2012

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

Luke A. Schlangen
Iowa State University

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

by

Luke Allen Schlangen

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:

Frank E. Peters, Major Professor

Matthew C. Frank

Vinay Dayal

Iowa State University

Ames, Iowa

2012

Table of Contents

Table of Figures

Acknowledgements

I would like to thank Dr. Frank Peters, my major professor, for his guidance during this project, but also for his excellent work in undergraduate education which was largely responsible for my pursuit of graduate education. My committee members Dr. Matthew Frank and Dr. Vinay Dayal also deserve credit for both guiding me in this project as well as teaching me about composite materials manufacturing.

Undergraduate research assistant Dan Chrusciel deserves a large amount of credit for sample creation, data collection, and operation of the CODA machine. Iowa State University's Wind Energy Manufacturing Lab made this thesis possible, and all of the students working in the lab deserve credit for some part of this research – either in teaching me how to perform an infusion or simply lending a hand.

Abstract

The purpose of this thesis is to test a new method known as shearing for the layup of Non-Crimp Fabric (NCF) plies for 2-dimensional and 3-dimensional composite components. This research includes the development of a machine capable of imparting shear on NCF plies. Results are presented with an equation for calculating machine settings for a given contour.

The machine is found to be capable of imparting a shear on the fabric, and the shear is found to have a significant positive impact on the quality of these samples during fabric layup. Fatigue tensile testing was conducted to understand the effect of the shearing method on the properties of composite components, and the samples produced by the machine display a fatigue life greater than samples produced by other methods. This research makes the automation of composite layup possible, which could replace high labor costs in industries such as wind turbine blade manufacturing.

Introduction

Composite materials are made up of two or more components that remain distinguishably unique even after they are combined. Fiber-reinforced polymers (FRP) are composite materials made of fibers within a polymer matrix. Carbon fiber and fiberglass are two very common types of composite materials due to their lightweight and high strength properties. This research focusses on the study of automated manufacturing of FRP composites.

Carbon fiber has superior weight and strength characteristics to fiberglass, which makes it the preferred material for aerospace and similar applications; however, it is nearly 10 times more expensive than fiberglass, and this cost difference makes fiberglass desirable in applications where cost has a larger impact on decisions. For cost reasons, the automation of manufacturing of carbon fiber and fiberglass has taken very different paths. The high-value aerospace applications of carbon fiber are typically able to justify costly automated manufacturing techniques. Carbon fiber material manufacturing has been highly automated using expensive machinery that is capable of very accurately placing small amounts of carbon fiber with a high level of precision; however, this method is very costly and has little application in industries where cost is a key decision factor. This research focusses on a potential solution for low-cost automated manufacturing of FRP components. This would reduce the cost to produce these parts and increase the quality of these parts by removing the cost and variability of human operators.

There are several options available for the manufacture of composite parts: (1) filament winding, (2) pre-impregnated lamination, (3) tape layup, (3) wet layup, and (4) vacuum assisted resin transfer molding (VARTM). (1) Filament winding is inexpensive, but it is incapable of producing many parts with complex geometry. (2) Pre-impregnated lamination uses material previously infused with resin to attain a precise ratio of fiber to resin. This raw material is more expensive because it requires pre-impregnation and the material must be stored at a cool temperature to prevent it from curing before production. (3) Tape layup is an automated process that places thin pre-impregnated “tapes” of several fibers on a mold with high precision and accuracy. This is very expensive and creates a high-quality end product. (4) VARTM is commonly used for large parts where cost is a significant factor, because it uses dry material which is less expensive than pre-impregnated material, and can deposit large sections of composite fabric at once which lowers the time and cost necessary for manufacturing.

The VARTM process begins with dry fabric made of fiberglass or carbon fiber that is woven or stitched together is placed into a mold. A plastic sheet is placed over the fabric to stop air bubbles from entering the part. Then a vacuum pulls resin through the dry fabric

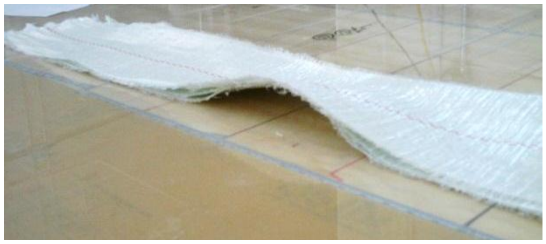


Figure 1: Wave in Dry Fabric

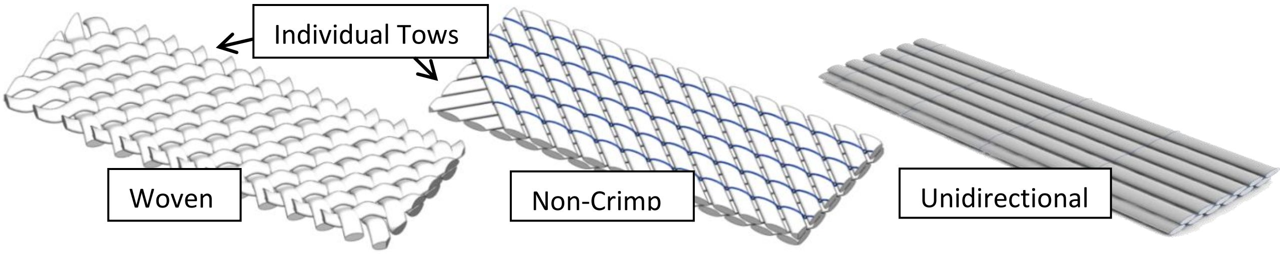


Figure 2: Woven and Non-Crimp Fabric [2]

to create the composite material which is called infusion. The machine discussed in this paper is designed to automate the dry fabric layup required for VARTM.

The fabric is originally a flat, two-dimensional sheet that is placed in a mold. If the fabric is too rigid to conform to the mold, non-conformities will appear in the part. An individual non-conformity is known as a wave (Figure 1). The presence of wave defects can lead to a significant reduction in the strength and can cause premature failure of a composite part [1].

Dry fiberglass fabric primarily comes in two forms. Fiberglass can be Woven or Non-Crimp Fabric (Figure 2). Woven fiberglass is produced by weaving the tows (individual bundle of composite fibers) together. However, this weaving induces small waves as the tow travels up-and-down through the weave as it passes over or under another fiber bundle, causing a slight reduction in structural properties. Non-Crimp Fabric (NCF) – fabric where all the tows in a single layer (ply) are travelling the same direction (unidirectional) and stitched together (stitch-bonded) – has become the more popular fabric choice because it has superior structural properties due to the direct path of each tow opposed to the up-and-down path of each woven tow. This paper will focus on unidirectional fabric where all tows in all layers are travelling the same direction.

When fabric is placed in a complex mold, it must be manipulated to conform to the mold, otherwise there will be a wave where it fails to conform. This manipulation causes the tows to move in relation to one another. For example, Figure 3 and Figure 4 show three tows travelling across a three-dimensional surface. Each tow is required to travel a different distance in order to lay flat against the mold. This creates an angle between the cross-tows connecting the three tows Figure 5. This angle is known as the shear angle and it changes throughout the fabric based on the shape of the mold. Every fabric has a maximum shear angle known as its shear locking limit where the fabric can no longer shear to conform to the mold and a wave must form at that point. The SLL varies between fabrics, but every fabric has a limit somewhere between 0°and 90°.

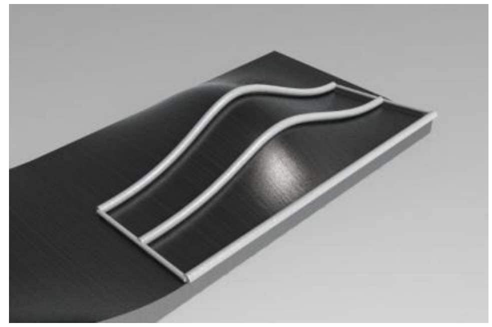


Figure 3: The Unidirectional Tows on a Mold

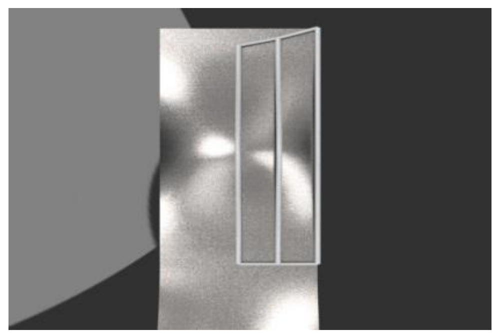


Figure 5: Top View of Figure 3

The work presented in this thesis is an extension of the work done by Meng in Pre-shearing planning for the layup of unidirectional fabrics [3]. Rather than introducing shear into the fabric by smoothing it on the mold, Meng suggested shearing the fabric before it was placed on the mold. Meng presented an algorithm through which the shear angle distribution obtained from kinematic simulation of the naïve layup approach could be utilized to generate a fabric pre-shearing plan prior to the layup process.

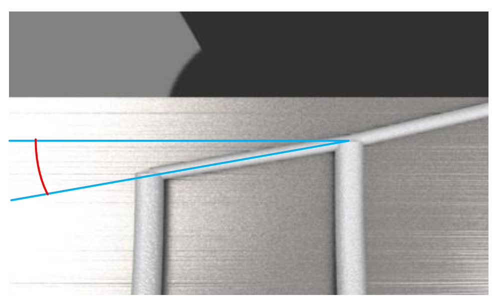


Figure 4: Shear Angle between Two Tows

Shearing refers to manipulation of the fabric in the number one direction (the direction of the fibers in NCF). This differentiates it from manipulation in the number two direction (the direction perpendicular to the fibers) known as shifting. Figure 6shows a representation of shearing and shifting.

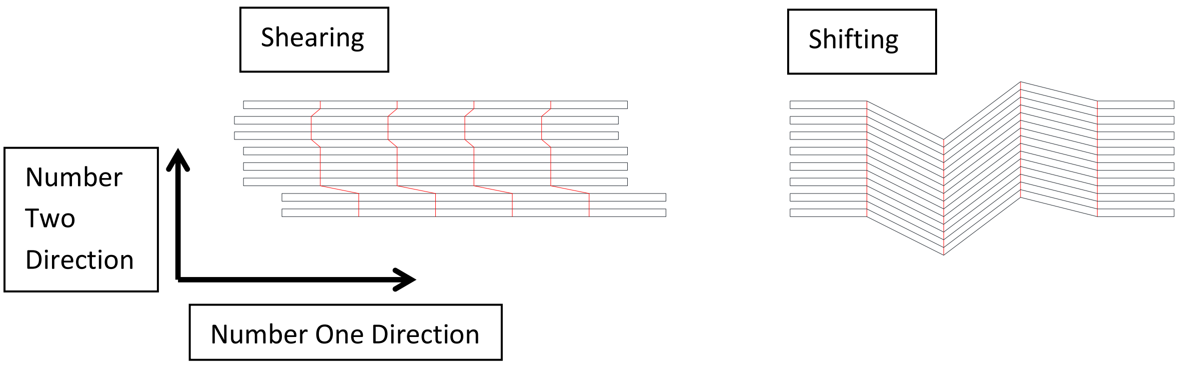


Figure 6: Shearing vs. Shifting

In shearing, tows are adjusted forward or backward relative to one another to avoid a buildup of excess material. In shifting, the cross-tows are adjusted forward or backward relative to one another to avoid the buildup of excess material. In Figure 7, the fabric is being maneuvered around a 90° turn, the first image shows steering where the fabric is “steered” around the turn. In this layup method, the excess length in each tow builds up throughout the turn and causes out-of-plane deformation on the inner side – deformation that is not contained to the two dimensions of the turn. This is similar to runners travelling around a track: the runner on the outside has a farther distance to travel. The second image shows shearing, where the excess length is all pushed to the end of the curve and the fabric on the inner tows travel farther around the turn than the outer tows to avoid excess material. The third image shows shifting, where the fabric is clamped and shifted perpendicular to the fiber direction. Eliminating the out-of-plane deformation is significant because out-of-plane deformation is responsible for the waves that cause severe strength reductions in the composite material.

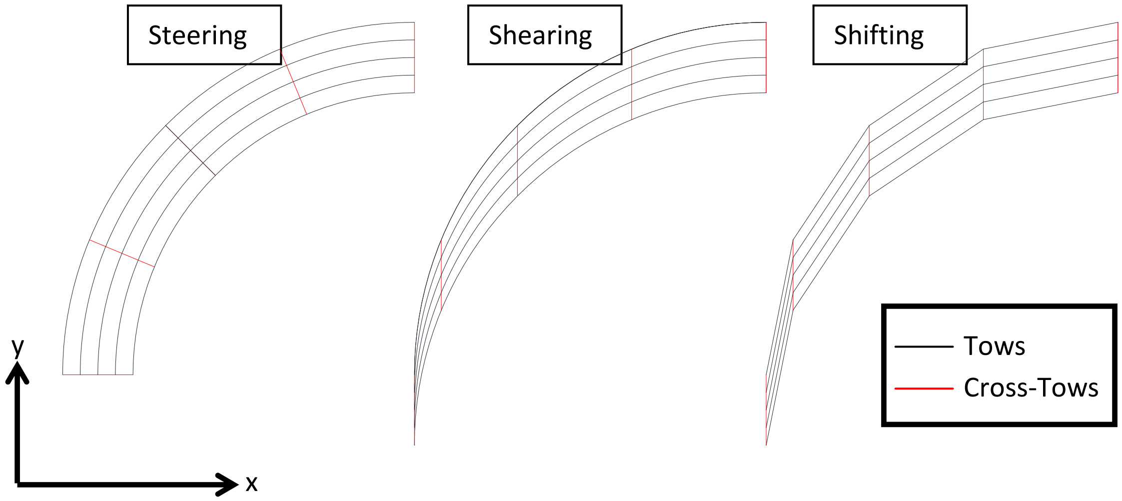


Figure 7: Steering, Shearing, and Shifting about a 90° Turn

This paper will attempt to unify shifting and shearing by showing that shearing is effectively the equivalent of shifting a fabric an infinite number of times. Figure 8 shows samples with different numbers of shifts. As the number of shifts increase, it becomes a better approximation of the

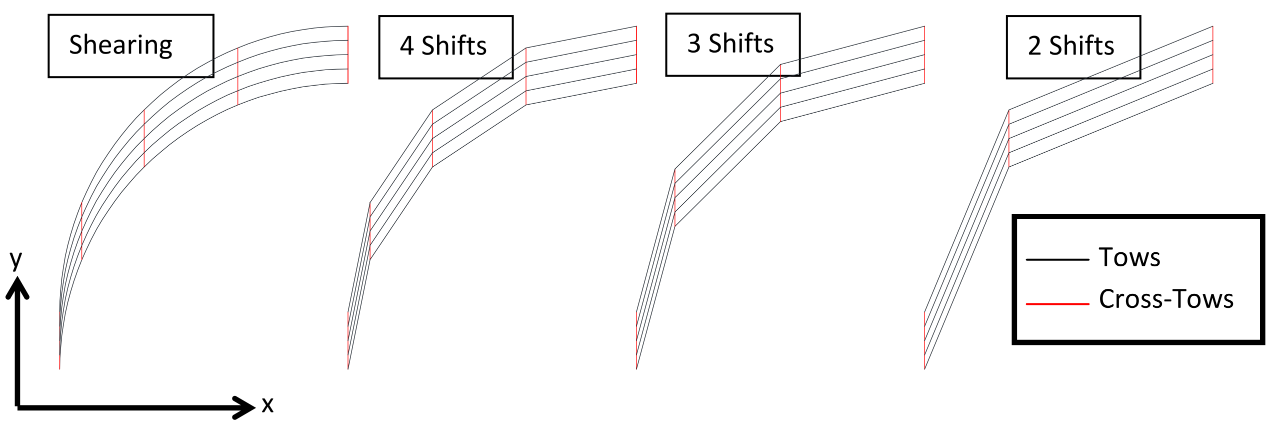


Figure 8: Shearing and Different Numbers of Shifts about a 90° Turn

sheared turn. Experiment 2 will show that the fatigue strength properties of a sheared sample are equal to the expected fatigue strength values of an infinitely shifted sample.

Meng suggested a potential multi-roller system that would be capable of imparting a shear on the fabric by displacing more or less fabric for each tow. The design for the machine in this work is based on the design of a multi-roller system in that article. The present paper tests a possible method for pre-shearing fabric for layup. A prototype machine is designed, built, and tested. Samples are created to test the effect of pre-shearing on part waviness.

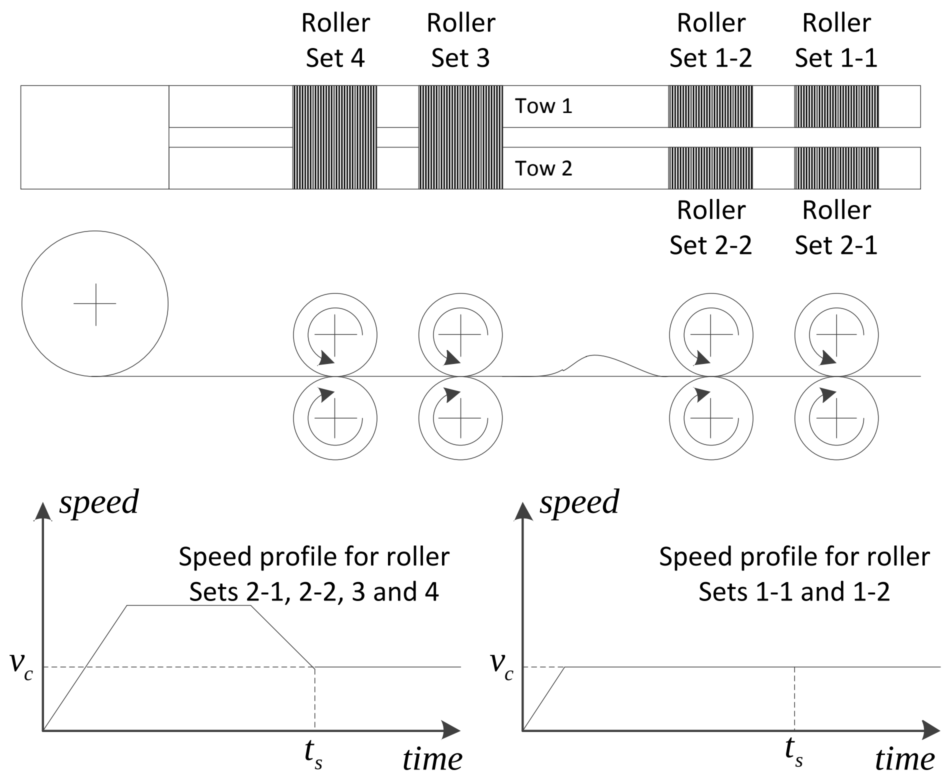


Figure 9: Machine Design by Meng

Literature Review

Current composites manufacturing methods require large quantities of human labor in the form of hand layup of composites. The lack of repeatability for each ply due to human variability makes automation of composite fabric layup challenging. This review will discuss prior attempts to automate the process, and fabric manipulation.

Prior Automation Techniques

The two most commonly used automation techniques in the composites market are (1) automated tape layup machines and (2) filament winding. (1) Automated tape layup precisely places narrow "tapes" of pre-

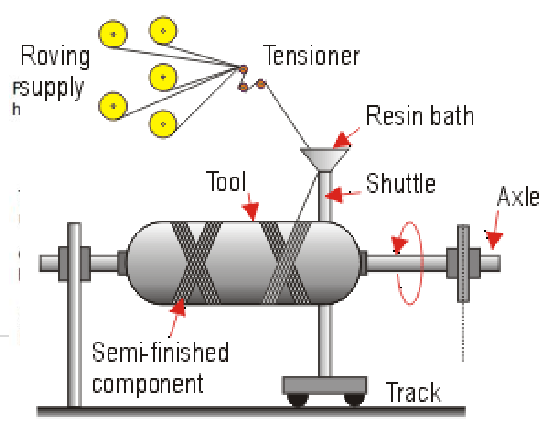
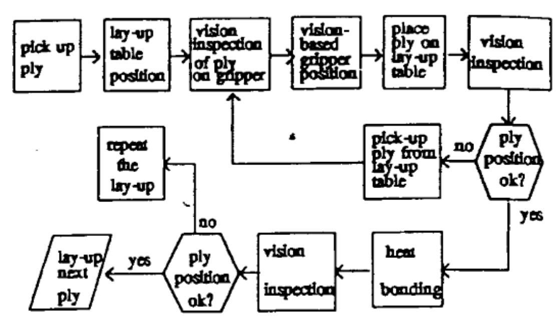


Figure 11: Filament Winding [5]

impregnated composite onto the surface of a mold (Figure 10); however, this process is generally considered too costly for the manufacture of low-cost composite parts as it requires very expensive machinery, requires expensive input material, and is very time consuming. (2) Filament winding wraps individual filaments around the part as the part is spun on a mandrel (Figure 11). Although it is inexpensive, it has limitations on the types of parts it is able to produce it: mostly relatively long, round, convex shells of constant wall thickness such as pressure vessels and pipes.

Mills pointed to three areas for manufacturing of affordable high-performance composites: to replace pre-impregnated materials (pre-pregs) with lower cost materials, to automate the material deposition process, and to produce components molded to net thickness [6]. In order to accomplish these objectives, the automation of dry fabric layup is necessary [7].

Several attempts have been made to automate the fabric layup process. Ruth [8] proposed a robotic work cell capable of ply acquisition, transfer, placement, stacking, and smoothing operations. The purpose of the robot was to replicate the operations done by hand layup. Sarahidi [9] presented a similar automation method that is detailed in Figure 12. Sarahidi also discussed the use of an electrostatic gripping device to improve upon conventional fabric handling techniques using pins which grab fabric by puncturing and hooking it. Challenges to this method include a system capable of placing the fabric, flattening it on the mold and a vision system capable of recognizing when it has been successfully positioned.



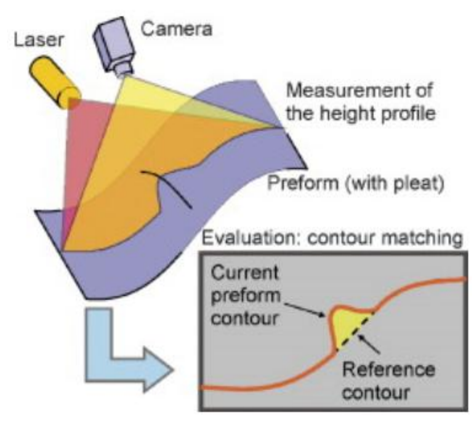


Figure 13: Vision System for Wave Detection [10]

The Sarahidi model requires a vision system capable of recognizing when the fabric is properly or improperly placed on the mold. The suggested

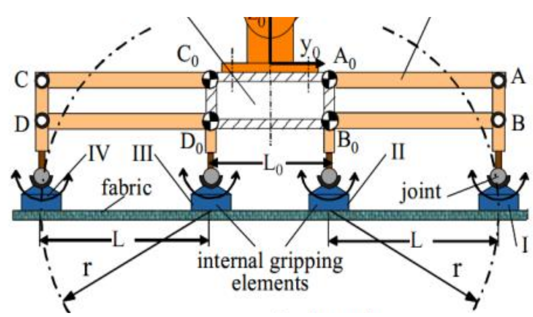


Figure 14: Robotic Pick and Place Machine [11]

vision system has been revisited many times including a recent article by Schmitt [10] that demonstrated the ability of multiple sensors to accurately detect fiber direction and height profile of composite materials (Figure 13).

One system designed from these principles was presented by Kordi, [11]. Figure 14 shows the machine that would pick, transport, and place the material. A second device would then smooth the fabric with a set of rollers.

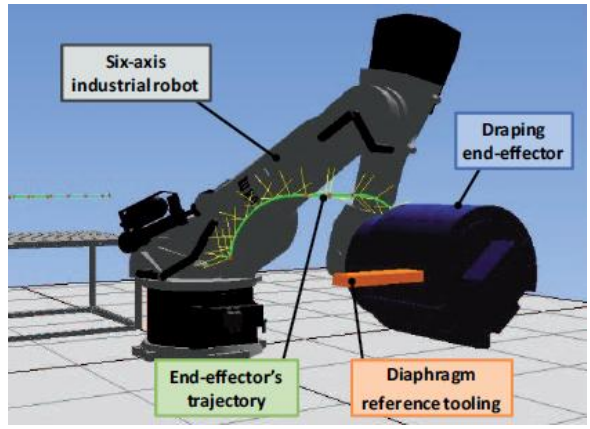


Figure 15: Vacuum System for Transporting and Placing Fabric [13]

Jarvis [12] suggested a pick and place system using a vacuum table. Angerer [13] suggested a vacuum system to pick specific pieces of fabric by opening small holes that would hold the pre-cut fabric and then close the holes to release the fabric (Figure 15). However, this system is not capable of manipulating the fabric to conform to the mold.

Fabric Manipulation

Deformation of the original fabric must occur for all parts that are not stitched in their final form. In hand layup, this deformation occurs when an individual places the fabric into the mold and applies pressure to conform the fabric to the mold. This process is called draping. Studies of draping have defined its impact on fibers. The pin jointed net (PJN) model, which treats the intersections between tows as pins, has become the most widely accepted model for this process [14]. This model then leads to the conclusion by Prodrodromou [15] that after a fabric reaches its maximum allowable angle – its shear locking limit (SLL) – it will buckle out of plane and create a wave. A fabric can be extended past its SLL if the mold geometry it is placed on is more complex than what the fabric can tolerate.

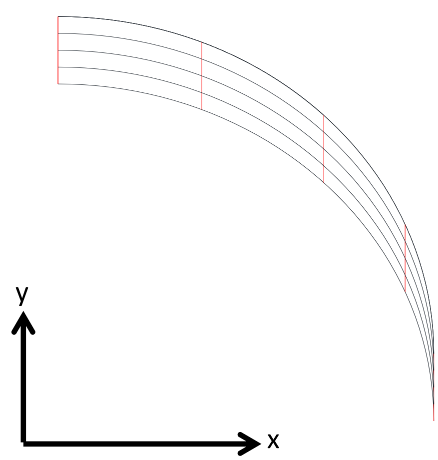


Figure 16: Sample Traveling around a Turn without Pre-Shear

For a 90° turn like Figure 16, this would occur somewhere between the top of the curve and the bottom of the curve. The fabric is constrained at its minimum x value and the shear angle is gradually increasing as it travels from around the turn from minimum x to maximum x. At the maximum x the shear angle is 90° which means that all of the tows are directly on top of one another. Given that the fabric has a width, this means out-of-plane deformation must occur (Potter).

Another way to see this is to notice that the distance between tows gets smaller as the angle increases. When the tows have no more spacing, they are forced out of plane [16].

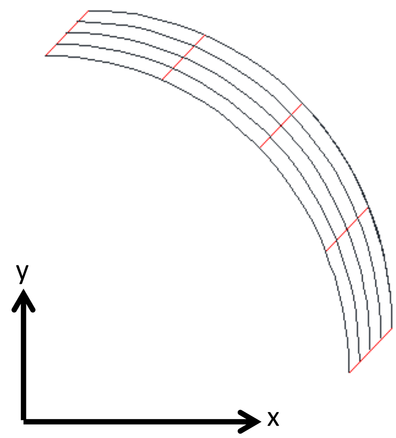


Figure 17: Sample Traveling around a Turn with Pre-Shear

Meng [3] proposed that by changing this angle before the fabric was placed in a mold, it would alter the effective SLL. This means that fabrics that would traditionally be unable to fit into a mold without reaching their SLL, could be sheared prior to layup (pre-shearing) and would then be able to fit into that mold. For the example of the 90° turn, it would look like Figure 17.

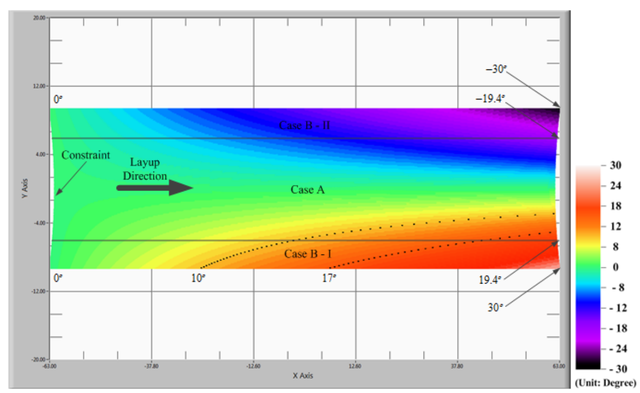


Figure 18: Fabric Layup without Pre-Shear

This is especially applicable for complex 3-dimensional molds where a bump or dip in the mold requires more length from the tows in the middle of the fabric than the tows on the edges of the fabric. Meng hypothesized that by planning for this excess fabric prior to layup by pre-shearing

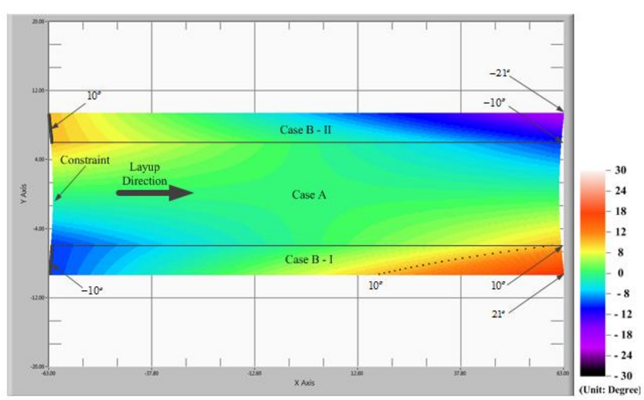


Figure 19: Fabric Layup with Pre-Shear

the fabric, it would be possible to eliminate the excess fabric and out-of-plane deformation. The software developed by Meng was based on a mold where the middle tows of the fabric would be required to travel a lesser distance than the outer tows. The fabric was constrained at one end and flattened against the mold. As the fabric was flattened against the mold, the shear angle increased: the difference in distance traveled by the middle tows and outer tows grew. Eventually, the SLL was reached, and out-of-plane deformation occurred. By pre-shearing the fabric prior to placing it in the mold, the SLL would be reached at a later point, or not at all.

Figure 18 shows a fabric without pre-shear being placed into the mold. By the time the fabric reaches the end of the mold, the shear angle has reached 30°. Figure 19 shows the same mold, but the fabric has a 10° pre-shear that eliminates the extreme shear from the layup.

Magnussen used this knowledge of in-plane-shear to avoid waves when constructing samples to travel around a radius. By clamping the fabric and shifting it discretely at specific locations, the in-plane-shear was used to avoid out-of-plane waves. The paper focused on eliminating excess fabric that is traditionally allowed to build up inside of the mold and create waves. However, discrete shifts would not be able to accommodate excess fabric tow length in 3-dimensional molds.

Research Goals

This research aims to:

1. Provide statistically significant evidence that shearing is capable of preventing out-of-plane deformation confirming the hypothesis of Fanqi Meng
2. Demonstrate a machine capable of continuously imparting shear onto non-crimp fabric (NCF)
3. Unify shifting and two-dimensional shearing as complimentary rather than contrasting manipulations

Methodology

A machine was designed by the author to impart a shear onto the fabric. Two experiments were conducted to analyze the capability of the machine to layup fabric for composite parts. The fabric used in these experiments was Saertex 930 g/m^2 unidirectional fiberglass that was 200mm wide.

The first experiment tests the capability of the machine to create samples for a 3-dimensional mold that are free of wave defects. The second experiment tests the fatigue properties of samples created by the machine to follow a curvature.

Shearing Machine

The Continuous One-Direction Adjustor (CODA) (Figure 20) was designed with two independent axles and adjustable wheels. For the experiments in this paper, the axle furthest from the roll of fiberglass fabric was held at its maximum speed for all experiments, while the axle closer to the roll was changed to impart a shear on the fabric. As the machine ran, excess fabric would build up behind the machine; a flattener was used to prevent this excess fabric from entering the machine.

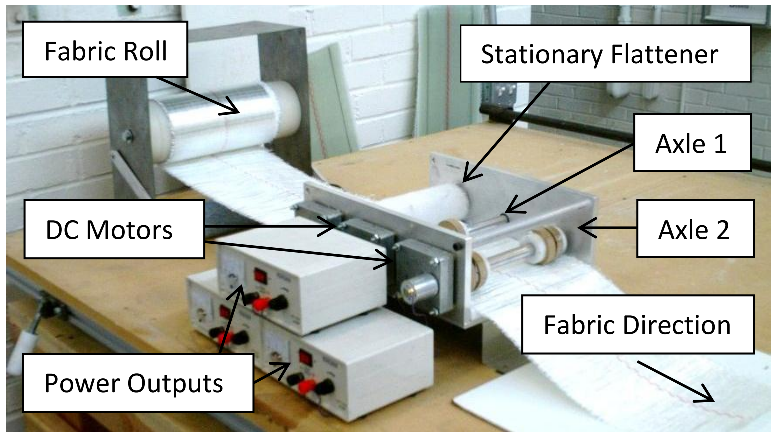


Figure 20: Continuous One-Direction Adjustor (CODA)

The axles were controlled using two 4 rpm, 40in.-lbs torque DC motors connected to two Tekpower HY152A DC power outputs. Axle 2 was left at a constant 15 Volts while Axle 1 was adjusted between 11.5 Volts and 15 Volts. The voltage input was found to directly relate to the speed of the wheels. Therefore, 77% voltage meant 77% speed. Although it was originally built with three DC motors and three power outputs, only two were used for this experiment. The third axle was not powered but was used to hold flattener in place that would apply pressure to the fabric.

The flattener was necessary to hold excess fabric behind the running axles of the machine. As the machine ran, excess fabric would build up behind the slower traveling tows. The flattener prevented this excess fabric from going under the rollers and causing out-of-plane deformation.

Experiment 1

The first experiment was designed to represent fiberglass layup in a three-dimensional mold where the outside tows would require more fabric than the inside tows. Conceptually, it would be desirable to place less fabric tow length for the inside tows. Figure 21 shows the machine setup for experiment 1. A single wheel was placed on Axle 1 to create this shear. Two wheels were positioned on each end of the maximum speed axle because as shear increases, fabric thins and a single wheel would slip off of the fabric.

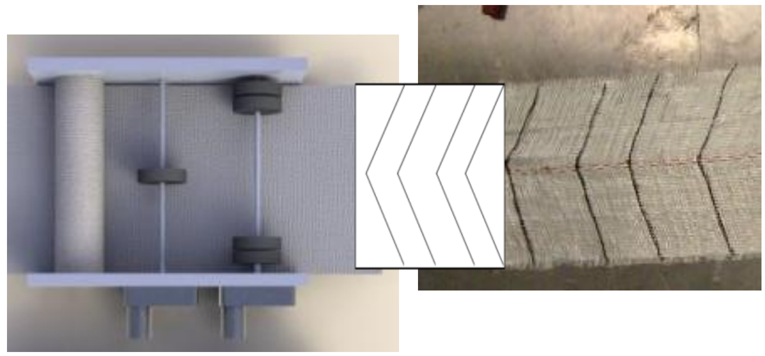


Figure 21: Machine setup for Experiment 1, Lines Demonstrating Shear, and 500mm-Long Sheared Sample Made by this Setup

Shear was imparted on the fabric by running the variable speed axle (Axle 1) slower than the maximum speed axle (Axle 2). Axle 1 was run at 100%, 97%, 93%, 90%, 87%, 83%, 80%, and 77% of Axle 2. This was done to relate the difference of speed with shear imparted on the fabric.

The samples made were 1300mm in length. The shear was measured every 100mm between 100mm and 1200mm by placing a straightedge perpendicularly across the fabric, following the cross-tow to its maximum distance from that line, and measuring the distance with a Mitutoyo NTD10-8” C Caliper. The 0mm point was the first fabric to go through the machine, and the 1300mm line was the last fabric to go through the machine. The width of samples created when Axle 1 was set at 77% (samples with the greatest shear) were also measured every 100mm to determine change in fabric width.

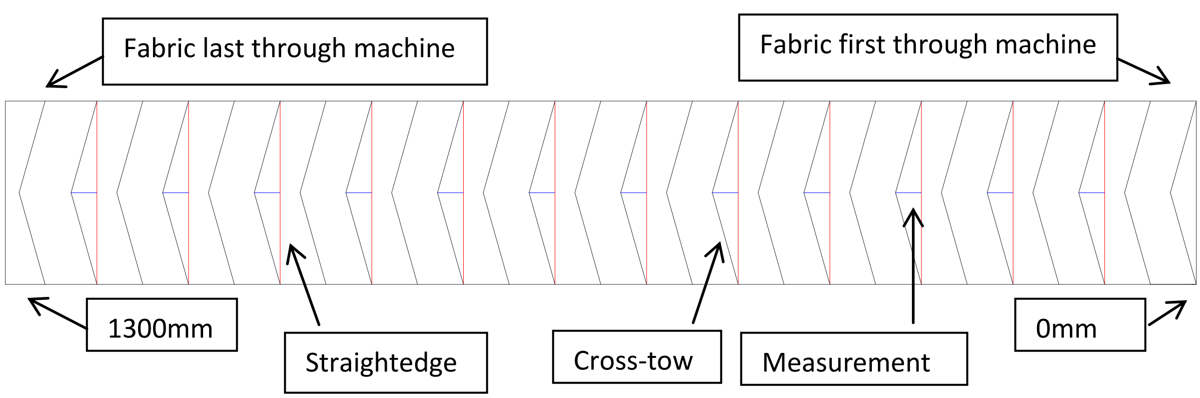


Figure 22: 1300mm Sample from Experiment 1

After these measurements were completed, the 750mm last through the machine were cut off and placed in the 3-dimensional mold. The mold consists of a 90° section of the inner-half of a torus. Figure 23 shows the mold has a toroidal radius (R1) of 19.050mm and a poloidal radius (R2) of 8.890mm. These dimensions were chosen to intentionally exceed the SLL for the chosen fabric without pre-shear.

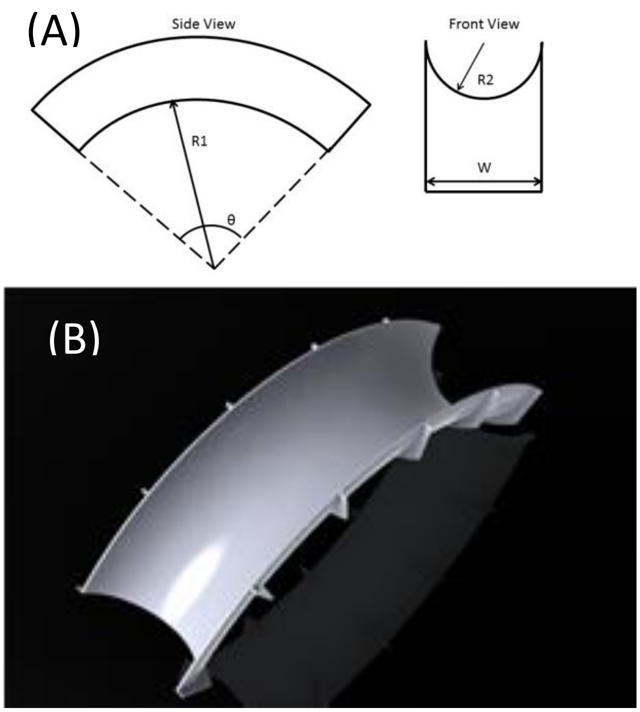


Figure 23: Mold Used for Experiment 1 (A) Drawing of Mold (B) Solidworks Drawing of Mold

For all samples, the fabric last through the machine was constrained between the mold and the wooden constraint shown in Figure 24. A second identical constraint was placed directly adjacent to the first wooden constraint and pulled to the other side of the mold one time (conforming the fabric to the mold). No hand smoothing was performed on these samples.

The number of waves was recorded. The height of the wave with the maximum height for each sample was measured using the caliper. Number of waves and wave height were selected as these are easy to measure and are known to have an impact on the properties of composite parts. These samples were never infused.

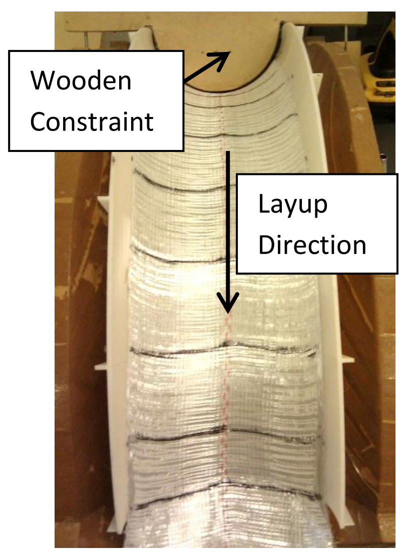


Figure 24: Actual Mold for Experiment 1 with Fabric

Experiment 1: Results

The machine imparted a shear on 88 samples for this experiment: 11 samples at 8 different settings. Figure 25 (A) shows that as the difference between axle speeds increases, the shear angle also increases. It is also important to note that the fabric does have some resistance to shearing. Because of the interactions between tows, small differences between Axle 1 and Axle 2 are not enough to impart a shear on this fabric.

Figure 25 (B) groups the samples by measured shear and reports the percentage of samples with that shear that displayed waves. The samples with a measured shear over 30mm were significantly less likely – with 99.5% statistical confidence there is a difference using a Chi-Square Test – to develop waves than those with no shear (6% vs. 100%).

One surprising result shown in Figure 25 (C) was that when waves were present, there was no difference between those with more shear or less shear. All models would predict that if waves were present in the high-shear samples, they would at least be far less severe, but there was no significant difference between them. The standard deviation in caliper measurements given by a gauge R&R study was 1.8mm, which explains the majority of this difference; no conclusive conclusions could be drawn from the wave height data.

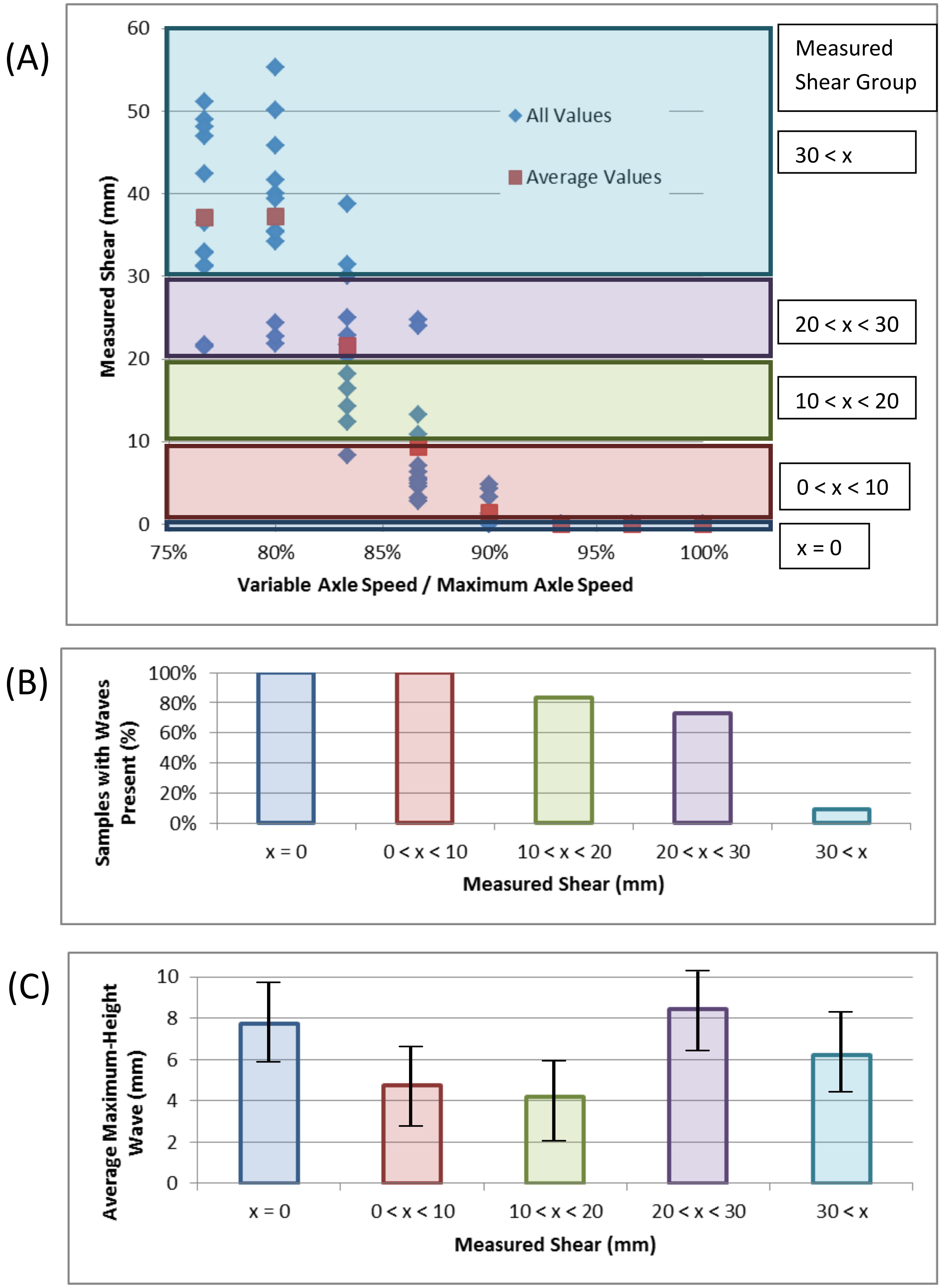


Figure 25: (A) The Relationship Between Machine Setting and Shear (B) Relationship Between Measured Shear and Percentage of Samples with Waves Present (C) Relationship Between Measured Shear and Average Height of Maximum Height Waves for Each Group when Waves were Present with Caliper Measurement Error Bars

The decrease in the number of samples with waves with the increase in shear confirms the hypothesis of Fanqi Meng that In-Plane Shear is capable of preventing out-of-plane deformation. The pre-shear imparted on the fabric by the machine was able to prevent the fabric from reaching its SLL. A sample with no observable shear and a sample with more than 30mm of shear are shown in Figure 27 before they are placed in the mold. Figure 26 shows the same samples after they are placed in the mold. The fabric with no shear prior to entering the mold, has two noticeable waves while the fabric with a significant shear, has no noticeable waves. This result was easily repeatable as 100% of samples with less than 10mm of shear experienced the presence of waves when they were applied to the mold, while only 6% of samples with 30mm of shear or more experienced the presence of waves.

Figure 27: Unsheared and Sheared Samples from the CODA

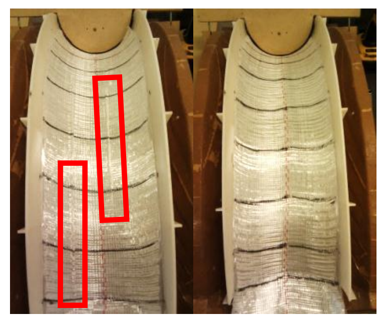


Figure 26: Unsheared and Sheared Samples Placed in the Mold

The measurements showed that the shear angle is larger for fabric that travels through the machine last. If Axle 1 is continuously travelling at 77% of Axle 2, the total excess fabric will increase with length (e.g. 77% of 100mm is less than 77% of 1000mm). Figure 28 shows this relationship between shear and length of fabric.

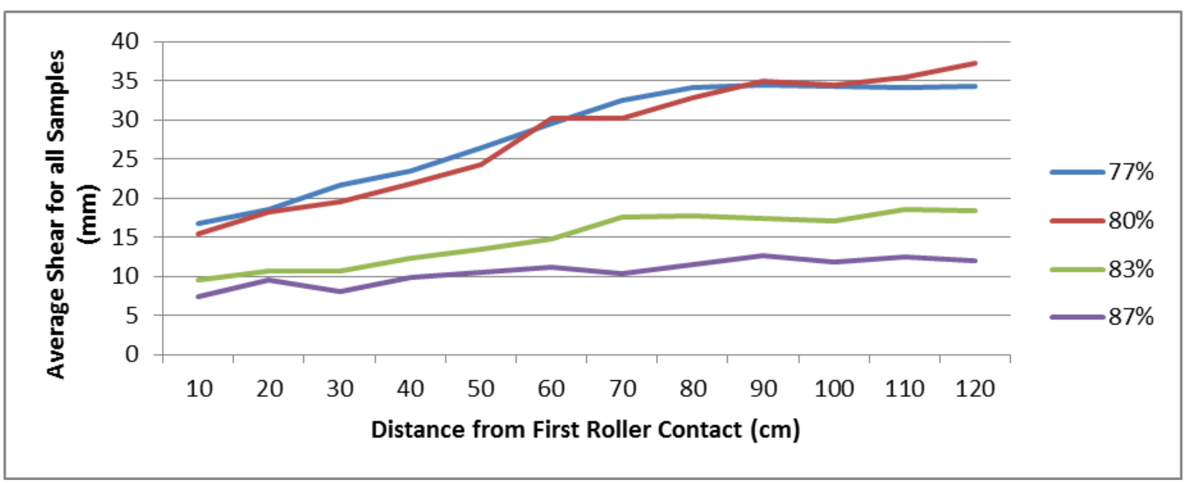


Figure 28: Relationship between Distance Sheared by CODA and Shear Angle

It can also be observed that the relationship is not perfectly linear. Longer samples were tested to determine that there is a maximum shear angle that a setting is capable of attaining. This means that running the machine for an infinite amount of time will not create infinite shear, but will reach a maximum shear and continue to impart that shear on the fabric. Figure 29 shows that these limits vary by the machine setting. These limits once again show the fabric's resistance to shear. If the fabric had no resistance to shear, these lines would linearly increase throughout the entire length of the fabric. If the machine had no slippage between the rollers and the fabric and the motors did were not slowed, the machine would reach a point where the SLL was exceeded or the fabric was seriously damaged.

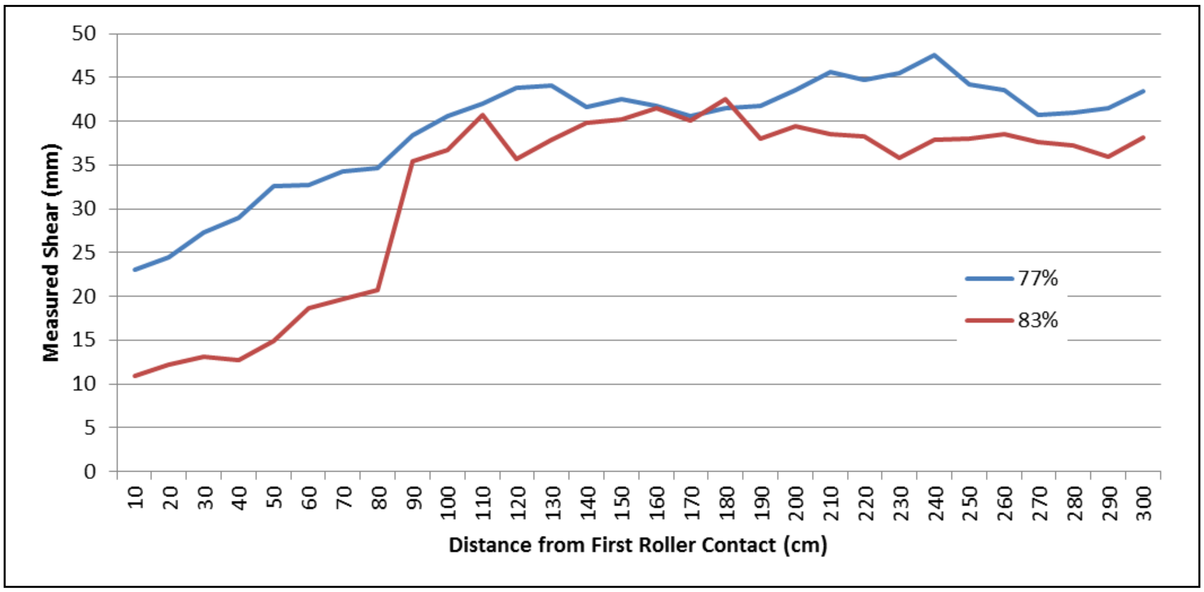


Figure 29: Relationship between Distance Sheared by CODA and Shear Angle for 3000mm Samples

In the final shear vs. distance test, it was shown that the machine was capable of imparting a shear and then imparting no shear along the length of a fabric. However, the length between transitions had a large impact on the fabric's ability to relax and distribute the shear. When Axle 1 ran at a low setting for 3000mm and then a high setting for 3000mm, the fabric relaxed to the point where there was no distinguishable difference between the fabric. When Axle 1 ran at a low setting for 1500mm and then a high setting for 1500mm, there was a clear difference between sections. Figure 30 shows the results of these trials.

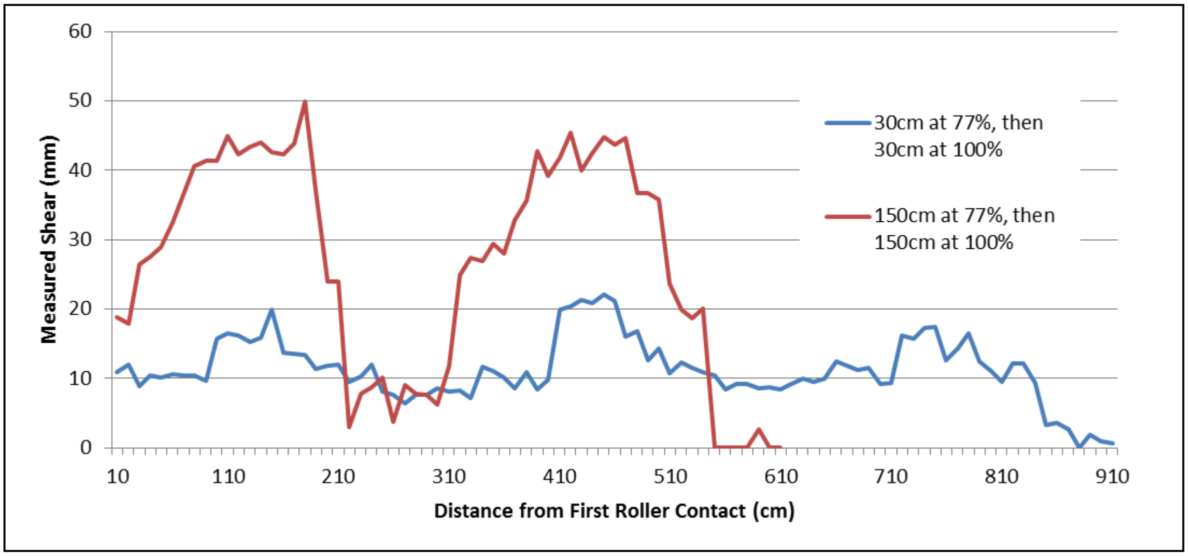


Figure 30: Relationship between Distance Sheared by CODA and Shear Angle for Cyclical Samples

The final width measurements were used to confirm that Pin Jointed Net (PJN) was appropriate for predicting layup these measurements. PJN predicts that as shear angle increases across this fabric, it will get narrower. This did occur to these samples. Figure 31 shows the actual values compared to the predicted line using PJN.

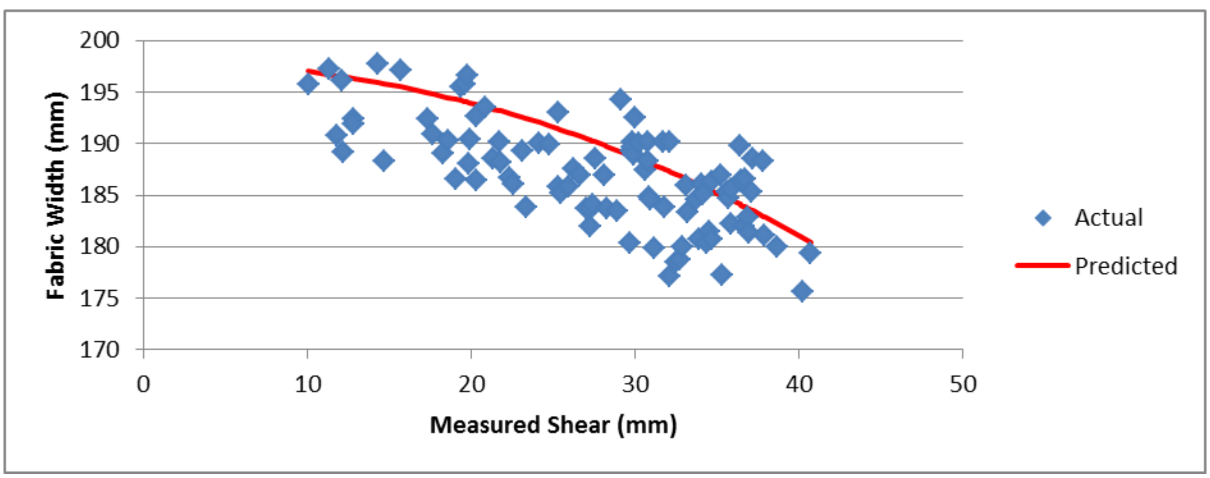


Figure 31: Relationship between Shear Angle and Actual Width vs. Predicted Width

The results strongly suggest that the machine designed for this experiment is capable of imparting a shear, and that an appropriate shear strongly influences the ability of a fabric to lay into a mold without wave defects.

Experiment 2

The second experiment aimed to represent fiberglass layup in a two-dimensional mold where the outside tows would require more fabric than the inside tows. Conceptually, it would be desirable to place less fabric tow length for the inside tows. Wheels were place on opposite sides of the machine to create this shear.

Figure 32: SolidWorks Drawing of Machine setup for turning experiment, lines demonstrating shear imparted on fabric, and 130cm-long 1.5m-radius sample made by this setup

To compare these results to previous results gathered from Experiment #1 of Magnussen [17], the methodology used in this experiment attempts to replicate the methodology used that paper. The samples made were 1.5m in length and comprised of four plies of Saertex 930 g/m^2 unidirectional fiberglass stacked on top of each other in the way that maximized overlap. Each sample had a uniform radius, with the three samples having radii of 3.0m, 9.2m, and 15.2m. Curvature was defined as the inverse of the radius in meters: 0.328, 0.109, and 0.0656 respectively.

Through experimentation, the correct settings for Axle 1 were found to be 85%, 93%, and 97% for these samples. The three samples were infused using vacuum resin transfer molding. All infusions were set up as shown in Figure 33. All infusions used Hexion EPICURE™ Resin MGS RIMR 135 and EPIKURE™ Curing Agent MGS RIMR 1366 mixed to 30% by weight. Samples were allowed to cure under heat.

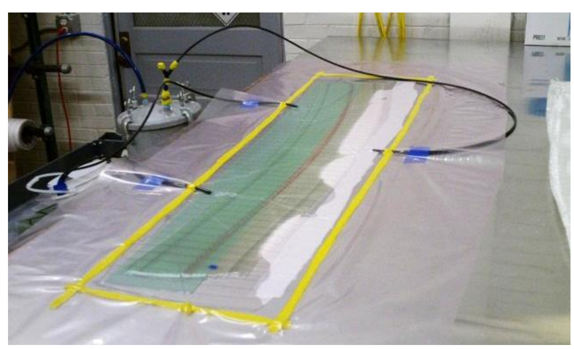


Figure 33: Infusion of Sample for Experiment 2

After the samples were fully cured, three coupons were cut from each sample at 533mm away from the edge of the fabric first through the machine (Figure 34). Magnussen chose this location because it represented the non-linearity of the fiber. Since all locations of this sample were equally non-linear, this location was chosen simply to replicate the same procedure. All coupons in this set were cut to 25.4mm by 152.4mm.

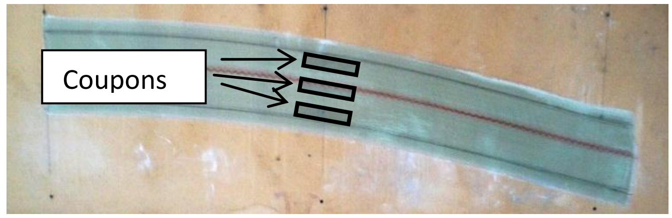


Figure 34: Coupon Locations in Cured Sample

Two loading tabs were bonded to each end of all coupons to prevent compressive damage of the sample in gripping. The tabs were 25.4mm in width and 25.4mm in length with a 45° taper on the gauge end. The tabs were cut from a 3.175mm 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 using Hexion EPIKOTE ™ Curing agent MGS BPH 137G to 40% by weight and allowed to cure. All coupons used the same loading setup shown in Figure 35.

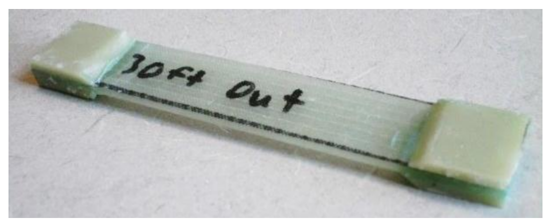


Figure 35: Coupon for Testing

The purpose of the testing in this experiment was to identically replicate the testing performed by Magnussen so that the data could be compared directly. The testing was carried out in three steps using an MTS 312.31 universal fatigue tester. (1) A preliminary modulus test was performed on each coupon. Each coupon was tested at 110MPa (16,000PSI) while measuring the strain with an MTS extensometer. (2) The coupons were then subjected to fatigue testing. Each coupon underwent 24,000 cycles of 296MPa at a frequency of 2Hz. (3) The samples with curvature 0.109 and 0.0656 were then tested to failure to be compared against Magnussen's Experiment #1 data. The samples with curvature 0.328 were cycled to failure to be compared against Magnussen's Experiment #2 data.

Experiment 2: Results

The coupons in this experiment were developed to be directly compared to the coupons developed and tested by Magnussen. The data in Figure 36 shows that samples from the shifting method and shearing method have a longer life than those from the steering method, especially as curvature increases. The only coupons from the steering method that survived were the two that showed no sign of out-of-plane deformation. The superior results of shearing relative to shifting can be attributed to the adhesive used to hold the shifted samples in place (that were shown to have a negative impact on strength qualities of the composite material), and the elimination of the sharp In-Plane-Shear created at the points clamped for shifting. These were both discussed by Magnussen. Magnussen then went on to show that the number of discrete shifts also played a role in determining the number of cycles to failure for a given turn. This was done by approximating a turn with one, two, or three discrete shifts. The samples were all taken from across a point of In-Plane-Shear. **Error! Reference source not found.** shows the results of the sheared samples relative to the hifted samples.

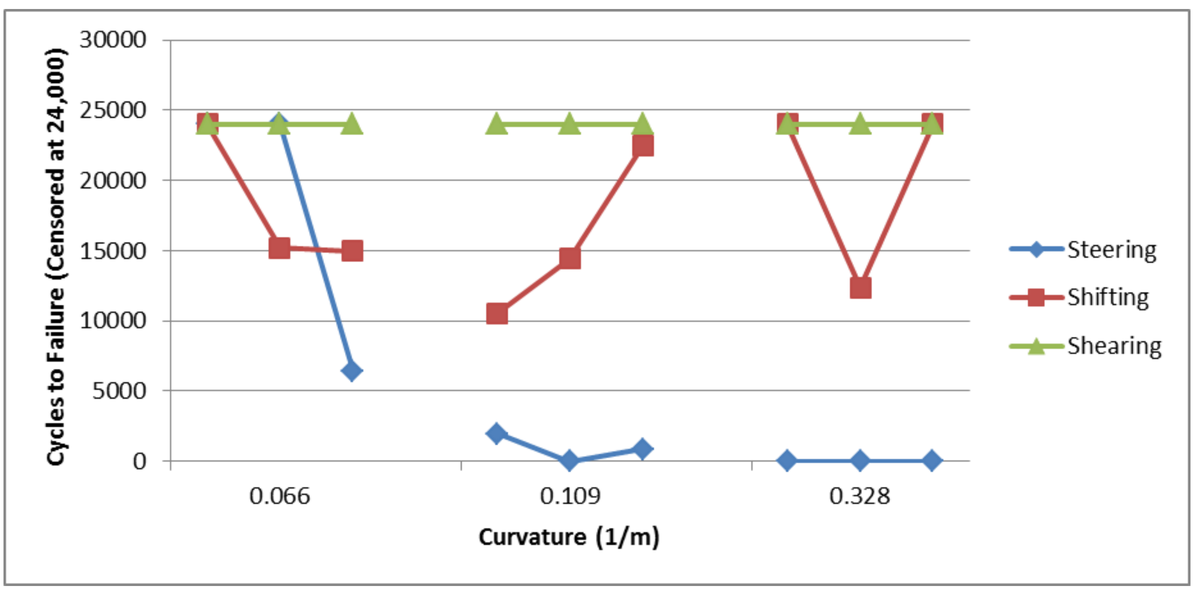


Figure 36: Steered, Shifted, and Sheared Samples Curvature vs. Cycles to Failure

When the sheared results are compared to the Magnussen results, they align with the limit predicted by Magnussen. This implies that shearing has fundamentally the same properties as an infinitely shifted sample. Magnussen developed a fit curve based on the number of shifts in sample that would predict the number of cycles to failure with a limit of 139,252 cycles which was the predicted number of cycles for a straight sample. Since it is impossible to outperform a straight sample, the limit was created at that point. The samples tested in this experiment lined up with the predicted limit which coincides with the theory that shearing is the equivalent of an infinitely shifted sample. Only two of the tests reached failure below 100,000 cycles, these tests are believed to have failed due to torsional stresses induced by the MTS machine by slowly twisting the sample over time. The three samples tested after this twisting was corrected never failed, but were censored due to time constraints.

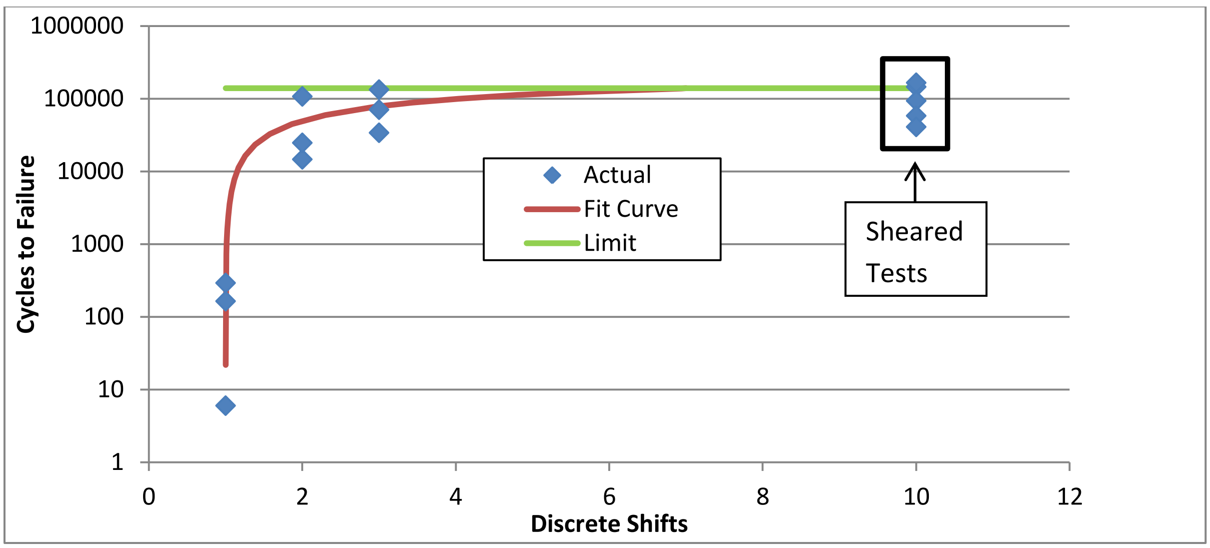


Figure 37: Discrete Shifts vs. Cycles to Failure with Sheared Tests Located at 10 Shifts

Conclusions and Future Work

This research has:

1. Provided statistically significant evidence that shearing is capable of preventing out-of-plane deformation confirming the hypothesis of Fanqi Meng
2. Demonstrated a machine capable of continuously imparting shear onto Non-Crimp Fabric
3. Unified shifting and two-dimensional shearing as complimentary rather than contrasting manipulations

Experiment 1 showed that pre-sheared fabric was significantly better than un-sheared fabric. The machine explained in the methodology was capable of imparting this shear, which leads to the possibility of automated fabric layup for composite parts.

Experiment 1 showed that the machine was not only capable of imparting a constant shear on the fabric, but a shear that varied throughout the length of the fabric. This could be useful for parts that have sections where certain tows would need additional length at a specific location, and then other tows would need additional length at another location. An example of this type of part can be seen in Figure 38. The overall distance traveled by any individual tow over the length of the part is the same as any other tow, but at a given location, the inner tows may need more fabric and the outer tows need less fabric and vice-versa. Potential causes of differences between fabric shear angles when at the same setting are slippage between the wheels and fabric, differences between the raw fabric entering into the machine, and the precision of the voltage settings. Potential causes of why fabrics with similar shear behaved differently when placed in the mold are how the shear was distributed across the fabric. If the shear does not align with the center of the mold, it may not conform to the mold. All of these potential causes require further research.

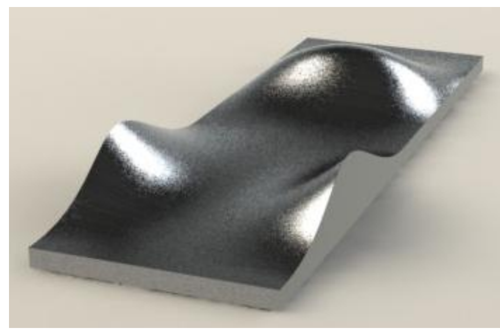


Figure 38: Example of Part Requiring Varied Shear

Experiment 2 showed that for parts traveling around a turn, the functional properties of a sheared fabric are equivalent to those of an infinitely shifted fabric and far greater than those of a steered fabric. This not only unifies shifting and shearing for 2-dimensional turns, but since the values for these experiments were the same as straight samples – the maximum attainable values – it shows that this process is capable of creating high-quality parts using an automated method. Because the samples in this experiment were small it was possible for the strength to approach that of a straight sample. Individual unit cells of sheared samples travelling around a turn can approach the strength of a straight sample; however, on a macro scale, regardless of how they are manufactured, composite parts will still be governed by the laws of statics and dynamics and will not behave identically to straight parts.

Future versions of the CODA machine (Figure 39) could be suspended from gantry systems for completely automated fabric layup. The fabric would be deposited by the machine as it flew over an open mold. Independently controlled wheels across a single line of contact with the fabric would allow virtually any composite layup to be automated. This could especially be of use to the wind turbine blade or boat-hull manufacturers. Eliminating a large portion of labor costs could also open doors for composite applications in fields where it is generally considered too expensive today (such as the automobile industry).

Figure 39: Potential Future Version of CODA Machine

Appendix A

Raw Data from Experiment 1

Table 1: Machine Settings, Shear, Wave Height, and Number of Waves

Trial #	Low Voltage Input	Pre-Shear Furthest from Machine (mm)	Pre-Shear Closest to Machine (mm)	Maximum Wave Height (mm)	Number of Waves
1	11.5	48.03	54.24	0	0
2	13.0	24.74	24.76	7.76	1
3	12.0	40.22	51.52	0	0
4	15.0	0	0	6.86	2
5	14.5	0	0	8.38	2
6	13.5	0	0	5.38	2
7	14.0	0	0	9.42	3
8	12.5	15.89	27.58	9.58	1
9	15.0	0	0	6.95	3
10	11.5	43.1	50.71	0	0
11	13.0	6.26	6.28	11.19	1
12	14.5	0	0	12.36	4
13	14.0	0	0	5.99	3
14	13.5	4.31	4.31	5.84	3
15	12.5	21.7	41.15	7.11	1
16	12.0	42.48	57.68	0	0
17	13.5	5.01	4.61	10.47	3
18	14.0	0	0	6.61	2
19	11.5	46.2	51.7	5.34	1
20	12.5	33.82	43.67	0	0
21	13.0	17.21	30.82	13	1
22	14.5	0	0	8.58	1
23	12.0	55.29	55.38	0	0
24	15.0	0	0	14.77	2
25	15.0	0	0	7.43	2
26	13.0	13.07	13.41	3.6	2
27	12.0	30.35	49.69	0	0
28	12.5	22.49	37.49	0	0
29	14.5	0	0	10.25	2
30	11.5	47.49	48.65	0	0

31	13.5	0	0	6.23	3
32	14.0	0	0	6.17	2
33	13.0	2.8	7.72	7.01	3
34	12.0	33.48	49.88	0	0
35	11.5	31.13	31.2	0	0
36	14.5	0	0	5.48	2
37	12.5	8.96	15.84	3.97	1
38	15.0	0	0	6.77	3
39	13.5	0	0	5.38	2
40	14.0	0	0	5.87	4
41	15.0	0	0	5.54	2
42	13.5	0	0	5.38	5
43	12.5	24.48	25.56	6.4	4
44	12.0	31.61	47.24	0	0
45	14.5	0	0	9.4	4
46	14.0	0	0	17.97	6
47	13.0	4.62	16.99	3.24	2
48	11.5	40.2	44.62	0	0
49	11.5	26.56	16.9	0	0
50	12.5	19.35	21.3	10.08	2
51	14.5	0	0	6.25	4
52	14.0	0	0	6.37	3
53	13.0	2.36	4.01	6.72	3
54	12.0	22.32	26.49	0	0
55	15.0	0	0	6.48	2
56	13.5	0	6.56	9.73	3
57	14.0	0	0	6.1	4
58	12.0	33.16	35.31	0	0
59	12.5	23.81	21.87	6.03	2
60	14.5	0	0	9.54	3
61	13.5	0	0	6.42	6
62	13.0	3.12	2.46	8.87	4
63	15.0	0	0	6.2	4
64	11.5	27.99	37.97	0	0
65	12.5	14.92	21.36	0	0

66	12.0	33.51	37.35	0	0
67	14.5	0	0	10.59	2
68	15.0	0	0	4.19	3
69	14.0	0	0	5.67	3
70	13.5	0	0	8.04	3
71	13.0	10.33	3.89	6.63	5
72	11.5	16.95	25.96	0	0
73	11.5	36.74	25.91	0	0
74	12.5	7.64	9.13	8.85	3
75	14.5	0	0	7.79	4
76	14.0	0	0	7.05	4
77	15.0	0	0	9.11	5
78	12.0	35.7	35.02	0	0
79	13.5	2.42	0	7.49	4
80	13.0	5	6.03	8.07	4
81	12.0	12.47	31.16	8.23	1
82	13.0	6.71	2.32	7.49	2
83	11.5	35.2	37.74	0	0
84	12.5	14.26	18.49	7.61	4
85	13.0	4.82	5.12	8.3	3
86	12.0	21.77	23.63	6.62	4
87	11.5	32.74	32.84	0	0
88	12.5	9.84	18.73	6.63	3

References

[1] Yerramalli, Chandra S., Thomas Miebach, Karthick Chandraseker, and Shu C. Quek. "Fiber Waviness Induced Strength Knockdowns in Composite Materials Used in Wind Turbine Blades."

[2] Wollner, Benjamin [2011]. *Development of a fabric winding system for the automated manufacture of prefabricated wind turbine blade roots.* Master of Science. Iowa State University. United States

[3] Meng, Fanqi [2011]. *Pre-shearing planning for the layup of unidirectional fabrics*. Doctor of Philosophy. Iowa State University. United States.

[4] Debout, Pierre, Helene Chanal, and Emmanuel Duc. "Tool Path Smoothing of a Redundant Machine: Application to Automated Fiber Placement." Computer-Aided Design 43 (2011): 122-32.

[5] "Thermosetting Composites - Fibres and Matrices." AZoM™. Web. 01 Mar. 2012. <http://www.azom.com/article.aspx?ArticleID=401>.

[6] Mills, A. "Automation of carbon fibre preform manufacture for affordable aerospace applications." Composites: Part A 32 (2001), 955-62.

[7] Potluri, P., and J. Atkinson. "Automated Manufacture of Composites: Handling, Measurement of Properties and Lay-up Simulations." *Composites Part A: Applied Science and Manufacturing* 34.6 (2003): 493-501.

[8] Ruth DE and Mulgaonkar P. Robotic layup of prepreg composite plies. Proceedings of IEEE international conference on robotics and automation, Cincinnati, OH (May 13-18, 1990) 1296-1300.

[9] Sarhadi M. Automated lay-up of non-rigid fabrics. Proceedings of the Manufacturing Technology Update, IEE; June 1993.

[10] Schmitt, R., T. Pfeifer, C. Mersmann, and A. Orth. "A method for the automated positioning and alignment of fibre-reinforced plastic structures based on machine vision." Annals of the CIRP, 57 (2008), 501-504.

[11] Kordi, Tarsha M., M. Hüsing, and B. Corves. "Development of a Multifunctional Robot End-Effector System for Automated Manufacture of Textile Preforms." Proceedings of IEEE international conference on advanced intelligent mechatronics, (Sept. 2007)

[12] Jarvis SDH, Wilcox K, Chen XQ, McCarthy R and Sarhadi M. Design of a handling device for composite ply lay-up automation. Proceedings of the international conference on advanced robotics, Pisa, 1991, IEEE, London, pp. 790-5.

[13] Angerer, Andreas, Claudia Ehinger, Alwin Hoffmann, Wolfgang Reif and Gunther Reinhart. "Design of an Automation System for Preforming Processes in Aerospace Industries." Proceedings of IEEE international conference automation science and engineering, (Aug. 2011)

[14] Potter, K. "The influence of accurate stretch data for reinforcements on the production of complex structural mouldingsPart 1. Deformation of aligned sheets and fabrics." Composites 10 (1979): 161-67.

[15] Prodrodromou AG, Chen J. "On the relationship between shear angle and wrinkling of textile composite preforms." Composites: Part A. 1997;28(A):491-503.

[16] Dolatabadi, Mehdi Kamali, and Radko Kovar. "Geometry of Plain Weave Fabric under Shear Deformation. Part III: 3D Model of Plain Weave Fabric under Shear Deformation." Journal of the Textile Institute 100.5 (2009): 387-99.

[17] Magnussen, Corey [2011]. A fabric deformation methodology for the automation of fiber reinforced polymer composite manufacturing. Master of Science. Iowa State University. United States