NUMERICAL ANALYSIS OF INTERLAMINAR STRESS ON
SYMMETRIC ANGLE-PLY LAMINATES INTERLEAVED WITH CNT
NETWORKS

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ABSTRACT

Delamination is one of the major initial damage forms for laminated composite structures, which is caused by relatively high interlaminar stress. In present study, glass fiber (GF)/epoxy (EP) symmetric angle-ply laminates, interleaved with carbon nanotube (CNT) networks at +θ/−θ interfaces (10°≤θ≤30°), were used to analyze and evaluate the effect of CNT networks on interlaminar stress. This was realized by using of finite element analysis (FEA), based on cohesive zone model (CZM). Interlaminar stress distribution at +θ/−θ interfaces (CZM region) with and without CNT networks was calculated and compared. Numerical results show that the introduction of CNT networks into the interlaminar region improves the major interlaminar stress, which controls initiation and propagation of delamination.

1. INTRODUCTION

Delamination beneath the surface of composite laminates will significantly degrade their mechanical properties and integrity, thus leading to abrupt structural failure. Delamination can be easily initiated by mode I and mode II loading [1-5], cyclic loading [6], impact [7]. It has also been shown that mode III-dominated delamination was tended to appear in symmetric angle-ply laminates due to the mismatch of mechanical properties in adjacent layers [8]. Therefore, delamination prediction is essential to the safe design for laminated composite structures. To date, intensive experimental and numerical investigations have already been conducted to obtain delamination data.

In terms of experimental investigations, non-destructive testing (NDT), like acoustic emission (AE) [9-11], is one of the mature experimental methods to detect delamination in composite laminates. However, external sensors like AE strongly depend on the experience of manipulating personnel and sometimes are not convenient for practical application. In view of this, embedded sensors [12-14] have been developed to monitor delamination damage in real-time mode, whereas these sensors generally have limitations in detecting orientation and cause a reduction of in-plane mechanical properties. Recently, a newly emerging CNT based nano-detectors could break through the mentioned restrictions to real-time detect delamination, especially the CNT networks based nano-detectors [15-17]. Because of the isotropic property in plane, the CNT networks based nano-detectors are capable of detecting whole interlaminar region. Meanwhile, the excellent mechanical properties and extraordinary electrical ability of CNT make it potential to detect delamination damage in target area without hurting the overall mechanical properties of the composite laminates.

On the other hand, it is worth noting that numerical simulation is an efficient and low-cost method to aid in understanding the complex mechanical behaviours and predicting damage process in composite structures. With the rapid development of computer technology, FEA has been extensively...
conducted to numerically investigate delamination. Since Virtual Crack Closure Technique (VCCT) has been proposed by Rybicki and Kanninen [18], it was available for calculating energy release rate of the delamination propagation [19-20]. The biggest weakness of VCCT is that it could only be used for predicting crack propagation rather than crack initiation. Extended finite element method (XFEM) is another common FEA approach [21-22], which was first put forward in 1999 by Belytschko and Black [23] to model delamination through simulating the opening or evolution of the crack. The introduced crack through XFEM is independent of the mesh, which constitutes a great advantage from the computational perspective. Besides, the crack’s propulsion path could be observed. However, XFEM is only applicable in the vicinity of the crack and this method is failed to simulate the multiple crack growth.

From the above-mentioned limitations, this paper adopts CZM, first introduced by Dugdale [24] and Barenblatt [25], as a finite element (FE) model to simulate delamination process by using ABAQUS commercial software. The cohesive layers can be located where delamination tended to occur with no need for specifying an initial defect or a pre-crack. Most researchers utilized CZM to simulate mode I and/or mode II delamination initiation and propagation in laminated composites [1-5], while lack of comprehensive studies investigated the aforementioned mode III-dominated delamination. This study focuses on the mode III-dominated delamination occurred in GF/EP symmetric angle-ply laminates, interleaved with CNT networks at +0/-0 interfaces (10°≤θ≤30°), to investigate and compare the delamination behavior of the composite laminates with and without CNT networks.

2. CHARACTERIZING THE LAMINATES

The constitutive properties of the composite materials were characterized by means of experiment tests and analytical method. The notations are reported in Figure 1, where 1, 2 and 3 refer to the fiber direction, transversal direction and thickness (normal) direction respectively.

Mode I and mode II critical strain energy release rate (G\textsubscript{IC}, G\textsubscript{IIc}) were obtained through DCB and ENF tests in accordance with ASTM D5528 standard for the specimens with and without CNT networks. And mode III critical strain energy release rate (G\textsubscript{IIIc}) can be considered to be equal to G\textsubscript{IIc} in general. Moreover, according to ASTM D3039 and ASTM D5379, uniaxial tensile tests and Iosipescu (V-notched) shear tests were performed respectively to obtain the in-plane (intralayer) mechanical performances, i.e. E\textsubscript{1}, E\textsubscript{2}, v\textsubscript{12}, and G\textsubscript{12}.

![Figure 1: Notations in unidirectional composite laminates.](image)

Conveniently, out-of-plane (interlaminar) mechanical properties are obtained through micro-mechanical law of composite materials. Out-of-plane shear modulus G\textsubscript{23} is deduced from the assumption of transverse isotropy:

\[
G_{23} = \frac{E_2}{2(1+\nu_{32})}
\]  

(1)

where poisson ratio \nu\textsubscript{32} is the strain in 3-direction (\epsilon\textsubscript{3}) with respect to the strain in 2-direction (\epsilon\textsubscript{2}) only when \sigma\textsubscript{2} exists, which is associate with volume fraction of fiber and resin.

Therefore, constitutive mechanical properties of the GF/EP composite materials are concluded in Table 1.
Table 1: The constitutive properties of the unidirectional composite laminates and cohesive element parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Glass fiber/epoxy</td>
<td>$E_1$</td>
<td>38.11 GPa</td>
</tr>
<tr>
<td></td>
<td>$E_2= E_3$</td>
<td>8.50 GPa</td>
</tr>
<tr>
<td></td>
<td>$G_{12}=G_{13}$</td>
<td>3.91 GPa</td>
</tr>
<tr>
<td></td>
<td>$G_{23}$</td>
<td>3.34 GPa</td>
</tr>
<tr>
<td></td>
<td>$\nu_{12} = \nu_{13}$</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>$\nu_{23}$</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>$G_{IC}$ (with/without CNT networks)</td>
<td>0.1/0.13 kJ/m$^2$</td>
</tr>
<tr>
<td></td>
<td>$G_{IIc}, G_{IIc}$ (with/without CNT networks)</td>
<td>0.6/0.78 kJ/m$^2$</td>
</tr>
</tbody>
</table>

3. COHESIVE ZONE MODELING

CZM associates the evolution of normal and tangential traction and their coupling with normal and tangential displacement in the potentially delamination area, located at $+\theta/-\theta$ interfaces of the symmetric angle-ply laminates in this paper. And bi-linear mixed-mode CZM was employed for the interfaces (cohesive layers). The behavior of it is described by using a bi-linear traction-displacement curve shown in Figure 2, with a linear-elastic behavior before critical displacement ($\delta_0$), at which point delamination initiates. Then, traction decreases linearly with displacement dropping to zero, which occurs at point $\delta_{max}$. Irreversible delamination damages are accumulated in this soft area. The area beneath the curve is equal to the interlaminar fracture toughness ($G_c$). Furthermore, the bi-linear traction-displacement law described by Turon et al. [26] can be written as follows:

$$T = \begin{cases} 
K\delta_i & \text{if } 0 \leq \lambda \leq \delta_0 \\
(1 - d)K\delta_i & \text{if } \delta_0 \leq \lambda \leq \delta_{max} \\
0 & \text{if } \delta_{max} \leq \lambda 
\end{cases}$$  \hspace{1cm} (2)

where $i$ presents the traction mode, $T$ is traction, $\delta$ is the corresponding displacement of the interfaces and $K$ is the penalty stiffness. In this equation, $d$ is a mixed mode damage parameter, and the equivalent displacement $\lambda$ is Euclidean norm of the displacement component, which is defined as:

$$\lambda = \sqrt{\langle \delta_i \rangle^2 + \delta_{II}^2 + \delta_{III}^2}$$  \hspace{1cm} (3)

where $\langle \rangle$ is Macaulay bracket.
Then, apply the above mentioned bi-linear mixed-mode CZM to delamination simulation carried out in this study. As shown in Figure 2, when equivalent stress $\sigma$ reaches $\sigma_{\text{max}}$, delamination initiates. Then $\sigma$ gradually decreases to zero, at which point delamination begins to propagate.

4. NUMERICAL SIMULATIONS

Figure 3 depicts the geometrical shape of GF/EP symmetric angle-ply laminates ([±$\theta_4$]s) with or without CNT networks introduced at +$\theta$/$\theta$ interfaces (cohesive layers) under tensile loading (F), where $\theta=10^\circ$, 15$^\circ$, 20$^\circ$, 25$^\circ$, 30$^\circ$. Finite element analysis (FEA) based on bi-linear mixed-mode CZM was used to study the effect of interleaved CNT networks on interlaminar stresses as well as the stress of delamination initiation and propagation at +$\theta$/$\theta$ interfaces. The numerical simulation was implemented in ABAQUS commercial software. The dimensions of each ply are 150 mm*20 mm*0.1 mm, and the thicknesses of the cohesive layers with and without CNT networks are 0.04 mm and 0.005 mm respectively. The FEA approach was carried out using 3D model with an 8-node 3D cohesive element (COH3D8) in cohesive layers and an 8-node continuum shell (SC8R) in ply region, shown in Figure 3.

Interlaminar normal ($\sigma_z$) and shear ($\tau_{yz}$, $\tau_{xz}$) stresses are three factors determining delamination mode and process. In order to research the effect of interleaved CNT networks at +$\theta$/$\theta$ interface on interlaminar stresses, the simulation was performed by setting the applied load as 1000N. At that point, none of the damage in ply region and delamination occurred. After calculation, extract $\sigma_z$, $\tau_{yz}$ and $\tau_{xz}$ data along y axis in midsection ($x=75$mm) from numerical simulation results. Through treating the results with Dimensionless Parameter Method (DPM), zero dimension interlaminar stress ($\eta$) is defined as the ratio of calculated stress to maximum stress. The corresponding values are presented with ply orientation angle from 10$^\circ$ to 30$^\circ$ in Figure 4, which indicates that for the [±$\theta_4$], laminates in this paper, $\tau_{xz}$ at the free-edge region is three or four orders of magnitude more than $\sigma_z$ and $\tau_{yz}$. That means $\tau_{xz}$ is the most critical factor leading to delamination, thereby confirming the major delamination mode-mode III (tearing mode).
Figure 4: The distribution of $\sigma_z$, $\tau_{yz}$ and $\tau_{xz}$ along $y$ axis.

The impact of interleaved CNT networks on $\tau_{xz}$ at free-edge (the maximal interlaminar stress) is presented in Figure 5. With an increasing ply orientation angle from $10^\circ$ to $30^\circ$, $\tau_{xz}$ has experienced non-linear increasing along $y$ axis ($0\leq y\leq 10$ mm), when $x=75$ mm. Also note that, interleaved CNT networks makes the $\tau_{xz}$ in cohesive layer at the free-edge improved slightly shown in Figure 5.

Figure 5: Distribution of $\tau_{xz}$ in cohesive layers at free-edge when $x=75$ mm.

5. CONCLUSION

FEA based on CZM can be used to predict the delamination initiation and propagation of the GF/EP symmetric angle-ply laminates. The results of numerical simulations indicate that interlaminar stress component $\tau_{xz}$ is the major stress component leading to delamination initiation in this paper, thereby mode III is the main delamination mode for the studied composite laminates. In addition, the interleaved CNT networks enhance the interlaminar stress $\tau_{xz}$ slightly.

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