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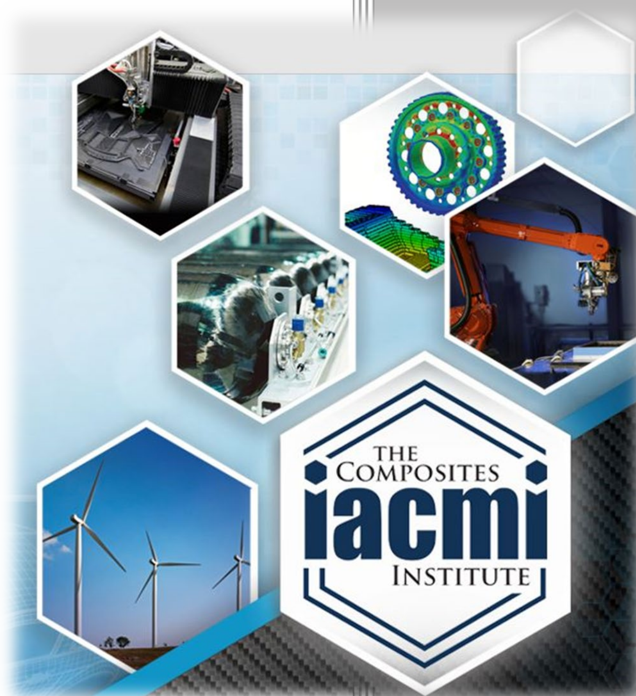
Performance Prediction for Non-standard Non-Crimped Fabrics



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March 8, 2019

PROJECT FINAL REPORT
0001-2019-7.04

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The Institute for iacmi Advanced Composites Manufacturing Innovation THE COMPOSITES INSTITUTE

U.S. DEPARTMENT OF ENERGY

Materials Science and Technology Division
Advanced Manufacturing Office

Performance Prediction for Non-standard Non-Crimped Fabrics

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ABSTRACT

A method has been developed to characterize a non-crimped fabric material with any fiber orientation for a draping analysis. PAM-FORM, a draping simulation tool, was used to perform draping simulations using this characterization and the results were validated experimentally on an identical geometry. Results show that PAM-FORM can accurately predict the shearing behavior of non-crimped fabric materials but that it cannot predict wrinkle formation accurately if the fabric is stitched in a non-orthogonal manner.

1.1 Performance Prediction for Non-standard Non-Crimped Fabrics

IACMI Project
9/18 – 3/19
Chomarat, ESI, Purdue University

1.2 BACKGROUND

The goal of this project is to demonstrate the ability to characterize non-orthogonal NCF fabrics for draping simulations and validate the simulations experimentally. In this case, a [0/45] NCF was selected by Chomarat to be the candidate non-orthogonal material and PAM-FORM, a draping code produced by IACMI member ESI Group, was selected to be the candidate software platform. A [0/90] NCF was also used as a reference material. A transparent L-shaped tool which was developed previous to this project for the purpose of draping validation was used for experimentally measure the draping behavior and for comparison to simulation.

1.3 TECHNICAL RESULTS

Standard characterization methods were employed where possible. For picture frame testing, where the standard method could not be used for a non-orthogonal fabric, an adapted method was developed which will allow for any angle of fabric to be characterized and adapted as a material input into the software tool. A draping simulation was validated on a previously made transparent tool. Comparisons between simulation and measurement show good agreement between measured and simulated shear behavior for both the 0-90 and 0-45 NCF materials. However, the prediction of wrinkles does not match well with the measured response because the software tool assumes a different kinematic scheme of the fabric than the stitched fabric actually has. Results show that PAM-FORM can accurately predict shearing behavior of NCF materials – even non-orthogonal NCF materials – but that non-orthogonal stitching schemes such as the tricot stitching scheme employed in these materials invalidate an assumption within PAM-FORM. It should be noted that PAM-FORM has the ability to explicitly describe the stitching scheme, which will ameliorate this effect. However, this ability is not currently a standard software option, but may become one in the future.

1.3.1 Theoretical Framework

The materials employed for this project were an orthogonal NCF material and a non-orthogonal (0/45) NCF material. The non-orthogonal NCF material was chosen as it is the purpose of this project to determine the ability to characterize and simulate the draping behavior of such materials. The orthogonal NCF material was chosen as a benchmark since it is a material that can be characterized using standard methods. There are currently no standards around material characterization for draping simulation, so Purdue best practices were used and will be outlined in the next section. All simulations were performed using PAM-FORM, an ESI tool which was developed to predict fabric draping. Since this work involves non-traditional materials, an ESI employee was involved in this project to ensure that all modeling techniques were implemented properly. The validation effort was done using a tool and method which has been developed by Purdue and will be described subsequently.

1.3.2 Results

1.3.2.1 Material Characterization

The material input parameters which PAM-FORM uses for a draping simulation are: axial modulus, bending stiffness, shear modulus, and friction. Subsequent paragraphs will present the measured data and the material properties which were taken from the data.

1.3.2.1.1 Material

The material selected for this project is a [0/45] carbon NCF dry fabric with a tricot stitch. In order to facilitate material orientation descriptions in this report, a local orientation system has been defined. Figure 1 shows the fibers which will be described as the 0 degree and 45 degree fibers.

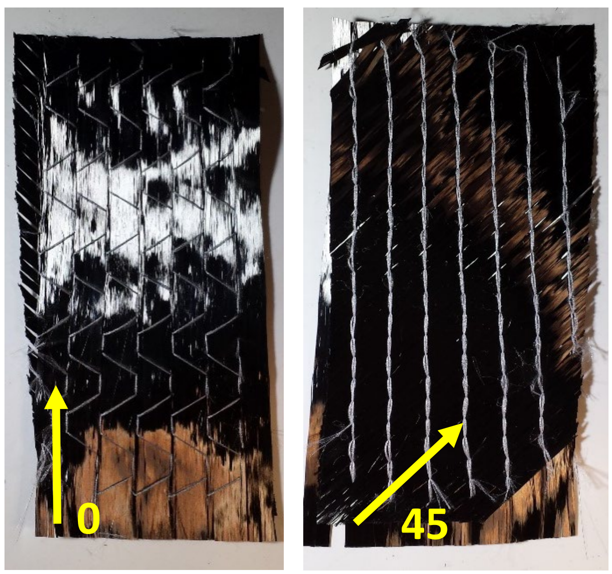
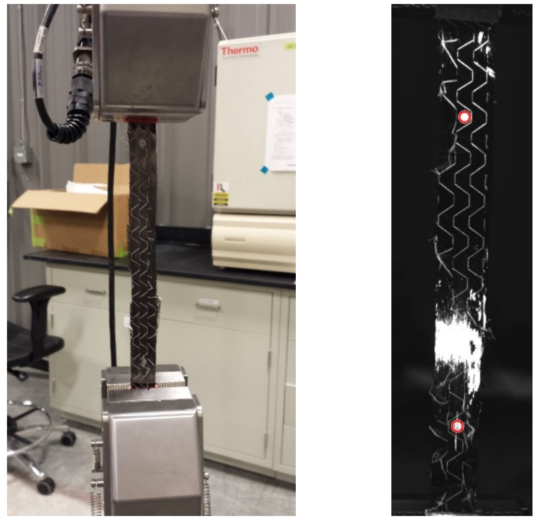


Figure 1: Images showing the defined material orientations of the Chomarat [0/45] tricot NCF fabric.

1.3.2.1.2 Axial Modulus

The axial modulus is the resistance of the NCF to stretching in the in-plane direction. Because there is no ASTM standard for measuring the tensile modulus of dry carbon fabrics, a modification of D4018 (for impregnated fiber tows) was used. The samples were cut to dimensions following D4018 and tabbed by bonding the ends to fiberglass tabbing material. Strain was measured with "virtual extensometer", wherein two marks are made on the material and a camera which is coupled to the load frame is used to measure the distance between the two marks visually. A Correlated Solutions camera (a camera developed specifically to take visual strain measurements) was used to take the strain measurements. Three specimens with the samples aligned to the 0 degree fibers were taken. It was assumed that the fabric would have the same modulus with the samples aligned to the 45 degree fibers since they are the same fibers and there is no other source of modulus in this test except for the fibers which are aligned to the test machine. The sample setup is shown in Figure 2 and the results are shown in Figure 3. The axial modulus as fit from the stress-strain data is 45 GPa.



(a) (b)

Figure 2: The experimetnal setup showing (a) the sample loaded in the load frame and (b) the marks located by the virtual extensometer used for measuring strain.

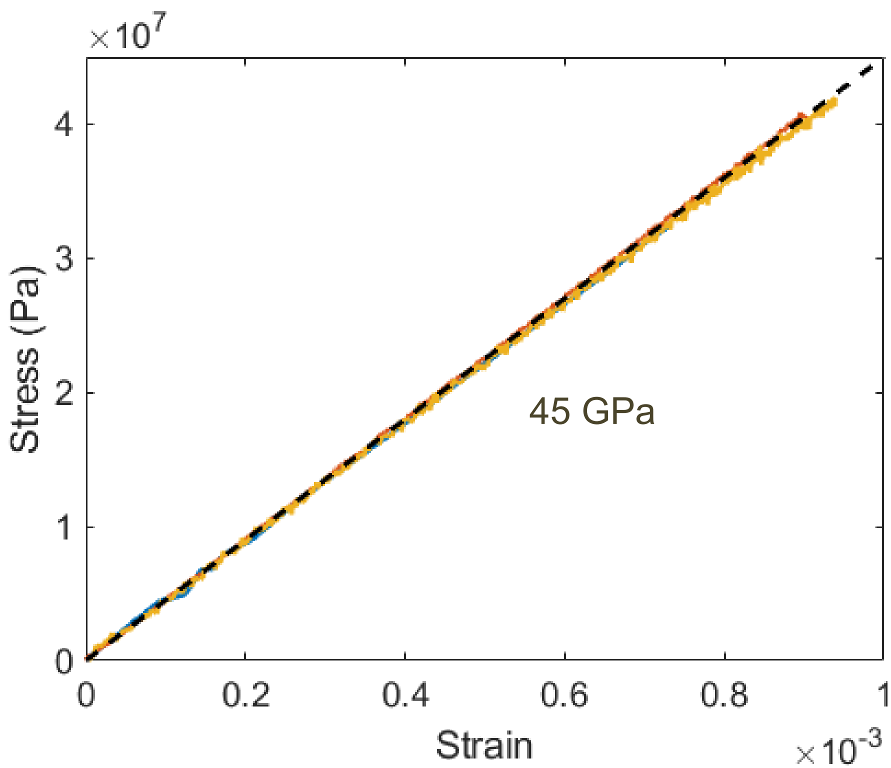


Figure 3: Plotted stress-strain data with fit line.

1.3.2.1.3 Bending Stiffness

ASTM D1388 is the standard method for measuring the bending stiffness of fabrics. However, this method has been developed for more traditional textile materials with much lower axial modulus and much tighter stitching and the results are very prone to measurement error. Therefore, a different method which was developed for this type of material was used instead[1]. This method uses a torsional rheometer with a custom built fixture to place a sample in bending and measure the torque required to maintain its position. The bending stiffness, or flexural rigidity, can be extracted from this measurement using Euler-Bernoulli beam theory:

$$EI = \frac{-\kappa}{M},$$

where M is the bending moment measured by the rheometer, κ is the curvature of the beam (measured from the fixture geometry), and EI is the flexural rigidity. Because the material is not symmetric, the bending stiffness will likely be different depending on which way the material is bent. Therefore, 4 different flexural rigidities were measured: 0 degrees, 0 outside; 0 degrees, 0 inside; 45 degrees, 45 outside; 45 degrees, 45 inside. Figure 4 shows a 0 degree, 0 outside test being run. The tests were run in a stress-relaxation type condition where the material was held at the fixed displacement and the torque was measured as a function of time. Dry woven fabrics do not typically show any relaxation with time; however, these fabrics did show significant relaxation, presumably from the stitching. The measurements were also compared with a [0/90] carbon NCF which was used as a baseline. Figure 5 shows the flexural rigidity results. As would be expected, the tests with the fibers aligned with the bending direction on the inside have a higher rigidity than those with the aligned fibers on the outside. Also as would be expected, the [0/45] stiffnesses are slightly higher that the [0/90] counterparts.

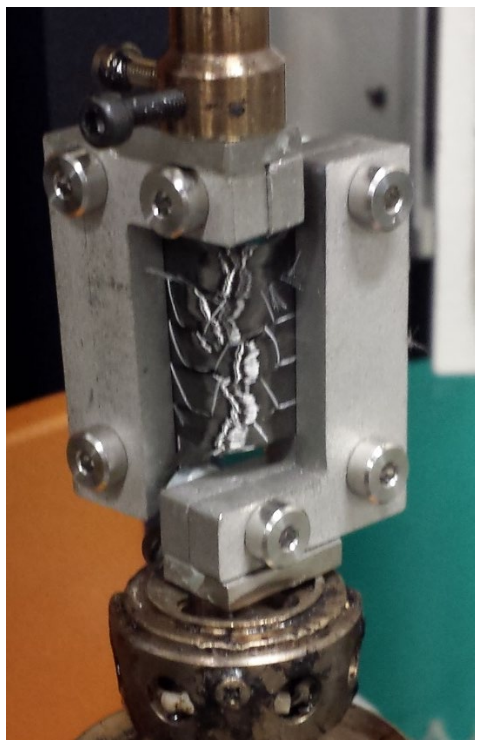


Figure 4: Bending stiffness experimental method for a 0 degree, 0 outside test.

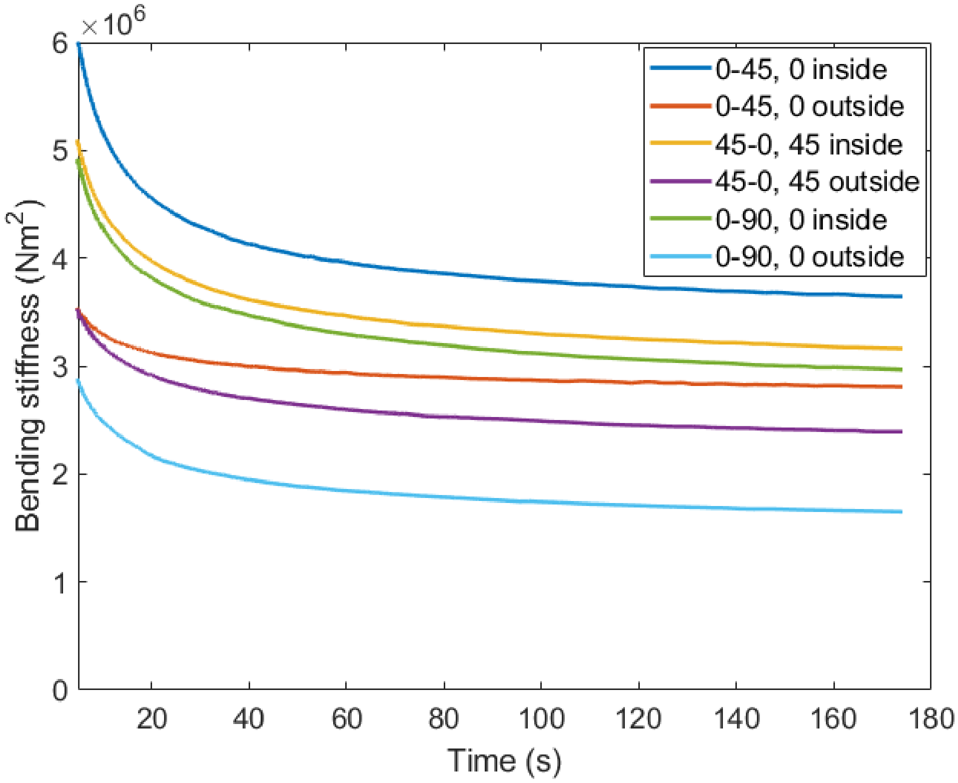


Figure 5: Bending stiffness results.

1.3.2.1.4 Shear Modulus

There is not ASTM standard for measuring in-plane shear modulus of composite fabric materials, but a modified method of ASTM D 8067 (for sandwich composites) was used in this case. A modification of the standard picture frame test procedure had to be used because the fabric is not orthogonal. Figure 6 shows the picture frame test setup for an orthogonal fabric (in this case the [0/90] NCF baseline fabric). However, if the same geometry was used for the [0/45] fabric, there would be fibers bridging between parallel arms and the test would essentially be measuring the axial modulus of the fibers instead of the shear modulus of the fabric. Therefore, the geometry had to be modified to accommodate the non-orthogonal fabric. Figure 7 shows the experimental setup for the [0/45] fabric for both “positive” (fibers shearing towards each other) and “negative” (fibers shearing away from each other) shear.

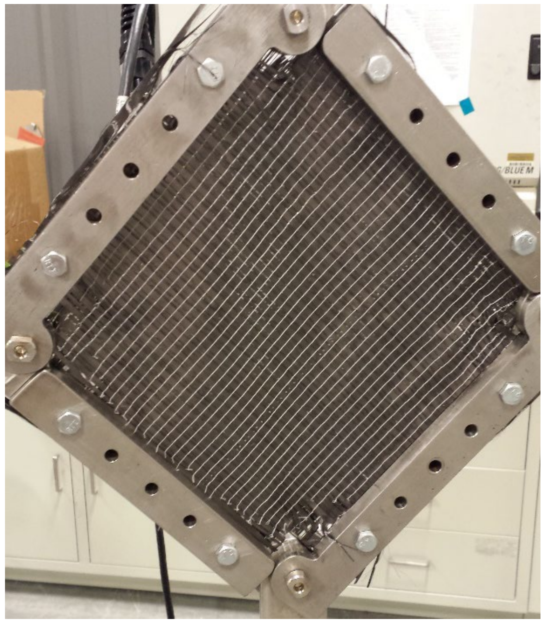
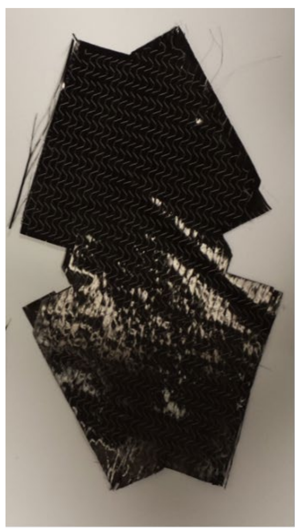
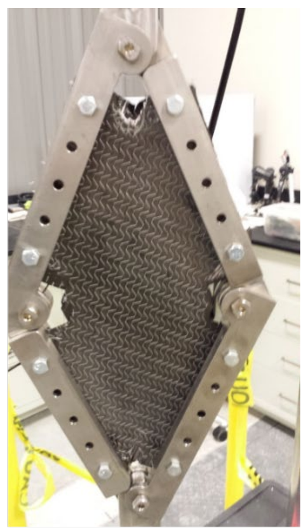


Figure 6: Picture frame experimental setup for orthogonal fabric.

(a) (b)

(c)

Figure 7: (a) fabric geometry, (b) positive shear experimental setup, (c), negative shear experimental setup.

The test is run by pulling the top and bottom of the fixture apart at 10 mm/min and measuring the accompanying force and displacement. The force-displacement is turned into a stress-strain curve using the following equations which can be derived using geometry of the test setup:

$$\gamma = \frac{\pi}{4} - 2\,\theta,$$

$$\tau = \frac{F}{2Ltsin(2\theta)}$$
$$\theta = cos^{-1}\left(\frac{Lcos\theta_0 + \frac{d}{2}}{L}\right),$$
where F is measured force, L is the length of each arm of the picture frame fixture, d is the measured displacement, and t is the fabric thickness. Sample results are shown in figure 8. It should be noted that it was observed experimentally that the 0-45 positive shear tests exhibited bending of the fabric immediately, so the “shear lock angle” will be 0 for the positive shear direction and 45 for the negative shear direction.

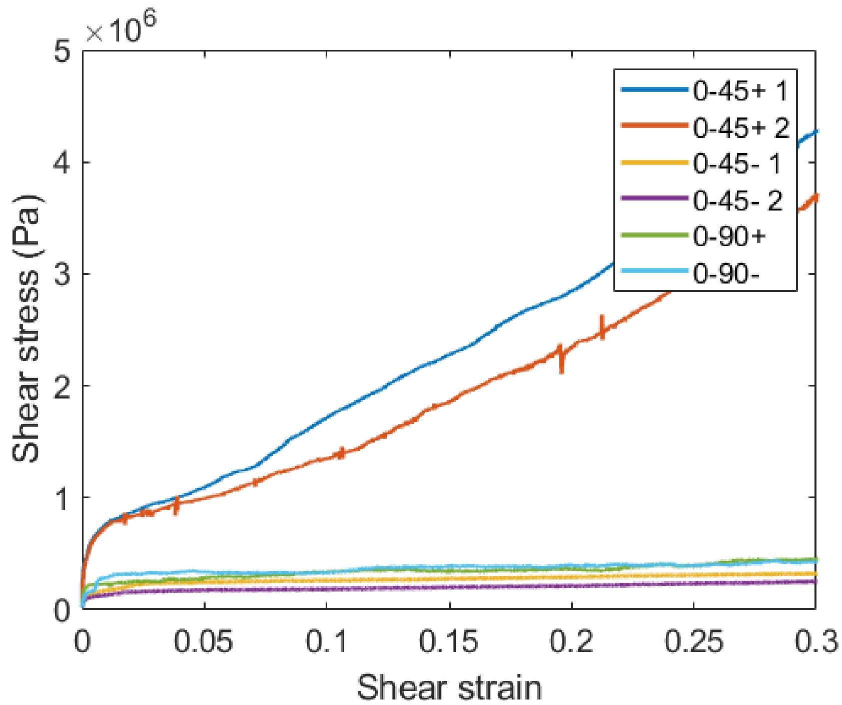


Figure 8: Picture frame stress-strain results.

For shear modulus, PAM-FORM does not take a value, but the force-displacement results are input directly into the software. However, PAM-FORM assumes an orthogonal fabric, so the results of the non-orthogonal experiment must be modified so that PAM-FORM will use them correctly. The strategy employed here is to modify the displacement values of the non-orthogonal fabric so that the computed shear strain from the displacement will match the correct shear strain for the non-orthogonal fabric. Based on the geometry of the picture frame test, the shear strain as a function of displacement for an orthogonal fabric will be:

$$\gamma_{0,90} = \frac{\pi}{2} - 2\,cos^{-1}\left(\frac{L\,cos\left(\frac{\pi}{4}\right) + \frac{D_{0,90}}{2}}{L}\right),$$

while the shear strain of a [0/45] fabric will be:

$$\gamma_{0,45} = \frac{\pi}{4} - 2\,cos^{-1}\left(\frac{L\,cos\left(\frac{\pi}{8}\right) + \frac{D_{0,45}}{2}}{L}\right).$$

The modification is made such that the shear strains are equivalent to each other by changing the displacement value:

$$D'_{0,45} = 2\left[-L\,cos\left(\frac{\pi}{4}\right) + L\,cos\left(\frac{\pi}{8} + cos^{-1}\left(\frac{L\,cos\left(\frac{\pi}{8}\right) + \frac{D_{0,45}}{2}}{L}\right)\right)\right],$$

where $D'_{0,45}$ is the modified displacement. This method can also be generalized for any non-orthogonal fabric. In this case we will assume a [0/X] fabric, where X is a value in degree between 0 and 90 (this covers any fabric with two layers). By following the method outlined above, the modification for a [0/X] fabric is:

$$D'_{0,X} = 2\left[-L\cos\left(\frac{\pi}{4}\right) + L\cos\left(\frac{\pi}{4} - \frac{\pi X}{360} + \cos^{-1}\left(\frac{L\cos\left(\frac{\pi X}{360}\right) + \frac{D_{0,X}}{2}}{L}\right)\right)\right].$$

1.3.2.1.5 Friction

Friction plays a role in draping as frictional forces resist the fabric from shearing, stretching, or bending. The friction coefficients were measured following ASTM D 1894 standard. Figure 9 shows the experimental test setup for measuring friction coefficient, in this case measuring tool-ply friction for the 45 degree fibers.

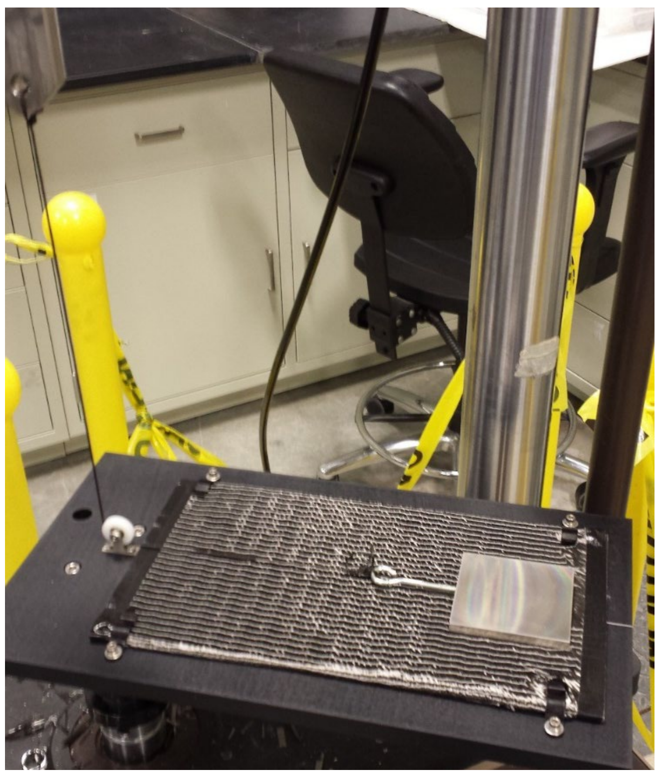


Figure 9: Experimental setup for friction tests.

The friction coefficient is estimated simply by measuring the force required to drag a block along the surface of the fabric and divide the measured force by the weight of the block. This test was performed for tool-ply and ply-ply interactions for both 0 and 45 degree fibers and the results are shown in Figure 10. As is shown, the tool-ply friction coefficient was measured at 0.15 for both cases and the ply-ply friction coefficient was measured at 0.25 for both cases.

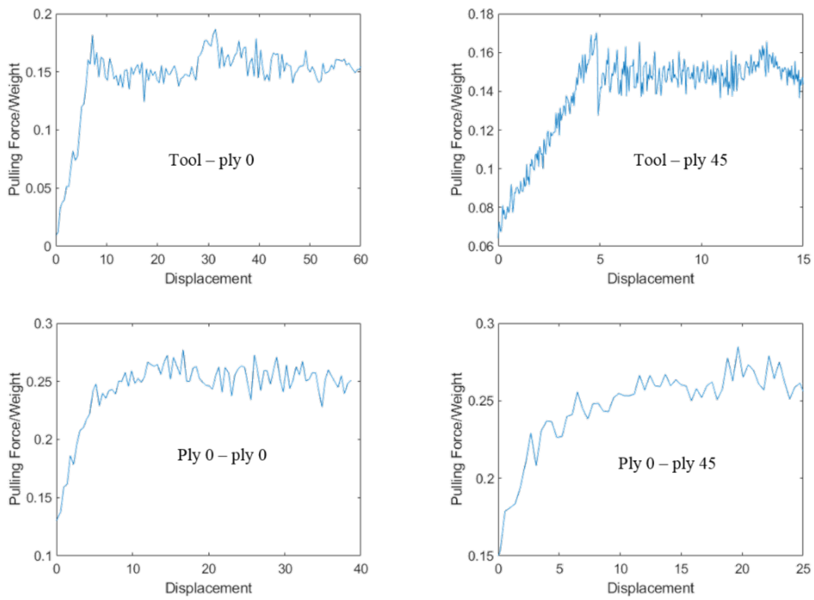


Figure 10: Friction coefficient measurements.

1.3.2.1.6 Material Property Results

The results have been gathered from the previous sections and compiled in Table 1. These material properties ware used to create the material card for the subsequent modeling.

Table 1: [0/45] carbon NCF draping material properties.

Axial Modulus

Property	Value
Axial Modulus (GPa)	45.0

Bending Stiffness

Property	Value
0 degree, 0 inside (Nm^2)	3.65e6
0 degree, 0 outside (Nm^2)	2.81e6
45 degree, 45 inside (Nm^2)	3.17e6
45 degree, 45 outside (Nm^2)	2.39e6

Shear Modulus

Property	Value
0/45 positive shear modulus (MPa)	15.2
0/45 positive shear lock angle (degrees)	0
0/45 negative shear modulus (MPa)	2.1
0/45 negative shear lock angle (degrees)	45

Friction

Property	Value
Tool-ply friction coefficient	0.15
Ply-ply friction coefficient	0.25

1.3.2.2 PAM-FORM simulation parameters

A PAM-FORM simulation was created using an L-shaped tool that matches the experimental fixture and applies the material properties that have been presented. Figure 11 shows the different pieces of the simulation. This geometry was used for all simulations with the only difference between different simulations being the material properties and initial fiber orientations of the plies.

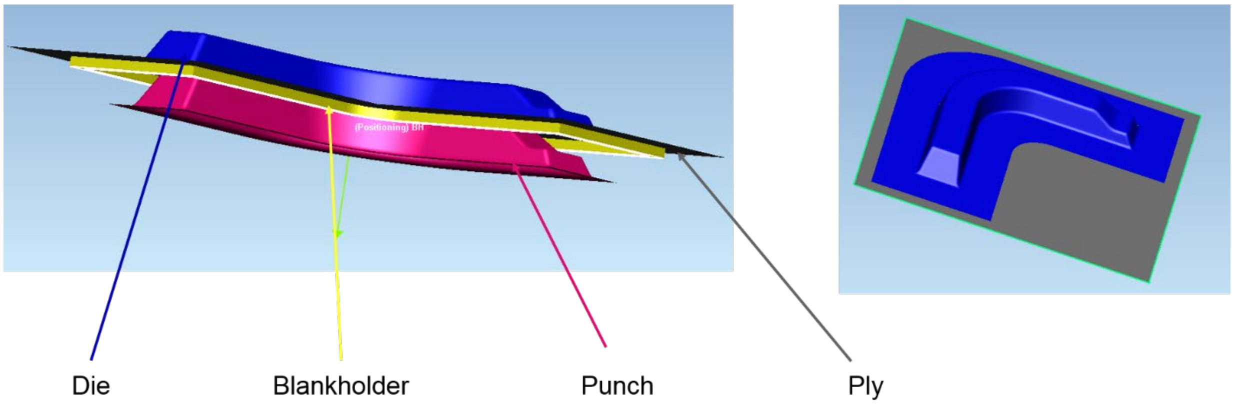


Figure 11: PAM-FORM simulation geometries.

1.3.2.3 Experimental measurements

Previous to this project, a transparent tool L-tool fixture was developed for measuring fabric deformation, shown in Figure 12. This tool was developed on a baseline IACMI project and the analysis method for traditional woven fabrics was also developed. The method will be outlined below and then the modifications which had to be made to adapt the measurements to NCF materials will also be briefly discussed.

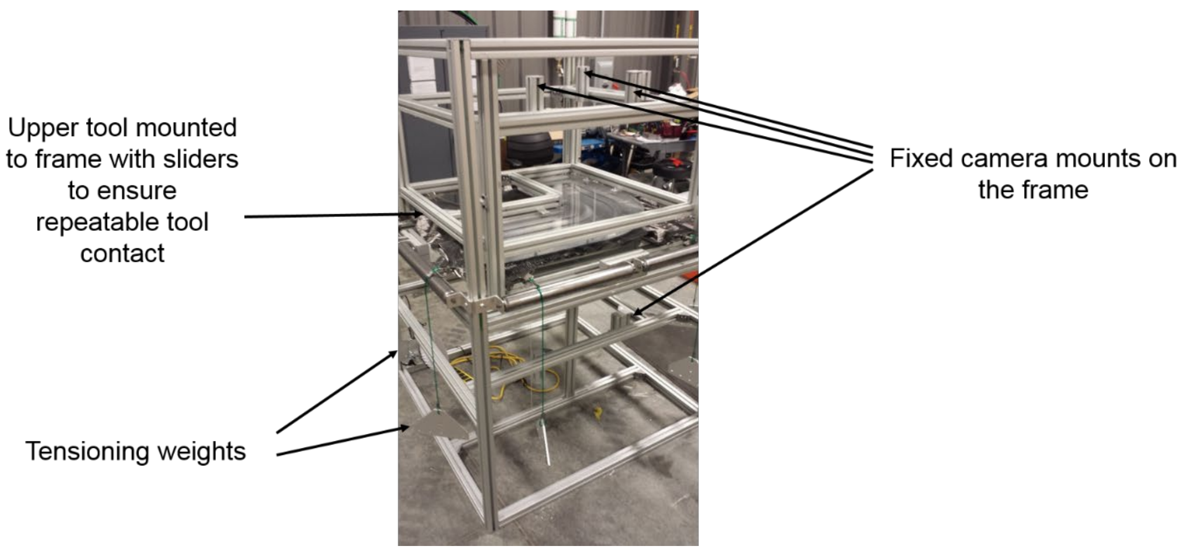


Figure 12: L-tool experimental fixture.

1.3.2.3.1 Measurement Procedures

Currently there is no standard way to measure fiber directions or shear angles. Therefore, a method has been developed to allow for quick and robust draping measurement. Figure 13 shows an image of a fabric (a grid pattern was stamped onto the fabric to make visual identification of shear easier). In order to estimate the two fiber directions in the fabric being picture, the image is first converted to a grayscale image. The image is then filtered to find the locations of large grayscale gradients. A window size is decided upon and the image is iterated across and the gradient magnitudes are thresholded to pull out the areas with the highest gradients, as shown in Figure 14. The directions of those gradients are estimated as shown in Figure 15.

Figure 13: Glass fabric with grid pattern stamped onto it for shearing measurement.

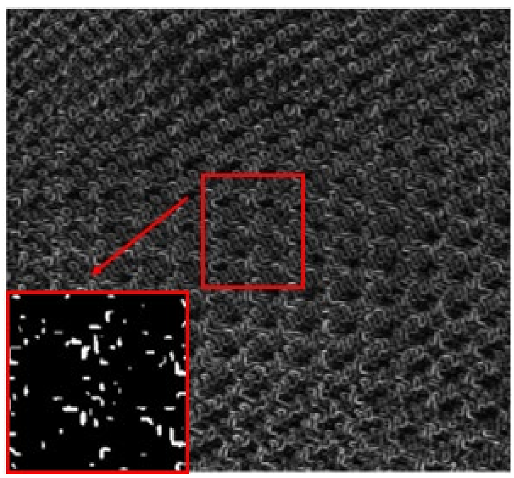


Figure 14: Windows are taken of the image and gradient magnitudes are thresholded to pull out areas with largest gradient magnitude.

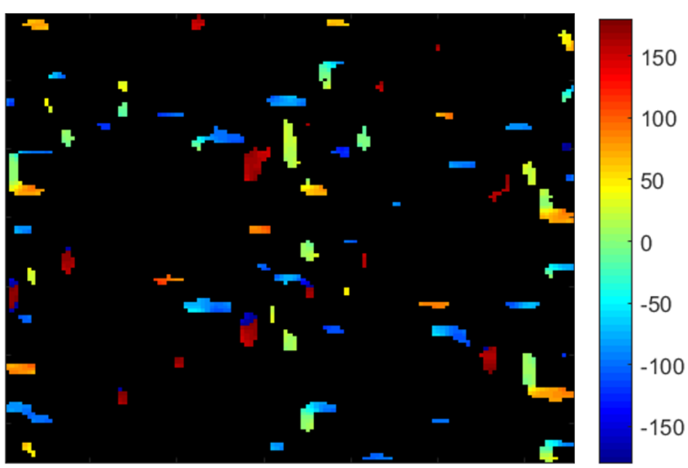


Figure 15: The directions of the gradients from figure 3 are estimated.

A histogram is created of the estimated gradient directions as shown in Figure 16. It is assumed that the fiber directions in the windowed area can be detected by the angles where the histogram of the gradient angles is a maximum. In order to pick out the 2 fiber directions, a smoothing spline is applied to the histogram and the peaks in the data are estimated fiber directions (note that the two ends of the plot, -90 and 90, are the same direction so a check must be included in the algorithm to make sure that two points near the ends are not selected). Figure 16 shows the histogram as well as a smoothing spline of the data and the 2 selected values.

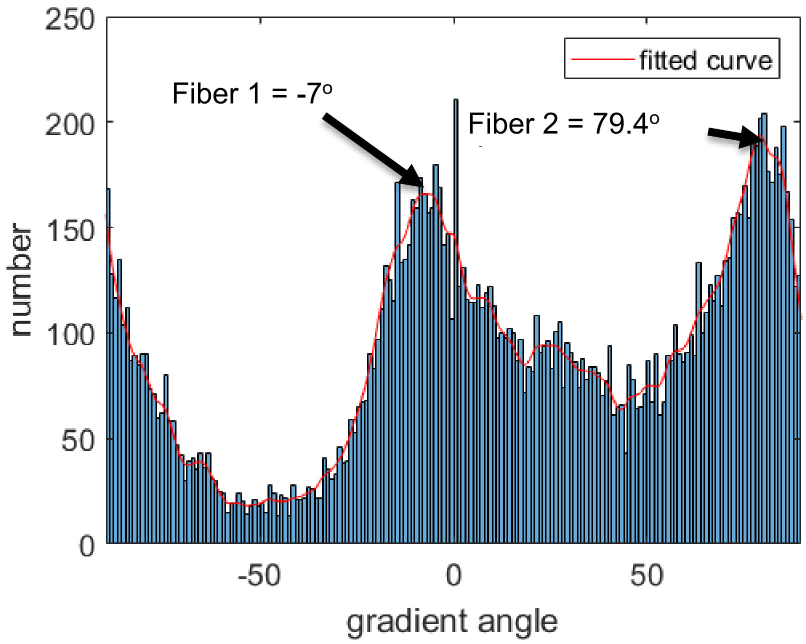


Figure 16: Histogram with smoothing spline and selected angle values for one location in determination of shearing angle.

By iterating this process over the fabric using a window size and step size of choice, the fiber directions can be estimated across the image. Figure 17 shows the image with the estimated local fiber directions overlayed on top of the image. By using the grid lines as a visual check, it can be seen that the algorithm estimates the fiber directions of the fabric quite accurately.

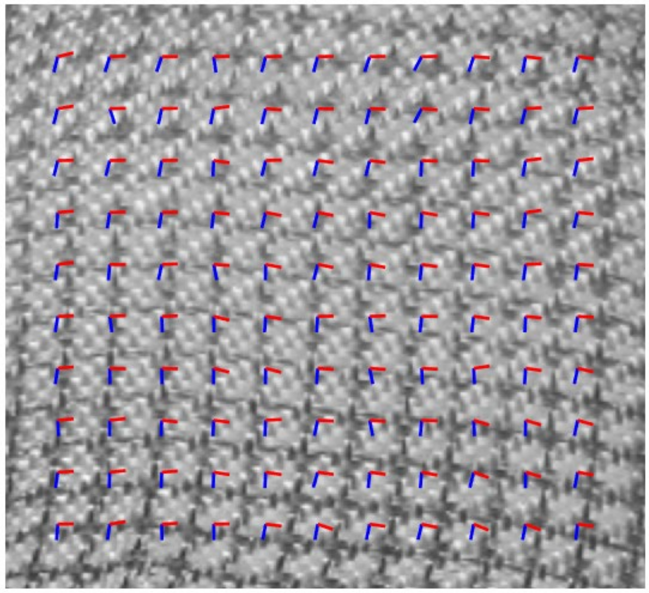


Figure 17: Estimated local fiber orientations.

Once the fiber directions have been estimated, the shear angles can be calculated simply by taking the angle between the two fiber directions. With the shear angles estimated, the fabrics can be compared qualitatively to a simulation result. Figure 18 shows the fabric from Figure 13 with colors overlayed corresponding to shear angle.

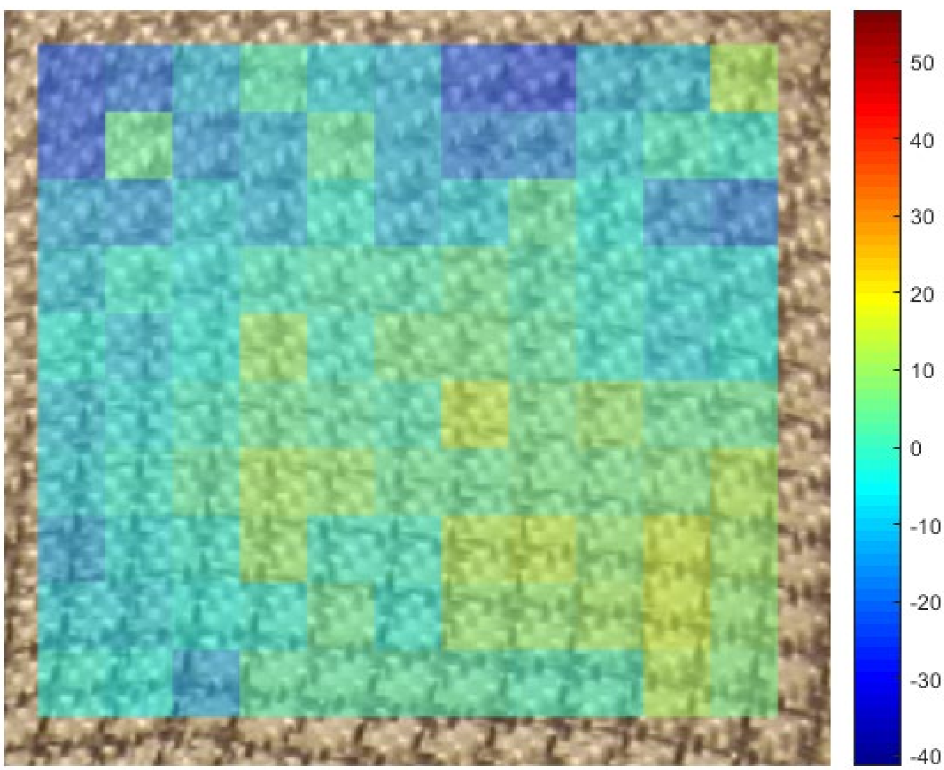


Figure 18: Shear angles calculated from image processing algorithm, referring to fabric image in Figure 2.

1.3.2.3.2 NCF modifications

In order to apply the algorithm described above to an NCF material, a few modifications needed to be made for this project. The reason for this is that only one fiber direction can be measured on each side.

Therefore, images need to be taken of both the top and bottom surfaces and the measured angles from the images correlated to one another. To create location reference points, nine round white stickers were placed on the top and bottom molds and the locations of the stickers were measured. Figure 19 shows the top surface of an NCF material with location reference stickers. In order to verify that these reference stickers allow for an accurate location correlation, three holes were punched in the fabric away from the reference stickers and the locations of these holes was estimated using the reference stickers as locations references. Figure 20 shows the bottom surface images with the three hole locations identified. Using the stickers to locate the images in space, the three hole locations were estimated on the top and bottom images and the locations of the points were compared. The results of this comparison are shown in Table 2 and show that the location estimates are all consistent within 1 mm, which is much smaller than the window size used to estimate fiber angle, so this is deemed an acceptable accuracy.

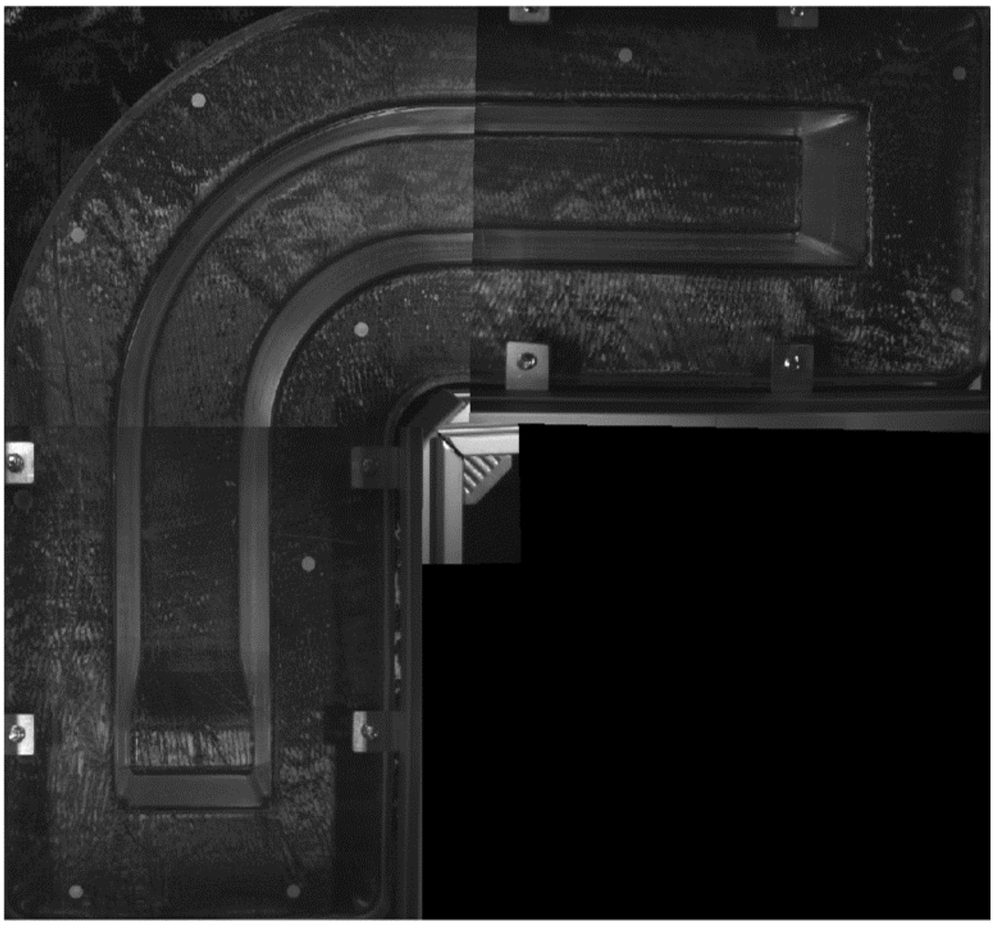


Figure 19: L-tool top surface with location reference stickers.

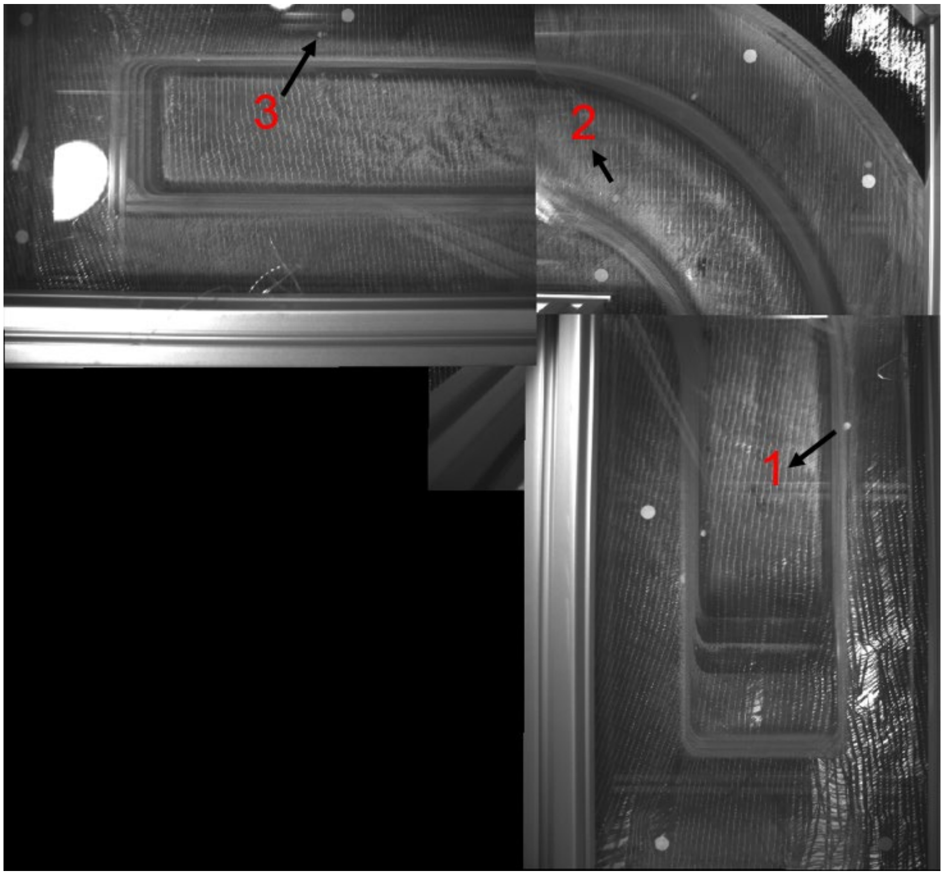


Figure 20: 3 holes used to verify location accuracy.

Table 2: Location accuracy results.

Point No.	Top	Bottom
1	[9.5, 40.3]	[10.0, 40.3]
2	[29.4, 61.8]	[30.1, 60.9]
3	[59.4, 77.1]	[59.5, 76.5]

1.3.2.4 Results Comparison

Using the methods described above, measurements and simulations were compared for both the 0/90 NCF and the 0/45 NCF. Figure 21 shows figures of the fabric wrinkles from the experimental and simulated draped fabric. The results show that the locations and overall amount of wrinkling compares favorably, but that the direction of the wrinkling does not match. This makes sense because the simulation assumes the fabric is connected as a woven 0/90 fabric would be, which would make the fabric tend to wrinkle along the 0 and 90 directions. However, the NCF material with a tricot stitch is connected along the 30 and 60 degree orientations, which makes the fabric tend to wrinkle along those directions. It should be noted that PAM-FORM does have an ability to define the stitching locations to ameliorate this problem, but this ability is not currently a part of the standard analysis, so it will not be considered here.

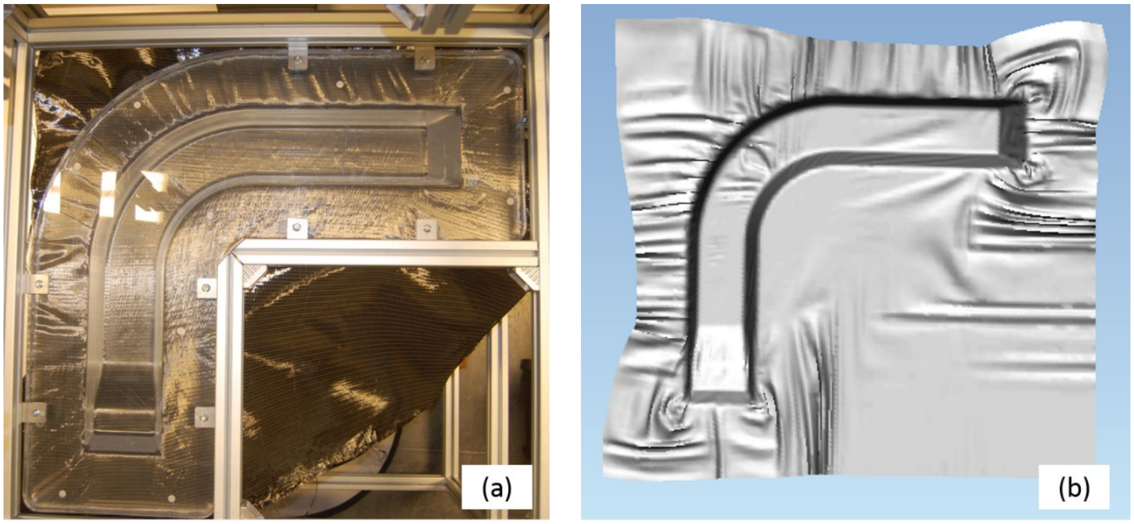


Figure 21: NCF 0/90 wrinkle comparison.

Figure 22 shows the shear angle comparison of the 0/90 NCF fabric. The results show that the results compare very well, with all of the predicted high shear regions matching up in the two.

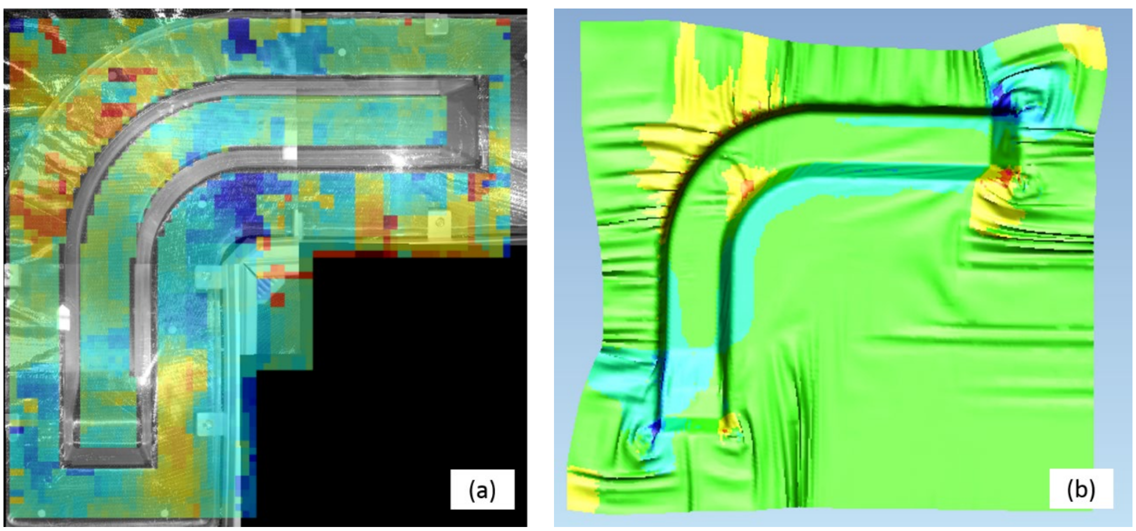


Figure 22: NCF 0/90 shear angle comparison.

Figure 23 shows the wrinkle comparison for the 0/45 fabric. Once again the main difference is that the simulation assumes the wrinkles will tend form along the fiber directions when it actually tends to wrinkle along the stitching directions. Figure 24 shows the shear angle comparison and shows that the fabric definitely has some different shearing behavior from the 0/90 fabric which is picked up in both the experimental and simulated results.

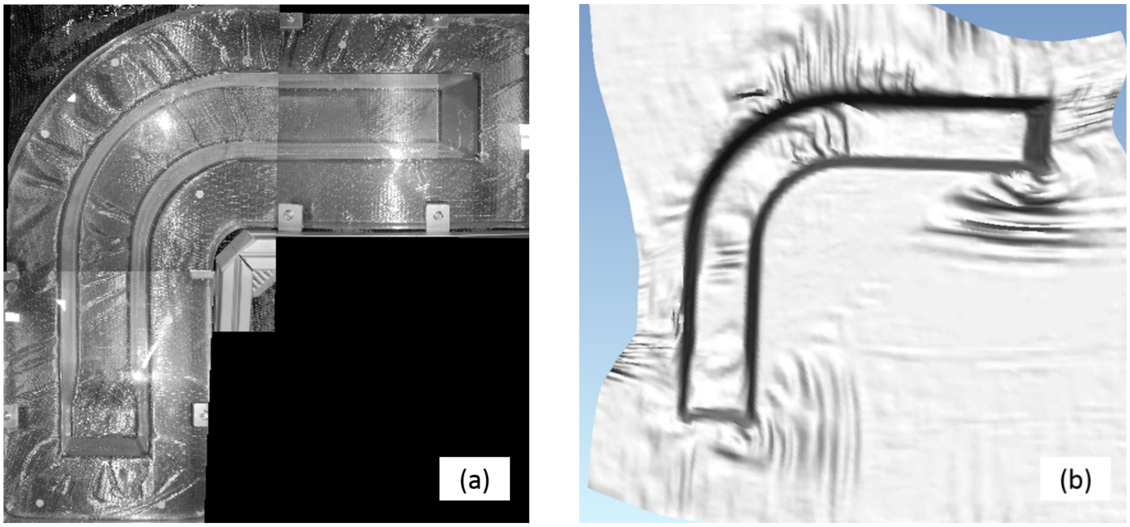


Figure 23: NCF 0/45 wrinkle comparison.

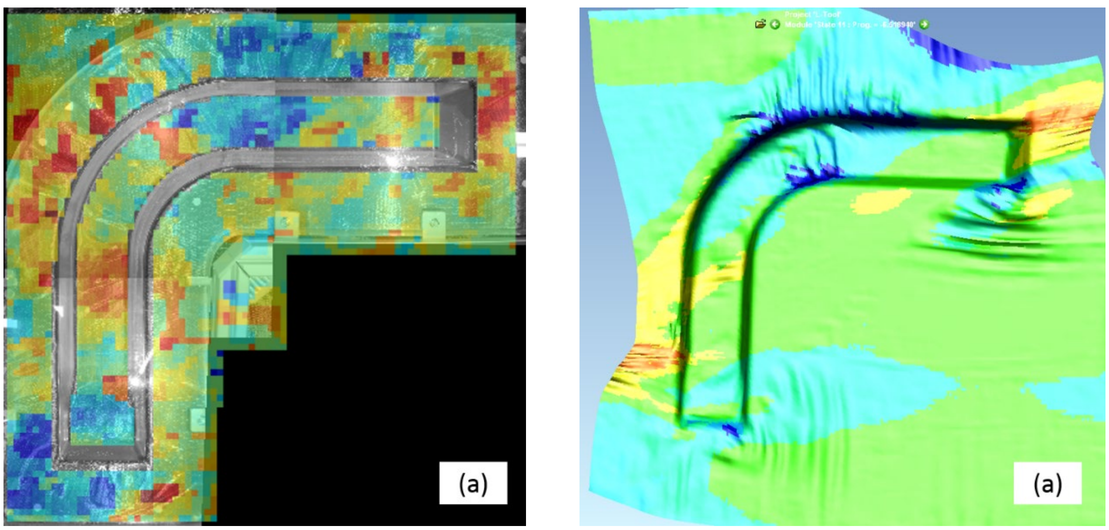


Figure 24: NCF 0/45 shear angle comparison.

Just for comparison (but not validated), the simulation was also run with the 0/45 fabric fiber orientations turned 90 degrees, shown in Figure 25, to show that the results are quite different in a 0/45 fabric depending on which direction the fibers are placed (which would not be the case in an orthogonal fabric).

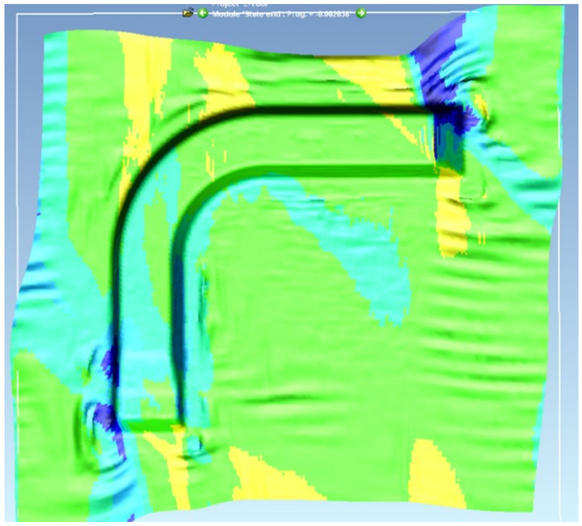


Figure 25: NCF 0/45 shear results if the fabric is rotated 90 degrees.

1.4 IMPACTS

The results of this project allow companies to use draping simulation with more confidence for orthogonal and non-orthogonal NCF materials.

1.5 CONCLUSIONS

This project demonstrated that non-orthogonal NCF materials can be characterized for draping with small adjustments to the characterization method which have been outlined in this report. The results of this project also showcased the abilities of PAM-FORM to predict NCF draping (good shear angle predictions and wrinkle location predictions) and the limitations (standard software cannot predict wrinkle directions accurately if the stitching direction differs from the fiber directions). Future work would focus on the interactions between the stitching direction and wrinkling and may result in improved predictive capability for the software.

2. LEAD PARTNER BACKGROUND

Chomarat is a global textile company with manufacturing sites in North America, Europe, Tunisia and China with approximately 1000 employees worldwide. Chomarat has three main businesses; Composite Reinforcements, Construction Reinforcements and Coatings and Films. This project was of specific interest for the Composite Reinforcements and specifically the Advanced Composites Reinforcements where we tailor our non-crimped carbon fiber fabrics (NCF) to meet the customers requirements. Historically textile fabrics have all been orthogonal and so fabric characterization is designed for orthogonal fabrics. With our advanced technology we are able to make non-orthogonal fabrics that are more efficient and this project provides our customers a method to characterize our non-orthogonal fabrics, allowing for more efficient processes and laminates.