Mechanics of Materials 99 (2016) 37–52

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Research paper

Micromechanical modeling and characterization of damage evolution in glass fiber epoxy matrix composites

Zhiye Li[a], Somnath Ghosh[b,*], Nebiyou Getinet[c], Daniel J. O'Brien[c]

[a] Department of Civil Engineering, Johns Hopkins University, Baltimore, MD 21218, United States
[b] Department of Civil, Mechanical and Materials Science & Engineering, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, United States
[c] Composite and Hybrid Materials Branch, U.S. Army Research Laboratory, Aberdeen, MD 21001, United States

ARTICLE INFO

Article history:
Received 6 March 2016
Revised 8 May 2016
Available online 20 May 2016

Keywords:
Glass fiber
Epoxy matrix
Non-local continuum damage mechanics
Strain-rate dependent
Cohesive zone models
RVE

ABSTRACT

This paper develops an experimentally calibrated and validated 3D finite element model for simulating strain-rate dependent deformation and damage behavior in representative volume elements of S-glass fiber reinforced epoxy-matrix composites. The fiber and matrix phases in the model are assumed to be elastic with their interfaces represented by potential-based and non-potential, rate-dependent cohesive zone models. Damage, leading to failure, in the fiber and matrix phases is modeled by a rate-dependent non-local scalar CDM model. The interface and damage models are calibrated using experimental results available in the literature, as well as from those conducted in this work. A limited number of tests are conducted with a cruciform specimen that is fabricated to characterize interfacial damage behavior. Validation studies are subsequently conducted by comparing results of FEM simulations with cruciform and from micro-droplet experiments. Sensitivity analyses are conducted to investigate the effect of mesh, material parameters and strain rate on the evolution of damage. Furthermore, their effect on partitions of the overall energy are also explored. Finally the paper examines the effect of microstructural morphology on the evolution of damage and its path.

1. Introduction

The utilization of glass-fiber epoxy-matrix based composites in a variety military and commercial applications, e.g. rotor-craft yokes and prop-rotor blades, is substantial. Noteworthy among these are the S-glass fiber reinforced composites, containing magnesium alumino-silicate or borosilicate fibers, that are known for their high stiffness and strength to weight ratio, impact resistance, and durability under extreme temperature or corrosive environments. Design of these materials for various structural applications, subject to dynamic loading conditions require considerations of a complex mix of properties contributing to weight, performance and reliability. Robust modeling, accounting for microstructural details, as well as material and interfacial properties, is an indispensable ingredient of the material design process. These models are crucial in unraveling the underpinnings of microstructure-property relationships.

The mechanical and damage response of fiber-reinforced polymeric composites depend on the microstructural morphology, as well the material and interfacial properties. Damage mechanisms are particularly sensitive to the local morphology, e.g. spatial distribution, size and interfacial strength. For dynamic conditions, strain-rate dependent material properties govern both the mechanical and damage behavior. While rate-dependent material properties have been extensively investigated for metals over a wide range of strain-rates, there is a paucity of information on experimentally observed strain-rate effects on mechanical and failure behavior of reinforced composites. For glass-fiber epoxy matrix composites, studies at a range of strain-rates have been conducted (e.g, in Davies and Magee, 1975; Lifshitz, 1976; Okoli and Smith, 2000; Staab and Gilat, 1995; Shokrieh and Omidi, 2009). Some of these studies demonstrated that while the elastic stiffness and failure strain are less sensitive to the strain rate, the dynamic failure stress could be $20-30\%$ higher than the static failure stress. Also, larger damaged regions have been observed with increasing strain-rates.

A variety of micro-mechanical computational models, using e.g., the finite element method, have been developed to predict deformation and failure in composite micro-structures. A number of these models define representative volume elements (RVEs) or statistically equivalent RVEs (SERVEs) of the microstructure as computationally tractable reductions of the actual microstructure. A majority of damage studies in composite materials use unit cell

---

* Corresponding author. Fax: +1 410 516 7473.
E-mail address: sghosh20@jhu.edu (S. Ghosh).

http://dx.doi.org/10.1016/j.mechmat.2016.05.006
0167-6636/

models implying periodic repetition of single cells. Incorporating the material constitutive relations and damage mechanisms along with appropriate boundary conditions, the micro-mechanical RVE/SERVE problems are solved for deformation and failure behavior, (e.g. in Voyiadjis et al., 2002, Ghosh et al. (2000)). Continuum damage mechanics (CDM) models have been used to represent the evolution of defect distribution, where an effective damage variable (either scalar or tensor) is used to depict material degradation leading to crack nucleation and propagation (Chaboche, 1981; Kachanov and Krajcinovic, 1987; Lemaitre and Chaboche, 1990; Nemat-Nasser and Hori, 1999). Micro-mechanics-based CDM approaches have been used to analyze RVE failure in Lene and Leguillon, 1982, Chaboche et al. (1998) Jain and Ghosh (2008), Chen and Ghosh (2012). On the other hand, initiation and growth of fiber-matrix interfacial de-bonding has been modeled with the cohesive volumetric finite element methods (e.g. in Needleman, 1992; Tvergaard, 1991; Costanzo et al., 1996; Geubelle, 1995). Two classes of cohesive zone traction-separation laws have emerged, viz. the potential-based model (e.g. in Park and Paulino, 2012) and non-potential model (e.g. in Needleman, 1992; Lin et al., 2001). In the potential-based models, the traction-separation relationships across the crack surface are obtained from a potential function that characterizes the normal and tangential fracture energy. The two-dimensional Voronoi cell finite element method (VCFEM) has been developed in Ghosh et al., 2000; Swaminathan and Ghosh, 2006; Ghosh, 2011 for modeling large micro-regions of reinforced composites undergoing interfacial decohesion and concurrent matrix cracking. The VCFEM models are able to provide a good understanding of the effect of different morphologies and constituent material properties on the overall cracking and failure behavior of complex multi-inclusion micro-structures.

The present paper develops a 3D micro-mechanical finite element model for simulating deformation and damage behavior in RVEs of S-glass fiber reinforced epoxy-matrix composites undergoing rate-dependent loading. The overall objective is to develop a modeling framework that can delineate failure characteristics of this class of materials at the micro and meso-scales. These models can be subsequently used in hierarchical and concurrent multi-scale models developed (e.g. in Ghosh et al., 2007; Ghosh, 2011; Massart et al., 2007; Fish, 2013).

The fiber and matrix phases in the model are assumed to be elastic with their interfaces are represented by potential-based and non-potential, rate-dependent cohesive zone models. Specifically a non-potential bilinear model (Ortiz and Pandolfi, 1999) and a potential-based PPR model (Park and Paulino, 2012) are implemented for interface characterization. Damage, leading to failure, in the fiber and matrix phases is modeled by a rate-dependent non-local scalar CDM model. The interface and damage models are calibrated using experimental results available in the literature, as well as from those conducted in this work. A limited number of tests in this study are conducted with a cruciform specimen that is fabricated to characterize interfacial damage behavior. Validation studies are subsequently conducted by comparing results of FEM simulations with experiments. Sensitivity analyses are conducted to investigate the effect of mesh, material parameters and strain rate on the evolution of damage. Furthermore, their effect on partitions of the overall energy are also explored. Finally the paper examines the effect of microstructural morphology on the evolution of damage and its path.

2. Micro-mechanical model of the Representative Volume Element

The representative volume element or RVE is defined as a micro-scale sub-domain, on which volume average of variables are taken to yield macro-scale model variables (Drugan and Willis, 1996; Kouznetsova et al., 2002; Kanit et al., 2003; Jain and Ghosh, 2008; Chen and Ghosh, 2012). The choice of the RVE depends on the material property of interest and can vary from one class of properties to another. Statistically equivalent RVEs have been developed from detailed characterization studies of non-uniformly distributed micro-structures in Swaminathan et al., 2006, Swaminathan and Ghosh, 2006. In this section, the RVE of a uniformly distributed unidirectional composite, shown in Fig. 1, is simulated for calibrating and validating the material constitutive and damage properties of the fiber-reinforced composite that will be modeled in this paper. In Fig. 1(c) the RVE is represented by a cuboidal matrix containing a cylindrical fiber with a cohesive fiber-matrix interface that is characterized by cohesive zone models (Lee and Mal, 1998; Jain and Ghosh, 2008; Chen and Ghosh, 2012).

Assuming periodicity of the RVE, the FEM model in Fig. 1(c) is subjected to incremental periodic boundary conditions. Following procedures in Pellegrino et al., 1999; Segurado and Llorca, 2002, the macroscopically applied strain increment on the RVE ΔE_{ij}, is obtained by decomposing the displacement increment ΔU_i on the RVE boundary into an RVE-averaged term and a periodically perturbed term, expressed as:

$$\Delta U_i = \Delta E_{ij} X_j + \Delta \breve{U}_i \tag{1}$$

The periodic displacement component $\Delta \breve{U}_i$ is equal for corresponding nodes on opposite faces of the RVE, e.g. nodes n_1 and n_2 in Fig. 1(b). Accordingly, the total displacements at the corresponding node-pair (n_1, n_2) are related in terms of the macroscopic strain increment as:

$$(\Delta U_i)_{n_2} - (\Delta U_i)_{n_1} = \Delta E_{ij}\left[\left(X_j\right)_{n_2} - \left(X_j\right)_{n_1}\right] \tag{2}$$

where $\left(X_j\right)_{n_1}$ and $\left(X_j\right)_{n_2}$ are coordinates of the node-pair on the RVE boundary. Details of implementation in commercial software for the dynamic simulations is given by Wu and Koishi, 2009. The validity of applying periodical boundary condition for moderate strain-rates has been tested in Chen and Ghosh, 2012.

2.1. Constitutive and damage models for the fiber and matrix phases in the microstructure

Constitutive models for the matrix and fiber phases, and models representing damage in the matrix and fiber phases including fiber-matrix interfacial de-cohesion, are briefly discussed in this section. The fiber material typically considered in this study is glass while the matrix is an epoxy material, discussed later. Both phases are represented by an infinitesimal strain, linear elastic-damage constitutive framework for their deformation and damage behavior. A finite rotation framework is adopted to allow for the relative motion between multiple phases. In an incremental/rate formulation, the coupled constitutive-damage relations for an isotropic material are expressed in an un-rotated configuration as:

$$\dot{\sigma}_{ij} = C_{ijkl}(D)\dot{\varepsilon}_{kl} \qquad \text{stress-strain relation} \tag{3a}$$

$$\dot{\sigma}_{ij} = R_{ki}\dot{\sigma}^{sp}_{kl}R_{lj},\ \dot{\varepsilon}_{ij} = R_{ki}\dot{\varepsilon}^{sp}_{kl}R_{lj} \qquad \text{un-rotated stress, strain} \tag{3b}$$

$$F_{ij} = \frac{\partial x_i}{\partial X_j} = R_{ik}U_{kj} \qquad \text{RU decomposition} \tag{3c}$$

$$C_{ijkl}(D) = 2G(D)\delta_{ik}\delta_{jl} + \left(K(D) - \frac{2}{3}G(D)\delta_{ij}\delta_{kl}\right) \text{elastic stiffness} \tag{3d}$$

$$G = E/[2(1+\nu)]\,\text{and}\,K = E/[3(1-2\nu)]$$

$$E = (1-D)^2E^0 \qquad \text{Damage-stiffness relation} \tag{3e}$$