<td>328</td>
<td>355</td>
<td>363</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[10]}$ [in]</td>
<td>0.0031</td>
<td>0.0036</td>
<td>0.0037</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[20]}$ [lbf]</td>
<td>392</td>
<td>463</td>
<td>360</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[20]}$ [in]</td>
<td>0.0038</td>
<td>0.0048</td>
<td>0.0037</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[30]}$ [lbf]</td>
<td>400</td>
<td>519</td>
<td>481</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[30]}$ [in]</td>
<td>0.0039</td>
<td>0.0055</td>
<td>0.0050</td>
</tr>
<tr>
<td>$P_{\max}$ [lbf]</td>
<td>6789</td>
<td>6659</td>
<td>6521</td>
</tr>
<tr>
<td>$\delta_{\max}$ [in]</td>
<td>0.0925</td>
<td>0.0956</td>
<td>0.0936</td>
</tr>
<tr>
<td>$\delta_{\text{final}}$ [in]</td>
<td>0.0925</td>
<td>0.0956</td>
<td>0.0936</td>
</tr>
<tr>
<td>$t_{\text{adhesive}}$ [in]</td>
<td>0.0021</td>
<td>0.0089</td>
<td>0.0091</td>
</tr>
<tr>
<td>$h_{\text{blunt}}$ [in]</td>
<td>0.0080</td>
<td>0.0083</td>
<td>0.0077</td>
</tr>
</tbody>
</table>
Table 7.10  Summary of key values from load versus displacement data for specimens with $\alpha = 3^\circ$, $h_{blunt} = 2$ ply

<table>
<thead>
<tr>
<th></th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit [lbf/in $\times 10^3$]</td>
<td>100</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.996</td>
<td>0.995</td>
<td>0.995</td>
</tr>
<tr>
<td>$P_{linear}^{[10]}$ [lbf]</td>
<td>263</td>
<td>306</td>
<td>444</td>
</tr>
<tr>
<td>$\delta_{linear}^{[10]}$ [in]</td>
<td>0.0028</td>
<td>0.0031</td>
<td>0.0047</td>
</tr>
<tr>
<td>$P_{linear}^{[20]}$ [lbf]</td>
<td>368</td>
<td>419</td>
<td>447</td>
</tr>
<tr>
<td>$\delta_{linear}^{[20]}$ [in]</td>
<td>0.0038</td>
<td>0.0043</td>
<td>0.0048</td>
</tr>
<tr>
<td>$P_{linear}^{[30]}$ [lbf]</td>
<td>495</td>
<td>421</td>
<td>547</td>
</tr>
<tr>
<td>$\delta_{linear}^{[30]}$ [in]</td>
<td>0.0052</td>
<td>0.0043</td>
<td>0.0060</td>
</tr>
<tr>
<td>$P_{max}$ [lbf]</td>
<td>4333</td>
<td>4878</td>
<td>5443</td>
</tr>
<tr>
<td>$\delta_{max}$ [in]</td>
<td>0.0540</td>
<td>0.0607</td>
<td>0.0735</td>
</tr>
<tr>
<td>$\delta_{final}$ [in]</td>
<td>0.0540</td>
<td>0.0608</td>
<td>0.0736</td>
</tr>
<tr>
<td>$t_{adhesive}$ [in]</td>
<td>0.0021</td>
<td>0.0019</td>
<td>0.0085</td>
</tr>
<tr>
<td>$h_{blunt}$ [in]</td>
<td>0.0164</td>
<td>0.0162</td>
<td>0.0149</td>
</tr>
</tbody>
</table>
Table 7.11 Summary of key values from load versus displacement data for specimens with $\alpha = 3^\circ$, $h_{blunt} = 3$ ply

<table>
<thead>
<tr>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit [lbf/in $\times 10^3$]</td>
<td>92</td>
<td>93</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.996</td>
<td>0.997</td>
</tr>
<tr>
<td>$P_{linear}^{[10]}$ [lbf]</td>
<td>466</td>
<td>446</td>
</tr>
<tr>
<td>$\delta_{linear}^{[10]}$ [in]</td>
<td>0.0051</td>
<td>0.0048</td>
</tr>
<tr>
<td>$P_{linear}^{[20]}$ [lbf]</td>
<td>517</td>
<td>454</td>
</tr>
<tr>
<td>$\delta_{linear}^{[20]}$ [in]</td>
<td>0.0057</td>
<td>0.0050</td>
</tr>
<tr>
<td>$P_{linear}^{[30]}$ [lbf]</td>
<td>572</td>
<td>552</td>
</tr>
<tr>
<td>$\delta_{linear}^{[30]}$ [in]</td>
<td>0.0064</td>
<td>0.0062</td>
</tr>
<tr>
<td>$P_{max}$ [lbf]</td>
<td>3525</td>
<td>3699</td>
</tr>
<tr>
<td>$\delta_{max}$ [in]</td>
<td>0.0463</td>
<td>0.0480</td>
</tr>
<tr>
<td>$\delta_{final}$ [in]</td>
<td>0.0464</td>
<td>0.0482</td>
</tr>
<tr>
<td>$t_{adhesive}$ [in]</td>
<td>0.0031</td>
<td>0.0022</td>
</tr>
<tr>
<td>$h_{blunt}$ [in]</td>
<td>0.0229</td>
<td>0.0227</td>
</tr>
</tbody>
</table>
Table 7.12  Summary of key values from load versus displacement data for specimens with $\alpha = 3^\circ$, $h_{\text{blunt}} = 4$ ply

<table>
<thead>
<tr>
<th></th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope of linear fit [lbf/in $\times 10^3$]</td>
<td>91</td>
<td>92</td>
<td>87</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.995</td>
<td>0.997</td>
<td>0.996</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[10]}$ [lbf]</td>
<td>456</td>
<td>262</td>
<td>453</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[10]}$ [in]</td>
<td>0.0051</td>
<td>0.0029</td>
<td>0.0053</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[20]}$ [lbf]</td>
<td>459</td>
<td>472</td>
<td>516</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[20]}$ [in]</td>
<td>0.0051</td>
<td>0.0053</td>
<td>0.0061</td>
</tr>
<tr>
<td>$P_{\text{linear}}^{[30]}$ [lbf]</td>
<td>509</td>
<td>507</td>
<td>551</td>
</tr>
<tr>
<td>$\delta_{\text{linear}}^{[30]}$ [in]</td>
<td>0.0058</td>
<td>0.0058</td>
<td>0.0066</td>
</tr>
<tr>
<td>$P_{\text{max}}$ [lbf]</td>
<td>2410</td>
<td>2264</td>
<td>1921</td>
</tr>
<tr>
<td>$\delta_{\text{max}}$ [in]</td>
<td>0.0332</td>
<td>0.0302</td>
<td>0.0281</td>
</tr>
<tr>
<td>$\delta_{\text{final}}$ [in]</td>
<td>0.0335</td>
<td>0.0303</td>
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<td>0.0305</td>
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This results in the longitudinal modulus of each adherend. These moduli are presented in Table 7.13. In all cases, the value of $R^2$ is 0.999 or greater. Comparably, the nominal longitudinal modulus for a $[\pm 15]_{3s}$ laminate was calculated using Classical Laminated Plate Theory (CLPT) to equal 16.3 Msi. All reported values are within 5% of this calculated value.

The load versus bending strain response for each specimen is not shown in this work as all specimens exhibited very little bending and no discernible trends as the applied load increased. Specifically, the magnitude of bending strain in the majority of test cases did not change by more than 50 $\mu$strain before failure occurred, indicating an overall lack of bending. The largest recorded magnitude of bending strain occurred in specimen 1 with $\alpha$ equal to 5° and $h_{\text{blunt}}$ of 3 ply. This specimen had a bending strain of 86 $\mu$strain at a load of 1,814 lbf compared to the extensional strain value of 1,217 $\mu$strain at the same load for the specimen. This was the largest ratio of bending strain to extensional strain of approximately 7% with the average for all specimens being approximately 2%.

7.3 Failure Surface Characterization

The general characteristics of the post mortem appearance of the failure surfaces of the test specimens is presented in this section. Photographs of the scarfed region of both adherends taken from the x-y plane as described in Chapter 6 are configured in the manner illustrated in Figure 7.3 for each specimen. As shown in this figure, in order to take photographs of both adherends, the “patch” adherend is rotated 180° about its x-centerline. Thus, the coordinate axis for the two adherends share a similar x-axis, but the y-axis and z-axis are opposite each other. This results in features of the failure surface taken from the x-y plane on one adherend being mirrored about the x-axis onto the failure surface of the other adherend. Photographs of the failure surfaces taken from the x-y plane for each specimen are shown in Appendix C.

Ignoring the key geometry that separates the different test cases (e.g. scarf angle and blunt tip height), a characterization of the general appearance of the failed surfaces taken from the x-y plane introduces two different groups. Based on the general appearance and
Figure 7.2  Load versus extensional strain for Baseline Specimen 2 ($\alpha = 10^\circ$, $h_{\text{blunt}} = 1$ ply).
Table 7.13 Longitudinal elastic moduli for all specimens from load versus extensional strain data

<table>
<thead>
<tr>
<th>Specimen Type</th>
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<th>Adherend</th>
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<th>Patch</th>
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Figure 7.3 Illustration of the configuration in which specimens are pictured in the post mortem photographs compared to the configuration of specimen during testing.
comparing the average cured adhesive thicknesses, all specimens can be grouped either into having a cured “thin adhesive” layer or having a cured “thick adhesive” layer. In Chapter 3, the film adhesive used is characterized as having a nominal uncured thickness of 0.008 inches and a nominal cured thickness of 0.0035 inches. In this work, specimens grouped as having a cured “thin adhesive” layer are characterized as having an average cured adhesive thickness less than or equal to 0.004 inches. Alternatively, specimens grouped as having a cured “thick adhesive” layer are characterized as having an average cured adhesive thickness greater than 0.004 inches. This value of 0.004 inches was chosen based on consideration of the post mortem photographs as the specimens in the two different groups show distinct differences in the overall appearance of the exposed film adhesive on the scarfed surface after failure. This is also close to the value of the nominal cured adhesive thickness. Representative photographs for the two different classes are shown in Figure 7.4 and Figure 7.5, where two specimens of the test case having a scarf angle equal to 10° and a blunt tip height equal to 2 plies are shown. Specimen 1 for this test case has an average cured adhesive thickness equal to 0.0027 inches, while specimen 3 for this test case has an average cured adhesive thickness equal to 0.0083 inches. Thus, specimen 1 is classified as having a cured “thin” adhesive layer, while specimen 3 has a cured “thick” adhesive layer.

All specimens classified as having a cured “thin” adhesive layer appear similar to the scarfed surfaces of specimen 1 shown in Figure 7.4. In these specimens, the failure surface of the “patch” and “base” adherend appear very similar. Adhesive material appears spread evenly and sparsely across both surfaces of the “patch” adherend and “base” adherend. This indicates cohesive failure across the scarfed surface. Alternatively, in specimens classified as having a cured “thick” adhesive layer, there are distinct regions on the failure surface that show an abundance of film adhesive and regions that show very little film adhesive as seen for specimen 3 on Figure 7.5. This indicates adhesive failure along the bondline surface. The “patch” adherend and “base” adherend are mirror opposites of each other meaning that the failure surfaces of the two adherends are antisymmetric. Beginning from the wide angle of the “base” adherend and heading towards the blunt tip, very little adhesive is
Figure 7.4 Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for representative specimen with a cured “thin” adhesive layer (specimen 1 with $\alpha = 10^\circ$ and $h_{blunt} = 2$ plies).
Figure 7.5 Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for representative specimen with a cured "thick" adhesive layer (specimen 3 with $\alpha = 10^\circ$ and $h_{blunt} = 2$ plies).
visible indicating adhesive failure. Progressing along the bondline, towards the blunt tip, this adhesive failure transitions to the opposite bondline, adjacent to the scarfed surface of the “base” adherend. This is indicated by a transition from a region of little film adhesive to a region of an abundance of film adhesive along the bondline in the “base” adherend. This is mirrored on the “patch” adherend.

In general, the majority of specimens classified as having either a cured “thin” adhesive layer or a cured “thick” adhesive layer show very similar characteristics of the failure surface along the scarfed plane as described. While the amount of visible adhesive in the specimens classified as “thin” varied amongst specimens, the appearance of an equal distribution was a common trait within the group. Similarly, in the group classified as “thick”, the size of the visible adhesive regions varied amongst test cases in this classification, and the point where adhesive failure visibly transitioned from one bondline to the adjacent bondline varied. However, the general appearance of the failed surface was similar for all cases under this classification. The one outlier was specimen 3 of the case having a scarf angle of 10° and a blunt tip height of 4 plies. This specimen had an average cured adhesive thickness of 0.0120 inches. In this case, the adhesive failure did not visibly transition from one bondline to the adjacent bondline, as the adhesive failure remained only along the “patch” bondline.

Further investigation shows that the failure surface in front of the blunt tip region is independent of this classification by cured adhesive thickness. Regardless of cured adhesive thickness, the failure surface in front of the blunt tip region is similar for all test cases as cohesive failure occurred. This is apparent as there is visible adhesive material on the y-z surface of the blunt tips. The regions in front of the “patch” blunt tip and corresponding “base” wide angle region are shown for a representative case in Figure 7.6. These photographs were taken of the y-z plane looking directly at these two features using the low-power microscope at a 4X magnification. The “base” blunt tip and “patch” wide angle are not shown as they display similar traits. Additionally, the wide angle region is not shown in other figures as any features shown along the blunt tip are mirrored on the wide angle region, such as the void region in Figure 7.6.
Figure 7.6 Magnified photograph comparing the blunt tip in the y-z plane of the “patch” adherend and the wide angle of the “base” adherend (specimen 3 with $\alpha = 3^\circ$, $h_{blunt} = 4$).
Photographs of magnified regions of the blunt tips in the y-z plane for representative specimens having a cured “thin” and cured “thick” adhesive layer are shown in Figure 7.7 at a magnification of 5X. The adhesive in front of the blunt tips indicates cohesive failure for all cases. In addition, voids are visible in front of the blunt tip. The largest variation is the size and location of the voids. In a majority of specimens with a cured “thin” adhesive layer, the voids are larger in size and spread along the corner of the scarf plane created by the blunt tip as seen in Figure 7.7(a). Alternatively, most specimens with a cured “thick” adhesive layer have voids that are smaller and circular in shape. These voids are also sporadic in location across the surface of the blunt tip region. This is seen in Figure 7.7(b).

These overall characteristics as described are the parts of the overall failure paths for the various specimens as illustrated in Figure 7.8. For the specimens classified as having a cured “thick” adhesive layer, cohesive failure occurs in front of the blunt region of one adherend and travels through the adhesive adjacent to the blunt edge and then crosses the film adhesive layer to be adjacent to the opposite bondline at the wide angle of the other adherend. This path of adhesive failure then follows the bondline away from the wide angle before transitioning back across the bondline. This meets a similar path from the other blunt edge. In the cured “thin” adhesive group, cohesive failure again occurs in the region in front of the blunt tip and continues as cohesive failure around the corner created by the blunt tip and along the bondline meeting cohesive failure from the opposite blunt tip.

In addition to the characteristics of failure described, several other unique features occurred in various test cases. Regardless of test case or cured adhesive thickness, all specimens exhibited voids in the adhesive layer resulting from the film adhesive curing process. While these voids are more noticeable in the specimens with cured “thick” adhesive, voids are still apparent in the specimens with cured “thin” adhesive. Voids are identified and confirmed by visually comparing the adhesive remaining on the scarfed surfaces of both adherends of a specimen and identifying regions of missing film adhesive that are co-located on the scarf planes of the two adherends. These regions are characterized by the high reflectivity of the visible surface that is caused by the smooth, glossy surface of the cured film adhesive around

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Figure 7.7 Magnified photograph of the blunt tips in the y-z plane of the “base” adherends for the two classifications: (a) cured “thin” adhesive layer (specimen 1 with \( \alpha = 3^\circ \) and \( h_{blunt} = 4 \) plies); and (b) cured “thick” adhesive layer (specimen 3 with \( \alpha = 3^\circ \) and \( h_{blunt} = 4 \) plies).
Figure 7.8  Illustration of overall failure path for a typical specimen in each classification: (a) cured “thick” adhesive layer; and (b) cured “thin” adhesive layer.
these voids. This high reflectivity is shown for both the cured “thick” and cured “thin” adhesive cases in Figures 7.9 and 7.10.

An additional feature that occurred along the failure surface of several specimens is delamination of the adherend material. In several specimens, small regions of adherend material failed via delamination along the edges of the specimen within the joint region at locations of \( y \) equal to 0 inch or \( y \) equal to 1 inch. This failure only occurred in specimens having a cured “thick” adhesive layer and only in test cases having a scarf angle of 5° or 3°. This feature is most noticeable in specimen 3 of the test case having a scarf angle of 3° and a blunt tip height of 4 plies, as shown in Figure 7.11. In the photograph of the “base” adherend, at \( y \) equal to 1 inch, a small region of adherend material from the “patch” adherend is visibly bonded to the adhesive layer along the bondline of the “base” adherend. Alternatively, at the co-located position of the “patch” adherend at \( y \) equal to 1 inch, the region of missing adherend material is visible where the delamination in the “patch” adherend occurred. This particular delamination in Figure 7.11 occurred between the fifth \((+15°)\) and sixth \((-15°)\) plies from the bottom of the “patch” adherend at \( y \) equal to 1 inch. In general, delamination occurring at this ply interface in the “patch” adherend and at \( y \) equal to 1 inch is the most common location of delamination. Four out of six total specimens examined with regions of delamination occurred at this location.
Figure 7.9 Magnified photograph of the scarfed surface from the x-y plane for a representative specimen for the cured “thick” adhesive class (specimen 3 with $\alpha = 5^\circ$ and $h_{blunt} = 4$ plies) showing void in “base” adherend.
Figure 7.10  Magnified photograph of the scarfed surface from the x-y plane for a representative specimen for the cured “thin” adhesive class (specimen 2 with $\alpha = 5^\circ$ and $h_{\text{blunt}} = 1$ ply) showing void in “base” adherend.
Figure 7.11  Magnified photograph from the x-y plane of the delamination within the joint region of the “patch” adherend (specimen 3 case with $\alpha = 3^\circ$, $h_{\text{blunt}} = 4$ plies).
Chapter 8

Discussion

A discussion of the results from the numerical work and the experimental work is the focus of this chapter. Further observations are made concerning these results in the context of the primary objective of this work, addressing the sensitivity of the composite scarf joint to the height of the blunt tip, as introduced in Chapter 3, and key conclusions are reached. In Section 8.1, the discussion is focused on the results from the numerical work with a discussion of the results focused on the experimental work in Section 8.2.

8.1 Discussion of Finite Element Work

In Chapter 5, the distributions of the normalized strains are presented in two different formats in order to consider the effects of the height of the blunt tip and of the laminate thickness. In each configuration, there is a large gradient near the blunt tip in both longitudinal strain and shear strain that dissipates along the bondline away from the corner of the blunt tip. This is evident in the distributions of the normalized longitudinal and shear strains in the adhesive at the “patch” nominal bondline of the joint. For each model, as shown in Figures 5.6 and 5.41 for the normalized longitudinal strain, there is a peak near the blunt tip of the “patch” adherend, but far from the blunt tip, the response is unaffected and identical to the “ideal” case with a feathered edge, with the exception of the case with
a BH of 25%. All these other configurations have a constant value of 1.8 in the adhesive at the center region of the “patch” bondline, with variation of approximately 1% amongst the configurations. The “ideal” case with a laminate thickness of [±15]_{3S} and a feathered edge (BH of 0%) has a peak value of 10.2 in the adhesive at the corner of the feather tip, and reaches within 10% of this constant value at a distance of 0.09 inches from the feathered edge. The case with a laminate thickness of [±15]_{3S} and a blunt tip height of 0.6t_{ply} (BH of 5%) has a peak value of 14.1, and reaches within 10% of the constant value at a distance of 0.11 inches from the corner of the blunt tip. Similarly, the case with a laminate thickness of [±15]_{3S} and a blunt tip height of t_{ply} (BH of 5%) has a peak value of 14.5, and reaches within 10% of the constant value at a distance of 0.15 inches from the corner of the blunt tip. The case with a laminate thickness of [±15]_{3S} and a blunt tip height of t_{ply} (BH of 8.3%) has a peak value of 15.1 at the corner of the blunt tip, and reaches within 10% of this constant value at a distance of 0.18 inches from the corner of the blunt tip. However, the case with a laminate thickness of [±15]_{3S} and a blunt tip height of t_{ply} (BH of 25%) has a peak magnitude of 24.9. Furthermore, this case does not reach the constant value along the center region of the bondline, but decreases to a local minimum of 2.2 at a point that is 0.097 inches from the corner of the blunt tip before increasing to a second peak near the blunt tip of the “base” adherend. A very similar response is visible in the distributions of the normalized shear strain in the adhesive at the “patch” nominal bondline of the joint, but with larger magnitudes and values that are negative.

These variations, and specifically the response in the case with a BH of 25%, indicate the effects of the finite thickness and of the blunt height ratio on the overall stress and strain fields. As the blunt height ratio increases, the size and magnitude of the gradient at the corner of the blunt tip increases. However, in larger values of BH, these gradients approach the center of the joint and the overall response no longer resembles the “ideal” case.

These gradients at the corner of the blunt tip are independent of any specific lengthscale. Instead, the size and magnitude of these gradients are directly related to the blunt height ratio as evident by the similarities between the two different cases that have a blunt height
ratio of 5%. This is shown in Figures 8.1 and 8.2, which show the normalized longitudinal strain and normalized shear strain in the adhesive at the “patch” bondline of the joint with the origin at the corner of the blunt tip of the “patch” adherend. These results have been cropped to only display the distributions of strain along the bondline between the blunt tips and the bondline distance is normalized by the total length of the bondline between the blunt tips for each configuration. These two cases with a BH of 5% have varying lengthscales, but a similar blunt height ratio, and similar stress and strain fields at the corner of the blunt tip and along the bondline. Therefore, it can be concluded that the gradients and overall mechanical response of the joint are due to finite thickness effects and the interactions of the stress and strain fields as the load travels through the joint, which is affected by both the height of the blunt tip and the thickness of the laminate.

Furthermore, these responses shown in Figures 8.1 and 8.2 demonstrate that for the two cases with a BH of 5%, which have different lengthscales of $h_{blunt}$ and $t_{adherend}$, the gradient near the corner of the blunt tip is the same. Thus, it can be concluded that the magnification of the strain at the corner of the blunt tip is not due to any specific lengthscales, but is simply due to the simple existence of the corner at the blunt tip as shown in the peak magnitudes of the gradients in the adhesive at the corner of the blunt tip. After closer examination of the gradient in the adhesive at the corner of the blunt tips, the case with a laminate thickness of $[\pm 15]_{3S}$ and a blunt tip height of 0.6$t_{ply}$ (BH of 5%) has a peak value of 20.1 in the normalized longitudinal strain and -36.9 in the normalized shear strain. The case with a laminate thickness of $[\pm 15]_{ss}$ and a blunt tip height of $t_{ply}$ (BH of 5%) has a peak value of 21.0 in the normalized longitudinal strain and -38.8 in the normalized shear strain. Due to the finite thickness effects of the joint, as the blunt height ratio changes, the gradient at the corner of the blunt tip changes. The case with a laminate thickness of $[\pm 15]_{3S}$ and a blunt tip height of $t_{ply}$ (BH of 8.3%) has a peak value of 26.1 in the normalized longitudinal strain and -35.3 in the normalized shear strain. Finally, the case with a laminate thickness of $[\pm 15]_{S}$ and a blunt tip height of $t_{ply}$ (BH of 25%) has a peak value of 36.5 in the normalized longitudinal strain and -33.6 in the normalized shear strain.
Figure 8.1  Distribution of normalized longitudinal strain in the adhesive at the normalized “patch” bondline for all configurations.
Figure 8.2  Distribution of normalized shear strain in the adhesive at the normalized "patch" bondline for all configurations.
In the through-thickness region of the blunt tip, the normalized longitudinal strain in the adhesive is significantly larger throughout the entire region (normalized values between 10 and 25) compared to the constant value of 1.8 along most of the bondline. This response in this blunt tip region is shown in Figures 8.3 and 8.4. In these figures, the distributions of the normalized strains in the adhesive along the axis of \( z_a \) just before the blunt tip of the “patch” adherend are presented with the origin at the corner of the blunt tip. In this region, this response is similar to that of a butt joint as the magnitudes of longitudinal strain of the adhesive increase along the blunt tip region and those of the shear strain decrease.

Along the scarfed region between the corners of the blunt tips, the general response has been previously described as a gradient near the corner of the blunt tip that dissipates along the length of the bondline, with the magnitudes of the strains in the adhesive indicating the behavior of the region. As shown in Figures 8.1 and 8.2, the magnitudes of the shear strain in the adhesive are significantly larger compared to those of the longitudinal strain. This indicates that the response between the two blunt tips, along the scarfed region, is dominated by shear in the adhesive, and that the bulk of the load is transferred from one adherend to the other via the adhesive undergoing shear deformation. Specifically, the magnitude of the normalized shear strain in the constant region along the bondline is approximately eight times larger compared to the normalized longitudinal strain with magnitudes of 14.6 and 1.8, respectively.

After examining these two regions, along the bondline and along the blunt tip, the mechanical response of the scarf joint can be characterized by considering the extremes. In the “ideal” case with a feathered edge, the magnitudes of the shear strain in the adhesive are significantly larger compared to those of the longitudinal strain. This indicates that the response is dominated by shear in the adhesive, and that the bulk of the load is transferred from one adherend to the other via the adhesive undergoing shear deformation. Alternatively, when the blunt height ratio equals 0.5, the joint is a butt joint and the load transfer occurs only by longitudinal strain rather than shear as in the scarf joint. This leads to a conclusion concerning the overall mechanical response of the scarf joint with a blunt tip. The basic
Figure 8.3  Distribution of normalized longitudinal strain through the thickness in z at a constant value of x equal to the location of $h_{\text{blunt}}$ (just before the blunt tip) for the configurations with a blunt tip.
Figure 8.4 Distribution of normalized shear strain through the thickness in z at a constant value of x equal to the location of $h_{\text{blunt}}$ (just before the blunt tip) for the configurations with a blunt tip.
response of a scarf joint with a blunt tip can be characterized as a hybrid of the "ideal" scarf joint and a butt joint where the response of the region between the two blunt tips is similar to an "ideal" scarf joint, and the blunt tip region is similar to a butt joint. These regions are acting in parallel.

The blunt tip changes the load transfer mechanisms of the scarf joint. This can be derived from equilibrium considerations. Per mechanical equilibrium, the net longitudinal stress resultant for any given cross-section in the joint region must equal the net longitudinal stress outside the joint. Thus, while the scarf joint configuration primarily transfers load through shear of the adhesive in the scarfed region, in the blunt tip region, there is an increased magnitude of longitudinal strain in the adhesive and a decrease in shear. Therefore, as the blunt height ratio increases, more load is transferred via longitudinal strain as opposed to shear of the adhesive. This response is visible in Figures 8.1 and 8.2, which show the normalized longitudinal strain and normalized shear strain in the adhesive at the normalized "patch" bondline of the joints. In both the longitudinal strain and shear strain, as the blunt height ratio increases, the normalized length between the two corners of the blunt tips decreases. This indicates that a larger ratio of the load must be transferred through the blunt tip region as longitudinal strain.

A normalized ratio can be defined to describe the impact of the blunt height ratio on the overall mechanical response of the scarf joint. This ratio is derived from the cross-sectional area of the scarf joint and the ratio of the different regions as controlled by the blunt height ratio:

\[
\frac{t_{\text{adherend}} - 2h_{\text{blunt}}}{t_{\text{adherend}}} = 1 - 2BH
\]

This is derived from Figure 8.5 where the general response of the scarf joint with a blunt tip is shown as a hybrid of the "ideal" scarf joint and butt joints acting in parallel. Due to equilibrium, all three regions must have the same strain.

However, the mechanics of each region vary as the "ideal" scarf region transfers load primarily via shear deformation, and the butt joint region transfers load primarily via longitudinal deformation. Therefore, this ratio demonstrates the influence of the finite thickness
of the laminate and the interactions of the stress and strain fields as they travel around the blunt tips. Specifically, this figure and equation demonstrate that the blunt height ratio is the controlling factor that determines the ratio of strain that is carried in each region. As the blunt height ratio increases, Equation 8.1 decreases in value meaning that the “ideal” scarf joint region has less ability to transfer load and more strain must be transferred through the butt joint region.

The response due to the blunt height ratio raises an additional question that needs to be investigated in more detail. Specifically, this relation between the height of the blunt tip and the thickness of the laminate should be further investigated to better understand the sensitivity of the scarf joint to these two length scales. It is recommended that thicker laminates be investigated while changing the height of the blunt tip. During this future work, the focus should be to reduce the effects of the finite thickness of the laminate by maintaining blunt height ratios on the order of 1% in order to focus on the direct effect, if any, of the blunt tip on the mechanical response of the joint. This would allow a better understanding of whether the height of the blunt tip contributes to the stress and strain gradients within the joint, and if so, its manner of contribution.

8.2 Discussion of Experimental Work

The results of the experimental work presented in Chapter 7 include the load-displacement response, load/stress versus extensional strain response, load versus bending strain response, and observations of the failure surfaces of each specimen. In general, the shape of the overall load-displacement response, which begins with a linear region and transitions to a nonlinear region with a monotonically decreasing slope with increasing load, is consistent for all specimens regardless of the geometric length scales or the maximum load capability of the specimen. This similar shape in the load-displacement response of every specimen is similar to that observed in work performed by Jones [27].

Other consistencies are shown in the longitudinal stiffness of the adherends derived by calculating the linear fits of the applied adherend stress versus the longitudinal strain.
Figure 8.5  Illustration of general configuration model of a scarf joint with a blunt tip as a hybrid of the "ideal" scarf joint and butt joints.
These measured longitudinal stiffnesses of the adherends show good consistency across all specimens and correlate well with the calculations via Classical Laminated Plate Theory (CLPT). Another consistency is that the magnitude of bending strain in the majority of test cases was less than 50 μstrain before failure occurred, indicating an overall lack of bending. The largest recorded magnitude of bending strain had a value of 86 μstrain at a load of 1,814 lbf compared to the extensional strain value of 1,217 μstrain at the same load for the specimen. This was the largest ratio of bending strain to extensional strain of approximately 7% with the average for all specimens being approximately 2%. This lack of bending and general extensional characteristics agree with the numerical analysis performed in this work and previous work, which shows that, while the blunt height ratio has an impact on the response of the joint, this response is localized to the region of the scarf joint. Away from this region, the response is unaffected and is the same for each case [13]. This demonstrates the expected characteristics of the values of far-field strain.

Looking specifically at the load-displacement responses, the slope of the linear region decreases as the height of the blunt tip increases and as the scarf angle decreases. More specifically, for a scarf angle of 10° and a blunt tip height of one ply, the average slope of the linear region for the specimens is $145 \times 10^3$ lbf/in, and decreases by 12% to a value of $128 \times 10^3$ lbf/in for a blunt tip height of four plies. The average slope of the linear region for specimens with a scarf angle of 5° and a blunt tip height of one ply is equal to $124 \times 10^3$ lbf/in, and decreases by 13% to a value of $108 \times 10^3$ lbf/in for a blunt tip height of four plies. Similarly, the average slope of the linear region of the case with a scarf angle of 3° and a blunt tip height of one ply is $101 \times 10^3$ lbf/in, and decreases by 11% to a value of $90 \times 10^3$ lbf/in for a blunt tip height of four plies. A similar trend in the change of the slope of the linear region is observed for the cases with blunt tip heights of two plies and three plies. Thus, it is evident that the slope of the linear region decreases linearly with an increase in the height of the blunt tip.

This trend of decreasing slope of the linear region is due to a decrease in the “effective” stiffness of the joint region, which can be explained through equilibrium considerations. As
the scarf angle decreases, the length of the bondline increases, thus allowing a greater region for associated stresses to act and equilibrate the resultant load. This agrees with previous numerical work by Adil, who shows that the scarf angle directly affects the “effective” cross-sectional stiffness within the joint region as the local cross-sectional stiffness contributions at any longitudinal location in the joint is affected by the scarf angle [15].

In addition, as described in the previous section, from the numerical work in this study, it was concluded that the scarf joint can be characterized by two different regions, one where the load is transferred primarily through shear (in the “ideal” scarf joint region) and a second region where the load is transferred primarily via longitudinal mechanisms (in the blunt tip region). As the height of the blunt tip increases, and thus the blunt height ratio increases, more load is transferred longitudinally than by shear. This results in a decrease of the overall “effective” stiffness of the joint. Due to mechanical equilibrium, assuming that these different regions act in parallel with the same overall longitudinal strain in each region, the net longitudinal stress resultant at any given longitudinal direction can be approximated to first order as the sum of the product of the longitudinal strain, the longitudinal modulus, and the thickness of the region for each region. The value of this net resultant for all longitudinal locations should equal the average far-field longitudinal stress per mechanical equilibrium. Thus, to a first order, the effective longitudinal stiffness of the configuration in the joint region is given by:

\[
E_{\text{eff}} = \frac{E_{\text{scarf}}(t_{\text{adherend}} - 2h_{\text{blunt}}) + E_{\text{blunt}}(2h_{\text{blunt}})}{t_{\text{adherend}}}
\]  

(8.2)

where \(E_{\text{eff}}\) denotes the effective longitudinal stiffness of the joint, \(E_{\text{scarf}}\) denotes the longitudinal stiffness of an “ideal” scarf joint with no blunt tip, and \(E_{\text{blunt}}\) denotes the longitudinal stiffness of a butt joint with no scarfed region.

Following the linear region, the load-displacement response of each specimen transitions to a nonlinear region with a monotonically decreasing slope as the load increases to the maximum load. This change in slope of the nonlinear region is shown by the calculated values of \(P_{\text{linear}}\), as described in Section 7.1. However, while the three values calculated at
an offset of 10, 20, and 30 $\mu$strain are similar for each specimen, regardless of the height of the blunt tip or the scarf angle, there is still significant variation with no discernible correlation. For these three offsets, the average values for all specimens considered are equal to 342 lbf, 438 lbf, and 474 lbf, respectively, with a variation of approximately 25% amongst all of the specimens. These three calculated values show a decrease in slope in that there is a smaller increase between the values calculated at the 20 $\mu$strain and 30 $\mu$strain offsets compared to the increase between the 10 $\mu$strain and 20 $\mu$strain offsets. This pattern is consistent for all configurations. However, while the trend is similar, this large variation prevents a clear correlation with the parameters considered. Therefore, as the nonlinear response of these test cases have not been examined in any numerical or finite element work, investigation of this nonlinear behavior is required before a correlation can be determined.

The key aspect of this study is to examine the effects of the blunt tip height on the maximum strength of the joint in order to understand the sensitivity of the scarf joint to this parameter. However, the numerical work in this study indicates that the mechanical response of the scarf joint is not directly affected by any individual lengths, and instead, is dependent on the blunt height ratio via considerations of finite thickness effects. Therefore, variations in the maximum strength of the joint are examined in relation to the blunt height ratios considered in this work. This relation is best characterized by comparing the maximum load carried by each specimen prior to failure versus the blunt height ratio for each specimen. This is shown in Figure 8.6. For each data set with a similar scarf angle, a linear fit is calculated using the least squares fit method. These linear fits for each data set with a scarf angle of 3°, 5°, and 10°, are shown in the figure with coefficients of variation equal to 0.97, 0.78, and 0.80, respectively. Several observations and questions, involving the sensitivity of the blunt height ratio on the response of the scarf joint, can be determined via consideration of this figure.

First, the results in this figure complement the results of previous numerical and experimental work performed. In previous work, it was found that increasing the scarf angle results in a decrease in the ultimate strength of the joint [12,20,21]. Specifically, these studies each
Figure 8.6  Maximum load-carrying capability versus blunt height ratio for each specimen.
agree that increasing the scarf angle beyond $2^\circ$ to $3^\circ$ shows a monotonic decrease in ultimate strength of the joint. This is shown in the figure where for any constant blunt height ratio, the maximum load gets significantly higher as the scarf angle decreases.

Second, the results in this figure show the effect of the blunt height ratio on the maximum load-carrying capability of the specimen. For each constant scarf angle, the load-carrying capability of the specimen increases as the blunt height ratio decreases. To a first order, this trend can be directly related to the blunt height ratio and the different stresses carried through the joint, as described previously via Equation 8.2. From examination of the linear fits in Figure 8.6, each line approaches a maximum at a blunt height of zero. This value of BH is equivalent to the configuration of an “ideal” scarf joint with no blunt tip. Therefore, for a BH of zero, the stress is directly related to the scarf angle. This stress is the maximum stress that the scarfed region can carry:

\[ \sigma_{\text{max}} = \sigma_{\text{scarf}} \]  

(8.3)

Alternatively, for a blunt height ratio of 0.5, the configurations are identical to a butt joint with no scarfed region. Thus, for a BH of 0.5, the max stress should be consistent for all configurations and equal the maximum stress that a butt joint can carry:

\[ \sigma_{\text{max}} = \sigma_{\text{butt}} \]  

(8.4)

However, as the blunt height ratio varies between 0 and 0.5, different stress is carried in each region of the joint, as per equation 8.2. This leads to an approximation to the cause of failure. Assuming that the region of the butt joint fails first ($\sigma_{\text{butt}} < \sigma_{\text{scarf}}$), two different scenarios can occur. Either the scarfed region can carry the additional load from the failed butt joint region, which implies that the scarfed region is the controlling factor and the butt joint is negligible, or the additional load causes the scarfed region to also fail, which implies that the butt joint is the controlling factor. Thus, two different intersecting lines, which are linear in BH, can be shown to characterize the load carried by each region.
These trends also introduce several questions that require further investigation. The true sensitivity of the scarf joint to variations in the height of the blunt tip remains unclear due to the blunt height ratios considered. Thus, in order to better understand the sensitivity of the height of the blunt tip on the ultimate strength of the scarf joint, the effects due to the finite thickness of the joint need to be mitigated. Specifically, building on the numerical work suggested in Section 8.1, it is recommended that experimental work be conducted with a constant blunt height ratio, on the order of 1%, to better understand the individual length scales that govern the maximum load-carrying capability of the scarf joint. Therefore, larger laminate thicknesses must be used with varying heights of the blunt tip.

In the description of the failure in chapter 7, all specimens were classified into two groups based on the cured film adhesive thickness in the specimens. Specimens are classified into having either a cured “thin” adhesive layer, with an average thickness less than or equal to 0.004 inches, or a cured “thick” adhesive layer, with an average thickness greater than 0.004 inches. These two classifications can be used in considering both the variations in load and in the failure surfaces of the specimens. In several test cases, two specimens are grouped together with a similar magnitude of maximum load and the third specimen is either slightly higher or lower in magnitude. This trend is also shown in the visible characteristics of the failure surfaces of the specimens within a specific test case. After comparison of these two trends, a correlation can be shown relating to the average cured adhesive thickness of each specimen.

In the specimens with a scarf angle of 10° and a blunt tip height of four plies, all of the specimens can be specified as having a cured “thick” adhesive layer and all reach a similar maximum load with less than 7% variation amongst the three cases. This is similar in the case of the specimens with a blunt tip height of three plies. In this case, all three specimens are classified as having a “thick” adhesive layer with less than 6% variation amongst the maximum loads. However, in the test case with a scarf angle of 10° and a blunt tip height of two plies, specimens 1 and 2 are classified as having a cured “thin” adhesive layer and have a much lower maximum load value compared to specimen 3, which is classified as having
a cured “thick” adhesive layer. The variation between specimens 1 and 2 is approximately 14% while the maximum variation between specimen 3 and the other two specimens is approximately 36%. Finally, all three specimens for the case with a scarf angle of 10° and a blunt tip height of one ply have a “thick” adhesive thickness and a maximum variation of the load equal to approximately 15% amongst the three specimens. While this variation is noticeable, it is still small compared to the 36% variation.

A very similar trend is noticeable in all of the test cases with a scarf angle of 5°. In all four test cases, with the four different blunt tip heights, specimens classified as having a cured “thick” adhesive layer show a noticeable variation in the maximum load compared to the specimens with a cured “thin” adhesive layer. Specifically, in each case, the specimens with a cured “thick” adhesive layer show a maximum load that is approximately 30% higher compared to the specimens of the same test case, but with a cured “thin” adhesive layer.

Alternatively, in the test cases with a scarf angle of 30°, the trend becomes less noticeable, and even contradictory in some cases. In the three specimens with a blunt tip height of one ply, despite the variation in cured adhesive thickness and classification between the three specimens, there is less than 4% variation in the maximum load. However, in the cases with a blunt tip height of two and three plies, the trend is noticeable where the specimens with a cured “thick” adhesive layer experienced a maximum load that is approximately 16% higher compared to the specimens with a “thin” adhesive layer. Finally, in the test case with a scarf angle of 30° and a blunt tip height of four plies, the results contradict this trend as the specimen with a cured “thick” adhesive layer shows a maximum load that is approximately 18% lower than the two specimens with a cured “thin” adhesive layer.

These variations in the film adhesive thickness amongst specimens of a test case also present a trend amongst differences in the failure surfaces. These two classifications based on the cured adhesive thickness are used to differentiate the failure surfaces of the specimens as each show differences in the type of failure along the bondline and the overall failure surface. Specimens classified as having a cured “thin” adhesive layer fail via cohesive failure in front of the blunt tip, and this continues as cohesive failure through the adhesive parallel
to the bondline and this meets a similar failure path from the other blunt tip. Alternatively, specimens classified as having a cured “thick” adhesive layer fail via cohesive failure in front of the blunt tip that travels through the adhesive adjacent to the blunt tip and crossing the film adhesive layer to be adjacent to the opposite bondline near the wide angle of the other adherend. This path of adhesive failure then follows the bondline and meets a similar failure path from the other blunt tip.

During this failure characterization, voids in the cured adhesive occurred in both classifications, but the size and location of the voids varied, especially in front of the blunt tip, depending upon the classification. This is very similar to the observations of previous experimental work performed by Jones [27]. In the specimens with a cured “thin” adhesive layer, the adhesive layer in front of the blunt tip had a significant number of voids, and a large number of these voids were located along the corner of the blunt tip. However, in the cases with a cured “thick” adhesive layer, the voids were more sporadic and smaller in size along the region in front of the blunt tip. This is important in the overall response of the scarf joint as the numerical analysis performed in this work, as well as previous work, show that large stress and strain gradients exist in the adhesive at the corner of the blunt tip. Therefore, in order to make statistically significant conclusions regarding the effect of the film adhesive thickness on the maximum load-carrying capability and failure surface, the film adhesive thickness and void characteristics should be controlled and systematically explored in a study involving more specimens per test case. Controlling the film adhesive will also allow better characterization of the maximum strength in relation to the scarf angle and the height of the blunt tip. One recommendation is to wrap a layer of film adhesive around the blunt tip with one layer rather than stack several individual layers in front of the blunt tip in an attempt to avoid voids at the corner of the blunt tip.
Chapter 9

Conclusions and Recommendations

As advanced polymer matrix composites continue to see increased use in primary structures for military and commercial aircraft, there is a growing need to understand the behavior of these composite structures after repair. The adhesive scarf joint offers several advantages in this application, namely maintaining the original surface profile after repair. This can be an important consideration for aerodynamic structures. There are a number of geometric and material parameters that drive the overall geometry of the adhesive scarf joint and its structural behavior. This work focused on examining the influence of the height of the blunt tip on the structural response of the scarf joint. To this end, numerical work was performed to understand the effects of the height of the blunt tip, the adherend thickness, and the ratio of the two parameters on the stress and strain fields within the scarf joint. Experimental work was also performed in order to examine the influence of the height of the blunt tip on the overall response, and particularly the ultimate tensile strength, of the scarf joint configuration. These experimental specimens were tested in uniaxial tension, and the load and displacement of each specimen, along with the strain in the adherends, were measured to characterize the behavior of each specimen.

The following conclusions can be drawn from the numerical work and the experimental work performed to investigate the influence of the height of the blunt tip on the behavior of the adhesive scarf joint:
1. The general response of a scarf joint is characterized by a large gradient of both the longitudinal strain and shear strain at the corner of the blunt tip which dissipates along the length of the bondline away from the blunt tip, and generally becomes relatively uniform.

2. As the blunt height ratio increases, the size and magnitude of the gradient in strain at the corner of the blunt tip increases and approaches the center of the joint.

3. Away from the corner of the blunt tip, for configurations with a blunt height ratio that is sufficiently small, the response is unaffected and similar to the response of the "ideal" configuration with a feathered tip.

4. The magnification of the strain at the corner of the blunt tip is not due to any specific lengthscale, but is simply due to the existence of the corner at the blunt tip.

5. The blunt tip region demonstrates similar behavior to that of a butt joint where the longitudinal response of the adhesive increases and the shear response decreases within this region.

6. In the "ideal" case with a feathered edge, the magnitudes of the shear strain in the adhesive are significantly larger compared to those of the longitudinal strain indicating that the response is dominated by shear in the adhesive, and that the bulk of the load is transferred from one adherend to the other via the adhesive undergoing shear deformation. This is similar to the behavior of the scarfed region between the blunt tips of a scarf joint.

7. The response of a scarf joint with a blunt tip can be characterized as a hybrid of the "ideal" scarf joint and a butt joint acting in parallel where the response of the region between the two blunt tips is similar to an "ideal" scarf joint, and the blunt tip region is similar to a butt joint.

8. As the blunt height ratio increases, a larger ratio of the joint consists of the blunt tip region and the length of the center scarfed region decreases, which results in more load...
being transferred in longitudinal strain as opposed to shear of the adhesive.

9. The local gradients at the blunt tip and general response of the scarf joint are due to the finite thickness of the joint and the interactions of the stress and strain fields as they travel around the blunt tips, which is affected by both the height of the blunt tip and the thickness of the laminate as represented by the blunt height ratio.

10. The general shape of the overall load-displacement response, which begins with a linear region that transitions to a nonlinear region with a monotonically decreasing slope up to a maximum load, is consistent for all specimens regardless of geometric parameters or maximum load capability of the specimen.

11. The measured longitudinal stiffnesses of the adherends show good consistency across all specimens and correlate well with calculations via Classical Laminated Plate Theory.

12. The specimens exhibit no bending in the far-field region of the adherends, as is calculated, as the magnitude of bending strain in the majority of test cases was less than 50 μstrain before failure occurred.

13. Increasing the height of the blunt tip and decreasing the scarf angle both cause the “effective” stiffness of the joint to decrease resulting in a decrease in the linear slope of the load-displacement response of the scarf joint. This can be directly modeled based on these parameters.

14. Variations in the maximum load-carrying capability amongst test cases indicate that decreasing either the blunt height ratio, or the scarf angle, increases the load-carrying capability of the specimen. This is consistent with previous work and modeling the effect of the blunt height ratio.

15. Specimens classified as having a cured “thin” adhesive layer fail via cohesive failure in front of the blunt tip, and this continues as cohesive failure through the adhesive parallel to the bondline and meeting a similar failure path from the other blunt tip.
16. Specimens classified as having a cured “thick” adhesive layer fail via cohesive failure in front of the blunt tip and travel through the adhesive adjacent to the blunt tip crossing the film adhesive layer to be adjacent to the opposite bondline near the wide angle of the other adherend. This path of adhesive failure then follows the bondline away from the wide angle before transitioning back across the bondline and meeting a similar failure path from the other blunt tip.

17. Differences in the sizes and shapes of the voids within the film adhesive layer are apparent between specimens with a cured “thin” adhesive layer and cured “thick” adhesive layer.

Based on the results of this work, the following recommendations for future work are made:

1. Additional finite element should be performed investigating a constant blunt height ratio on the order of 1% with varying heights of the blunt tip in order to reduce the effects of the finite thickness of the laminate and understand the sensitivity of the height of the blunt tip on the stress and strain fields.

2. A finite element study considering the effects of the blunt tip, the laminate thickness, and the blunt height ratio, should also be conducted with laminated adherends to determine the particular effects of ply-to-ply stiffness variations that will exist in a real scarf joint repair.

3. Numerical and experimental work should also examine other laminate configurations that are not considered in this work to understand their contributions to the behavior of the scarf joint.

4. This finite element work should transition to experimental work using thicker laminates and a constant blunt height ratio on the order of 1% with varying heights of the blunt tip to characterize the sensitivity of the strength of the scarf joint to the height of the blunt tip.
5. As the nonlinear responses of the test cases in this experimental work have not been examined in any numerical or finite element work, nonlinear modeling of the scarf joint is required before a significant correlation can be made as to the cause of the variations amongst test cases. This would also improve the understanding of how the stress and strain fields around the corner of the blunt tip change with associated lengthscales.

6. In order to make statistically significant conclusions regarding the effect of the cured film adhesive thickness and void characteristics in experimental results, and particularly the maximum load-carrying capability of the scarf joint configuration, these two factors should be controlled and systematically explored in a study involving more specimens per test case.

7. In future experimental work, the cured film adhesive thickness should also be controlled to allow better characterization of the maximum strength in relation to key lengthscales, such as the scarf angle and the height of the blunt tip.
Appendix A

Load Versus Displacement Plots

The load carried by the specimen measured at the testing machine load cell is plotted versus the displacement of the testing machine crosshead in this appendix for all specimens. The format of these plots and the key values associated with each are identified and presented in Chapter 7.
Figure A.1  Load versus displacement for Baseline Specimen 1 ($\alpha = 10^\circ$, $N_{blunt} = 1$ ply).
Figure A.2  Load versus displacement for Baseline Specimen 2 ($\alpha = 10^\circ$, $h_{blunt} = 1$ ply).
Figure A.3  Load versus displacement for Baseline Specimen 3 ($\alpha = 10^\circ$, $h_{\text{blunt}} = 1$ ply).
Figure A.4  Load versus displacement for Specimen 1 ($\alpha = 10^\circ$, $h_{\text{blunt}} = 2$ plies).
Figure A.5  Load versus displacement for Specimen 2 ($\alpha = 10^\circ$, $h_{\text{blunt}} = 2$ plies).
Figure A.6  Load versus displacement for Specimen 3 ($\alpha = 10^\circ$, $h_{blunt} = 2$ plies).
Figure A.7  Load versus displacement for Specimen 1 ($\alpha = 10^\circ$, $h_{blunt} = 3$ plies).
Figure A.8  Load versus displacement for Specimen 2 ($\alpha = 10^\circ$, $h_{\text{blunt}} = 3$ plies).
Figure A.9  Load versus displacement for Specimen 3 ($\alpha = 10^\circ$, $h_{blunt} = 3$ plies).
Figure A.10  Load versus displacement for Specimen 1 ($\alpha = 10^\circ$, $h_{blunt} = 4$ plies).
Figure A.11  Load versus displacement for Specimen 2 ($\alpha = 10^\circ$, $h_{blunt} = 4$ plies).
Figure A.12  Load versus displacement for Specimen 3 ($\alpha = 10^\circ$, $h_{blunt} = 4$ plies).
Figure A.13  Load versus displacement for Specimen 1 ($\alpha = 5^\circ$, $h_{blunt} = 1$ ply).
Figure A.14  Load versus displacement for Specimen 2 ($\alpha = 5^\circ$, $h_{blunt} = 1$ ply).
Figure A.15  Load versus displacement for Specimen 3 ($\alpha = 5^\circ$, $h_{blunt} = 1$ ply).
Figure A.16  Load versus displacement for Specimen 1 \((\alpha = 5^\circ, h_{\text{blunt}} = 2 \text{ plies})\).
Figure A.17  Load versus displacement for Specimen 2 ($\alpha = 5^\circ$, $h_{\text{blunt}} = 2$ plies).
Figure A.18  Load versus displacement for Specimen 3 ($\alpha = 5^\circ$, $h_{blunt} = 2$ plies).
Figure A.19  Load versus displacement for Specimen 1 ($\alpha = 5^\circ, h_{\text{blunt}} = 3$ plies).
Figure A.20  Load versus displacement for Specimen 2 ($\alpha = 5^\circ$, $h_{\text{blunt}} = 3$ plies).
Figure A.21  Load versus displacement for Specimen 3 ($\alpha = 5^\circ, h_{\text{blunt}} = 3$ plies).
Figure A.22  Load versus displacement for Specimen 1 ($\alpha = 5^\circ$, $h_{blunt} = 4$ plies).
Figure A.23  Load versus displacement for Specimen 2 ($\alpha = 5^\circ$, $h_{blunt} = 4$ plies).
Figure A.24 Load versus displacement for Specimen 3 ($\alpha = 5^\circ$, $h_{\text{blunt}} = 4$ plies).
Figure A.25  Load versus displacement for Specimen 1 ($\alpha = 3^\circ$, $h_{\text{blunt}} = 1$ ply).
Figure A.26  Load versus displacement for Specimen 2 ($\alpha = 3^\circ$, $h_{blunt} = 1$ ply).
Figure A.27  Load versus displacement for Specimen 3 ($\alpha = 3^\circ$, $h_{\text{blunt}} = 1$ ply).
Figure A.28  Load versus displacement for Specimen 1 ($\alpha = 3^\circ$, $h_{blunt} = 2$ plies).
Figure A.29  Load versus displacement for Specimen 2 ($\alpha = 3^\circ$, $h_{blunt} = 2$ plies).
Figure A.30  Load versus displacement for Specimen 3 ($\alpha = 3^\circ$, $h_{blunt} = 2$ plies).
Figure A.31  Load versus displacement for Specimen 1 ($\alpha = 3^\circ$, $h_{blunt} = 3$ plies).
Figure A.32  Load versus displacement for Specimen 2 (\(\alpha = 3^\circ\), \(h_{blunt} = 3\) plies).
Figure A.33  Load versus displacement for Specimen 3 ($\alpha = 3^\circ$, $h_{\text{blunt}} = 3$ plies).
Figure A.34  Load versus displacement for Specimen 1 ($\alpha = 3^\circ$, $h_{blunt} = 4$ plies).
Figure A.35  Load versus displacement for Specimen 2 ($\alpha = 3^\circ$, $h_{\text{blunt}} = 4$ plies).
Figure A.36  Load versus displacement for Specimen 3 ($\alpha = 3^\circ$, $h_{blunt} = 4$ plies).
Appendix B

Load Versus Extensional Strain Plots

The load carried by the specimen is plotted versus the extensional strain in the adherends for each specimen. The load is measured at the testing machine load cell, and the extensional strain is calculated as the point-by-point average of the strains measured by the two gages on opposite sides of each adherend. The format of these plots and the key values associated with each are identified and presented in Chapter 7.
Figure B.1  Load versus extensional strain for Baseline Specimen 1 ($\alpha = 10^\circ$, $h_{\text{blunt}} = 1$ ply).
Figure B.2  Load versus extensional strain for Baseline Specimen 2 ($\alpha = 10^\circ$, $h_{blunt} = 1$ ply).
Figure B.3 Load versus extensional strain for Baseline Specimen 3 ($\alpha = 10^\circ$, $h_{blunt} = 1$ ply).
Figure B.4  Load versus extensional strain for Specimen 1 ($\alpha = 10^\circ$, $h_{blunt} = 2$ plies).
Figure B.5  Load versus extensional strain for Specimen 2 ($\alpha = 10^\circ$, $h_{blunt} = 2$ plies).
Figure B.6  Load versus extensional strain for Specimen 3 ($\alpha = 10^\circ$, $h_{\text{blunt}} = 2$ plies).
Figure B.7  Load versus extensional strain for Specimen 1 ($\alpha = 10^\circ$, $h_{blunt} = 3$ plies).
Figure B.8  Load versus extensional strain for Specimen 2 ($\alpha = 10^\circ$, $h_{blunt} = 3$ plies).
Figure B.9  Load versus extensional strain for Specimen 3 ($\alpha = 10^\circ$, $h_{blunt} = 3$ plies).
Figure B.10  Load versus extensional strain for Specimen 1 ($\alpha = 10^\circ$, $h_{\text{blunt}} = 4$ plies).
Figure B.11  Load versus extensional strain for Specimen 2 ($\alpha = 10^\circ$, $h_{blunt} = 4$ plies).
Figure B.12  Load versus extensional strain for Specimen 3 ($\alpha = 10^\circ$, $h_{blunt} = 4$ plies).
Figure B.13  Load versus extensional strain for Specimen 1 \((\alpha = 5^\circ, h_{\text{blunt}} = 1 \text{ ply})\).
Figure B.14  Load versus extensional strain for Specimen 2 ($\alpha = 5^\circ$, $h_{\text{blunt}} = 1$ ply).
Figure B.15  Load versus extensional strain for Specimen 3 ($\alpha = 5^\circ$, $h_{\text{blunt}} = 1$ ply).
Figure B.16  Load versus extensional strain for Specimen 1 ($\alpha = 5^\circ$, $h_{blunt} = 2$ plies).
Figure B.17  Load versus extensional strain for Specimen 2 ($\alpha = 5^\circ$, $h_{blunt} = 2$ plies).
Figure B.18  Load versus extensional strain for Specimen 3 ($\alpha = 5^\circ$, $h_{blunt} = 2$ plies).
Figure B.19  Load versus extensional strain for Specimen 1 ($\alpha = 5^\circ$, $h_{blunt} = 3$ plies).
Figure B.20 Load versus extensional strain for Specimen 2 ($\alpha = 5^\circ$, $h_{blunt} = 3$ plies).
Figure B.21 Load versus extensional strain for Specimen 3 ($\alpha = 5^\circ$, $h_{blunt} = 3$ plies).
Figure B.22  Load versus extensional strain for Specimen 1 (\(\alpha = 5^\circ\), \(h_{blunt} = 4\) plies).
Figure B.23 Load versus extensional strain for Specimen 2 ($\alpha = 5^\circ$, $h_{blunt} = 4$ plies).
Figure B.24  Load versus extensional strain for Specimen 3 ($\alpha = 5^\circ$, $h_{\text{blunt}} = 4$ plies).
Figure B.25  Load versus extensional strain for Specimen 1 ($\alpha = 3^\circ$, $h_{\text{blunt}} = 1$ ply).
Figure B.26  Load versus extensional strain for Specimen 2 ($\alpha = 3^\circ$, $h_{blunt} = 1$ ply).
Figure B.27  Load versus extensional strain for Specimen 3 ($\alpha = 3^\circ$, $h_{blunt} = 1$ ply).
Figure B.28  Load versus extensional strain for Specimen 1 ($\alpha = 3^\circ$, $h_{blunt} = 2$ plies).
Figure B.29  Load versus extensional strain for Specimen 2 ($\alpha = 3^\circ$, $h_{blunt} = 2$ plies).
Figure B.30  Load versus extensional strain for Specimen 3 ($\alpha = 3^\circ$, $h_{blunt} = 2$ plies).
Figure B.31  Load versus extensional strain for Specimen 1 ($\alpha = 3^\circ$, $h_{blunt} = 3$ plies).
Figure B.32  Load versus extensional strain for Specimen 2 ($\alpha = 3^\circ$, $h_{blunt} = 3$ plies).
Figure B.33  Load versus extensional strain for Specimen 3 ($\alpha = 3^\circ$, $h_{blunt} = 3$ plies).
Figure B.34  Load versus extensional strain for Specimen 1 ($\alpha = 3^\circ$, $h_{blunt} = 4$ plies).
Figure B.35  Load versus extensional strain for Specimen 2 ($\alpha = 3^\circ$, $h_{blunt} = 4$ plies).
Figure B.36  Load versus extensional strain for Specimen 3 ($\alpha = 3^\circ$, $h_{blunt} = 4$ plies).
Appendix C

Photographs of Specimen Failure Surfaces

The photographs of the failure surface of both adherends for each specimen under consideration are presented in this appendix. The photographs of all three specimens of each case are grouped in one figure for each test case. The configuration of the failure surface of the x-y scarf planes of the two adherends is illustrated in Figure C.1. As shown in these figures, the patch adherend is rotated 180° about its x-centerline in order to show both adherends simultaneously. Thus, the coordinate axis of each adherend shares a common x-direction, but the y-direction and z-direction are opposite each other for each adherend.
Configuration for Testing  

Configuration for Post Mortem Photographs

Patch adherend

Base adherend

Patch adherend (rotated 180° about x-centerline)

Pictured region

Base adherend

Figure C.1 Illustration of the configuration in which specimens are pictured in the post mortem photographs compared to the configuration of specimen during testing.
Figure C.2 Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens of the baseline configuration ($\alpha$ equal to 10° and $h_{\text{blunt}}$ equal to 1 ply).
Figure C.3  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to $10^\circ$ and $h_{blunt}$ equal to 2 plies.
Figure C.4  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to 10° and $h_{\text{blunt}}$ equal to 3 plies.
Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to $10^\circ$ and $h_{blunt}$ equal to 4 plies.
Figure C.6  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to $5^\circ$ and $h_{blunt}$ equal to 1 ply.
Figure C.7  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to $5^\circ$ and $h_{blunt}$ equal to 2 plies.
Figure C.8  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to 5° and $h_{\text{blunt}}$ equal to 3 plies.
Figure C.9  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to 5° and $h_{\text{blunt}}$ equal to 4 plies.
Figure C.10  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to 3° and $h_{blunt}$ equal to 1 ply.
Figure C.11  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to $3^\circ$ and $h_{blunt}$ equal to 2 plies.
Figure C.12  Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to 3° and $h_{\text{blunt}}$ equal to 3 plies.
Figure C.13 Photographs of the failure surfaces of the scarf planes of the adherends from the x-y plane for all specimens with $\alpha$ equal to 3° and $h_{blunt}$ equal to 4 plies.
References


