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# Micromechanical Study of Fiber Kinking and Debonding in Fiber Reinforced Composites

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**Micro Abstract**
The objective of this work is to study the fiber kinking and subsequent fiber/matrix debonding in FRP composites under unidirectional compressive loading. On the micro-scale, geometrically nonlinear cohesive elements are used in order to model the shear failure of the matrix material at its interface with the fibers which results in initiation and evolution of local splitting between fiber and matrix and drives the rotation of fibers up to kink band formation.

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## Introduction

Due to their high strength and stiffness to weight ratio, unidirectional fibre-reinforced polymer composites are one of the most widely used materials in advanced structures in aerospace and automotive applications. The most important limiting factor for the application of this type of composite materials is their low compressive strength, due to the occurrence of different compressive failure mechanisms, such as matrix shear failure, fiber crushing and most importantly, fiber kinking. Significant amount of research has been devoted to study the fiber kinking phenomenon during the past few decades. Early analytical studies [6] attempted to model fiber kinking as elastic micro-buckling of the fibers, while experimental results showed that these assumptions significantly overestimate the compressive strength of the composite. These models were later modified by taking into account the matrix nonlinearities and initial misalignment of fibers, which are crucial factors driving matrix shear failure and kink band formation [1]. Due to the advancements in computer technology, numerical approaches have become demanding for modeling essential steps of fiber kinking. Most of these numerical studies are restricted to micromechanical level [4], by taking into account different material behaviours for matrix and fiber, and considering the effects of interaction between kinking and other failure modes in limiting compressive strength of the composite laminates [3]. The aim of the present work is to study the interaction between kinking and fiber/matrix debonding by using an appropriate cohesive element formulations for large displacements. In the first section of this paper a brief review of cohesive element formulation and the Finite Element approach for modeling kinking and debonding will be presented. Subsequent sections will focus on numerical examples and discussion.

## 1 Micro-mechanical Analysis

### 1.1 Finite Element Model

A 2-D micro-model consisting of layers of fiber and matrix and 2-D line shaped cohesive elements placed between each pair of fiber and matrix is built for the kinking analysis. The schematic of geometry and boundary conditions of the model is shown in Figure 1.

Each fiber has a thickness equal to its nominal diameter $\phi_f = 7\mu m$, and the thickness of the matrix layers is equal to $t_m = 7\mu m$. A sine shaped waviness is applied as initial misalignment

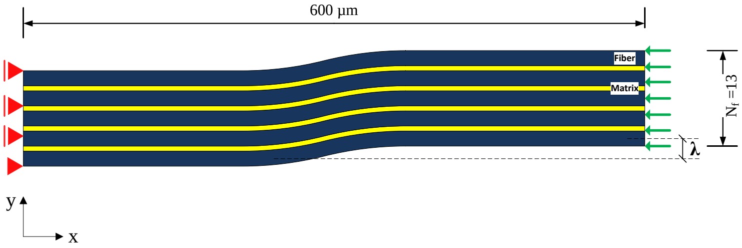


**Figure 1.** Geometry and boundary conditions of the numerical model.

with the function:

$$y_0 = \lambda(1 - \cos(\tfrac{\pi x}{l})) \tag{1}$$

where $\frac{\lambda}{l}$ is assumed to be 0.005

### 1.2 Large Displacement Cohesive Element

The interface between each pair of fiber and matrix is modeled with a finite deformation cohesive element, appropriate for geometrically nonlinear simulations [5]. The element internal load vector is obtained from the following equation:

$$f^e_{int} = \int_{S_0} \left( \mathbf{RB} + \frac{\partial \mathbf{R}}{\partial \mathbf{d}} \mathbf{Bd} \right)^T \boldsymbol{\tau} \, dS \tag{2}$$

where $\mathbf{R}$ is the rotation matrix from the global coordinate to the local coordinate system of the element and $\frac{\partial \mathbf{R}}{\partial \mathbf{d}}$ is a linear function of the displacement $\mathbf{d}$. $\mathbf{B}$ is the matrix of derivatives of shape functions for the cohesive element. The cohesive traction vector $\boldsymbol{\tau}$ is obtained from the mixed-mode constitutive equation of the cohesive element, which in this case is assumed to have an exponential form:

$$\boldsymbol{\tau} = e \frac{\tau_c}{\delta_c} e^{-\alpha/\delta_c} \mathbf{C} \boldsymbol{\delta} + K \mathbf{I}_c \boldsymbol{\delta} \tag{3}$$

In this equation $\mathbf{C}$ is a matrix for applying different weights to mode I and shear modes, and $\mathbf{I}_c$ is the penalty matrix for preventing penetration of layers in case of compressive mode I loads [2]. $K$ is the penalty stiffness and $\alpha$ is the internal variable associated to the maximum value of mixed-mode strain in each step of the solution, in order to ensure the irreversibility of damage. $\tau_c$ and $\delta_c$ are the critical traction and displacement jump for mode I, respectively (Figure 2).

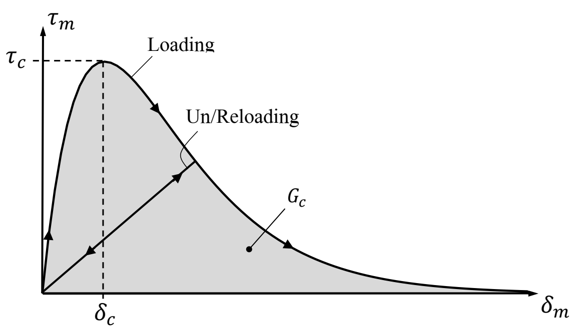


**Figure 2.** Mixed-mode cohesive law with exponential behaviour

The material tangent stiffness matrix then reads as:

$$\mathbb{C} = \mathcal{F} e \frac{\tau_c}{\delta_c^2} e^{-\alpha/\delta_c} (\mathbf{C}\boldsymbol{\delta})(\mathbf{C}\boldsymbol{\delta})^T + e \frac{\tau_c}{\delta_c} e^{-\alpha/\delta_c} \mathbf{C} + K \mathbf{I}_c \tag{4}$$

where $\mathcal{F}$ is a loading function distinguishing loading/reloading from unloading.

## 2 Numerical Results

Mechanical properties of the fiber and matrix components are listed in Table 1. Fibers are assumed to have elastic isotropic behaviour, while an elastic-plastic behaviour of $J_2$ type with isotropic hardening is considered for the matrix. Mechanical properties of the cohesive element are chosen adoptively in order to investigate the fiber/matrix interface properties on the compressive strength of the composite layer.

| | | | | |
|---|---|---|---|---|
| Carbon Fiber | | | $E(GPa)$ | $\nu$ |
| | | | 225.0 | 0.22 |
| Polymer Matrix | $E(GPa)$ | $\nu$ | $Y_0(MPa)$ | $H_{iso}(GPa)$ |
| | 4.08 | 0.38 | 90.0 | 0.10 |

**Table 1.** Mechanical properties of the micro-model components

Two types of fiber/matrix interfaces are examined. In the first case, the interface is considered perfectly bonded and in the second case, debonding is allowed through the insertion of cohesive elements. In case of using cohesive elements the value of fracture toughness plays a key role in the buckling behaviour of the fibers. The results are compared in Figure 3 for two cases of $G_{IIc} = 50J/m^2$ (for ductile interface) and $G_{IIc} = 5J/m^2$ (for brittle interface). In both cases the shear and normal strength is chosen to be $100MPa$.

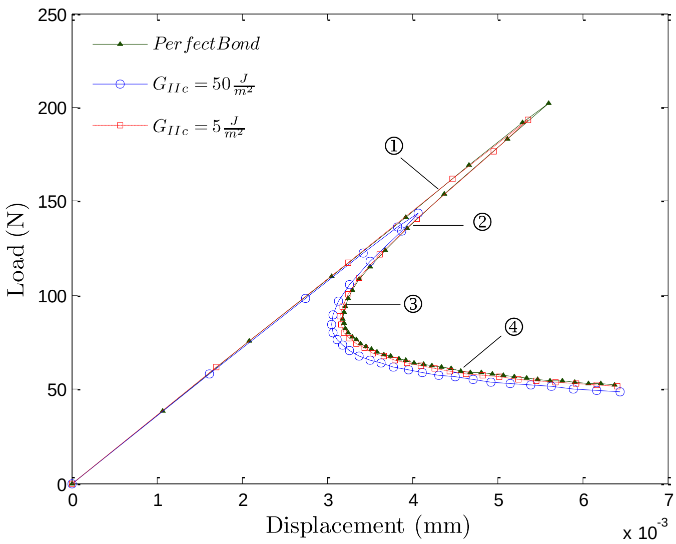


**Figure 3.** Axial load vs. displacement under compressive load

The results show that by increasing the fracture toughness of the cohesive layer the maximum value of the stress/load drops considerably and the post-peak behaviour shows a slightly softer response. The points marked on this figure are associated to different stages of kink band formation, and are depicted in Figure 4 by highlighting the stress distribution in fibers. From point 1 to 4, by increasing the compressive load, the matrix starts yielding due to the initial imperfection and forms a yield band. Within this band fibers lose their lateral support and tend to rotate (from point 1). By further increasing the load the yield band grows and the fibers reach their instability point. Beyond this point an unstable equilibrium path is observed in the form of snap-back which, from the experimental point of view, can be interpreted as a sudden drop in stress at constant strain. At point 4 the kink band is completely formed by fibers lock-up, together with the increase in debonding between fibers and matrix. The stress distribution in Figure 4 shows how bending of the fibers increases during kink band formation.

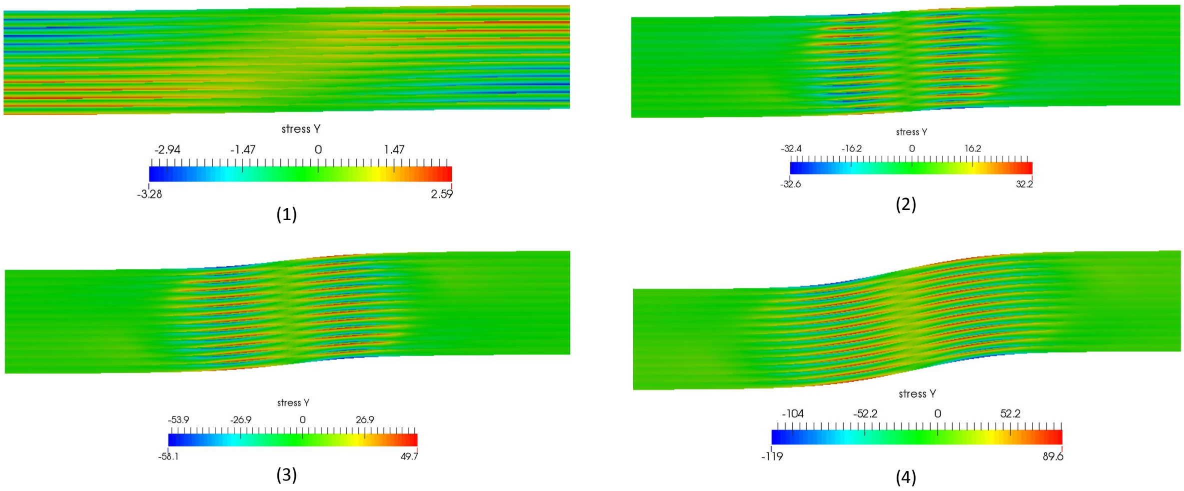


**Figure 4.** Stress distribution in fibers during kink band formation ($G_{IIc} = 5\frac{J}{m^2}$)

## Conclusions

A 2-D micromechanical study of kink banding process and the subsequent debonding between fiber and matrix was performed using cohesive elements. Since the kinking phenomenon is a geometrically nonlinear numerical problem, an augmented formulation was adopted for the cohesive element to become compatible for mixed-mode debonding under large displacements. The results explain the dependency of kinking behaviour on the mechanical properties of fiber/matrix interface which has to be taken into account cautiously in numerical modeling of various composite materials.

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