EFFECT OF IN-PLANE WAVINESS IN UNIDIRECTIONAL CFRP COMPOSITES – MECHANICAL BEHAVIOR AND FAILURE CONSIDERATIONS

Mariana P. Alves¹, Carlos A. Cimini Jr.¹, Sung K. Ha², Pedro H. Cabral³, Gustavo H. C. Silva³, Alex P. Prado³

¹Structural Engineering Department, Universidade Federal de Minas Gerais, UFMG
Av. Antônio Carlos 6627, Belo Horizonte, 31270-901, MG, Brazil
Email: maripimenta8@gmail.com, cimini@ufmg.br

²Department of Mechanical Engineering, Hanyang University
222 Wangsimni-ro, Sageun-dong, Seongdong-gu, Seoul, South Korea
Email: sungkha@gmail.com

³Technology Development, EMBRAER S.A.
Av. Brigadeiro Faria Lima, 2.170, São José dos Campos, 12227-901, SP, Brazil
Email: pedro.cabra@embraer.com.br, gustavo.caprio@embraer.com.br, alex.prado@embraer.com.br

Keywords: Fiber reinforced composites, Defect, Fiber Waviness, Finite element analysis.

ABSTRACT

This work consists of an investigation of the effects of waviness in key structural properties of carbon fiber reinforced composites. Fiber waviness is a type of manufacturing defect commonly found in composite material parts. Finite element modeling using the commercial platform Abaqus® was performed to simulate unidirectional laminae containing in-plane graded undulations in the shape of sinusoidal waves. The peak misalignment angle was taken as sole influence parameter. Automated model generation was performed through the use of parametric Python scripting. Composites were subjected to in-plane loading and boundary conditions, with analyses being divided into tensile and compressive loads. Results proved that fiber curvature affects local stresses distribution, changing the normal longitudinal stress field and inducing the appearance of normal transverse and in-plane shear stresses. Initial failure was predicted by Hashin failure criterion, which distinguishes between fiber and matrix failure. A strength knock-down effect was observed as misalignment angle increased, favouring a matrix dominated failure mode. The influence on effective elastic modulus was less significant than on strength values. The goal was to provide a computationally efficient analysis framework to support decisions in quality control.

1 INTRODUCTION

There is a growing demand for manufacturing processes to be more robust, quicker and cheaper. However, every process has a degree of variability that can not be totally extinguished but still needs to be controlled. In composites manufacturing, several are the sources of variability: The material as received, such as prepregs and fabrics can present significant variation in density, thickness or even in fiber orientation. Process strategy also plays a role in the final result, needing to be carefully planned and detailed in terms of lay-up sequence and curing parameters. Final fabrication stages such as machining, assembly, handling and even storage must also be properly handled, otherwise unwanted features can be induced. Therefore, a successful manufacturing from composites is only achieved by a combination of decisions in design stages, manufacturing planning and control of materials and processes variabilities [1].

Once that variation is present in the output of every fabrication process, it is then important to state at what point a feature becomes a defect. In the context of structural manufacturing, defect can be defined as an imperfection which exceeds geometrical tolerance, degrades structural performance or in some other way fails to meet the design specifications and acceptance criteria.
In practice, composites parts can be subjected to several types of defects during manufacturing. Waviness is one geometrical type of defect characterized by fiber misalignment of an otherwise straight ply or group of plies. Its occurrence is normally linked to inherent undulations presented in the feedstock material or is a result of local deformation induced during processing. Manufacturing aspects such as non-uniform pressure from other composite layer or wrinkles in bagging, residual stresses due to tooling or when different layers of materials are co-cured in differing configurations [2], cooling rate, tool plate material and length of cure [3] were identified as parameters that can lead to the development of waviness in laminates. A proper understanding on how defects are generated in manufacturing is required to drive processing development.

The wavelength of waviness defects varies in size from a few millimeters, when it matches tow or ply dimensions, to some centimeters, when they provide truly weak points for the structure [4]. Waviness can occur both in the in- and out-of-plane directions. This work will focus on in-plane defects. Three sections of composites containing different configurations of in-plane fiber waviness are shown in Figure 1.

![Figure 1: (a) In-plane waviness in a fabric specimen [2]; (b) in-plane waviness in unidirectional material [2]; (c) in-plane waviness in a single-ply laminate of Carbon Fiber/Epoxy processed by RTM [5].](image)

The purpose of this work is to study the effect of in-plane fiber waviness in unidirectional carbon reinforced composites under uniaxial load. Once these defects can not always be totally eliminated from fabrication processes, the goal is to develop an analysis-based methodology that provides quantitative prediction of key structural properties. Influence with regard to initial failure will be evaluated through finite element analyses (FEA), providing a computationally efficient framework to substantiate decisions in quality control.

2 METHOD AND MATERIAL

2.1 Waviness geometry characterization

For the purpose of describing the intensity degree of the defect, several authors proposed the identification of parameters to characterize the defective region. By approximating fibers undulated shape to a sinusoidal curve, a non-dimensional parameter entitled Severity Factor (SF) is defined as the ratio between wave amplitude and length, as can be seen in Equation 1. Waviness severity has also been investigated as a function of the peak misalignment angle ($\theta$) [4] and this will be the approach followed throughout this work. The identification of this parameter and its relation with wave amplitude and length are also presented in Figure 2 and Equations (1)-(2).
Figure 2: Wave profile and its main geometric features

\[ SF = \frac{\delta}{\lambda} \]  

(1)

\[ \overline{\phi} = a \tan\left(\frac{\delta \pi}{\lambda}\right) \]  

(2)

Waviness was represented as an embedded graded imperfection in order to simplify accurate simulation of real defects. Model geometry was constructed as rectangular plates of dimensions \( L \times H \). The defective wavy region was confined to a central area of \( l \times h \), so that in all other plate regions the fibers remained straightly aligned. This approach avoids the extension of waviness to the edges, where it would lead to stress concentration and premature failure, and it approximates to defects found in sufficient large components.

In the wavy region, fibers are represented as in-phase sine-waves with the same wave length (\( \lambda \)). The amplitude of a central wave presents a maximum value (\( \delta \)) while the amplitude of the adjacent waves decreases linearly from plate center to the boundary of the wavy region where it reaches zero, i.e., fibers become straight. This geometry is shown in Figure 3.

Figure 3: Sketch of plate geometry and waviness distribution

Defect severity and its influence on failure behaviour were investigated taking the peak misalignment angle (\( \overline{\phi} \)) as the sole influence parameter. Peak misalignment angles were considered as 5°, 20° and 40°, in order to simulate moderate, severe and very severe defects, respectively. All other plate dimensions were taken as described in Equations (3)-(6).

\[ l = \lambda \]  

(3)

\[ L = 2\lambda \]  

(4)

\[ h = 3\delta \]  

(5)
2.2 Finite element modeling approach

Finite element modeling was performed using the commercial platform Abaqus® [7]. Plate geometry automated generation was accomplished by means of a plug-in specially built for this purpose, based on a parametric Python-scripting for Abaqus®.

A two-dimensional (2D) linear elastic analysis was developed. The examined material followed a plane stress assumption, considering stress components perpendicular to the plate to be negligible. Two-dimensional 4-node plane stress shell elements (type CPS4R) were used.

Lamina was subjected to in-plane load and boundary conditions such as presented in Figure 4. Simulations were divided into compressive and tensile loads, both applied as prescribed displacements \((u)\) on the edge opposite to the supported one.

Material was taken as a homogeneous media and fiber waviness orientation was accomplished by partitioning the plate in a number of small regions across the height and assigning each region with a local orientation based on a sinusoidal curve. This was achieved by the use of Abaqus/CAE® feature “discrete orientation”, which defines continually varying orientation that can follow the shape of a curve, as illustrated in Figure 4.

The analysed material was a unidirectional carbon/epoxy composite (AS4/3501-6) and its elastic mechanical properties are summarized in Table 1.

Table 1: Elastic mechanical properties of unidirectional carbon/epoxy (AS4/3501-6) [8]

<table>
<thead>
<tr>
<th></th>
<th>(E_1) [GPa]</th>
<th>(E_2) [GPa]</th>
<th>(G_{12}) [GPa]</th>
<th>(\nu_{12}) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>142</td>
<td>10.3</td>
<td>7.2</td>
<td>0.27</td>
</tr>
</tbody>
</table>

2.3 Failure

Hashin failure criterion (HFC) was used to predict damage initiation [9]. HFC is a physically based criterion that captures the heterogeneous nature of the material, i.e., distinguishing between fiber and matrix failure. The first is governed by longitudinal stresses and the second is governed by transversal and tangential stresses. This lead to four different failure indices with separate treatment of matrix and fibers. Equations (7)-(10) represent failure indices for Hashin under a plane stress state:

- Fiber tension \((\sigma_{11})>0)\):
  \[
  IF^2_{f} = \left(\frac{\sigma_{11}}{X_T}\right)^2 + \alpha \cdot \left(\frac{\sigma_{22}}{S_T}\right)^2
  \]  
  \[
  \alpha = \frac{1}{\left(1 + \frac{C}{\nu_X}\right)}
  \]  
  \[
  X_T \geq X_{f1} \quad \text{and} \quad X_T \leq X_{f2}
  \]  
  \[
  S_T \geq S_{f1} \quad \text{and} \quad S_T \leq S_{f2}
  \]
\textbf{Fiber compression} ($\sigma_{11} < 0$):

$$IF_{JC}^2 = \left(\frac{\sigma_{11}}{X^C}\right)^2$$  \hspace{1cm} (8)

\textbf{Matrix tension} ($\sigma_{22} > 0$):

$$IF_{mT}^2 = \left(\frac{\sigma_{22}}{Y^T}\right)^2 + \left(\frac{\sigma_{12}}{S^L}\right)^2$$  \hspace{1cm} (9)

\textbf{Matrix compression} ($\sigma_{22} > 0$):

$$IF_{mc}^2 = \left(\frac{\sigma_{22}}{2S^T}\right)^2 + \left[\frac{Y^C}{2S^T} - 1\right] \cdot \frac{\sigma_{22}}{Y^C} + \left(\frac{\sigma_{12}}{S^L}\right)^2$$  \hspace{1cm} (10)

where $X^T$ and $X^C$ denote longitudinal tensile and compressive strengths, respectively; $Y^T$ and $Y^C$, transverse tensile and compressive strengths, respectively; $S^T$, longitudinal shear strength; $S^C$, transverse shear strength and $\alpha$, the coefficient that determines shear stress contribution to the fiber initiation criterion. The present analysis takes $\alpha = 0$ and $S^T = S^C/2$. The allowable strength values adopted in this work are presented in Table 2.

\begin{table}[h]
\centering
\begin{tabular}{cccccc}
\hline
\hline
2280 & 1440 & 57 & 228 & 71 \\
\hline
\end{tabular}
\caption{Allowable stresses of the unidirectional carbon/epoxy (AS4/3501-6) [8]}
\end{table}

4 RESULTS AND DISCUSSION

The apparent axial stiffness $E_{1w}$ was obtained by Equations (11)(13). The results are summarized in Table 3 and show that the apparent elastic modulus is affected by the presence of in-plane fiber waviness, although moderate and even severe defects present little effect (less than 5%).

$$E_{1w} = \frac{\sigma_{\text{avg}}}{\epsilon_{\text{avg}}}$$  \hspace{1cm} (11)

$$\sigma_{\text{avg}} = \frac{\text{Total\ Force}}{\text{Cross-sectional\ area}}$$  \hspace{1cm} (12)

$$\epsilon_{\text{avg}} = \frac{\text{End\ displacement}}{\text{Specimen\ length}}$$  \hspace{1cm} (13)

\begin{table}[h]
\centering
\begin{tabular}{ll}
\hline
Defect classification & $E_{1w}/E_1$ \\
\hline
Moderate ($\phi = 5^\circ$) & 0.9991 \\
Severe ($\phi = 20^\circ$) & 0.9678 \\
Very severe ($\phi = 40^\circ$) & 0.8455 \\
\hline
\end{tabular}
\caption{Apparent elastic axial modulus ($E_{1w}$) at different values of peak misalignment angle ($\phi$) for $\phi = 20^\circ$ model.}
\end{table}

The presence of fiber waviness, however, proved to significantly alter the stress field surrounding the defect. Figure 5 presents contours of local plane stresses normalized to the remote applied uniaxial stress ($\sigma_{1u}$) for $\phi = 20^\circ$ model. This general behavior is observed in the analyses with different peak misalignment angles. For a uniaxially loaded specimen, the modification of material orientation causes
local stiffness changes and the occurrence of normal transverse and shear stresses. Note that, if no waviness is present, the maximum values were to be $\sigma_{11} = 1$ and $\sigma_{22} = \sigma_{12} = 0$.

Results show a longitudinal stress concentration in the region right above the peak of the central wave, whilst the wavy region below presents longitudinal stress relaxation. This can be all related to local stiffness changes induced by fiber curvature. In-plane waviness also induced the emergence of normal transverse stresses according to the presented pattern and in-plane shear stresses, as presented in Figure 5. Particularly for the shear stress cases, it can be identified an alternating positive and negative shear pattern around the peak misalignment angle positions. Sjölander et al. [10] have related this pattern as an indicator of waviness appearance when comparing forming FE-simulations with experimental forming studies, naming it “marcelling regions”.

![Figure 5](image-url)

Figure 5: Linear elastic stress fields normalized to remote stress $\sigma_{xx}$, for $\phi = 20^\circ$ in-plane waviness: (a) normal longitudinal stress in local 1-direction $\sigma_{11}$, (b) normal transverse stress in local 2-direction $\sigma_{22}$, (c) local in-plane shear stress in 12-direction $\sigma_{12}$, and (d) local coordinate axes.

Figure 6 compares the global x-displacement from a plate with no waviness under tension with a plate in the presence of the defect. It can be seen that the central part experienced greater deformation once that the waviness induces a reduction in axial stiffness.

![Figure 6](image-url)

Figure 6: Displacement in x-direction for a tensile loaded model plotted on undeformed shape: (a) plate with $\phi = 20^\circ$ in-plane central waviness, and (b) plate with no defect.
Maximum values of $\sigma_{11}$, $\sigma_{22}$ and $\sigma_{12}$ normalized to remote uniaxial stress are summarized in Figure 7. Graphs indicate that the increase in misalignment angle provoked a trend for increase in maximum stresses, following an approximately linear relationship for both normal longitudinal and transverse stresses and an approximately quadratic relationship for shear stress. The order of magnitude varies according to the nature of the stress in question: while normal longitudinal stresses may experience a bigger variation, the smaller variation of shear stresses will be significant in terms of failure, once that its allowable values are much lower (around 20 times lower for compressive strength, 32 times for tensile).

![Graphs showing maximum normalized stresses as a function of peak misalignment angle](image)

Figure 7: Maximum normalized stresses for uniaxially loaded plates as a function of peak misalignment angle.

Analysis of HFC indices proved that failure will be initiated by matrix compression index for compressive loading, as presented in Figure 8. For tensile loading, matrix tension index will be the trigger for failure. Failure is mainly dominated by shear stresses and its initiation point is localized in regions with maximum fiber inclination.

![Graph showing strength reduction influenced by peak misalignment angle](image)

Figure 9 shows the strength reduction at initial failure influenced by the peak misalignment angle. The results, separated for tensile and compressive cases, are presented as a percentage ratio of the strengths of the plate with central waviness normalized with respect to the plate with perfectly straight and aligned fibers. Similar responses were found by Altmann et al. [11] when investigating the degradation of mechanical properties of unidirectional laminae containing out-of-plane waviness using analytical and numerical models. Small waviness regions have failure dominated by fiber strength. As peak misalignment angle increases, a different mode of failure is triggered and matrix properties dominate the strength behavior.

When comparing the apparent stiffness reduction with the strength knock-down, the lamina strength appears to be more sensitive to peak misalignment angle increase.
5 CONCLUSIONS

Once that fiber waviness is a manufacturing defect that cannot be entirely avoided, it is of vital importance to understand the mechanical behavior transformations in the presence of these alterations. In-plane waviness proved to have a strong effect on local stiffness, affecting the stress field of the surrounding region. The induced shear stresses favour a matrix dominated failure mode under uniaxial load, which presents a much lower strength in comparison with straight fiber regions. As peak misalignment angle grows, the stronger these effects appear, leading to matrix cracking appearance. Stiffness reductions were less significant than strength ones.
ACKNOWLEDGEMENTS

The authors are thankful for the assistance of the Structural Engineering Department of UFMG and the Department of Mechanical Engineering of Hanyang University. This work was supported by CAPES, CNPq, and FAPEMIG.

REFERENCES


