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Revealing complex aspects of compressive failure of polymer composites – Part I: Fiber kinking at microscale

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ABSTRACT

The fact that complex simulation can be carried out at present days allows to go further to answer new questions in the compressive failure of polymer composites. A thorough understanding of fiber kinking is essential for the prediction of stiffness and strength of fiber reinforced composites. The goal of this paper is to give a deep understanding of some topics which are still unclear in the micro modeling of fiber kinking. Such are the kinking mechanism and the difference in the kinking mechanics between global and local imperfections, the determination of kink band angle and consideration of statistical distributions of fiber waviness.

3D micro models are presented in Part-I in order to simulate the compressive failure in continuous fiber reinforced composites under pure compression considering the effect of fiber kinking. It is shown that the kinking mechanism is changed by changing the type of fiber waviness, the angle of the kink band is depend on the tensile strength of the fibers and the kink bands in a model with statistical distributions of fiber waviness are located at the edges of the specimen.

1. Introduction

Fiber kinking is the decisive mechanism leading to compressive failure of fiber reinforced composites. It is responsible for the relatively low compressive strength of unidirectional laminates compared to the tensile strength, the longitudinal compressive strength of IM7/8551-7, for instance, is about 62% of its longitudinal tensile strength, see Kaddour and Hinton [15]. In early analytical studies of fiber kinking, an elastic buckling of aligned fibers has been assumed by Rosen [25]. He presented a model for micro buckling of glass fiber-epoxy laminates under compression considering the fibers as plates supported by an elastic matrix. However, it is now widely acknowledged that initial fiber misalignments accompanied by matrix nonlinearities are responsible for the initiation of kink bands. This observation was published for the first time by Argon [1]. He reported that initial misalignment produces an interlaminar shear stress. When this stress reaches the yield limit, a sliding and rotation process will begin for the fibers in this area. Argon's model considered the initial misalignment angle, but did not take into account the increased fiber rotation angle during the kinking process.

Budiansky [2] and Budiansky and Fleck [3,4] showed through their analytical and experimental evidence that long fiber polymeric composites fail under compression by plastic kinking. Their compressive strength is sensitive to the misalignment of the fibers. They showed that the kinking stress for misaligned fibers is about 25% of the elastic microbuckling stress of perfectly aligned fibers.

The analytical model based on the kinking theory of Budiansky and Fleck [3] was applied by Guimard et al. [9] and Feld et al. [6]. Guimard et al. combined the model with the statistical distribution of fiber misalignment from Paluch [20] to obtain an accurate distribution of peak loads. The fibers were assumed to be inextensible in tension/compression and their bending behavior is modeled by Euler–Bernoulli beams. The matrix constitutive law is based on Prandtl–Reuss elastoplastic law with positive isotropic hardening. Feld et al. [6] consider a shear pre-stress and a damageable behavior of the matrix. Their micro model was a one-dimensional representative volume element using the finite element formulation, as described by Guimard.

In addition to analytical models, numerical simulations of the fiber kinking process were performed as well. Kyriakides et al. [17] and Kyriakides and Ru [16] used a two-dimensional model based on elastic fibers and inelastic matrix behavior. The matrix was modeled as an elastic–plastic solid with J_2 plasticity, the carbon fibers are represented using an anisotropic nonlinear elasticity

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law. Furthermore, two kinds of imperfections were imposed: a uniform sinusoidal waviness and a sinusoidal waviness with variable amplitude. In Vogler and Kyriakides [29], two- and three-dimensional models regarding local and global imperfections were used to study the initiation and growth of kink bands in fiber composites. Fiber waviness as a local imperfection is added at the free edge in order to initiate the kink band. The results showed insensitivity of the characteristics of the kink band with respect to amplitude and wavelength. In order to determine the effect of the fiber diameter on the compressive strength a 3D model was presented by Yerramalli and Waas [34]. The numerical results of the 3D micro model demonstrated an increase of the compressive strength with an increase of the fiber diameter. These results were also observed in the experiments from Yerramalli and Waas [33] and Yerramalli [32].

Numerous models have been suggested in literature in order to explain the phenomenon of fiber kinking and to determine the compressive strength of fiber reinforced composites. Despite all of this effort, there are still unclear topics which will be addressed in this paper: the influence of the imperfection type on the resulting kinking mechanism, the determination of the kink band angle and how to consider the statistical distributions of fiber waviness in the micro model. Different types of fiber waviness were investigated first by Vogler and Kyriakides [29]. They introduced a local imperfection to initiate a kink band in the numerical simulation. In this study, it is shown that two different kinking mechanisms exist: kink bands initiated by local fiber waviness and kink bands initiated by global fiber waviness. It is revealed that the kinking mechanism depends on the type of imperfection. Moreover, the effect of different strength values on the kink band angle is examined and it is shown that the kink band angle depends on the tensile strength of the fiber. In the last section of this work a 3D micro model is created considering the statistical distributions of fiber waviness. The amplitude, half wavelength, out of plane misalignment angle and the equivalent fiber diameter are taken from four statistical distributions, according to Paluch [20], to built the 3D finite element model and to investigate the kinking behaviour of this model.

2. Micro modelling

Two finite element analyses were performed for two types of carbon fiber reinforced polymer: IM7/8551-7 and AS4/8551-7. Fig. 1 shows the 3D micro model used in the analysis. The diameter of the cylindrical fibers were $d = 5.2\ \mu m$ for IM7 carbon fiber and $d = 7.1\ \mu m$ for AS4 carbon fiber. A fiber volume fraction of $v = 57\%$ is considered for both models. The mechanical properties of the selected materials are listed in Tables 1 and 2. A change in

Table 1
Mechanical properties of IM7 and AS4 carbon fibers as used in the numerical models, from Kaddour and Hinton [15] and Hinton et al. [13].

	IM7 carbon fiber	AS4 carbon fiber
d (μm)	5.2	7.1
E_1 (GPa)	276	225
E_2 (GPa)	19	15
G_{12} (GPa)	27	15
G_{23} (GPa)	7	7
υ_{12}	0.2	0.2
υ_{13}	0.2	0.2
$\varepsilon_{11}^{f,t}$ (%)	1.87	1.49
$\sigma_{11}^{f,t}$ (MPa)	5180	3350

the compressive strength was observed by changing the size of the micro models, see Prabhakar and Waas [22]. To avoid this change, the sizes of the two calculated computational models are selected in a systematic manner by keeping a fixed aspect ratio between the dimensions of the models, see Table 3.

8-node brick elements were used for the finite element discretization. The commercial implicit Finite Element Analysis (FEA) software Abaqus/Standard, see Hibbit et al. [12], was employed and the isotropic elastic–plastic model for the epoxy resin and the orthotropic model for the fibers were implemented in an user defined subroutine (UMAT). Because of the expected sharp snap-back of the stress–strain response, the arc-length control method is used to determine the unstable path of this curve. A schematic of the boundary conditions is shown in Fig. 2. A compressive load is applied to the top face (T) of the model parallel to the fiber, while the boundary conditions for the micro mechanical model are applied at nodal positions, so that the bottom face (B) is fixed in x-direction and the left corner is fixed in y-direction.

2.1. Elastic–plastic material model for epoxy resin

The plastic behavior of epoxy resin exhibits a prominent pressure dependency, which results in a completely different yielding behavior in tension, shear and compression. Under uniaxial and biaxial tension, epoxy resin is quite brittle, however, a pronounced ductile behavior can be observed under shear and uniaxial compression, Schlimmer and Troost [26], Rolfes et al. [24] and Vogler [27]. Not only the plastic behavior, but also failure and material softening depend on triaxiality. To account for these effects, a phenomenological material model proposed by Ernst et al. [5] is used, which is based on models proposed by Raghava et al. [23], Schlimmer and Troost [26], Fiedler et al. [7] and Vogler et al. [28].

Due to the different yielding behavior under uniaxial tension, uniaxial compression and simple shear, a plasticity model with a

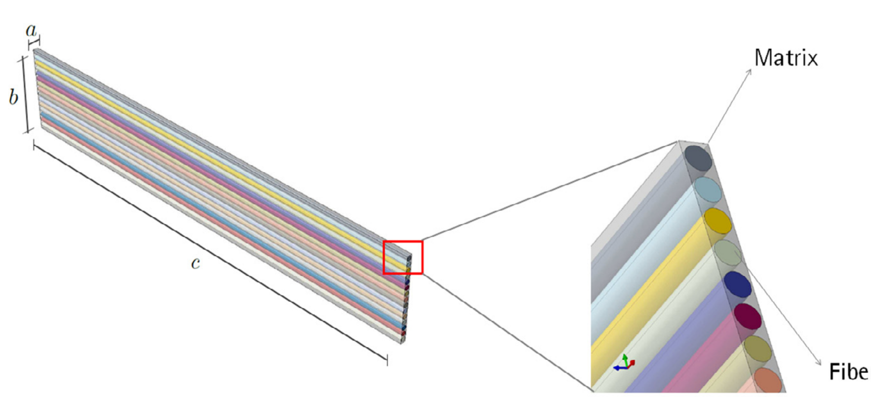

Fig. 1. Micro model consisting of cylindrical fiber and matrix.