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3-D FEM Modeling of fiber/matrix interface debonding in UD composites including surface effects

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Abstract. Fiber/matrix interface debond growth is one of the main mechanisms of damage evolution in unidirectional (UD) polymer composites. Because for polymer composites the fiber strain to failure is smaller than for the matrix multiple fiber breaks occur at random positions when high mechanical stress is applied to the composite. The energy released due to each fiber break is usually larger than necessary for the creation of a fiber break therefore a partial debonding of fiber/matrix interface is typically observed. Thus the stiffness reduction of UD composite is contributed both from the fiber breaks and from the interface debonds. The aim of this paper is to analyze the debond growth in carbon fiber/epoxy and glass fiber/epoxy UD composites using fracture mechanics principles by calculation of energy release rate $G_{II}$. A 3-D FEM model is developed for calculation of energy release rate for fiber/matrix interface debonds at different locations in the composite including the composite surface region where the stress state differs from the one in the bulk composite. In the model individual partially debonded fiber is surrounded by matrix region and embedded in a homogenized composite.

1. Introduction

Many engineering structures made from polymer composites such as wind turbine blades, aircraft wings, etc., are subjected to thermal and mechanical fatigue loads. Due to overload or initial manufacturing defects, microdamage such as fiber breaks or matrix cracks may occur after certain amount of load cycles. The presence of microdamage not necessarily means that the structure is not suitable for further service. However, due to further cyclic loading the propagation of microdamage will occur and after a certain number of applied load cycles the mechanical properties will be significantly degraded leading to failure of the structure.

In polymer composites microdamage in form of fiber breaks or matrix cracks is the most common. Under small-medium stress tension-tension fatigue of a UD polymer composite matrix cracks may occur after some number of load cycles. In further fatigue loading the matrix cracks are deflected and the propagation of damage is in form of growing fiber/matrix interface debond cracks. In high stress mechanical fatigue loading, fiber breaks occur in random positions after few loading cycles. Due to energy released during the breaking of the fibers, partial fiber/matrix interface debonding typically occurs in vicinity of fiber breaks. Also in this case the further propagation of damage will be in form

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of growing interface debond cracks. In this paper only the latter scenario of damage initiation and propagation is studied. Characterizing the growth of damage propagation is important to estimate the lifetime and serviceability of the structure. Analytical [1] and numerical [2] models have been earlier developed to characterize the growth of debond crack when the broken and partially debonded fiber is in the bulk of the composite. The main objective of the present paper is to analyze the fiber/matrix debond growth as dependent on the fiber position with respect to the specimen surface.

2. Mechanics of debond propagation
Analyzing cyclic loading Paris law, well known for single crack growth in metals, may be suitable for characterization of the debond growth along fiber/matrix interface as a function of applied number of load cycles \( N \). Paris law expression describes the increase of the debond surface area \( dA \) as:

\[
\frac{dA}{dN} = B(\Delta G_{II})^m
\]

where: \( B \) and \( m \) are unknown parameters, which have to be determined experimentally; \( \Delta G_{II} \) is the energy release rate difference between values corresponding to \( \varepsilon_{\text{max}} \) and \( \varepsilon_{\text{min}} \) in a cycle. The cyclic loading type considered in this study is mechanical tension-tension fatigue (\( \varepsilon_{\text{max}} > 0 \) and \( \varepsilon_{\text{min}} > 0 \)). Notation \( \Delta G_{II} \) with index II is used since only Mode II debond crack propagation is relevant - for the studied polymer composites the matrix Poisson’s ratio is higher than for the fibers and therefore in purely mechanical tension loading the radial stresses on fiber surface will always be compressive, the interface crack is closed and pure Mode II crack propagation will occur. Debond length increment for circular fiber is related to debond surface increment as

\[
dl = dA \cdot \left(2\pi \cdot r_f\right)^{-1}.
\]

Interface debond growth related energy release rate \( G_{II} \) can be calculated by various analytical and numerical methods as described in Section 3 of this paper. The values of two parameters in Paris law (\( B \) and \( m \) in (1)), however, can only be determined experimentally. Having a reliable model for energy release rate \( G_{II} \) calculation in hand, and performing experimental measurements of debond length as a function of applied load cycles \( N \) would allow finding the values of Paris law parameters \( B \) and \( m \) from the best fit. However, performing experimental measurements of fiber/matrix interface debond crack growth in the bulk of UD composite is a challenging task. Still it could be done using, for example, microtomography techniques. Since Paris law parameters for interface debond growth can be considered as fiber/matrix interface property, a more convenient method would be measuring the debond crack growth in a single fiber composite. Observing single fiber embedded in a transparent block of resin is convenient and can be performed in an optical microscope. In [3,4], for example, debond crack growth in single fiber composites was measured during quasi-static loading. Other option would be to measure debond growth on a composite specimen surface, as, for example, in [5], which can be done in an optical microscope as well. However, the debond growth in vicinity of UD composite surface is different than in the bulk of composite due to edge effects. The high scatter in the experimental measurements in [5] could be an indication that the interface debond growth is very sensitive to the actual distance from the observed fiber to the surface of composite. Therefore, one of the aims of this paper is to calculate the dependency of energy release rate \( G_{II} \) on the distance from fiber to composite surface. The change in energy release rate \( G_{II} \) is expected due to change in the stress state around the partially debonded fiber when it is in vicinity of composite surface. It is expected that the stress state around debonded fiber will have higher deviation from axisymmetric stress state, which we have when the fiber is in the bulk of composite, when it is closer to the surface.
of composite. In such case 3-D numerical models have to be used for calculation of energy release rate $G_{II}$.

However, at a certain distance from the composite surface the deviation from axisymmetric stress state will become negligible and more convenient axisymmetric models developed in [1] and [2] can be used for $G_{II}$ calculation.

3. Strain energy release rate for long and short debonds
The debond crack propagation can be considered as self-similar when the tip of the fiber/matrix debond crack is far away from the fiber break where it was initiated and also far from another debond which may be approaching from the other end of the fiber. If the fiber is also sufficiently far from the surface of composite, the stress state around the fiber is axisymmetric and analytical solution for energy release rate $G_{II}$ can be found. In [1] expressions of analytical model for calculation of strain energy are presented.

In case of short debonds, the debond crack tip is close to the fiber break where it initiated from and the stress perturbation regions related to fiber break and debond crack tip interact. Due to interaction, $G_{II}$ is magnified. The shorter is the debond the higher will be the interaction and thus $G_{II}$ will be higher. Since the stress states interact, the self-similar conditions are no longer in power and analytical closed form solution is not possible. Therefore finite element method FEM calculations are useful for determination of $G_{II}$ for short debond lengths. As an output from FEM calculations stress and displacement distributions are available and $G_{II}$ can then be easily calculated, for example, using the virtual crack closure technique [6] as described further. Virtual crack closure technique was used, for example, in [2] to calculate magnification of $G_{II}$ at short debond lengths.

4. Material properties
In this paper two different UD composites were studied – carbon fiber/epoxy resin composite (CF/EP) and glass fiber/epoxy resin composite (GF/EP). The properties of composite constituents are given in Table 1. The accuracy of the values listed in Table 1 are important for correct calculations of the elastic properties of the composite. Importance of this accuracy is discussed in [1].

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_L$ [GPa]</th>
<th>$E_T$ [GPa]</th>
<th>$G_{LT}$ [GPa]</th>
<th>$\nu_{12}$ [-]</th>
<th>$\nu_{23}$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF</td>
<td>500</td>
<td>30</td>
<td>20.00</td>
<td>0.2</td>
<td>0.45</td>
</tr>
<tr>
<td>GF</td>
<td>70</td>
<td>70</td>
<td>29.20</td>
<td>0.2</td>
<td>0.20</td>
</tr>
<tr>
<td>EP</td>
<td>3</td>
<td>3</td>
<td>1.07</td>
<td>0.4</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Properties of CF/EP and GF/EP unidirectional composites were calculated using the Concentric Cylinder Assembly (CCA) model introduced by Hashin [7,8] for the bonded case. The transverse shear modulus was obtained using the Christensen’s self consistent model [9]. Only fiber volume fraction equal to $V_f = 0.5$ was studied in this paper. Fiber radius for all cases was equal to $r_f = 4 \mu$m.

5. FEM model
5.1. Geometry of the model
For analysis of debond growth in the bulk of composite, axisymmetric FEM models have been developed previously [2]. However, for the case when the fiber is in vicinity of composite surface, axisymmetric model may not be applicable due to edge (surface) effects.

In this study a 3-D FEM model consisting of partially debonded fiber surrounded by a matrix cylinder and embedded in a large block of effective composite was generated using finite element code ANSYS [10]. The geometry of the 3-D FEM model is shown in figure 1. As it is shown in figure 1
only one half of the model was generated in FEM code ANSYS, taking advantage of the symmetry conditions.

In figure 1, $z$, $x$ are the axes in Cartesian system and $\varphi$ is polar angle, $l_d$ is the variable interface debond crack length, $L_s$ is the total length of model ($\frac{1}{2}$ of fiber fragment), $l_c$ is the variable coordinate of depth of the fiber (distance from fiber center axis to composite surface), $d_c$ is the size of the effective composite surrounding the fiber and matrix in the y-direction.

The values of geometrical parameters $L_s$ and $d_c$ were taken from convergence analysis performed in [2] where it was found that model length $L_s = 90 \cdot r_f$ (where $r_f$ is the fiber radius) and the effective composite size $d_c = 5 \cdot r_f$ are efficient for modeling accuracy to represent a long partially debonded fiber in an infinite composite.

Contact elements were used on the surfaces of fiber and matrix in the debonded region. The effect of friction was neglected.

The model was meshed with mesh refinements near the tip of the debond crack in order to obtain accurate solution of stress and displacement distributions which are needed for $G_{II}$ calculations.

Figure 1. Geometry fragment of the 3-D FEM model.

**Figure 1.** Geometry fragment of the 3-D FEM model.

Figure 2. Detail of the FEM model used for $G_{II}$ calculations. F – fiber, M – matrix, C – effective composite.

**Figure 2.** Detail of the FEM model used for $G_{II}$ calculations.
Since the virtual crack closure technique was used for $G_{II}$ calculations, the finite element mesh refinement was optimized for the chosen integration length. Figure 2 shows the detail of the FEM model, including the length of integration $dl_d$.

Following the convergence analysis performed in [2] the length of integration in all calculations was set equal to $dl_d = 1 \cdot r_f$.

5.2. Virtual crack closure technique

The crack closure technique states that the energy released due to debond crack growth by $dA$ is equal to the work which is required to close the newly created surface from size $A + dA$ back to size $A$. Figure 2 can be used for geometric representation of the further statements.

Closing the debond crack by length $dl_d$ (from $l_d + dl_d$ to $l_d$) by applying tangential tractions, points at the debonded surface in the region $z \in [l_d; l_d + dl_d]$ which have relative tangential displacement

$$\Delta u_{l_d + dl_d}^l(z) = u_{l_f + dl_d}^l(z) - u_{mz}^l(z)$$

are moved back to coinciding positions. Here and in following the upper index for stress and displacement shows the length of the debond used in calculations.

At the end of this procedure the shear stress in point $z$ is equal to $\sigma_{xz}^l(z)$, which is the shear stress in front of the crack with size $l_d$. For the case when fiber is in the bulk of composite and the stress state around it is axisymmetric, the work required to close the crack by $dl_d$ can be expressed as:

$$dW(dl_d) = 2\pi \frac{1}{2} \int_{l_d}^{l_d + dl_d} \Delta u_{l_d + dl_d}^l(z) \sigma_{xz}^l(z) dz$$

In (3) $\sigma_{xz}$ is the shear stress component relevant to Mode II crack propagation.

For a general 3-D stress state, which may not be axisymmetric the expression (3) can be rewritten as:

$$dW(dl_d) = \frac{1}{2} \int_0^{2\pi} \int_{l_d}^{l_d + dl_d} \Delta u_{l_d + dl_d}^l(z) \sigma_{xz}^l(z) r_f dz$$

Within the virtual crack closure technique it is assumed that due to small value of $dl_d$ the relative sliding displacement at the tip of the crack with size $l_d + dl_d$ is the same as at the tip of the debond crack with size $l_d$:

$$\Delta u_{l_d + dl_d}^l(z) = \Delta u_{l_d}^l(z - dl_d)$$

The usefulness of this assumption is that only one stress state calculation for a given debond length is required.

The energy release rate is defined as:

$$G_{II} = \frac{dW}{dA}$$
where \( dA = 2\pi l_d dl_d \). Thus \( G_{II} \) can be easily calculated from a single stress state by combining equations (4), (5) and (6):

\[
G_{II} = \lim_{dl_d \to 0} \frac{1}{4\pi l_f dl_d} \int_0^{2\pi l_f + dl_d} \int_{l_f}^{\Delta u_f + dl_f} (z - dl_d, \varphi) \sigma_{xz}^{l_f} (z, \varphi) r_f d\varphi dz
\]

(7)

As mentioned, in all calculations performed in this study the length of integration was equal to \( dl_d = 1 \cdot r_f \), which as found in [2] can be assumed as sufficiently small to satisfy conditions of (7) (where \( dl_d \to 0 \)) and at the same time sufficiently large to obtain accurate stress and displacement distributions. Distributions of displacement \( \Delta u_z \) and shear stress \( \sigma_{xz} \) were obtained by performing post-processing (path operations) in ANSYS. Since non-axisymmetric stress state was studied, pre-defined paths were generated along the whole circumference of the fiber/matrix surface. To facilitate the path operations, the finite element mesh was uniform along the circumference. Code comprising (7) in incremental form was generated for convenience of calculations as an input. Although the stress state around partially debonded fiber which is close to composite surface may not be axisymmetric, the crack growth was considered as uniform – the shape of the interface debond crack front was assumed to be circular with same \( z \) coordinates for all points of the tip of the cylindrical crack.

6. Results and discussion

6.1. \( G_{II} \) calculations

Figures 3 and 4 show results of interface debond growth related energy release rate \( G_{II} \) calculations for CF/EP and GF/EP composites. In all cases uniform axial displacement \( u_z = 0.01 \cdot L_s \) was applied at the end surface of the FEM model (see figure 2).

Results in figures 3 and 4 are presented as functions of normalized debond length \( l_{dn} = l_d r_f \). The calculations were performed for different cases by varying the fiber depth parameter \( l_c \) (distance from composite surface). For CF/EP calculations were done for three cases: \( l_c = 10, 15 \) and \( 20 \) \( \mu \)m as shown in figure 3. For GF/EP calculations were done for two cases: \( l_c = 10 \) and \( 15 \) \( \mu \)m as shown in figure 4.

First of all it can be noted from both cases (CF/EP in figure 3 and GF/EP in figure 4) that the values of energy release rate are higher for shorter debond lengths. It is expected that for shorter debond lengths due to interaction of stress states the energy release rate will be magnified. However, when the debond length is sufficiently long, the growth of the debond crack becomes self-similar as it was shown in [2]. In the present paper a range of debond lengths from \( l_{dn} = 1.5 \cdot r_f - 4 \cdot r_f \) has been studied. As it can be seen from the trends in figure 3 and figure 4, this range of debond lengths corresponds to interaction region and a further increase of debond length will result in smaller values of \( G_{II} \) approaching the asymptotic self-similar value.

Concerning the dependency of \( G_{II} \) on fiber distance from surface (parameter \( l_c \)) it can be noted for both CF/EP in figure 3 and for GF/EP in figure 4 that \( G_{II} \) is higher when the fiber is closer to the surface of composite. Since the energy release rate is higher, it follows that the growth of the interface debond crack will be faster for the fibres which are closer to the composite surface compared to the fibers in the bulk of composite. From calculation results for CF/EP in figure 3 it can be noted that there is no significant difference between results for cases when fiber distance from surface \( l_c = 15 \)
µm or $l_c = 20 \, \mu m$. This distance $l_c = 15 \, \mu m$, at which energy release rate $G_{II}$ becomes independent of distance from composite surface indicates the boundary between the close-to-surface region and bulk of composite region.

![Figure 3](image_url)

**Figure 3.** Energy release rate $G_{II}$ as a function of normalized debond length $l_{dn}$ for CF/EP. $l_c$ values are in µm.

![Figure 4](image_url)

**Figure 4.** Energy release rate $G_{II}$ as a function of normalized debond length $l_{dn}$ for GF/EP. $l_c$ values are in µm.

To analyze the stress state around the broken and partially debonded fiber and how it depends on the distance from composite surface ($l_c$) a comparison between the shear stress $\sigma_{xz}$ and axial displacement $\Delta u$ distributions was performed. As it can be seen from results shown in figures 5 and 6 (for CF/EP and GF/EP respectively), where stress distributions are shown for the case when angular coordinate $\varphi = 0^\circ$, there is a minimal dependence on the distance $l_c$ within the observed range from $l_c = 10$ to $20 \, \mu m$. In fact, the differences in calculated energy release rate $G_{II}$ values in this range were also relatively small (less than 4%), therefore small differences in stress distributions were expected.
Regarding the axisymmetry of the stress distribution, dependency of shear stress $\sigma_{xz}$ distribution on angular coordinate $\phi$ was investigated. In figures 7 and 8 stress distributions at 3 different angular directions $\phi = 0^\circ$, $45^\circ$ and $90^\circ$ are presented for CF/EP and GF/EP respectively. The results in both figures 7 and 8 indicate that there is no significant dependence of shear stress $\sigma_{xz}$ distribution on the angular coordinate $\phi$, which means that an axisymmetric approximation is applicable. The same can be concluded from analysis of displacement distributions as shown in figure 9.

**Figure 5.** Shear stress $\sigma_{xz}$ distribution in front of the tip of the debond crack for CF/EP. $z = 0$ is location of the debond crack tip. Angular coordinate in all cases $\phi = 0^\circ$. $l_c$ values are in $\mu$m.

**Figure 6.** Shear stress $\sigma_{xz}$ distribution in front of the tip of the debond crack for GF/EP. $z = 0$ is location of the debond crack tip. Angular coordinate in all cases $\phi = 0^\circ$. $l_c$ values are in $\mu$m.
Figure 7. Shear stress $\sigma_{xz}$ distribution in front of the tip of the debond crack for CF/EP. $z = 0$ is location of the debond crack tip. Distance from surface in all cases $l_c = 10 \, \mu m$.

Figure 8. Shear stress $\sigma_{xz}$ distribution in front of the tip of the debond crack for GF/EP. $z = 0$ is location of the debond crack tip. Distance from surface in all cases $l_c = 10 \, \mu m$. 
Figure 9. Axial displacement $\Delta u_z$ distribution behind the tip of the debond crack for CF/EP. $z = 0$ is location of the debond crack tip. $l_c$ values are in $\mu m$.

The results show that within the observed region of distances from composite surface, the changes in energy release rate $G_{II}$ values are approximately 1.5-2%.

This means that in the selected range of distances from composite surface $l_c$, the stress state is very close to the stress state in the bulk of composite. Using the present FEM model geometry (figure 1) the minimal distance from composite surface $l_c$ is limited to approximately $2 \cdot r_f$ and new geometry model with explicit heterogeneous microstructure of the surrounding composite has to be generated to analyze cases when the distance $l_c$ is smaller.

7. Conclusions
The calculation results proved dependency of energy release rate $G_{II}$ on distance from composite surface for both CF/EP and GF/EP composites. The energy release rate is larger for debonds closer to the specimen surface. However, within the observed range ($l_c = 10$ to $20 \mu m$) the changes in absolute values of $G_{II}$ are small. It was proved that differences due to fiber location in shear stress and axial displacement distributions in front and behind the crack tip were even smaller. Furthermore, dependency of stress distributions on angular coordinate $\phi$ was also small, therefore, it can be concluded that axisymmetric approximation can be used in the studied region.

8. References