Fiber Volume Fraction around Stitch in NCF Composites

V. YAVARI\textsuperscript{1a}, and M. H. KADIVAR\textsuperscript{1}

\textsuperscript{1}Department of Solid Mechanics, Mechanical Engineering School, Shiraz University, Shiraz, Iran

Abstract

The aim of this paper is to compute the variations of fiber volume fraction around stitches in multi-axial multi-ply Non-Crimp Fabric (NCF) composites. The microstructure of NCF composites are investigated experimentally using scanned images. Observations show that the stitch yarn forces the fibers to deviate from their straight alignment which leads to the creation of crack-shaped defects or continuous channels result from connecting and merging of collinear crack-shaped defects. Another observation is that the fibers are compacted in the fiber distorted region. The path of fibers is then simulated with a third order polynomial and linear functions and a two-variable fiber volume fraction function is obtained at last. The function is able to predict the fiber volume fraction in any point in fiber distorted region.

Keywords: Non-Crimp Fabrics, fiber, volume fraction, experiment.

1. INTRODUCTION

By introduction of non-crimp fabrics (NCF), application of this type of composites is widening. Combination of unidirectional placement of fiber bundles on each other and using an advanced stitching process (LIBA) to join the plies results in a product suited for critical and highly loaded parts of composite components and structures. However, the mechanical performance of NCF composites is greatly dependent to their meso-scale structure. The stitch yarn forces the fibers to deviate from straight alignment and fiber waviness occurs. The fiber waviness results in variations of fiber volume fraction around the stitch locations. Therefore, in order to compute the mechanical properties of NCF composites precisely, one should be able to estimate the variations of fiber volume fraction in textile perform.

\textsuperscript{*} Corresponding author: Email: yavari@yavari.info
The internal microstructure of NCF composites has different fiber and matrix areas, in this regard, precise investigation of microstructure is essential. Experimental investigation of the internal geometry of a multiaxial multiply carbon composite is performed by Lomov et. al. (2002) with the aid of textile modeling software wisetex, which serves as preprocessor for meso-mechanics and permeability modeling. Observation show that cracks and channels in the plies occupy a significant volume inside the fabric, creating resin-rich zones in the NCF composites. This research is extended to the geometry of sheared carbon composites (Loendersloot et. al., 2006). Several fabrics are analyzed to reveal the dependence of the width and length of stitch yarn induced distortions as a function of the shear angle.

The aim of this work is evaluation of fiber volume fraction around the stitches in NCF composites. This includes characterization of microstructure of NCF composites, parameterization of microstructure, and obtaining of fiber volume fraction using a mathematical model.

2. EXPERIMENTAL ANALYSIS

2.1. Samples

Three fabrics are chosen for investigating. A piece of each fabric is scanned at 1000, 1500, 2000, and 2500 dpi with a high resolution scanner. Analysis of digital images shows enough meso-scale quality with 2000 dpi resolution (Figure 1). The fabrics parameters including number and orientation of plies, stitching pattern, gauge, fabric areal mass, etc. are listed in Table 1.

![Figure 1: Samples of NCF composites, face and back.](image)
Table 1: Parameters of NCF composites

<table>
<thead>
<tr>
<th>NCF ID</th>
<th>Description</th>
<th>Manufacturer</th>
<th>Manufacturer ID</th>
<th>Number of plies</th>
<th>Orientation of Plies, degrees</th>
<th>Gauge (needle per inch)</th>
<th>Areal weight of 1st ply (g/2 sq m)</th>
<th>Areal weight of 2nd ply (g/2 sq m)</th>
<th>Stitch thread</th>
<th>Areal weight of stitch thread (g/2 sq m)</th>
<th>Total Areal weight (g/2 sq m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Bidirectional Carbon Fabric</td>
<td>SAERTEX</td>
<td>S32CX010</td>
<td>2</td>
<td>-45 +45</td>
<td>5</td>
<td>167</td>
<td>167</td>
<td>PES</td>
<td>Warp</td>
<td>343</td>
</tr>
<tr>
<td>G</td>
<td>Bidirectional Glass Fabric</td>
<td>SAERTEX</td>
<td>S32EX010</td>
<td>2</td>
<td>-45 +45</td>
<td>5</td>
<td>401</td>
<td>401</td>
<td>PES</td>
<td>Warp</td>
<td>811</td>
</tr>
<tr>
<td>K</td>
<td>Bidirectional Aramid (Kevlar) Fabric</td>
<td>SAERTEX</td>
<td>S32AX000</td>
<td>2</td>
<td>-45 +45</td>
<td>5</td>
<td>173</td>
<td>173</td>
<td>PES</td>
<td>Warp</td>
<td>352</td>
</tr>
</tbody>
</table>
2.2. Fiber distortion around stitch

Advanced stitching process (LIBA) in the manufacturing of NCF composites results in a certain distortion of fibers in a ply from their uniform and straight placement. The stitch induced fiber distortion produces resin-rich defect zones around the stitch locations. The resin-rich zone can be in shape of a crack defect or continuous channels result from connecting and merging of collinear crack-shaped defects. These defects cause the variation of fiber volume fraction around stitches and mechanical performance of NCF composites subsequently. The focus in this paper is on the crack-shaped defects.

Dimensions of the Stitch Induced Defects (SIDs) are measured by analysis of digital images. In this regard, one hundred SIDs are investigated in face and back side of NCF. With the evolution of this relatively large number of SIDs, one can briefly see the stochastic nature of microstructure of NCF composites.

2.3. Mathematical model

The needle threads are inserted into the laminate through the thickness and the fibers are forced to spread around the stitches. Therefore, the fiber volume fraction and fiber orientation in NCF composites vary from point to point around the stitch and the accurate measurement of them is very difficult to perform from experiment. A mathematical model is then developed to describe the fiber volume fraction and fiber orientation based on the investigation on the microstructure of NCF composites.

Figure 2 shows a cell around a typical stitch. Because of symmetry, only a quarter of the cell is illustrated.

![Figure 2: Cell around stitch](image)

Wei and Zhang (2008) developed a fiber distortion model in stitched unidirectional composite laminates, with the assumption of cosinusoidal fiber path in distorted region. For generality, in this paper, the path of a fiber in fiber distorted region is represented by a third order polynomial function as follows:

\[
\begin{align*}
    y &= ax^3 + bx^2 + cx + d \\
    y_{\min} &\leq y \leq y_{\max}
\end{align*}
\]  

\(0 \leq x \leq l\)  

(1)
The function should pass the following conditions:

\[ y = y_0 \quad \text{for} \quad x = 0, \] (2)

\[ y = y_1 \quad \text{for} \quad x = 1, \] (3)

\[ \frac{dy}{dx} = 0 \quad \text{for} \quad x = 0, \] (4)

\[ \frac{dy}{dx} = 0 \quad \text{for} \quad x = 1. \] (5)

Eq. (2)-(5) allows the determination of constants \( \alpha, b, c, \) and \( d \) as follows:

\[ \alpha = \frac{2}{l^3} (y_0 - y_1) \] (6)

\[ b = -\frac{3}{l^2} (y_0 - y_1) \] (7)

\[ c = 0 \] (8)

\[ d = y_0 \] (9)

Hence Eq. (1) becomes:

\[ y = 2(y_0 - y_1) \left( \frac{x}{l} \right)^3 - 3(y_0 - y_1) \left( \frac{x}{l} \right)^2 + y_0 \] (10)

For simplicity, the relation between \( y_0 \) and \( y_1 \) is assumed to be a second order polynomial which passes the following conditions:

\[ y_1 = 0 \quad \text{for} \quad y_0 = R, \] (11)

\[ y_1 = R + w \quad \text{for} \quad y_0 = R + w \] (12)

Eq. (12) gives:

\[ y_1 = R + w + b'[y_0 - (R + w)] + c'[y_0 - (R + w)]^2 \] (13)

Eq. (11) results the relation between constants as follows:

\[ R + w - b'w + c'w^2 = 0 \] (14)
Substitution of Eq. (13) in Eq. (10) and differentiating yields:

\[
\frac{dy}{dy_0} = [1 - b' - 2c'y_0 + 2c'(R + w)2(\frac{x}{R})^3 - 3(\frac{y}{R})^2] + 1
\]  
(15)

By assuming that the total fiber volume between any two fibers is constant and does not vary around the stitch, we have:

\[ V(x, y) dy = V(0, y_0) d y_0 = V(l, y_1) d y_1 \] 
(16)

Hence:

\[ V(0, y_0) = V_0 \left[ b' + 2c'y_0 - 2c'(R + w) \right] \] 
(17)

Applying the condition \[ V(0, R + w) = V_0 \] to the Eq. (17) results:

\[ b' = 1, \quad c' = -\frac{R}{w} \] 
(18)

By investigating Eq. (16), it follows that:

\[ V(x, y) = V_0 \frac{1+2x^2-3y^2-\sqrt{1+4x(2x^2-3y^2)(y-R-1)}}{(2x^2-3y^2)(1+4x(2x^2-3y^2)(y-R-1))} \] 
(19)

\[ R = \frac{R}{w}, \quad R = \frac{x}{l}, \quad y = \frac{y}{w} \]

With the same procedure and assuming a linear fiber path curve, we obtain:

\[ y = (y_2 - y_0) \left( \frac{x}{l} \right) + y_0 \] 
(20)

\[ V(x, y) = V_0 \frac{x-1+\sqrt{1-4x(3x-3x)}(y-R-1)}}{x(1-4x)(y-R-1)} \] 
(21)

Figure 3 illustrates the variation of fiber volume fraction around stitch in C NCF as a three-dimensional plot. The fiber volume fraction reaches its maximum value of 0.7 at the stitch region boundary. This value decreases gradually to the lower values at any location in the fiber distorted region. At last, the volume fraction reaches the average value of \( V_0 = 0.5 \) at the boundary of distorted region. As can be seen in the figure, the edge of the three-dimensional plot, in the \( y \)-direction (\( x = 0 \)), is a linear function with higher values at beginning (\( V = 0.7 \)) and lower values at the end (\( V_0 = 0.5 \), Eq.(17). The fiber volume fraction variations around the stitch have the same trend for other NCF composites. Figure 4 illustrates the variation of fiber volume fraction based on the linear assumed fiber path, too. The fiber volume fraction has a maximum value of 0.69.
Figure 3: Fiber volume fraction around - third-order polynomial fiber path

Figure 4: Fiber volume fraction around - linear fiber path

3. CONCLUSIONS

The fiber volume fraction is of great importance in composite materials as it affects their elastic constants and mechanical performance. Therefore, the focus is on the variations of fiber volume fraction due to the deviations of fibers around the stitch location in NCF composites. Different textile composites
are investigated. Their microstructure is then parameterized and formulated with a mathematical model. For a bi-diagonal carbon fabric, results show about 38.3% increase in volume fraction for linear assumed path and 39.8% increase for third-order polynomial path.

REFERENCES