A fabric deformation methodology for the automation of fiber reinforced polymer composite manufacturing

by

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Abstract

This thesis presents a new fabric deformation method, referred to as shifting, for the layup of non-crimp fabric (NCF) plies with the intent of creating an automated layup solution. The mathematical model for the new method has been presented to describe the method and provide the ground work for future path planning of an automation solution. Testing has been completed to show that shifting can produce layups with 2 dimensional geometry without generating out-of-plane distortion.

Fatigue tensile testing was conducted in order to understand the effect of the shifting method on the properties of composite components. Coupons with constant curvature and varying discrete shift quantities were tested to failure. Results are presented with an equation relating discrete shifting quantities to the fatigue life. This equation also predicts the lifetime of a coupon with continuous shifting. This relationship will be necessary in optimizing the path planning for an automated solution.

Finally, a conceptual design and process schematic are presented to show the feasibility of using the shifting method for an automated system.

Chapter I: Introduction

Composite materials have become much more common place as a manufacturing material. They are currently used in everything from playground slides to aerospace components. Composites are also seen in nature, as in the composition of wood. These materials have a vast array of advantages for many situations. Many composite materials offer high strength, light weight properties and are highly customizable for unique situations.

Composites are manufactured by combining two different materials including reinforcement and matrix. This work will focus on composites using a fiber reinforcement known as fiber reinforced polymers (FRP). In FRP fiber material provides high strength, but is a flexible material. Because of this, the matrix provides structure in order maintain the position of the fiber and transfer strength between fibers. This combination allows for a highly customizable material because the fiber can be placed in any orientation so that strength is provided only in directions where it is needed.

There are vast options in materials for both fiber and matrix to provide the specific properties desired. The combinations of fiber and matrix materials offer a wide variety of material properties and associated costs. This offers the designer a great deal of flexibility. Common fibers include carbon, glass, and aramids (eg. Kevlar®). Each of these provides different strength and weight properties, and has a different cost. Each fiber material is also available in a wide variety of forms and qualities offering even more customization.

While the fiber material is often regarded as the most important component to a composite structure, the matrix is also important in defining the composition of the part. The matrix is generally a thermoset polymer made up of a mixture of a resin and a catalyst. The most common polymers used in the composite industry are polyester, vinylester, and epoxy. These polymers, like the fibers, provide different properties at different costs. This offers a wide range of combinations for a customized component.

Because of the great deal of flexibility in the design of composite parts there are many common uses from light-weight, high-strength structural members to primarily aesthetic free-form shapes. This work will focus on the structural use of composites, while taking advantage of the flexibility to create unique geometries. Commonly, composites are used to create non-prismatic geometries because of the flexibility of the fiber. Because of this flexibility, composites are generally manufactured in a mold. The mold provides the geometry for the fiber and a boundary for the matrix to create the final desired geometry.

Another consequence of the flexibility of the fiber is that the placement of fiber in the mold is often done by hand. The process of placing fiber into the mold is referred to as the layup process. The layup process for large structural components can be very time consuming because of the size and amount of fiber that needs to be placed. When layup is done manually the worker makes many hand motions to manipulate the fabric to fit the mold geometry. These hand motions are very difficult to replicate with a machine because the movements are sensory based and are not the same for multiple replications.

In order to reduce labor costs and increase quality in composite manufacturing, it would be desirable to implement automation solutions. This work has the motivation of developing a manipulation method for use in the automation of the layup process.

Composite materials can be obtained as two separate components or as one previously combined entity. If obtained separately (dry fiber and matrix), the fiber is mixed with the matrix as, or after, it is placed in the mold. This can be done by soaking the fiber in resin before applying it to the mold, which is referred to as a wet layup, or by pumping the resin into the mold after the layup of fiber is complete; known as infusion. The latter is most commonly done using vacuum resin transfer molding (VRTM). In this case a vacuum is created around the fiber to evacuate the air, and resin is allowed to flow among the fiber until saturated. Composite materials are also obtainable in pre-impregnated (prepreg) form where the resin is already mixed with the fiber and partially cured to give it a tack quality while remaining flexible. This work will focus on dry fiber layups.

Fibers are commonly grouped together for placement into the mold. A bundle of fibers is referred to as a tow, which can be of various shapes and sizes. Tows are commonly placed together in varying orientations as a sheet to create a fabric. One layer of fabric is referred to as a ply. Plies reduce handling time and provide a framework for tow orientation. Fabrics can be either woven or stitched to create

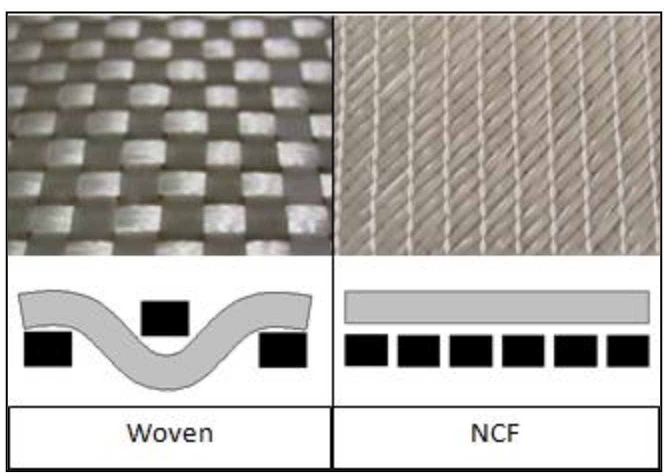


Figure 1: Woven Fabric [1] and NCF [2]

individual plies. In woven fabrics, tows are entwined much like a textile fabric, alternating between under and over perpendicular tows as seen in Figure 1. Woven fabrics have reduced strength because the fibers are not linear. In stitched fabrics this does not exist so the fabric is called a non-crimp fabric (NCF). In this case, tows are held together by small threads so that all tows in a layer are linear and oriented in the same direction as seen in Figure 1. This work will focus on the use of NCF rather than woven fabrics.

NCF can be obtained in many forms with varying tow orientations. Unidirectional (UD) fabrics are created by stitching a group of tows in the same orientation together. The direction of these tows is referred to as the "number 1" direction (Figure 2). Smaller tows, called cross tows, are commonly stitched in perpendicular to the main tows to provide structure. This is referred to as the "number 2" direction. Bias fabrics are created by stitching multiple layers of tows together, with each layer having its own tow orientation. A bias fabric can be described as multiple unidirectional fabrics with different tow orientations stitched on top of one another. Because fibers are present in multiple directions, cross tows are generally not used for bias fabrics. This work will focus solely on unidirectional fabric.

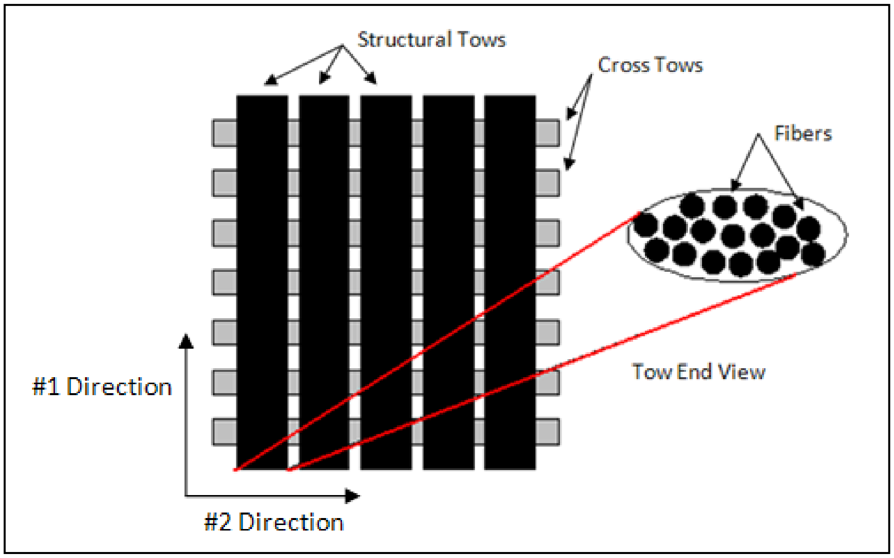


Figure 2: Unidirectional Fabric and Terms

While there are advantages to using fiber plies, as stated above, this also causes problems in the layup process. Fabric plies are created as two dimensional sheets, but composite materials are often used to create three dimensional, non-prismatic shapes. In order to place the fabric in contact with a mold surface, deformation of the fabric ply must occur.

Fabric deformations are classified into *in-plane* and *out-of-plane* deformations. In-plane deformation is classified by changes to the tow orientation while maintaining contact with the mold. Out-of-plane deformation is realized when some portion of the fabric is no longer in contact with the mold. In this case the mold could be either the actual mold or a previously deposited fabric ply. Out-of-plane deformation is commonly referred to as a *wave*. If the wave is large enough that it folds on itself it is referred to as a *wrinkle*. In the layup process, it is often desirable to orient the fiber tows so that they follow a non-linear path. As the plies are created with the tows as straight entities, this again requires deformation of the fabric.

New method: Shifting versus Steering

In the process of, for example, applying a roll of fabric to a mold, it may be intuitive to "steer" the fabric along the desired path, as seen in Figure 4. In this example, one wanted to have the fabric follow a gentle arc, but waves immediately form on the inside of the curve. When the fabric is manipulated in this way, it will create an excess of material toward the center of the curve because arc length decreases as radius decreases. This causes the cross tows to change orientation throughout the layup so that they are closer together toward the inside of the curve. The structure provided by the cross tows and stitching in NCF forces the excess material between cross tows into compression which causes these tows to buckle; hence a wave erupts.

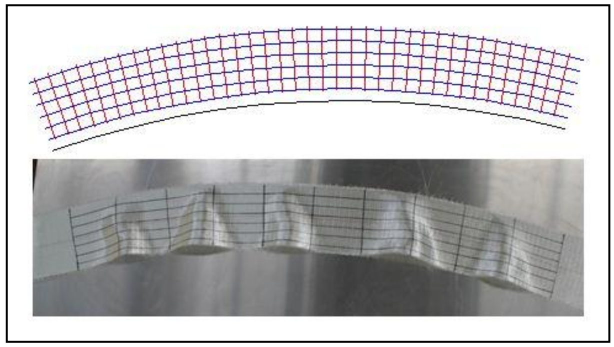


Figure 4: Steering – Schematic and Actual

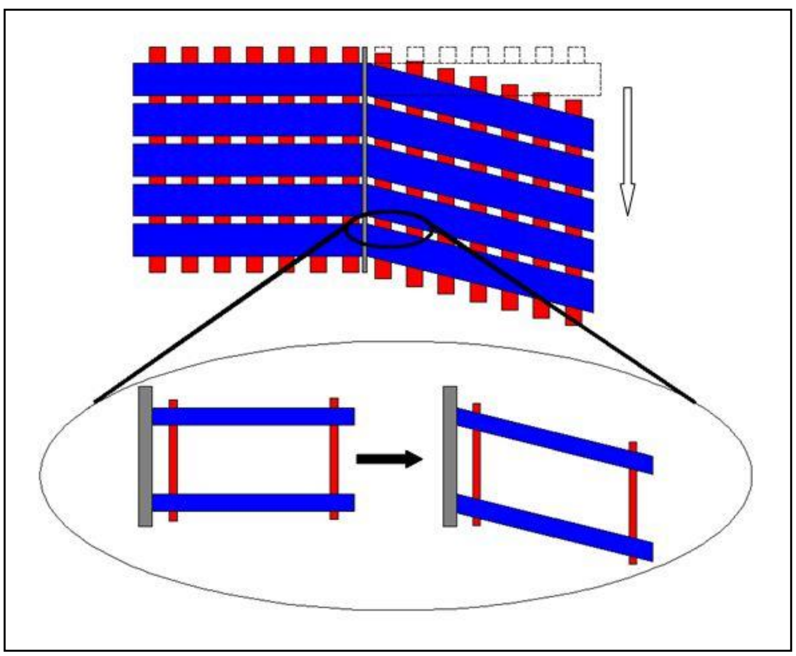


Figure 3: Shifting Explanation

Alternatively, a new method is

proposed in this thesis; one referred to as “shifting”. The act of shifting includes holding the fabric along one of the fiber directions and “sliding” the free end parallel to the hold in order to change the direction of the fiber. This can be thought of as similar to deforming a rectangle into a parallelogram as seen in Figure 3. In this method, all cross tows remain parallel to one another; therefore, fibers maintain equal lengths throughout the width of the fabric and do not form out-of-plane deformation. This process is repeated creating a linear piecewise path. This method does; however, reduce the width of the fabric as more deformation occurs. Shifting can be seen in Figure 5.

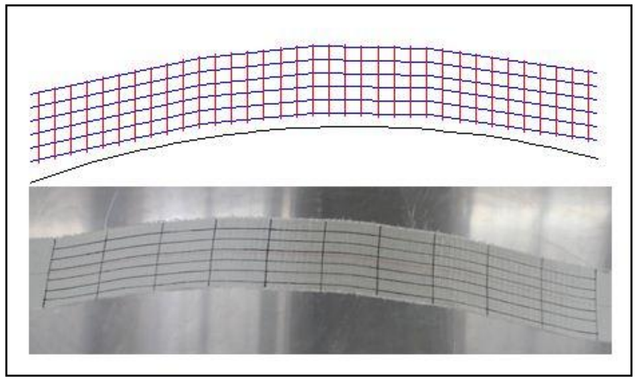


Figure 5: Shifting Schematic and Actual

This thesis proposes the use of shifting as a means to prevent out-of-plane deformation when considering the automated layup of fabric for composites. The method of shifting utilizes the acceptable in-plane deformations to avoid out-of-plane deformation. The goal of this current research is to investigate the following specific aims to determine the physical plausibility of the shifting method:

1. Can in-plane deformation in the form of shifting be used to prevent out-of-plane deformation?
2. What impact does the act of shifting have on the properties of composite materials?

These fundamental questions, if answered, will show whether shifting is a viable means of placing fabric without out-of-plane deformation, and whether it will have detrimental effects on the mechanical properties of a composite part. This would enable further research and testing of the method to determine whether or not its automation is physically and commercially viable.

In the remainder of this work, Chapter 2 will discuss literature relating to the research questions above. Chapter 3 will present a manuscript containing the solution methods and results pertaining to the proposed method of shifting. Finally, Chapter 4 will provide general thesis conclusions and possibilities for future work.

Chapter II: Literature Review

This review of literature will be comprised of three sections: (1) fabric manipulation, (2) fabric layup automation techniques, and (3) composite testing.

Fabric Manipulation

There has been much literature pertaining to the manipulation of fabric plies. Often, the deformation of fabric to fit into a specific shape is referred to as the draping process. Many studies have been done which include draping materials over multiple shapes in order to describe the process.

Many aspects of the draping process have been defined. Work has been done to mathematically define the surfaces created, the fiber orientation on that surface, and the interactions between fiber tows. Work has also been done to create simulations of the deformations and the process itself. Researchers have used many shapes in order to define these traits such as hemispheres, cones, and boxes. [3, 4, 5, 6, 7, 8, 9]

To describe the deformation occurring when manipulating the fabric to a certain shape, multiple deformation modes have been investigated. [5] Of these deformation modes, the pin jointed net (PJN) has emerged as the most widely accepted, especially in NCFs. In the PJN model, the fabric is assumed to be inextensible, and the joint between different fiber directions is represented as a pin. The angle between fibers at these pins is then changed to deform the fabric. The angle between tows is referred to as the shear angle. This has been shown to describe the behavior and deformability of the fabric well. [10]

As theoretically modeled, the maximum and minimum shear angle should be 180° and 0° respectively, making the two tows parallel. Because the tows are not of zero width, this is not possible in reality. Thus, a shear locking limit is defined where no more in-plane deformation can occur without creating an out-of-plane deformation. [10, 11]

Much research has been done to quantify different aspects of the PJN mode of deformation. Wang used the PJN to describe the draping process. He attempted to define an optimal deformation pattern to minimize deformation. He also noted that this mode of deformation does not perfectly describe the deformation of the fabric, as there is some slippage of the tows on deformation. [12]

Zhu describes the common test developed to evaluate the shear locking limit for a given fabric. In the picture frame test, a bolt of fabric is clamped into a four-sided fixture that is allowed to pivot at the intersections. The frame can be deformed into a parallelogram until the fabric erupts into an out-of-plane deformation. He also noted that the individual tows, at the edges near the clamps, are bent, changing the overall effect of the test. This effect; however, is minimal in relation to the overall deformation of the fabric. [13]

The PJN mode of deformation has been characterized using a finite element model. In these models the fabric tows are represented as rigid, straight sections that are allowed to move at intersections. To represent the force needed in deformation a soft element is placed diagonally between intersections. The strength of the soft element changes with respect to the strain placed on the element. This also reflects the shear locking limit. [14, 15]

In a three part study Dolatabadi et al. mathematically modeled woven fabric. Using this mathematical representation, they applied a shear deformation to fabric and studied the effect on multiple properties. They were able to mathematically show the reduction of tow spacing as shear angle increased and its effect on the packing density of the fabric. [16, 17]

Hancock and Potter used the PJN method to create a model to inform the hand layup of fabric. They incorporate the idea that the fabric is not constrained to starting the layup as an orthogonal net, but with some deformation already incorporated. This model tells the user how to start the layup and in what order features should be formed in order to distribute the shear angle correctly so that the shear locking limit is not reached. [18]

Fabric Layup Automation Techniques

The automation of fabric layup has been successful in many areas; however, many of these techniques are only useful for a small subset of the composite layup problem.

One common way of automating the fitting of fabric to a mold is the use of vacuum forming. In vacuum forming, a positive mold is pulled onto a negative mold using a vacuum force. This is often done in experiments to assess the PJN mode of deformation. This allows for a link between draping and the PJN. When using vacuum forming, the least resistive shear angle distribution is achieved. [19, 20]

While this method provides a way to create concave and convex curvature effectively, it is often not practical for the production of composite parts. The need for a second mold creates issues with both cost and logistics for large components. Another problem is that vacuum forming is not capable of manipulating fiber orientation, and is often not useful for layups of multiple layers or layups with plies that cover only part of the mold. Also, vacuum forming is often shown on extreme geometries where shear angles near the shear locking limit are reached. This provides substantial force, creating a uniform deformation, but these shear angles are not often realized in production, especially for large parts. [18]

Another common composite automation solution is tape layup. In this process, a narrow strip of prepreg is applied to the appropriate locations and fiber orientation in the mold. This is made possible by the tack quality of the prepreg material, which makes the material stick to the mold. These machines have shown capability in laying material successfully; however, they often create near-net-shape components of uniform thickness, and do not consider geometry. [21]

Buckingham and Newell developed a system that uses a multi-axis robot to place the prepreg material. After the material is placed in the mold, multiple systems are used to compress the material to rid it of air inclusions. Tools used included foam compression, compressed air and common tools used in hand layup. These tools were capable of removing air inclusions but minimally considered the in-plane deformation for complex shapes. [22]

A similar robot was designed by Shirinzadeh et al. to study path planning for prepreg layups. This machine utilized real-time feedback to apply the correct amount of force for ridding the material of air inclusions. [23]

While tape layup is often a useful method for depositing prepreg material, it has little application for use in dry fabric because of the lack of a tack quality. It is also incapable of any curvature within the tow, and must lay many narrow strips at differing angles rather than placing one large sheet, making it impractical for very large components.

An automation method that is capable of placing large plies of fabric into a mold is referred to as robotic pick up. Researchers have studied the deformations that occur within the fabric as it is picked up and moved and modeled the process. [24, 25]

Other researchers have studied effective ways to grip the fabric using flexible means that are capable of conforming to geometries in the mold surface. Work has also been done to find ways of manipulating the fabric on a small scale to conform to the specific geometry of the mold using tools attached to robotic arms to create the deformations. [26]

While robotic pick up is capable of placing fabric into the mold and is often able to deform the fabric to the mold geometry on the local scale, these works do not consider the mathematical deformation modes described above. There is currently a gap between the models used to represent the fabric and the actual deformation occurring. This leads to uninformed manipulation, which can cause out-of-plane deformations.

Testing

Fatigue testing is commonly used to understand the strength of material over its lifetime. This is beneficial because many structural components are not continuously loaded, but rather loaded and unloaded many times throughout their lifetime. The high complexity of composite materials makes fatigue testing difficult because many variables must be considered including fiber orientations, materials, and loading sequence. Also, for composite materials, no absolute *failure* point is defined as the material tends to degrade throughout its fatigue life. For this reason, failure of these materials is often based on the specific intended use. Common failure points include delamination, reduced modulus, or complete fracture. [27]

One method that has been used in attempting to quantify the degradation of a composite material in fatigue testing is the Miner's Sum. In this method, ultimate failure is assumed to be a result of cumulative damage throughout the fatigue testing lifetime. This method assumes a linear degradation of properties until final failure. [28]

Many studies have shown that, while Miner's Sum is very applicable for the metals it was developed for; however, it is a poor model for use in composite components. There have been many efforts conducted to develop models that accurately predict the strength degradation over time as well as the ultimate failure point. One model that uses the cumulative damage theory is presented by Epaarachchi et al. This model is loosely based on the Miner's Sum, but other parameters are added to increase the accuracy of the model. For this model, testing is needed in order to obtain values for parameters used in the model. [29]

Constitutive models are often used in attempt to fulfill these needs. [30] One such constitutive model was developed by Yokozeki et al. This model separates the elastic and plastic strains and assumes a linear stress-strain relationship (although non-linear functions could be included) to develop the model. This model shows good fit to actual test data. This model also requires some level of testing prior to implementing the model to define certain parameters. [31]

Another approach to this modeling effort is to use the dissipated energy density as a function of strain. This method requires a large database of tested materials to pull coefficients from. The testing for this database is complex but has been developed to quickly and automatically test specimens. [32]

While there are many models that can describe the accumulation of damage leading to the failure of composite parts in fatigue testing, it is important that the testing of these parts accurately represents the actual scenario a component would undergo in service. Testing has been done to understand the sensitivity of fatigue life to multiple testing parameters.

One important parameter that must be set for fatigue testing is the frequency of loading. This has a large impact on the testing because higher frequency testing shortens the testing process so it is desirable to use the highest frequency possible. Testing was performed at Montana State University under many different frequencies and load levels. This work found that while testing is highly sensitive to loading levels, frequency does not appear to have a large effect on the fatigue life. [33]

Another parameter for fatigue testing is the loading spectrum used. Different spectrums have been developed that load the coupons to a wide variety of load levels throughout the testing process. Coupons are commonly loaded to one stress level throughout the test, but other models randomize the load in order to represent the actual loading of components in service. It has been shown that loading spectrum does not have a large impact on the fatigue life. [34]

Many of the developed models and testing have been focused on perfectly aligned fiber composites. It is also necessary to understand the effect of both in-plane and out-of-plane deformation on the fatigue life of composite components.

Research has shown that, for many cases, deformation can be characterized by the amplitude and wave length of the deformation. The ratio of these characterizing factors, commonly referred to as aspect ratio, provides an index to compare deformations and decide if the deformation is acceptable. It has also been shown that for a common aspect ratio, increasing the number of plies with deformation decreases the strength approximately linearly. This is attributed to the increased dependence on the matrix material. [35, 36, 37] These works only include nominally straight layups with included deformations and do not account for a nominally curved layup.

Chapter III: Manuscript:

A fabric deformation methodology for the automation of fiber reinforced polymer composite manufacturing

C. Magnussen, M. Frank, F. Peters

To be submitted to Composites Part A

Abstract

This work presents a new fabric deformation method, referred to as shifting, for the layup of non-crimp fabric (NCF) plies with the intent of creating an automated layup solution. The mathematical model for the new method has been presented to describe the method and provide the ground work for future path planning of an automation solution. Testing has been completed to show that shifting can produce layups with 2 dimensional geometry without generating out-of-plane distortion.

Fatigue tensile testing was conducted in order to understand the effect of the shifting method on the properties of composite components. Coupons with constant curvature and varying discrete shift quantities were tested to failure. Results are presented with an equation relating discrete shifting quantities to the fatigue life. This equation also predicts the lifetime of a coupon with continuous shifting. This relationship will be necessary in optimizing the path planning for an automated solution.

Finally, a conceptual design and process schematic are presented to show the feasibility of using the shifting method for an automated system.

Introduction

Composite materials have become much more common place as a manufacturing material. They are currently used in everything from playground slides to aerospace components. Composites are also seen in nature, as in the composition of wood. These materials have a vast array of advantages for many situations. Many composite materials offer high strength, light weight properties and are highly customizable for unique situations.

Because of the great deal of flexibility in the design of composite parts there are many common uses from light-weight, high-strength structural members to primarily aesthetic free-form shapes. This work will focus on the structural use of composites, while taking advantage of the flexibility to create unique geometries.

Commonly, composites are used to create non-prismatic geometries because of the flexibility of the fiber. Because of this flexibility, composites are generally manufactured in a mold. The mold provides the geometry for the fiber and a boundary for the matrix to create the final desired geometry.

Another consequence of the flexibility of the fiber is that the placement of fiber in the mold is often done by hand. The layup process for large structural components can be very time consuming because of the size and amount of fiber that needs to be placed. When layup is done manually the worker makes many hand motions to manipulate the fabric to fit the mold geometry. These hand motions are very difficult to replicate with a machine because the movements are sensory based and are not the same for multiple replications.

In order to reduce labor costs and increase quality in composite manufacturing, it would be desirable to implement automation solutions. This work has the motivation of developing a manipulation method for use in the automation of the layup process.

Fibers are commonly grouped together for placement into the mold. Plies reduce handling time and provide a framework for tow orientation. Most commonly non-crimp fabric (NCF) is used for structural members as it provides the benefits of using plies without the tow waviness of woven fabrics. As such, this work will focus on the use of unidirectional (UD) NCF.

While there are advantages to using fiber plies, as stated above, this also causes problems in the layup process. Fabric plies are created as two dimensional sheets, but composite materials are often used to create three dimensional, non-prismatic shapes. In order to place the fabric in contact with a mold surface, deformation of the fabric ply must occur.

Fabric deformations are classified into *in-plane* and *out-of-plane* deformations. In-plane deformation is classified by changes to the tow orientation while maintaining contact with the mold. Out-of-plane deformation is realized when some portion of the fabric is no longer in contact with the mold. In this case the mold could be either the actual mold or a previously deposited fabric ply. Out-of-plane deformation is commonly referred to as a *wave*. If the wave is large enough that it folds on itself it is referred to as a *wrinkle*. In the layup process, it is often desirable to orient the fiber tows so that they follow a non-linear path. As the plies are created with the tows as straight entities, this again requires deformation of the fabric.

New method: Shifting versus Steering

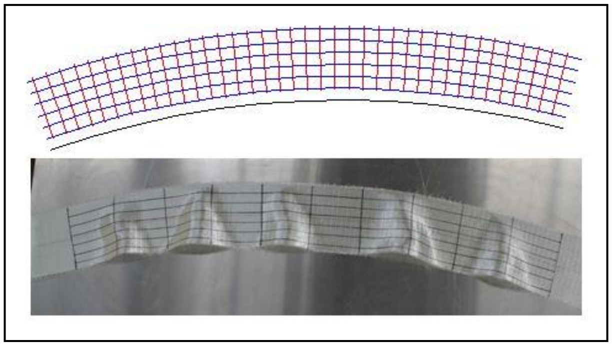


Figure 6: Steering Schematic and Actual

In the process of, for example, applying a roll of fabric to a mold, it may be intuitive to "steer" the fabric along the desired path, as seen in Figure 6. In this example, one wanted to have the fabric follow a gentle arc, but waves immediately form on the inside of the curve. When the fabric is manipulated in this way, it will create an excess of material toward the center of the curve because arc length decreases as radius decreases. This causes the cross tows to change orientation throughout the layup so that they are closer together toward the inside of the curve. The structure provided by the cross tows and stitching in NCF forces the excess material between cross tows into compression which causes these tows to buckle; hence a wave erupts.

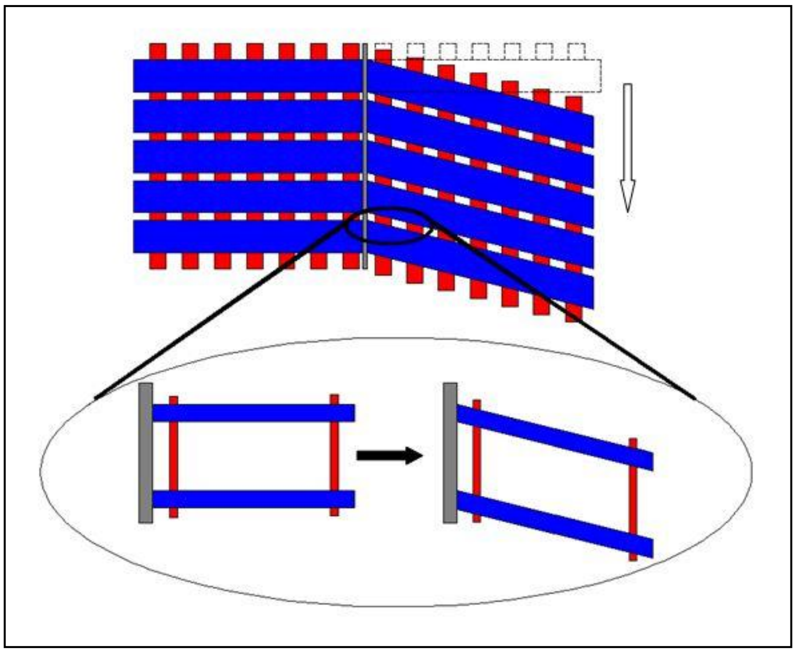


Figure 7: Shifting Diagram

Alternatively, a new method is proposed in this work; one referred to as "shifting". The act of shifting includes holding the fabric along one of the fiber directions and "sliding" the free end parallel to the hold in order to change the direction of the fiber. This can be thought of as similar to deforming a rectangle into a parallelogram as seen in Figure 7. In this method, all cross tows remain parallel to one another; therefore, fibers maintain equal lengths throughout the width of the fabric and out-of-plane deformation does not occur. This process is repeated creating a linear piecewise path. This method does; however, reduce the width of the fabric as more deformation occurs. Shifting can be seen in Figure 10.

This work proposes the use of shifting as a means to prevent out-of-plane deformation when considering the automated layup of fabric for composites. The method of shifting utilizes the acceptable in-plane deformations to avoid out-of-plane deformation. The goal of this current research is to investigate the following specific aims to determine the physical plausibility of the shifting method:

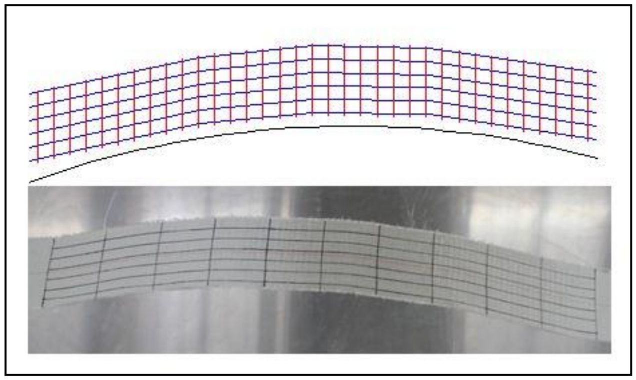


Figure 8: Shifting Schematic and Actual

1. Can in-plane deformation in the form of shifting be used to prevent out-of-plane deformation?
2. What impact does the act of shifting have on the properties of composite materials?

These fundamental questions, if answered, will show whether shifting is a viable means of placing fabric without out-of-plane deformation, and whether it will have detrimental effects on the mechanical properties of a composite part. This would enable further research and testing of the method to determine whether or not its automation is physically and commercially viable.

Related Work

There has been much literature pertaining to the manipulation of fabric plies. Often, the deformation of fabric to fit into a specific shape is referred to as the draping process. Many studies have been done which include draping materials over multiple shapes in order to describe the process.

Many aspects of the draping process have been defined. Work has been done to mathematically define the surfaces created, the fiber orientation on that surface, and the interactions between fiber tows. Work has also been done to create simulations of the deformations and the process itself. Researchers have used many shapes in order to define these traits such as hemispheres, cones, and boxes. [3, 4, 5, 6, 7, 8, 9]

Many different models have been developed to characterize the deformation of the fabric, with the pin-jointed net (PJN) being the most widely accepted. [5] The most important part of the PJN model is the shear angle which is the angle between tows. When this angle becomes larger than the shear locking limit, in-plane deformation results in out-of-plane deformation. [10 ,11]

Dolatabadi et al. mathematically described the fabric using the PJN by shearing the fabric and studying multiple properties. [16, 17] Also, Hancock and Potter created a model based on the PJN to inform hand layup. This model also recognizes that the layup does not have to start as an orthogonal net. [18]

The automation of fabric layup has been successful in many areas; however, many of these techniques are only useful for a small subset of the composite layup problem. Three prevalent automation techniques include vacuum forming, tape layup, and robotic pick-up.

Vacuum forming uses a positive and negative mold and utilizes vacuum pressure to consolidate the fabric. Thus, it is not practical for large components. [18, 19, 20] In tape layup, a robot is used to place prepreg tapes. This however is very limited because more expensive prepreg materials must be used and it is very time-intensive for large parts. [21, 22, 23] Finally, robotic pick-up is used to move large sheets of dry fiber from one location to another. This can be used for fiber placement, and some machines have included tools to create local in-plane-distortion; however, the PJN is often not considered in the deformation process. Again, this is impractical for large components. [24, 25, 26]

The high complexity of composite parts makes fatigue testing difficult and highly variable. This, along with the large number of variables involved, makes predictive modeling difficult. Many models have been developed to predict the lifetime of composite components under fatigue including those based on cumulative damage [28, 29], constitutive models [30, 31], and dissipated energy density models [32].

It is also important in fatigue testing to represent the actual loading conditions of the part in service. Some factors that play a part are frequency, spectrum, and load level. It has been shown that load level has a significant impact, while frequency and spectrum do not. [33, 34]

Research has also been done to show the effect of deformations on fatigue life. [35, 36, 37] However, these have only shown the effect of deformation on nominally straight samples, and not nominally curved samples where deformation must exist.

Solution Methodology

This work proposes the use of shifting as a means to produce composite components free from out-of-plane deformation via automation taking into account the local in-plane deformation of the fabric plies.

The solution methodology for this work will be broken into two sections, reflecting each of the two specific aims above. Specific aim 1 will address whether shifting can be used to create geometries using in-plane deformation to prevent out-of-plane deformation. Specific aim 2 will investigate the effects of shifting on the mechanical properties of the composite material.

Specific Aim 1: Out-Of-Plane Deformation Prevention

Recall that out-of-plane deformation is the case where some portion of the fabric ply is no longer in contact with the mold surface, whether that is the actual mold, or a previously laid fabric ply.

In this work, the shifting method is proposed to prevent these out-of-plane deformations. In order to mathematically describe the shifting method, a guide curve, P(u), must first be defined. This defines the nominal center of the fabric. Next, the fabric thickness and placement tolerance are used to create a tolerance zone. See Figure 10. To create these tolerance zones the guide curve is offset in both directions by one half of the fabric width to form the nominal edge location curves. Each nominal edge location curve is then offset in both directions by the amount of the placement tolerance to form the tolerance curves. The area around each nominal edge location curve between the tolerance curves is then the acceptable region for the fabric edge, referred to here as Tolerance Zone 1 (TZ 1) and Tolerance Zone 2 (TZ 2).

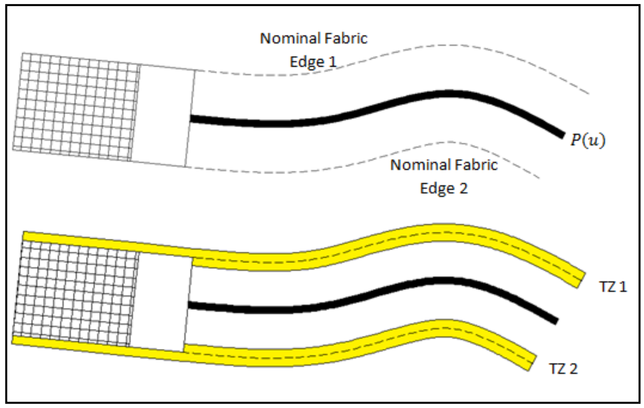


Figure 10: Guide Curve and Tolerance Zones

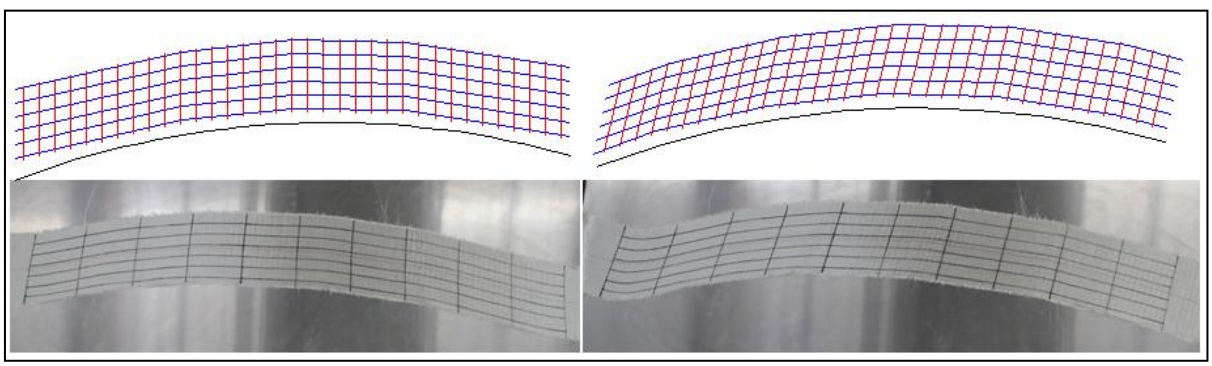


Figure 9: The effect of pre shear on shear angle distribution

Mathematical Model

The beginning position of any tow, j, as seen in Figure 11, can be calculated as:

$$T_j^0 \begin{bmatrix} x \\ y \end{bmatrix} = P(0) + [2(j - 0.5) - M]\omega_1 \begin{bmatrix} \cos{(\beta + \alpha_1)} \\ \sin{(\beta + \alpha_1)} \end{bmatrix} \quad (1)$$

Where M is the number of tows in the fabric, α_0 is the nominal shear angle, and ω_0 is the tow spacing at α_0. For unidirectional fabrics, α_0 is 90°. Also, α_1 is the pre-shear as seen in Figure 9. Pre-shear is the shear angle of the fabric at the beginning of the layup. This can be changed to minimize the overall shear angle or change the shear angle in specific locations throughout the layup. All values for α must remain between $-\alpha_c$ and α_c, which represent the negative and positive shear lock limits.

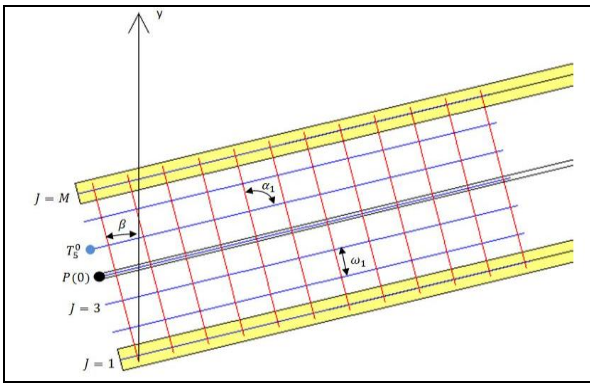


Figure 11: Starting Position

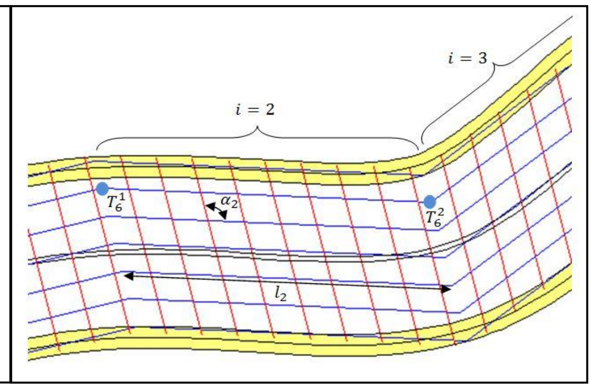


Figure 12: Fabric Variables

The location of any tow j at the end of any section, i, can be represented as:

$$T_j^i \begin{bmatrix} x \\ y \end{bmatrix} = T_j^{i-1} \begin{bmatrix} x \\ y \end{bmatrix} + l_i \begin{bmatrix} \cos(\beta + \alpha_i) \\ \sin(\beta + \alpha_i) \end{bmatrix} \quad (2)$$

Where l_i is the length of each tow in section i, and α_i is the shear angle in section i (Figure 12).

To determine these values, T_1^{i+1} and T_M^{i+1} are evaluated within TZ 1 and TZ 2 respectively. To do this, TZ 2 is translated along $[T_1^i - T_M^i]$ so that T_1^i and T_M^i are at the same point. The possible locations for T_1^{i+1} are, then, any point between $-\alpha_c$ and α_c that is visible from T_1^i without intersecting one of the four tolerance

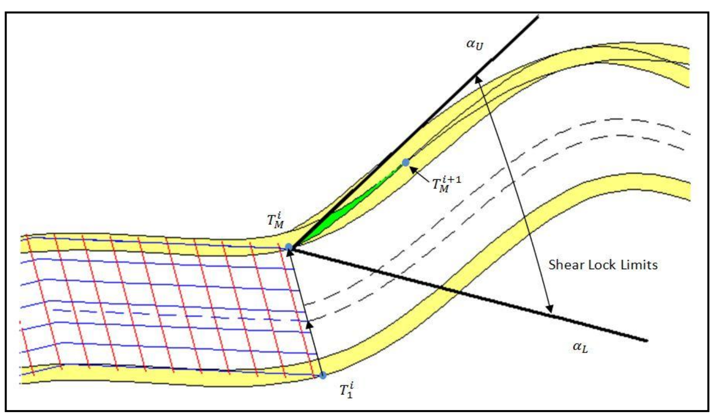


Figure 13: Path Calculation for T_j^{i+1}

curves as shown in Figure 13. The point in this region furthest from T_1^i is then selected as T_1^{i+1}. From this, l_{i+1}, α_{i+1}, ω_{i+1}, and all other T_j^{i+1} values can be calculated.

Calculating the path based on the tolerance zones is preferable to other methods such as chordal deviation because it takes into account the decrease in width of the fabric, w_i, as shear angle deviates from 90° as described in equation 3 and 4.

$$w_i = \omega_i M \quad (3)$$

$$\omega_i = \omega_0 \cos(\alpha_i) \quad (4)$$

Defining paths for tows in the steering method would result in a much different set of equations because the method is continuous and does not use discrete changes. This is also realized in shifting as l_i values approach zero, or *continuous shifting*. In steering each tow path can simply be represented as an offset of the guide curve. In this way, fabric width and tow spacing remain constant throughout the path. However, the length of individual tows is not equal for the steering method.

This can be seen in equation 5 where θ is the angle between the normals at either end of the guide curve, P(0) and P(1). This represents the radians traversed by the fabric. The excess arc length (Δ) for a given tow can be calculated as:

$$\Delta = \theta w \quad (5)$$

Where w is the distance from the longest single path to the tow in question, normal to the curve. Because of the structure provided by the cross tows and stitching, this extra material must result in an out-of-plane deformation. This states that the waves get larger as the radius decreases and that the waves are larger toward the inside of the curve. If this equation is shown to be valid, it will show that waves must occur for steered samples

Experimental Design

To investigate specific aim 1 and validate equation 5, samples of varying curvature were created for both the shifting and steering methods. The samples made were 1.5m (5ft) in length and comprised of four plies of Saertex 930 g/m^2 unidirectional fiberglass NCF placed directly on top of one another. Each sample had a uniform radius, with the five samples having radii ranging

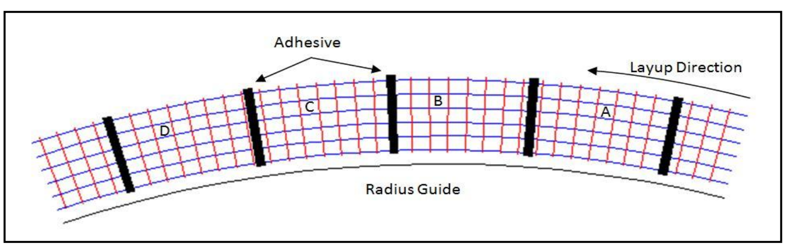


Figure 14: Steering Layup Design

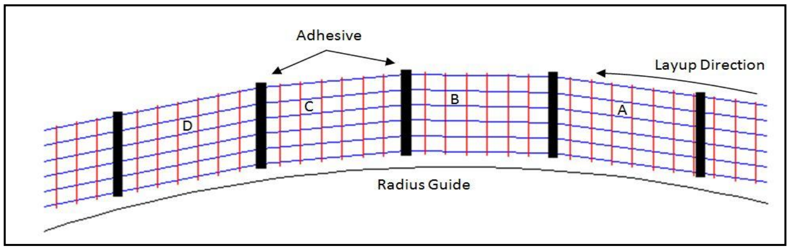


Figure 16: Shifting Layup Design

from 3.0m (10ft) to 15.2m (50ft) in increments of 3.0m (10ft). One straight sample was also produced, for a total of eleven samples. Curvature was used to quantify these radii values in order to have a finite value for the straight sample. Curvature was defined as the inverse of the radius in meters.

Each sample had four, 0.3m (1ft) sections, marked A through D, with A being the starting section. A 25.4mm (1In) wide area of 3M Spray Adhesive #77 was applied across the width of the fabric between the table and the first layer and between each successive layer at either end of each section to hold the fabric in place once it had been deformed. (Figure 14- steering, Figure 16- shifting) This prevented any relaxation for all samples. It should be noted that the friction in the fabric was enough to maintain the deformed shape in the shifting method, but the adhesive was used to keep the experimental method consistent.

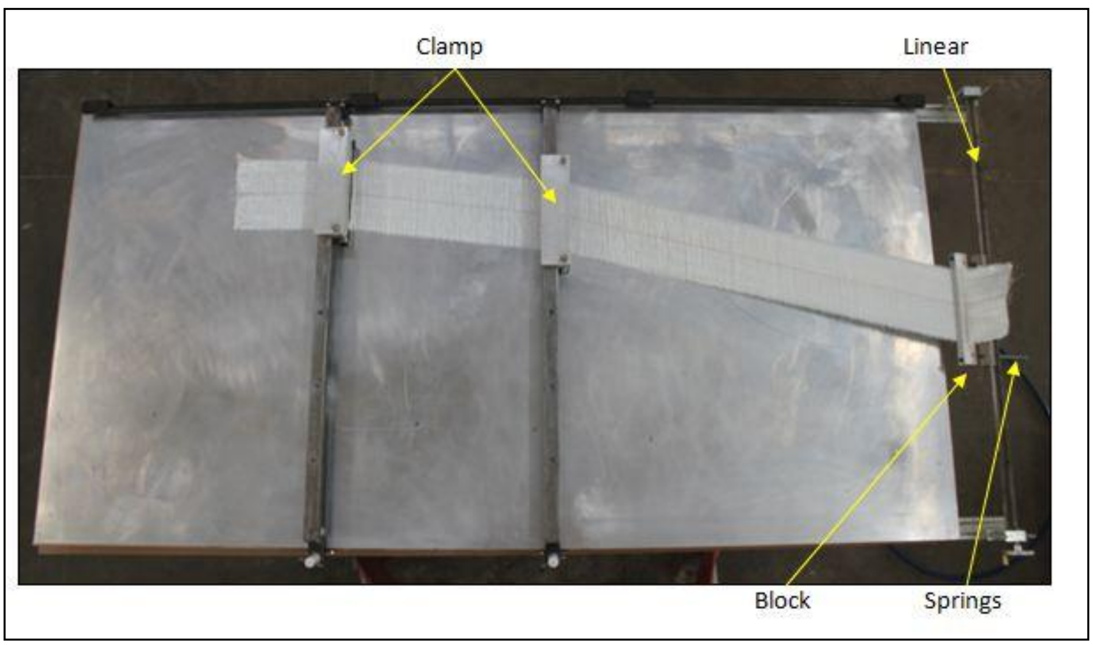


Figure 15: Mechanism Used to Produce Shifting Layup

Shifting samples were produced using the mechanism seen in Figure 15. The fabric was first secured in the block on the linear. It was then put in tension by pulling against springs incorporated into the block. The tension was applied to provide sufficient force to deform the fabric. The fabric was then aligned with the starting location and a clamp was applied parallel to the cross tows directly over the adhesive. The linear was then adjusted until the fabric was in the correct location for the second clamping point. Once the second clamp was tight, the first clamp was removed and the process continued until the last constraint on "D" was in place. The fabric was then released from the block and cut to size before releasing the clamp.

The samples for the steering method were created by placing a fabric roll in a carriage that was guided along a guide having the appropriate radius as seen in Figure 17. The fabric was placed on the first constraint over the adhesive and clamped in place. The carriage was then guided along the radius to the next constraint where another clamp was placed. This was repeated until the last constraint on "D" was in place, and the fabric was cut from the roll.

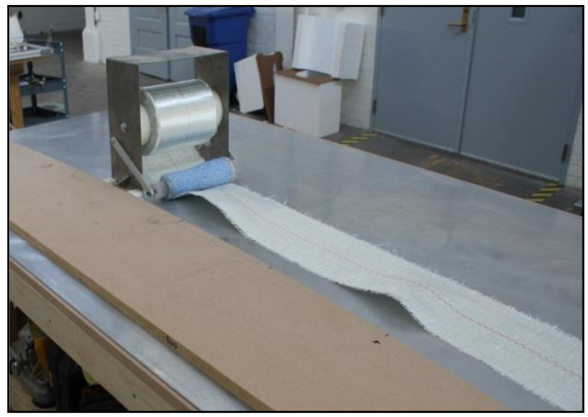


Figure 17: Mechanism Used to Produce Steering Layups

Each section of each sample was scanned with an Optix 400 digital laser scanner after layup as seen in Figure 18. A plane was included in every scan image so that the normal of this plane could be used as the z axis. The data was separated into the area to be analyzed and the area to be used for the plane using RapidForm software. A LabView program developed in the ISU lab was used to process the data.

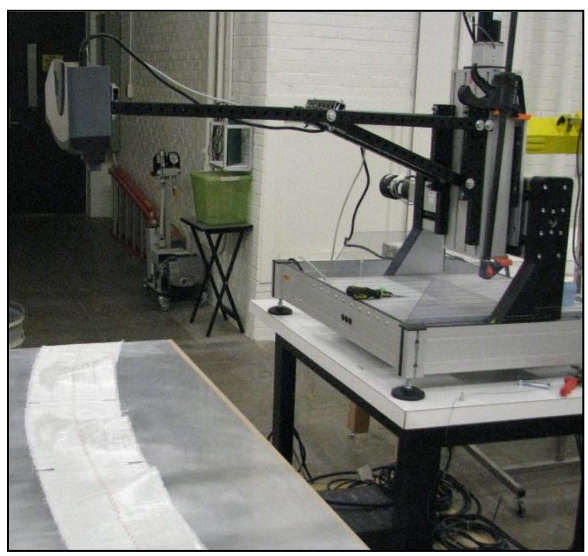


Figure 18: Laser Scanning Setup

The LabView program uses the plane provided to best fit the z axis of the scan. The scan image is then rotated about that axis so that the unidirectional fibers are oriented with the x axis. The program then analyzes the scan as a number of slices the width of the scan in the x direction and .635mm. (025 inches) in the y direction. For the dry fabric, a smoothed curve is then fit to the data along each slice and the arc length of the curve is calculated. The width of the slice is then subtracted from the arc length to give the excess arc length.

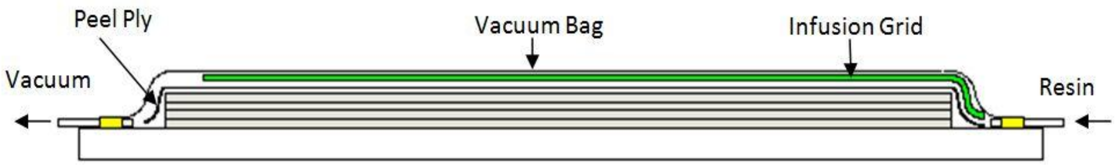


Figure 19: Infusion Setup

After scanning, all samples were infused using vacuum resin transfer molding. The infusion was setup as displayed in Figure 19 for all infusions. All infusions used Hexion EPICURE™ Resin MGS RIMR 135 and EPIKURE™ Curing Agent MGS RIMR 1366 mixed to 30 percent by weight. Samples were allowed to cure under heat. The cured samples were scanned and analyzed using the same program.

Results

Data for the dry fabric using the steering method was compared to calculated values obtained from equation 5. This relationship is proven experimentally by comparing predicted values to measured values for excess arc length, given know curvatures. When these are compared using an R^2 statistical test, a value of .772 is obtained, meaning that 77.2% of variation in arc length is predicted by this equation.

Much of the unpredicted variation; however, is attributed to two reasons. The first reason is some *relaxation factor* for the fabric makeup. This relaxation is caused by tows sliding past each other and some unpreventable shifting of the fabric during manipulation. This relaxation is seen mostly in the first section of the layup. It is also more noticeable for the smaller radii because excess arc length is not as large and can be overshadowed by the relaxation factor.

The second cause for unpredicted variation is the edges of the scan. At the edges of the scan, error is introduced because some points may be included that do not actually represent the fabric. When the relationship is tested using the R^2 test on the center of the fabric on the largest radius in the center sections, a value of .996 is obtained. This shows the validity of the calculation and that steering of fabric does, in fact, create waves.

In the shifting method, no difference in arc length is predicted across the width of the fabric, resulting in a nominally flat layup. Because the predicted excess arc length for each data slice is equal, a simple average with error bars is appropriate. The steering method can also be evaluated in this way, but the result is the average excess arc length over the width of the fabric. This does not represent the worst arc length in the sample, but roughly half of the worst arc length. The results for this are seen in Figure 20.

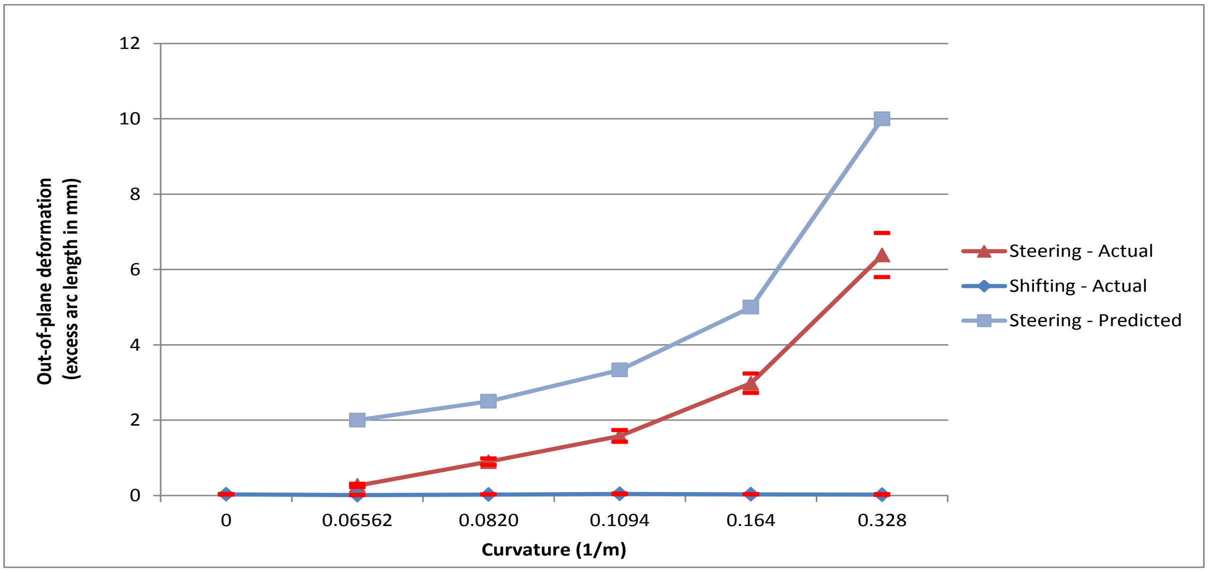


Figure 20: Out of Plane Deformation as Excess Arc Length prior to Infusion

This shows that there is little difference in excess arc length across the width of the fabric for the shifted samples. For the steering samples; however, the arc length is highly dependent on the radius as predicted. Figure 20 also shows the effect of the relaxation factor, as actual values are a consistent value below predicted.

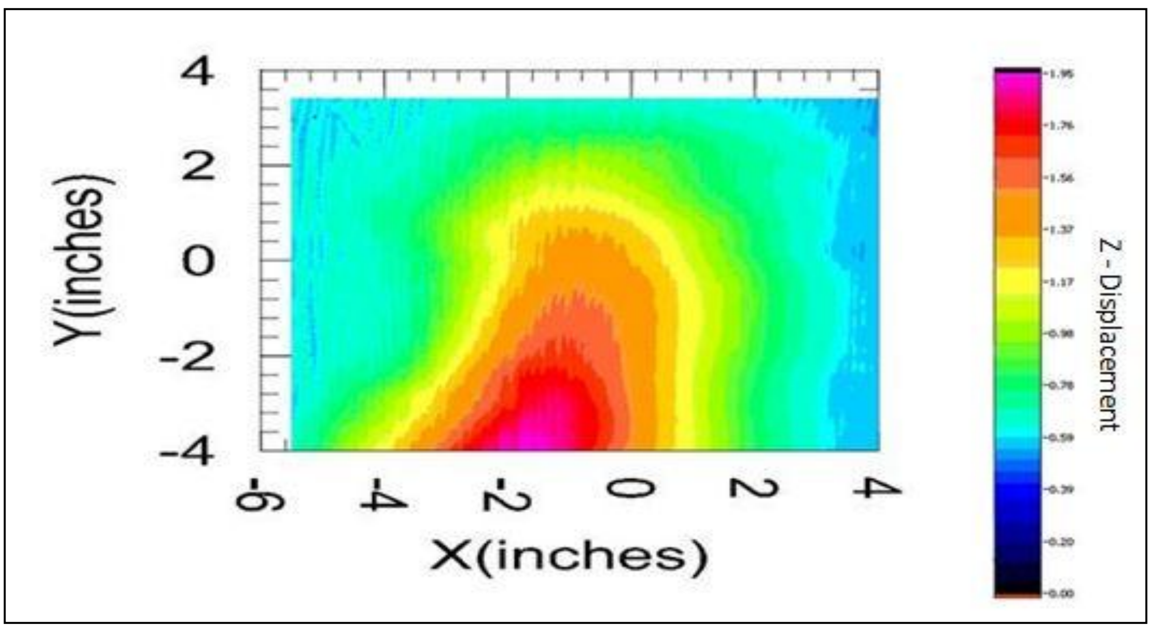


Figure 21: Example Laser Scan

Figure 21 is included to show a typical wave formed by the steering method. This scan was taken from section D of the 0.164 curvature steering layup. This scan represents an average excess arc length value of 4.77mm (.188In).

Characterizing waves in infused composite materials via the scanning method is more difficult than it is with dry fabric. When the layup is put under vacuum pressure for infusion, excess fabric is compressed together. This combined with resin filling voids makes measuring arc length with the scanning method very inaccurate. Instead, the maximum range in height was measured (maximum z –

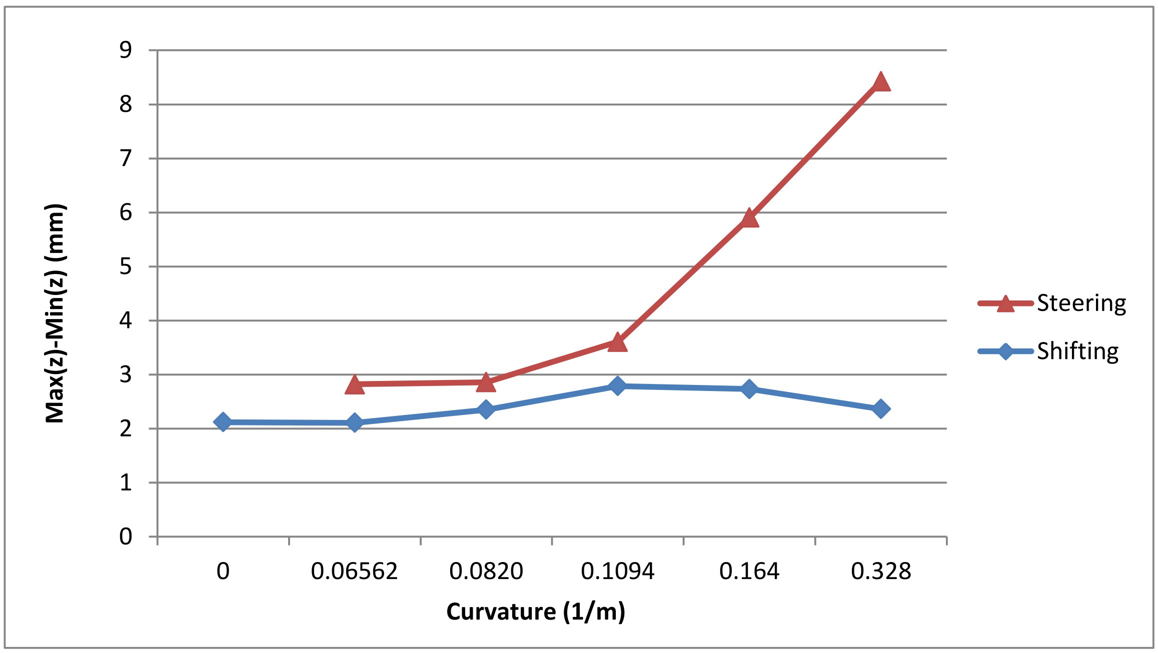


Figure 22: Out-Of-Plane Distortion as Max Z Range after Infusion

minimum z). Because some alignment error exists, this data is only useful for comparison between methods. This shows clearly that out-of plane deformation for the steering method is much greater than for the shifting method. (Figure 22)

Specific Aim 2: Impact on Properties

One potential concern with using the shifting method is the discrete shift locations. These could cause stress concentrations reducing the strength of the component, especially in fatigue. To test the effect of the shifting and steering methods on mechanical properties, fatigue tensile testing was performed. These tests were performed on two sets of coupons. One set of coupons was used to quantify the effect of the layup method (shifting vs. steering) on fatigue life when compared to one another and straight samples (*Experiment #1)*. The second set of coupons was used to further investigate the shifting method. These samples were created to quantify the effect that discrete shift quantities has on fatigue life (*Experiment #2)*. The testing setup and procedures will be described first, following by description and results for Experiments 1 and 2.

Testing Setup

Two loading tabs were bonded to each end of all coupons to prevent compressive damage of the sample in griping. These tabs were cut to the width of the coupon and 25.4mm (1In) in length with a 45° taper on the gauge end. The tabs were cut from a 3.175mm (.125In) thickness G10 Epoxy glass sheet. The tabs were then sanded using 80-grit sand paper to increase bond strength. The coupons were also sanded using 80-grit sand paper in the bonding location. The tabs were then bonded to the coupons using Hexion EPIKOTE™ Resin MGS BRP 135G3 mixed with EDPIKURE™ Curing Agent MGS BPH 137G to 40% by weight and allowed to cure. All coupons used the same loading tab setup, shown in Figure 23.

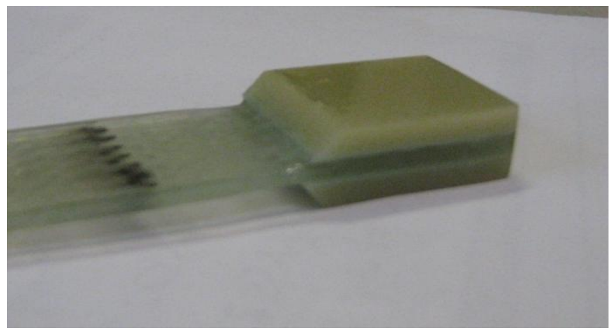


Figure 23: Loading Tab Setup

The testing was carried out in three steps using an MTS 312.31 universal fatigue tester. First, a preliminary modulus test was performed on each coupon. This included placing the specimen under 110MPa (16,000PSI) and relieving the stress while measuring the strain with a MTS extensometer and recording stress in order to calculate the modulus. The coupon was then subjected to fatigue cycling as described in detail below. Coupons that did not break after the prescribed number of cycles were then tested for modulus a second time using the same method as the preliminary modulus test.

In order to set parameters for the fatigue testing, 6 coupons were tensile tested to determine the average ultimate strength of the material. These coupons were cut from a straight sample created in the same manner as the samples create for specific aim 1. The coupons were cut to 25.4mm (1In) by 254mm (10In) with the 254mm (10In) length being in the direction of the fibers. The samples were tested to single load tensile failure.

The average yield strength was calculated to be 658.55 MPa (95,514 PSI). This was used to set parameters for the fatigue testing. $S/_{S_0}$was set at 0.45 with $R = 0.1$. This high stress level was chosen to accelerate the testing process. These parameters were used for all tests to provide comparative data between samples. Because of the high stress level, this data is not intended to be used for design or specification purposes but to compare effects across coupons.

One cycle consisted of loading to 296MPa (43,000PSI) and relieving the coupon to 29.6MPa (4,300PSI). The frequency of testing was set at 3Hz for Experiment #1 and 2Hz for Experiment #2 because of machine capabilities. The number of cycles to failure for these coupons was estimated to be 48,000 (Mandel 1992) so 24,000 cycles was chosen so that modulus could be compared before and after testing.

Experiment #1: Effect of Layup Method on Fatigue Life

The first set of coupons was cut from layup samples produced for specific aim 1. This included 9 shifted coupons, 9 steered coupons and 6 straight coupons. The shifted and steered coupons consisted of three curvatures including 0.328, 0.109, and 0.0656, with three coupons representing each curvature for each method. This is summarized in Table 1. All coupons in this set were cut to 25.4mm (1In) by 152.4mm (6In) with the 152.4mm length being aligned with the fiber direction.

Table 1: Experiment #1 Coupon Summary

Curvature (1/m)	Layup Method	Coupon # - With Adhesive	Layup Method	Coupon # - No Adhesive
0.328	Shifting	1	Steering	13
		2		14
		3		15
0.109	Shifting	4	Steering	16
		5		17
		6		18
0.0656	Shifting	7	Steering	19
		8		20
		9		21
0	N/A - Straight	10	N/A - Straight	22
		11		23
		12		24

For shifting and steering coupons, the cut location in the sample was not the same. This is because the non-linearity of fiber for each method occurs in different locations within the sample. Coupons 1 through 9 were cut from the shifted layup samples at the location of the shift between sections B and C (Figure 24). This location was chosen because it represents the non-linearity of the fiber, in the form of in-plane-deformation. Each section, i, contains linear fibers, so in order to realize the effect of the curvature, the samples were taken from between two linear sections at the location of the shift.

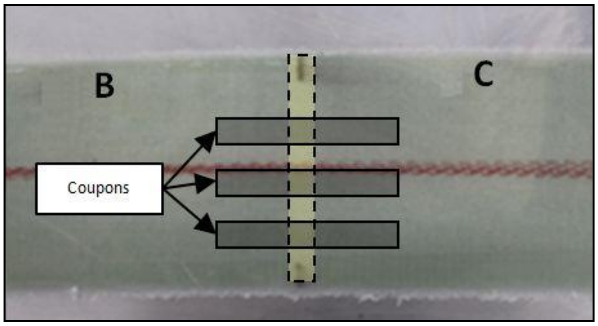


Figure 24: Coupon Location for Shifted Coupons (1-12)

For these samples, the location of the fiber non-linearity is also the location of the adhesive used to hold the sample for layup and infusion. This necessitated the testing of straight samples that also included adhesive in order to quantify any effect it may have on the life of the coupon. To do this, coupons 10 through 12 were cut from the same location between B and C on the straight sample. This represents the effect of the adhesive in the absence of curvature.

Coupons 13 through 21 were cut from the steered samples at the center of the B section, as seen in Figure 25. This represents the location of the fiber non-linearity in the form of out-of-plane deformation for the steered samples. There was no adhesive present at this location. All of these coupons except coupon 20 and coupon 21 had visibly evident waves or wrinkles. These two coupons were taken from the outside of the least severe curvature samples. In this location a small amount of excess arc length is predicted and the relaxation factor overshadowed this excess arc length. Coupons 22 through 24 were cut from the same location in section B on the straight sample. These samples were included to quantify the fatigue life without any effects (curvature, shifting, steering, and adhesive).

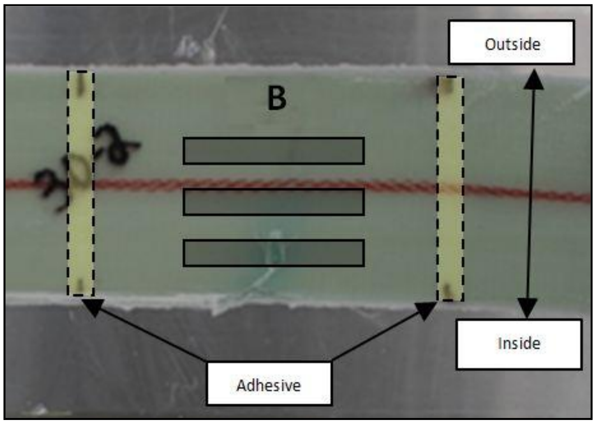


Figure 25: Coupon Location for Steered Coupons (13-24)

The samples were tested using the aforementioned testing procedure. In the testing, many coupons did not survive the prescribed 24,000 cycles, so no secondary modulus was recorded for these samples. Because of this, coupons were compared based on the number of cycles that the coupon remained intact, referred to as the fatigue life of the coupon.

Coupons that did survive the fatigue testing were recorded as *right censored* values, meaning that the only information available about these coupons is that their life is greater than 24,000. This is "Type 1" or "time censoring." All coupons were not tested to failure due to time and resource constraints. Because the manufacturing of the coupons was randomized, and was all done by the same process, it is assumed that time of manufacture did not have an impact on the coupons life. Therefore, it is reasonable to pool this data and analyze it with censored values included. [38] Results of fatigue life are presented in Figure 26, showing the difference between shifted and steered samples.

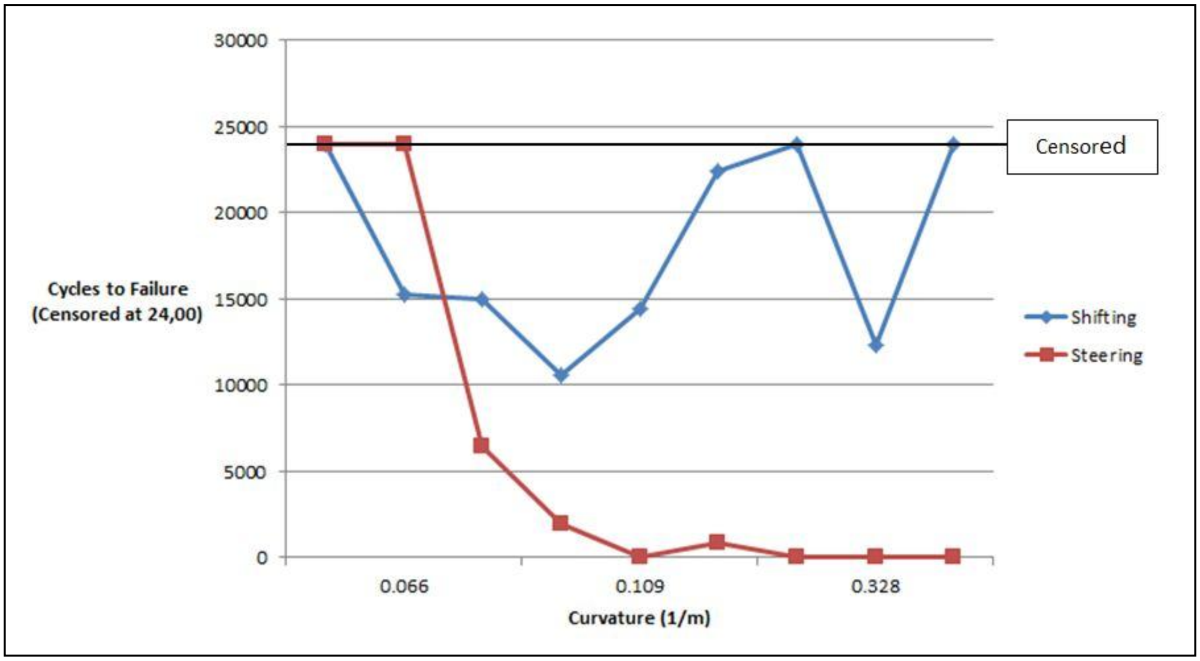


Figure 26: Fatigue Life - Shifting vs. Steering

This data shows that samples from the shifting method have longer life than those from the steering method, especially as curvature increases. The only coupons from the steering method that survived were the two listed above that showed no sign of out-of-plane deformation. It can be seen that even the coupon from the inside of the sample for the least severe curvature had a very low fatigue life. This coupon is representative of the layup as a whole because a failure at the inside of the layup where the wave was present would compromise the entire component.

While this shows an advantage for the shifting method, the extent of the improvement is not clearly known because of the presence of adhesive in the shifting coupons. To account for this the straight samples with and without adhesive were compared. JMP statistical software was used to fit the life of the coupon by presence, or lack of adhesive. (Table 2)

Table 2: JMP Analysis - Effect of Adhesive

Parameter	Estimate	STD Error	Lower 95%	Upper 95%
Mean Cycles To Failure (No Adhesive)	182,407	6,381	--	--
Mean Cycles To Failure (Adhesive)	18,958	1.21	12,964	27,611
Standard Deviation	1.36	1.19	0.97	1.91

This analysis shows that the mean predicted life for coupons without adhesive is an order of magnitude higher than mean predicted life for coupons with adhesive. However, because of censoring, the confidence interval for coupons without adhesive ranges from zero to infinity. It cannot be said that this effect is statistically significant. Even so, the mean life for coupons with adhesive is 18,958 cycles. While the confidence interval for these coupons does include 24,000 cycles, it is reasonable to conclude that the adhesive had a large effect on the life of the coupons. A literature review of the effect of adhesives on material properties has shown that increasing the amount of adhesive is known to decrease the interlaminar shear strength as well as decrease the permeability of the resin in certain directions during infusion. [39, 40] The combination of these effects may be the reason for the decrease in strength.

This data used for this analysis is presented in Figure 27. The fatigue life of coupons with adhesive appears to be completely random despite any other effect while straight coupons without adhesive all survived the fatigue cycling in the absence of waves. The inference made from Figure 27 is also supported by statistical analysis. In this analysis life of the coupon was fit to the data based on the curvature. The 12 coupons with adhesive were analyzed separately from the 12 coupons without adhesive. A log normal distribution was used yielding the results seen in Table 4 and Table 3.

Table 4: JMP Analysis - With Adhesive

Parameter	Estimate	Std Error	Lower 95%	Upper 95%
β_0	9.8450	0.1920	9.4686	10.2214
β_1	1.2536	3.6138	-5.8292	8.3365
σ	0.4162	0.1217	0.1776	0.6548

Table 3: JMP Analysis - No Adhesive

Parameter	Estimate	Std Error	Lower 95%	Upper 95%
β_0	12.0607	1.2434	9.6236	14.4977
β_1	-124.0118	19.8354	-162.8884	-85.1352
σ	2.1717	0.6099	0.9763	3.3672

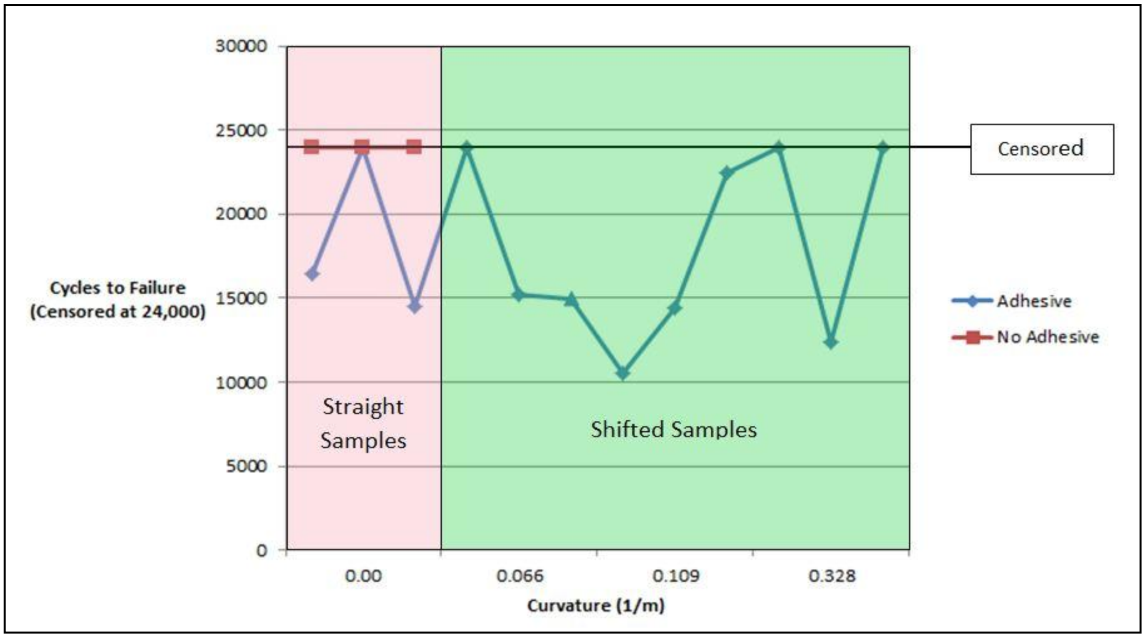


Figure 27: Effect of Adhesive on Fatigue Life Visually

For this analysis Y represents the fatigue life, β_0 represents the log mean life without curvature, β_1 represents the log effect of curvature on life, and σ represents the standard deviation in the form of:

$$\ln(Y) = \beta_0 + \beta_1 * Curvature \quad (6)$$

For coupons with adhesive, it can be seen that the confidence limits for β_1 encompass zero, which shows that the curvature had no statistical effect on the life of the coupon. It is known that adding curvature to structural composite components decreases strength because the composite becomes more dependent on the relatively weak matrix. This implies that the effect of adhesive in the coupons far overshadowed the effect of curvature on fatigue life.

This analysis can also be used to predict the life of a straight coupon that does or does not contain adhesive. Predicted life for a coupon with adhesive is 18,863 cycles while predicted life for a coupon without adhesive is 172,819. While this is a very limited prediction because of censored values, it does show that adhesive had a large effect on the life of coupons used for this experiment.

Experiment #2: Effect of Discrete Shift Quantities on Fatigue Life

The second set of coupons was created as individual layups at the desired size. These coupons were comprised of 4 layers of Saertex 930 $g/_{m^2}$ unidirectional fiberglass NCF cut to 25.4mm (1In) wide to prevent cutting of tows as seen in Figure 28. The proportion of cut tows would be different for different discrete shift quantities and would; therefore, cloud the effect of the discrete shift quantities.

All coupons included a 10° angle of deviation from straight and were 254mm (10In) long. The coupon was divided into 2, 3, or 4 equal length sections to produce the angle. (Figure 29) These correspond to 1, 2, and 3 discrete shifts respectively.

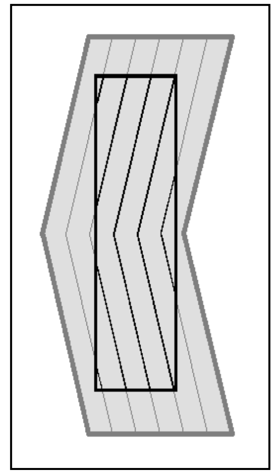


Figure 28: Cut Tows

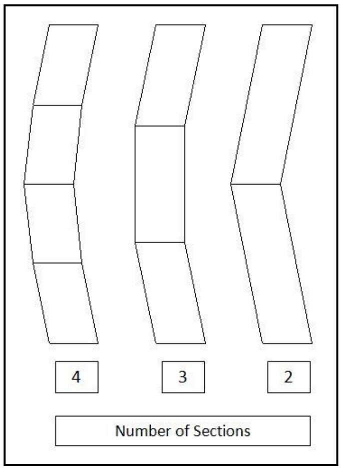


Figure 29: Coupon Set 2

To understand the actual effect of the shifting method, the coupons for this experiment were created with a constant curvature and no adhesive using only the shifting method. This allowed the isolation of the effect of discrete shifting quantities. An example coupon can be seen in Figure 30.

These coupons were then fatigue tested under the conditions listed above, except that all coupons were fatigued to failure with no maximum cycle restriction. The fatigue life data for the 9 coupons is presented in Figure 31. Life, expressed as cycles to failure, for samples with one discrete shift was very low as compared to samples with 2 or 3 discrete shifts. This shows that a large stress concentration exists at the point of the discrete shift, where all coupons with 1 discrete shift failed.

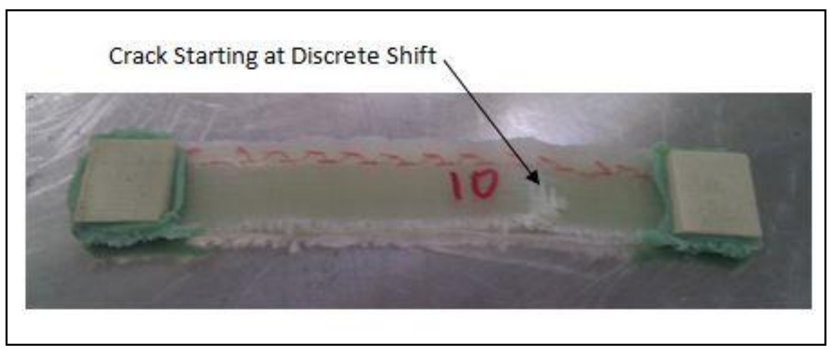


Figure 30: 3-Shift Coupon after 24,000 Cycles

The life of the coupons increased very quickly as the number of discrete shifts included in the coupon increased. The fit curve for the data is in the form of:

$$Y = a - b * e^{-c*x} \tag{7}$$

In this equation Y is the number of cycles and x is the number of discrete shifts. The values for a, b, and c for this angle and material are 139,424; 191,073; and 0.367 respectively, which were determined by minimizing the mean square error. In this equation, the parameter "a" represents the predicted life of a coupon with infinite shifts (continuously shifted), while "b" and "c" define the shape of the curve. The actual data along with the fit curve and limit as x approaches infinity can be seen in Figure 31.

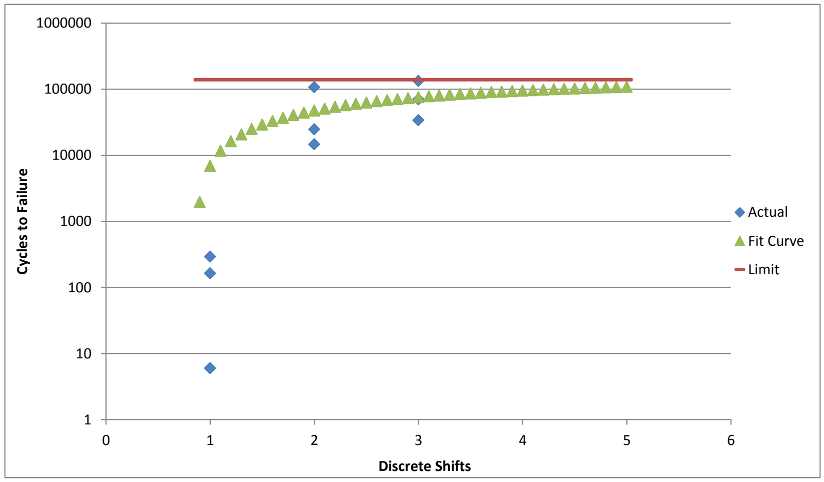


Figure 31: Effect of Discrete Shift Quantity on Fatigue Life

Conclusions and Future Work

This work has proposed the use of shifting as a fabric manipulation method for the automation of composite components. The automation of the fabric layup process would have major benefits for large scale NCF components as it would decrease labor costs, increase quality and repeatability, and potentially reduce mold cycle times. Two specific aims were investigated to determine the plausibility of the shifting method:

1. Can in-plane deformation in the form of shifting be used to prevent out-of-plane deformation?
2. What impact does the act of shifting have on the properties of composite materials?

These two specific aims have been experimentally researched and results have been presented. The discussion will be broken down into three sections including specific aim 1, specific aim 2, and overall discussion.

Specific Aim 1

In specific aim 1, layup samples were created with multiple curvatures and laser scanned before and after infusion to study the out-of-plane deformation caused by both the steering and shifting methods. The results show that the shifting method is capable of producing layups without out-of-plane deformation. Also, out-of-plane deformation, as measured in excess arc length, showed no correlation to the curvature of the layup for the shifting method. Mathematical descriptions of the shifting process were also given. The presentation of the shifting process mathematically is intended to provide a basis for process planning of shifting as a new automation method; analogous to tool path planning for NC machining.

Conversely, steering samples showed a high correlation between curvature and out-of-plane deformation. Out-of-plane deformation was shown to be predictable based on the radians traversed and the offset distance from the longest tow path. This is limited due to the relaxation factor of the fabric, but does reflect that out-of-plane deformation is predicted for the steering method. Using the same principal for the shifting method shows no out-of-plane deformation because the arc length for each tow is equal.

Specific Aim 2

In specific aim 2, tensile fatigue testing was performed to investigate the effect that shifting has on the properties of the composite material. Two experiments were conducted; the first to compare the shifting and steering method to one another and to straight coupons (Experiment #1). The second to understand the effect of discrete shift quantities (Experiment #2).

Experiment #1 cycle to failure data for the steering method showed a high dependence on curvature. The dependence of the steering coupon's life on curvature can be attributed to the presence of out-of-plane deformation in the form of both wrinkles and waves. Two coupons from the steering method did not have waves and did not fail before the end of the test. All of the other 7 coupons contained out-of-plane deformation and failed at 27% or less of the total test length (24,000 cycles) with 4 failing at 10 cycles or earlier.

Conversely, coupons produced with the shifting method showed no dependence on curvature; however many of the coupons still failed before the test was complete. These failures may be attributed to the presence of spray adhesive in these coupons. This is evident in the significant difference in predicted fatigue life between the straight coupons with spray adhesive and those without.

Further work should be conducted to understand the relationship between fatigue life and curvature for the shifting method without the presence of adhesive by testing without a cycle limit. Also, work should be done to understand the effect of adhesive with respect to application technique and quantity present.

For experiment #2, coupons were created with a constant curvature. Different discrete shift quantities were evenly placed within the coupon to quantify its effect on fatigue life. The data from this testing showed that the number of shifts has a significant effect on the fatigue life. Coupons with only one shift showed a drastic decrease in fatigue life, with none surviving more than 300 cycles. Coupons with 2 or 3 shifts; however, were shown to have a 300% to 500% higher average fatigue life respectively.

An equation for a fit curve was presented to predict fatigue life for increasing discrete shift quantities. There exists a limit to this increase where the life of the coupon is equal to that of a coupon produced with continuous shifting (i.e. all fibers are an exact copy of the guide curve). For the case of discrete shifting, the number of shifts could be optimized to minimize both cycle times and degradation of material properties. Future work should be done to create an automation solution to provide continuous shifting, which would eliminate the problem of stress concentrations caused by discrete shifting.

Further work should be completed in order to develop the equation parameters for different radii. Also, for production applications the curvature is rarely constant. This would require knowledge of the effect of curvature on the equation parameters so that this equation could be used for non-uniform curvatures. Another area for future research would be the effect of dispersing the shift locations throughout the thickness of the layup. For this experiment, shift locations were consistent through the thickness; however major gains in lifetime may be realized by staggering these throughout the thickness.

Overall Conclusions

To show the extents of the capability of the shifting method to create layups with curvature, a component was produced that utilized the full extent of the shear lock limit of the fabric. The fabric was first pre-sheared until the shear locking limit was reached. The fabric was then shifted around a curve until the opposing shear locking limit was reached. The maximum curvature of this component was calculated to be 0.72 (1/m) encompassing an angle of 53°. This component can be seen in Figure 32.

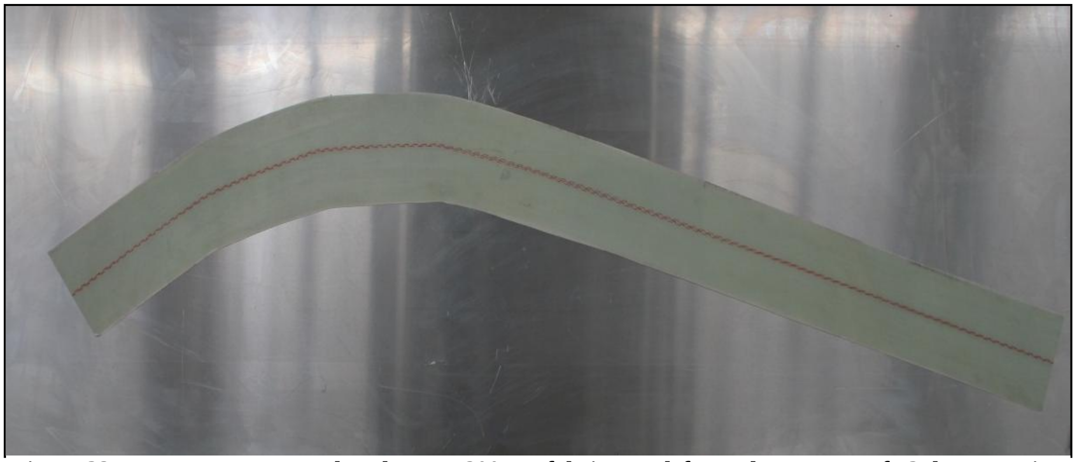


Figure 32: Extreme case example, where an 200mm fabric was deformed to a curve of 53 degrees using the proposed shifting method.

The work presented in this manuscript was performed with the intent of developing a deformation method that could be utilized in an automation solution designed for the layup of NCF composite components. It has been shown that the shifting method can be utilized to produce 2 dimensional layups containing curvature without producing out-of-plane waves. It has also been shown that the effect of the shifting method on mechanical properties can be significantly reduced through increasing the number of discrete shifts present in a component.

The number of shifts present in a layup can be optimized through understanding the parameters for the equation defining the relationship between discrete shift quantities and fatigue life presented above. This would be particularly useful in planning for an automated solution. Also, when utilizing an automation technique, shift locations could also be strategically placed in order to alternate locations between layers and minimize their presence in critical strength locations.

To give an idea of the feasibility of shifting as an automated method, a conceptual design was produced. A pinch roller system was used that would doll out fabric above the mold with the necessary shifts in place to create the correct geometry. Some human interaction may still be necessary, but the machine would be capable of producing the majority of the deformation; increasing quality and decreasing layup time. The conceptual design is pictured in Figure 33.

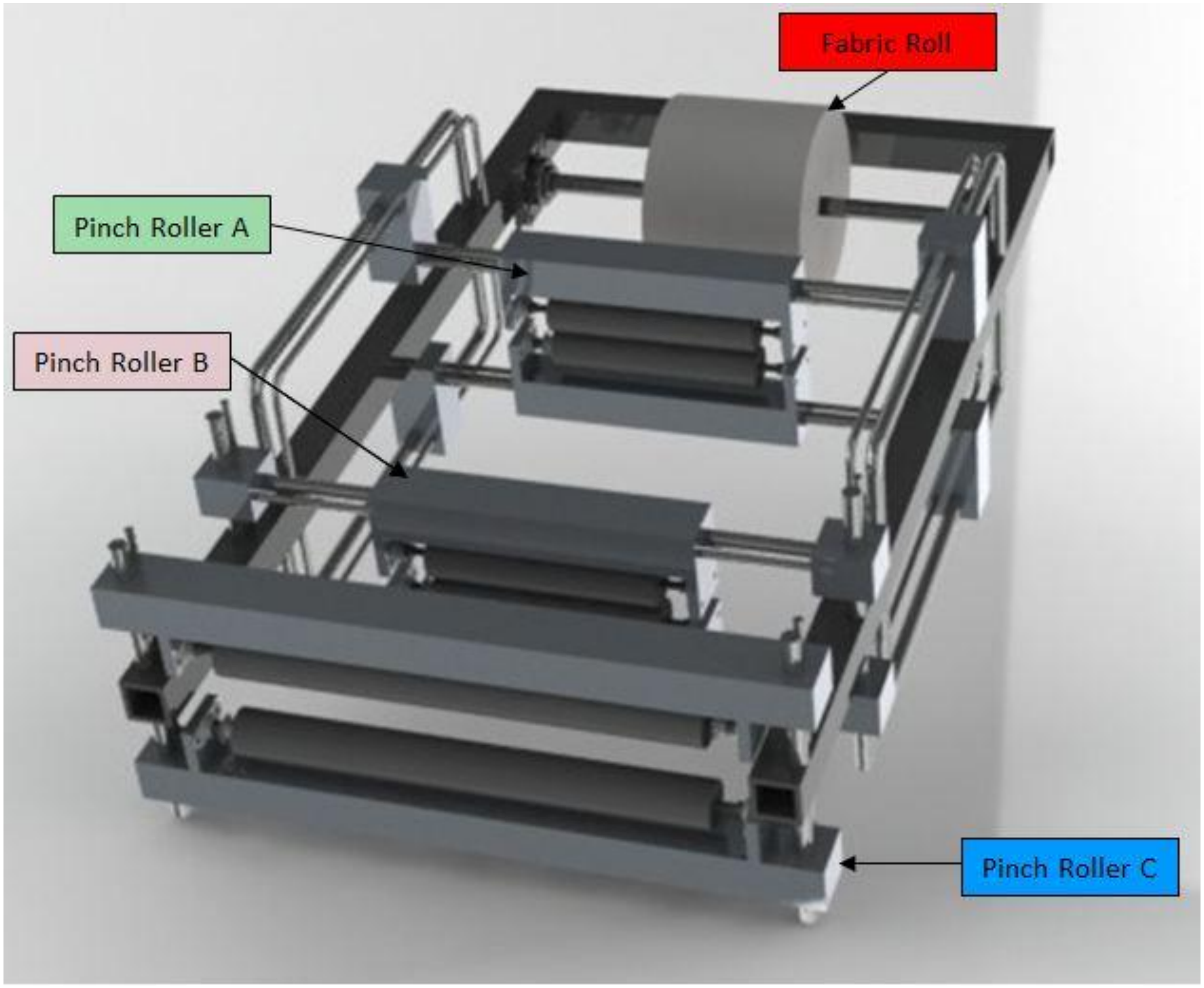
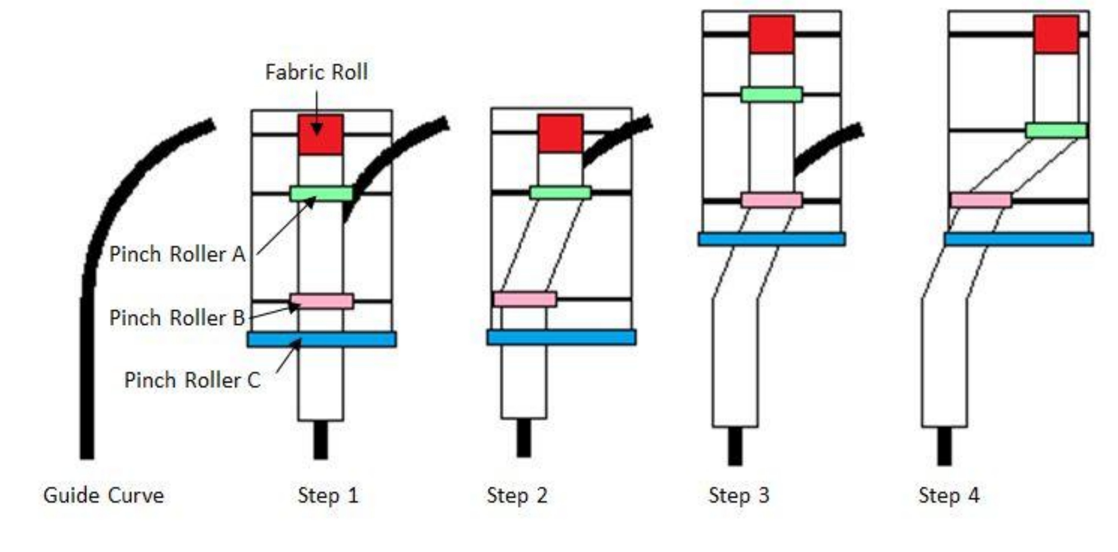


Figure 33: Conceptual Automated Shifting Machine

Figure 34 shows the process by which the conceptual automated shifting machine would place fabric. Machine path planning could be derived from the equations presented. Each step can be described as follows.



Pinch Roller A	Closed	Closed	Closed	Closed
Pinch Roller B	Closed	Closed	Open	Closed
Pinch Roller C	Open	Open	Closed	Open

Figure 34: Conceptual Automated Shifter Process Diagram

- Step 1: The shifting machine moves into position above the first shift location.
- Step 2: Pinch Roller A and Pinch Roller B clamp the fabric with Pinch Roller C open. The entire frame moves to position Pinch Roller A while Pinch Roller B synchronously moves the opposite direction to maintain its position, creating a shift.
- Step 3: Pinch Roller B is released and Pinch Roller C clamps the fabric. The entire frame moves forward as Pinch Roller A and Pinch Roller C feed fabric accordingly. Pinch Roller B moves back into position over the fabric.
- Step 4: Pinch Roller B clamps the fabric and Pinch Roller C releases. Pinch Roller A feeds fabric in reverse while synchronously moving into position. The entire frame moves to position while Pinch Roller A and Pinch Roller B create the shift synchronously.

For this work a manually operated machine was used to create shifted layups as shown above. The concept should be transferable to an automated system as shown. Also, the mathematical model of the shifting method has been developed and presented to aid in the process planning for an automated solution. Further work should be done to build an actual prototype to understand limitations of the method and gain an understanding of the actual costs associated with building and operating the machine. Future research in this area should be completed to further understand the feasibility of the automation method for shop floor application.

In this work, shifting has only been tested in the number 2 direction for 2 dimensional layup geometries. However, it is know that fabric of this nature can be shifted in both directions as represented by the pin jointed net (PJN) model. For practical applications, shifting in both directions would be required to conform to freeform surfaces and double curve geometries. Future research should focus on an automation technique capable of shifting the fabric in both directions.

Chapter IV: General Conclusions and Future Work

In this work, efforts have been made to develop a fabric deformation method that is plausible for the automation of the layup process. In the manuscript presented above, future work is presented directly pertaining to the testing done and the possibility for automation. There are also broader possibilities for the shifting method including alternative materials and applications outside of automation.

For this work, the materials considered were minimized to focus on the method of shifting itself. In future work this could be expanded to study the use of carbon fiber, prepregs, alternative fabric compositions, and alternative matrix materials.

Carbon fiber is commonly used for high cost per weight products, such as aerospace applications. While fabric structure is often similar to that of glass fabric, carbon fiber has a much higher sensitivity to deformations both in-plane and out-of-plane. Further research would be needed to understand the effect of the shifting deformation method on the properties of this material.

Prepregs are commonly used for the production of parts with high quality standards. Often stitching is not used because the resin in the material has sufficient tack quality to maintain the fiber orientation and structure. This presents problems in using the PJN model to describe the fabric deformation process. This also makes plies more sensitive to tow miss-alignment during the deformation process. Further testing would be needed in order to understand the deformation model and the use of shifting in the deformation process without causing miss-alignment.

There is also available a wide range of fabric compositions that were not directly considered in this work. Some of these include woven fabrics and multiple orientation fabrics. Woven fabrics are known to follow the PJN deformation model in that same way as NCF. Clamping of woven fabrics; however, may prove more difficult because of the interactions between fiber layers.

Both NCF and woven fabrics are available in multiple fiber direction fabrics. Examples of these include biaxial and triaxial fabrics with multiple combinations of fiber directions. Biaxial fabrics act similarly to the unidirectional fabrics used for this work, but with different orientations. Some work will be needed to develop a manipulation device capable of providing constraint along the fiber direction and shearing in directions other than parallel to the fabric roll. Triaxial fabrics will require further research as, with 3 tow orientations; it is not evident if it is possible to manipulate the fabric while maintaining equal lengths for all tows.

Alternative matrix materials may also have an effect on properties of components produced with the shifting method due to their effect on the strength of the composite material after deformation. As fibers are deformed from the primary loading direction, the matrix becomes more important to understanding the properties of the part as a whole. Further research should be done in testing the properties of composites with varying matrix materials.

While the primary goal of this work was to provide a fabric deformation method that would be useful for an automation system; other applications for the method exist as well. One important application for understanding of the shifting method is to inform workers in hand layup procedures. Understanding the way in which this deformation occurs will lead to better practices on the shop floor. This includes the way in which fiber is presented to the mold, the use of adhesives to constrain the fabric, and manipulation methods used to form fabrics to meet the geometry of the mold.

It has been demonstrated that the shifting method is capable of producing 2 dimensional layup with curvature while preventing out-of-plane distortion. It has also been shown that this method can be implemented with limited degradation of mechanical properties. A conceptual design has been presented that demonstrates the possibility of the method to be utilized as an automated layup solution.

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