Evaluation of Failure Criteria for Transversely Loaded Unidirectional Model Composites

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Abstract

A leading reason for the limited use of laminated composite materials in primary structural applications is that failure initiates in the ply oriented transverse to the direction of the applied load at a much lower strain than that which would cause the ultimate failure of the laminate. Previous studies indicate that transverse failure is manifested as either cavitation induced brittle failure of the matrix system or fiber-matrix debonding. The mechanism initiating the failure event is not conclusively known and depends on the local stress field of the constrained matrix that is a function of fiber spacing. In this work a model composite system using a transparent matrix is employed in a cruciform shaped specimen to evaluate several transverse failure theories. The cruciform shaped specimen utilizes a brittle 828/D230 RT cured epoxy and stainless steel wires arranged such that a fiber is placed at the intersection of the face diagonals of the four remaining fibers located at the corners of a square. The transverse failure mechanism is observed in situ via the reflected light method and recorded utilizing high resolution, high magnification microscope cameras. Three dimensional finite element models are used to analyze the stress state in the specimen at failure initiation. The results of the 3-D FE models in conjunction with the experimental observations is used to evaluate the transverse failure theories suggested in the literature. In addition this data will be used to develop a comprehensive failure criterion for transversely loaded multi-fiber composites that encompasses the dependence on fiber spacing.

Introduction

The object of this study is to investigate the failure initiation mechanism and evaluate several failure criteria of unidirectional composite materials loaded transverse to the fiber direction. A literature review of past work reveals that two competing mechanisms, namely cavitation induced matrix cracking and fiber-matrix debonding, are responsible for the damage initiation event [1,2,6]. In addition the quality of the fiber-matrix interface can cause a shift in the competing mechanisms. In previous studies fiber-matrix debonding has been observed for single fiber cruciform specimens in transparent and semi-transparent matrices by the reflected light method [3,5,6]. However, multi-fiber cruciform specimens have been limited to metal matrix composites making observation of debond initiation impossible [7].

The approach for this investigation employs a model composite system consisting of stainless steel wires and a transparent epoxy system in a cruciform specimen shape. The transparent model composite system allows in-situ observation of the failure initiation as the specimens are loaded transverse to the direction of the fiber. The specimen geometry also accommodates varying fiber spacing to observe any changes in failure mechanism. A 3-D finite element model (FEM) is employed to analyze the stress field at failure initiation for evaluation of several failure criteria under transverse loading.

Experimental Technique

The experimental technique utilizes the reflected light method to detect failure initiation in a model cruciform shape specimen tested in tension. The cruciform shaped specimen, as shown in Figure 1, nullifies free edge effects that typically dominate the failure of straight sided specimens, by concentrating the applied load in the center of the specimen. Figure 2 shows the stress concentration factor (normal stress in the loading direction normalized by the external applied stress) as a function of distance measured from the center of the specimen for an Al/epoxy composite [8]. The maximum stress concentration factor for the cruciform shape occurs in the interior region of the specimen rendering the free edge singularity ineffective because the wings of the specimen carry very little load. Therefore, failure initiates in the central region of the specimen devoid of the influence of the free edge stresses at the fiber ends. In this study the model composite system consists of multi-fiber cruciform specimens having a five-fiber arrangement and single fiber cruciform specimens. The multi-fiber cruciform specimens have a fiber arrangement in which four fibers are located at the corners of a square and the fifth, center, fiber is placed at the intersection of the face diagonals of the four corner fibers. Figures 3a and 3b, respectively, show a schematic of the cross section of the fiber wing for a multiple fiber. The fiber spacing is defined as the center-to-center distance of the corner fibers and is expressed as a ratio to the fiber diameter. Multi-fiber cruciform specimens having a fiber spacing of 6d, 2.5d, and 1.9d, as well
as the single fiber specimen are considered, where \( d_f \) is the fiber diameter. Table 1 (see Figure 1 for nomenclature) gives the specimen dimensions and is based on previous optimization studies [5].

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( 2l ) (mm)</th>
<th>( 2h ) (mm)</th>
<th>( 2a ) (mm)</th>
<th>( R ) (mm)</th>
<th>( t ) (mm)</th>
<th>( 2g ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9( d_f )</td>
<td>40.4</td>
<td>5.15</td>
<td>12.8</td>
<td>6.35</td>
<td>1.87</td>
<td>107.58</td>
</tr>
<tr>
<td>2.5( d_f )</td>
<td>40.4</td>
<td>5.15</td>
<td>12.8</td>
<td>6.35</td>
<td>2.53</td>
<td>107.58</td>
</tr>
<tr>
<td>6.0( d_f )</td>
<td>40.4</td>
<td>5.15</td>
<td>12.8</td>
<td>6.35</td>
<td>3.64</td>
<td>107.58</td>
</tr>
</tbody>
</table>

Table 1: Cruciform specimen dimensions

The model composite consists of a transparent room temperature cured epoxy and stainless steel wires for the fibers. The transparent epoxy is the Epon 828 using 35% by weight Jeffamine D-230 curing agent. It cures in approximately seven days and has a linearly elastic response to loading. The fibers used in the model composite system are isotropic stainless steel wires having a diameter of 0.36 mm. The stainless steel wires are large enough to handle for precise placement in the specimen to represent resin rich/fiber rich areas common to commercially produced composites. In addition specimens can be made with specific fiber spacing in order to validate the failure criteria by providing multiple points on the failure surface. The stainless steel wires also reflect light well enabling the use of the reflected light method [3] to capture the debond initiation and quite possible, the cavitation of the matrix at or near the fiber-matrix interface. They also are known to bond to the resins being used in this work without the use of any surface treatments or sizing.

Figure 1: Cruciform specimen geometry.

![Cruciform specimen geometry](image1)

Figure 2: SCF as function of normalized distance from center of sample.

![Stress Concentration Factor](image2)

Figure 3: Schematic of cross section of model cruciform specimen wing end for (a) multi-fiber arrangement and (b) single fiber arrangement.

![Cross section of model cruciform specimen](image3)

The reflected light method is used to observe failure initiation in the model composite specimen as the cruciform specimens are loaded to failure [6]. The reflected light method utilizes the change in light reflected off the surface of the fiber, in the case
of fiber-matrix debond, or off the surface of a micro-crack or caviation, in the case of matrix failure, for initial damage detection. This method used in conjunction with a high power video microscopes allows in-situ observation of the damage initiation and growth [3]. All specimen tests are video taped to capture the failure initiation and subsequent damage growth to complete fracture of the specimen. Since changes in the fiber spacing will change the failure initiation location due to changes in the stress distribution around the fiber and also from interaction with its nearest neighbors multiple video cameras are used to view different areas of the specimen. Consequently, the location of failure initiation for all spatial distributions is captured. A through frame-by-frame review of the video with respect to time relates the failure initiation to loading. Since all tests are video taped to failure and the testing equipment captures the load and time histories, the complete load history of each specimen is known. From the instant of complete fracture the time is measured back to the instant of failure initiation detection thus, the load at failure initiation is determined.

Experimental Results

Our initial effort is focused on the influence of fiber spacing on the failure initiation. As previously mentioned, three multi-fiber spacing cruciform specimens are tested for this study. The 6d, 2.5d, and 1.9d, fiber spacing represent isolated, closely packed and densely packed fiber distributions.

Table 2 lists the far-field applied stress at failure initiation of multi-fiber cruciform specimens having a fiber spacing of 6d for the top, center, and bottom fiber. In each case the observed failure initiation is fiber matrix debonding. It must be pointed out that for the multi-fiber specimens there exist multiple interfaces associated with the 5 different fibers that can either debond simultaneously or separately with increasing load. The values in italics call out the far-field stress at the debond initiation for that specimen and the location of the damage initiation. In five of the six specimens tested, debonding initiates at a point on the interface in the loading direction in either the top or bottom fiber. In four of the six specimens the outside fiber debonds first followed by the center fiber then the other outside fiber. The average far-field stress at debond initiation is 10.91 MPa. Figure 4 is a photomicrograph showing multiple fiber-matrix interface debonds in a model composite cruciform specimen having a fiber spacing of 6d.

![Figure 4: 6d specimen showing multiple debonds](image)

Seven multi-fiber specimens having a fiber spacing of 2.5d are also tested and in every specimen failure initiated as a fiber-matrix debond. In all but one of the 7 specimens tested failure initiated on the outside fiber. Table 2 also lists the far-field applied stress at failure initiation for the top, center, and bottom fibers. In 5 of the 6 specimens that exhibited multiple debonds, the outside fiber debonded before the center fiber debonded. The average far-field stress at debond initiation for the 828 matrix is 11.82 MPa.

<table>
<thead>
<tr>
<th>828 Matrix</th>
<th>Far-field stress at debond initiation (MPa)</th>
<th>828 Matrix</th>
<th>Far-field stress at debond initiation (MPa)</th>
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</thead>
<tbody>
<tr>
<td>6d</td>
<td>Top Fiber</td>
<td>Center Fiber</td>
<td>Bottom Fiber</td>
</tr>
<tr>
<td>6d -1</td>
<td>-</td>
<td>18.46</td>
<td>-</td>
</tr>
<tr>
<td>6d -2</td>
<td>10.32</td>
<td>14.24</td>
<td>12.85</td>
</tr>
<tr>
<td>6d -3</td>
<td>19.49</td>
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<td>12.48</td>
<td>10.42</td>
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<td>6d -5</td>
<td>17.49</td>
<td>16.60</td>
<td>10.68</td>
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<tr>
<td>6d -6</td>
<td>10.34</td>
<td>14.01</td>
<td>16.07</td>
</tr>
<tr>
<td>2.5d -7</td>
<td>-</td>
<td>13.56</td>
<td>13.86</td>
</tr>
</tbody>
</table>

Table 2: The far-field applied stress at debond initiation in multi-fiber specimens having the 6d and 2.5d fiber spacing.

Five specimens are tested with the narrower fiber spacing equivalent to 1.9d in the 828 matrix. Unlike the multiple-fiber composite with 6d fiber spacing and the 2.5d fiber spacing, the fiber-matrix interface does not debond first. Instead damage initiates in the form of matrix caviation and appears as white spots in the matrix. Figure 4 are photomicrographs of a multi-fiber composite with 1.9d fiber spacing when (a) in an unloaded state and (b) with a far-field stress of 12.8 MPa. The
development of white spots in the matrix due to cavitation is clearly seen, as marked in Figure 5(b). Subsequently the fiber-matrix interface also debonds with increasing applied load as shown. Table 3 lists the far-field stress at which damage initiates as matrix cavitation and the far-field stress levels at which the fiber-matrix interface debonds. It is observed that failure initiates as matrix cavitation for all but one sample tested so far. The average stress values for cavitation and subsequent fiber-matrix debonding for the 1.9d fiber spacing specimens are 6.34 MPa and 12.14 MPa respectively.

![Figure 5(a): photomicrograph of 1.9d fiber spacing model composite in an unloaded state](image1)

![Figure 5(b): photomicrograph of 1.9d fiber spacing model composite under a far-field stress of 12.8 MPa.](image2)

<table>
<thead>
<tr>
<th>828 Matrix</th>
<th>Far-field stress at Cavitation (MPa)</th>
<th>Far-field stress at debond initiation (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.9d</strong></td>
<td>Top Fiber</td>
<td>Middle Fiber</td>
</tr>
<tr>
<td>1.9d, -1</td>
<td>7.53</td>
<td>-</td>
</tr>
<tr>
<td>1.9d, -2</td>
<td>6.87</td>
<td>-</td>
</tr>
<tr>
<td>1.9d, -3</td>
<td>8.98</td>
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<tr>
<td>1.9d, -4</td>
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<td>2.71</td>
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<td>1.9d, -5</td>
<td>2.24</td>
<td>-</td>
</tr>
<tr>
<td>1.9d, -6</td>
<td>10.3</td>
<td>18.63</td>
</tr>
<tr>
<td>1.9d, -7</td>
<td>2.1</td>
<td>14.34</td>
</tr>
</tbody>
</table>

Table 3: Far-field applied stress at damage initiation in multi-fiber specimens having a 1.95 d fiber spacing.

**Analytical Results**

A 3-D finite element model (FEM) of the multi-fiber cruciform specimen using the ANSYS code is performed to analyze the stress field at the fiber matrix interface and in the matrix between the fibers [9]. Due to the symmetrical fiber arrangement only 1/8 of the total cruciform specimen is modeled. Figure 6 shows a portion of the 3-D FEM focusing on the mesh density around the fibers where the stress intensity is high. The FEM employs 113,448 solid95 8-node brick elements which result in 1,426,584 degrees of freedom. The planes of symmetry, namely at X = 0, Y = 0, and Z=0 are constrained by symmetry boundary conditions, whereas the outer surface is traction free. The FEM is loaded by applying tension perpendicular to the fiber axis, in the X direction, by means of constant displacement for the parametric study and applying the far-field stress at failure initiation for the different fiber spacing analyzed. Material properties for the matrix elements have a modulus of 3.44 GPa and a Poisson’s Ratio of 0.34 whereas the stainless steel fibers have a modulus of 207 GPa and a Poisson’s Ratio of 0.3. The fiber-matrix interface is assumed to be perfectly bonded.

A 3-D finite element analysis is done to see the effects of fiber spacing on the matrix interface stress distribution as the fiber spacing is made to vary. This is accomplished by keeping the specimen geometry constant when analyzing the multi-fiber spacing and its single fiber counterpart. The analytical runs are designated as Xd for the multi-fiber analysis and as SF-Xd for the single fiber analysis having the same model geometry as the multi-fiber model and assigning matrix properties to the corner fiber. The study involved analyzing multi-fiber model composites having fiber spacing of 1.57d, 1.9d, 2.5d, 6d and 12d and their single fiber model counterpart. The 1.57d and 1.9d represent varying degrees of densely packed fibers where the 2.5d represent closely packed fibers and the 6d and 12d represent varying degrees of isolated fibers. Figure 8 shows the variation of the radial stress concentration normalized by the far-field stress in the matrix at the fiber interface for (a) the center fiber and (b) the corner fiber.

The multi-fiber analysis having the largest fiber spacing, 12d, has a maximum tensile stress concentration factor (SCF) at θ = 90°, in the direction of the load, and its minimum SCF of near zero, normal to the direction of the load, at θ = 0° for the center fiber. The SF-12d analysis has practically the same radial stress distribution as its multi-fiber counterpart around the center fiber. Similar results are seen for the multi-fiber 6d fiber spacing and the single fiber 6d fiber spacing around the center fiber.
However, when comparing the center fiber 6d; analysis to the SF-6d; analysis we see a deviation at its radial maximum SCF, at $\theta = 90^\circ$, where the 6d; maximum SCF is less than the SF-6d;. This deviation is greater between the maximum radial SCF for the 2.5d; multi-fiber analysis compared to its single fiber counter part although both maximums are tensile and at $\theta = 90^\circ$.

![Figure 6: 3-D FEM of model of multi-fiber composite showing mesh density ($\theta = 0$ at $Y = 0$, measured clockwise from Y axis).](image)

It is also seen that the minimums are now diverging in that for the 2.5d; analysis its minimum radial SCF is still tensile at $\theta = 0^\circ$ whereas it becomes compressive for the SF-2.5d; analysis at $\theta = 0^\circ$. As the fiber spacing decreases further to the 1.9d; analysis case the radial stress distribution becomes significantly different around the center fiber. For the multi-fiber 1.9d; analysis its radial stress distribution becomes more uniform at $\theta \sim 45^\circ$ continuing around the fiber matrix interface to its maximum tensile SCF at $\theta = 90^\circ$ while its minimum radial SCF continues to increase over the 2.5d; analysis at $\theta = 0^\circ$. The SF-1.9df analysis follows the trend of the other single fiber analysis cases continuing the have a maximum tensile radial SCF at $\theta = 90^\circ$ and a minimum compressive radial SCF at $\theta = 0^\circ$. At the 1.57d; spacing a significant shift occurs for the location of the maximum radial SCF. Its maximum radial SCF now reaches a peak at $\theta \sim 45^\circ$ instead of at $\theta = 90^\circ$ and its minimum radial SCF at $\theta = 0^\circ$ has almost the same magnitude as at $\theta = 90^\circ$. The SF-1.57df radial stress distribution behaves as expected following the trends of the other single fiber analysis cases with its maximum being tensile occurring at $\theta = 90^\circ$ and its minimum being compressive occurring at $\theta = 0^\circ$.

![Figure 7: Variation of the Radial Stress Concentration Factor in the matrix at the fiber-matrix interface along the circumference of the fiber for (a) the center fiber and (b) the corner fiber.](image)

Figure 8(b) shows the radial stress distribution for the corner fibers. It is seen that the maximum radial SCF is always tensile and at $\theta = 270^\circ$ and increases in magnitude as the fiber spacing decreases. However, for the 1.57df spacing it reaches a peak at $\theta \sim 234^\circ$ and stays practically uniform for the rest of the fiber circumference until reaching its maximum at $\theta = 270^\circ$. It is also seen that the minimum SCF is always occurring at $\theta = 180^\circ$ and becomes more compressive as the fiber spacing decreases.
Comparing the 12d corner fiber radial stress distribution to its center fiber radial stress distribution for the multi-fiber and single fiber analysis cases there exist practically no difference.

The hoop stress distributions in the matrix at the fiber-matrix interface, as shown in Figure 8, is very similar to the radial stress distributions at the fiber-matrix interface. In all cases examined, the magnitude of the hoop stress in the matrix is lower than the corresponding radial stresses at the interface.

![Center Fiber Hoop SCF vs Fiber Spacing](image)

![Corner Fiber Hoop SCF vs Fiber Spacing](image)

Figure 8: Variation of the Hoop Stress Concentration Factor in the matrix at the fiber-matrix interface along the circumference of the fiber for (a) the center fiber and (b) the corner fiber.

Figure 9 shows the variation of the shear stress distribution in the matrix at the fiber-matrix interface for the center fiber and corner fiber. The stress distribution for the multi-fiber and single fiber analysis at the 12d spacing around the center fiber is almost identical. Comparing the center fiber stress distribution to the corner fiber stress distribution at the 12d spacing for all analysis cases very little difference exists. Couple this behavior at the 12d spacing with its radial and hoop stress distributions and it can be concluded that at this spacing the fiber behaves as an isolated fiber.

Similar to the radial and hoop stress distributions, deviations in the magnitude and location of the maximum shear stress concentration factor between the multi-fiber analysis and the corresponding single fiber analysis is observed at the center fiber, as shown in Figure 9(a), as the fiber spacing is decreased. Furthermore the location of the peak maximum SCF is consistent with the corresponding peak radial and shear stress concentration factor at the center and corner fibers for the multi-fiber analysis cases. As the fiber decrease the maximum shear SCF shifts from the location where the fibers are closest together at θ = 45° for the center fiber and at θ = 225° for the corner fiber to θ = 39° for the center fiber and to θ = 219° for the corner fiber.

![Center Fiber Shear SCF vs Fiber Spacing](image)

![Corner Fiber Shear SCF vs Fiber Spacing](image)

Figure 9: Variation of the Shear Stress Concentration Factor in the matrix at the fiber-matrix interface along the circumference of the fiber for (a) the center fiber and (b) the corner fiber.

From the parametric study nearest neighbor fiber interactions begin manifesting themselves with the 6d fiber spacing by the shift in the location of the maximum magnitude of the radial, hoop, and shear stress concentration factors of the multi-fiber analysis. This is clearly demonstrated by the 1.57d spacing analysis where the maximum radial stress SCF shifts from θ = 90° to θ = 45° for the center fiber and from θ = 270° to θ = 225° for the corner fiber. Furthermore for the 1.57d spacing the
maximum radial stress distribution at the corner fiber is almost uniform between $\theta = 225^\circ$ to $\theta = 270^\circ$ around the circumference of the fiber at the fiber matrix interface. Similar behavior is seen for the hoop stress concentration factor of the $1.57d_i$ multi-fiber spacing. For the shear stress distribution of the $1.57d_i$ multi-fiber spacing the interaction is seen where a shift in the peak SCF occurs at $\theta = 39^\circ$ instead of at $\theta = 45^\circ$ for the center fiber and at $\theta = 219^\circ$ instead at $\theta = 225^\circ$ for the corner fiber. The center fiber peak shear SCF, at $\theta = 39^\circ$, corresponds to $\theta = 231^\circ$ for the corner fiber whereas the corner fiber peak shear SCF, at $\theta = 219^\circ$, corresponds to $\theta = 51^\circ$ for the center fiber. This behavior illustrates that an area exists at the fiber-matrix interface between $\theta = 39^\circ$ to $\theta = 51^\circ$ for the center fiber and between $\theta = 219^\circ$ to $\theta = 231^\circ$ for the corner fiber, where stress field interactions take place.

Due to the stress field interactions in this region, an investigation of the strain field in the matrix between the fibers is done. Because a change in the failure mechanism occurred with the $1.9d_i$ multi-fiber spacing from a fiber-matrix debond to cavitation of the matrix, the strain invariant is analyzed for the matrix region between the fibers. A review of the literature indicates that the first strain invariant or the dilatational energy density (which is a function of the strain invariant), are potential criteria to describe the strain state at matrix cavitation [1,2,10]. The first strain invariant is defined as sum of the principal strains and is expressed as shown in equation (1)

$$J_1 = \epsilon_1 + \epsilon_2 + \epsilon_3$$

(1)

For this study the $J_1$ analytical results are normalized to the critical first strain invariant obtained from neat resin tensile tests. The critical value for $J_1$ for the matrix, $J_{1m}$, is shown in equation 2

$$J_{1m} = (1 - 2v)\epsilon_f$$

(2)

where $v$ is Poisson’s ratio and $\epsilon_f$ is the failure strain. We assume that the deviation of the stress-strain curve from linearity corresponds to failure initiation. The average failure initiation strain obtained from 15 specimens tested is 0.0189. Figure 10 shows the first strain invariant, $J_1$, normalized to the critical first strain invariant obtained from neat resin tensile tests for the multi-fiber $1.57d_i$ spacing and the multi-fiber $6d_i$ spacing. From Figure 10(b) the $J_1$ is highest at the poles of both fibers, $\theta = 90^\circ$ for the center fiber and $\theta = 270^\circ$ for the corner fiber. It decreases in magnitude around the interface of the fiber reaching a minimum at $\theta = 0^\circ$ for the center fiber and at $\theta = 180^\circ$ for the corner fiber. Interior to the matrix at the $6d_i$ fiber spacing the strain invariant reaches a somewhat constant value. As the fiber spacing is decreased to the $1.57d_i$ spacing as shown in Figure 10(a) the strain invariant magnitude in the matrix region between the fibers changes considerably.

![Figure 10](image)

Figure 10: Strain invariant contours in the matrix region between the fibers for (a) the $1.57d_i$ fiber spacing and for (b) the $6d_i$ fiber spacing

From Figure 10(a) the $J_1$ maximum occurring at the pole of the center fiber, at $\theta = 90^\circ$, for the $1.57d_i$ spacing compared to the $6d_i$ spacing, at $\theta = 90^\circ$, is now dramatically reduced in magnitude. However, the $J_1$ value at $\theta = 0^\circ$ for the $1.57d_i$ spacing is increasing when compared to the same location for the $6d_i$ spacing. Figure 10(a) seems to suggest that as the fiber spacing is decreasing the influence of the strain invariant the center fiber as evidence by the change in contours around it. It also indicates that as the fiber spacing is decreasing the strain invariant is increasing at the equator of the center fiber, i.e. at $\theta = 0^\circ$.

Discussion

This study investigated multi-fiber model composites having fiber spacing equivalent to isolated configurations, closely packed configurations, and densely packed configurations under loading transverse to the fiber direction in a transparent matrix. For
the model composites having the wide fiber spacing of 6d, and a closely packed fiber spacing of 2.5d, the predominate failure initiation event is fiber-matrix debonding. The experimental results for the 6d fiber spacing indicate that the fiber-matrix debonding occurs randomly at the fiber poles by evidence that in 4 of the 6 specimens the outside fiber, either the top or bottom fiber, debonded first followed by the center fiber then the other outside fiber, either the remaining top or bottom fiber, debonded last. The 2.5d fiber spacing experimental results indicate a pattern of debond failure initiation in that of the specimens that contained multiple debonds, the outside fiber, either the top or bottom fiber, always debonded first followed by debonding of the center fiber. In every case of the 2.5d fiber spacing experimental results the fiber-matrix debond occurred at the fiber pole. For the model composite having the densely packed fiber spacing of 1.9d, the predominate failure initiation event is cavitation of the matrix followed by fiber-matrix debonding.

A 3-D finite element analysis is done to investigate the influence of fiber matrix spacing on the stress field distribution. The analytical results for the of the single-fiber and multi-fiber simulations of the wide fiber spacing, namely 12d, and the 6d, show that the interfacial stress at the fiber-matrix interface are almost identical. For the single-fiber and multi-fiber cases at the fiber-matrix interface around both the center fiber and corner fiber, the radial stress distribution and hoop stress distribution is tensile and maximum at the fiber pole in the direction of the applied load, i.e. at $\theta = 90^\circ$ for the center fiber and at $\theta = 270^\circ$ for the corner fiber, and near zero normal to the direction of the applied load i.e. at $\theta = 0^\circ$ for the center fiber and $\theta = 180^\circ$ for the corner fiber. The shear stress for the single-fiber and multi-fiber 12d spacing at the fiber-matrix interface for both the center fiber and corner fiber is a maximum at the midpoint around the circumference of the fiber, i.e. at $\theta = 45^\circ$ for the center fiber and at $\theta = 225^\circ$ for the corner fiber. The analysis of the wide fiber spacing multi-fiber specimens indicates that the fibers behave as isolated fibers. This correlates with the experimental results of the wide fiber spacing as they exhibit a random failure initiation indicative of isolated fibers.

The analytical results for the multi-fiber 2.5d spacing reveal that neighboring fibers begin to interact by the change in the magnitudes of the maximum SCF for the radial, hoop and shear stress components at the center fiber compared to the single-fiber 2.5d analysis. Further evidence if the stress field interaction at the 2.5d spacing shows a shift in the maximum shear stress location between the multi-fiber analysis and the single-fiber analysis. The multi-fiber maximum shear SCF for the center fiber is now located at $\theta = 39^\circ$ whereas the single-fiber maximum SCF for the center fiber is located at $\theta = 45^\circ$. The manifestation of the stress field interaction is further demonstrated by the 1.57d fiber spacing analysis. For the 1.57d, the peak in the radial and hoop stress components occur at the point where the fibers are the closest, at $\theta = 45^\circ$ for the center fiber and at $\theta = 225^\circ$ for the corner fiber. Evidence of the stress field interaction is also shown in the behavior of the shear stress component for the 1.57d fiber spacing where the maximum shear stress is achieved at $\theta = 39^\circ$ for the center fiber and at $\theta = 219^\circ$ for the corner fiber. The maximum shear stress interaction location for the 1.57d fiber spacing at the center fiber translate to a location on the corner fiber at $\theta = 231^\circ$ likewise the corner fiber maximum shear SCF location translate to the center fiber at a location of $\theta = 51^\circ$. Thus it appears that a region of maximum stress field interaction is established between $\theta = 39^\circ$ and $\theta = 51^\circ$ for the center fiber and between $\theta = 219^\circ$ and $\theta = 231^\circ$ for the corner fiber. Consequently failure initiation is likely to occur within this region as the fiber spacing is decreased.

The analytical results for the strain invariant normalized to the critical strain invariant obtained from neat resin tensile test show a changing strain field as the fiber spacing decreases. These results indicate an increase in J1 at the corner fiber pole, i.e. at $\theta = 270^\circ$, and an increase in J1 at the center fiber equator, i.e. at $\theta = 0^\circ$. It appears that J1 increases in the region bonded by the maximum interfacial stress interaction location for both the center fiber and the corner fiber. However, at the center fiber pole a decrease occurs in the J1 as the fiber spacing decreases.

The analytical results for the densely packed fiber spacing, namely the 1.57d and the 1.9d, are consistent with the experimental results presented in this work. Experimental results for the densely packed 1.9df fiber spacing show that cavitation failure of the matrix occurs first followed by fiber-matrix debonding. The cavitations are located with in the bounds of the interaction region and the increased J1 region predicated by the FE analysis.

Future work is currently underway to develop a micromechanics based failure criteria to completely understand the transverse failure initiation phenomenon. Efforts will be on refining the finite element analysis and performing a full parametric study to see which parameters dominate the stress field and to fully investigate those effects. In addition, full characterization of the material system are being undertaken to analyze the effects of temperature and moisture on the failure behavior.

References


