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A micro–meso-model of intra-laminar fracture in fiber-reinforced composites based on a discontinuous Galerkin/cohesive zone method

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ABSTRACT

The recently developed hybrid discontinuous Galerkin/extrinsic cohesive law framework is extended to the study of intra–laminar fracture of composite materials. Toward this end, micro-volumes of different sizes are studied. The method captures the debonding process, which is herein proposed to be assimilated to a damaging process, before the strain softening onset, and the density of dissipated energy resulting from the damage (debonding) remains the same for the different studied cell sizes. Finally, during the strain softening phase a micro-crack initiates and propagates in agreement with experimental observations. We thus extract a resulting mesoscale cohesive law, which is independent on the cell sizes, using literature methods.

1. Introduction

The engineering fracture theories developed for homogeneous materials cannot always be directly applied when considering new engineered heterogeneous materials, such as composites. Indeed, fracture mechanisms of composites are complex and require a multiscale approach: from the microscale within a ply to the laminate macroscale. Although some numerical solutions have been developed to address these particular topics, such as the damage-based micro–meso–macro-approaches for composites proposed by Ladevèze et al. [1], or such as purely numerical approaches as discussed by LLorca et al. [2], it is still challenging to predict explicitly the composite fracture behavior using microscale simulations.

One way to predict a mesoscale fracture criterion from numerical simulations at the microscale is to analyze the microscale deformation mechanisms using finite elements combined to models accounting for the fracture processes ranging from micro-crack initiation to micro-crack propagation. A natural way to achieve this goal is to enhance the finite-element model with the so-called cohesive zone method (CZM).

The cohesive zone method was pioneered by Barenblatt [3] and Dugdale [4] to introduce traction between crack lips during the separation process. In particular in Barenblatt's model the traction separation law (TSL) decreases monotonically

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Nomenclature

$\boldsymbol{A}$	orthotropy direction in initial configuration
$\boldsymbol{B}$	volume forces
C	right Cauchy tensor
$\mathbb{C}$	material tensor
d_f	fibers diameter
E	Young's modulus
E_L	longitudinal Young modulus
E_T	transverse Young modulus
$\mathbf{f}_{\text{ext}a}$	nodal external forces
$\mathbf{f}_{\text{I}a}$	nodal interface forces
$\mathbf{f}_{\text{int}a}$	nodal internal forces
$\mathbf{F}$	deformation gradient
$\mathbf{F}^e$	elastic deformation gradient part
$\mathbf{F}^p$	plastic deformation gradient part
G	energy release rate
$\mathcal{G}$	compliance tensor
$\mathcal{G}_0$	initial compliance tensor
G_C	fracture energy
G_{LT}	longitudinal transverse shear modulus
G_{TT}	transverse shear modulus
h	hardening modulus
h_k	height of a k by k-fiber cell
I_j	jth invariant
j	Jacobian
K	kinetic energy
K_{IC}	mode I fracture toughness
K_{IIC}	mode II fracture toughness
L_k	length of a k by k-fiber cell
m	fifth transverse anisotropy parameter
$\mathbf{M}_{ab}$	nodal mass matrix
n	sixth transverse anisotropy parameter
$\boldsymbol{N}$	outward normal in the reference configuration
$\boldsymbol{N}^-$	outward normal of the minus element
N_a	shape function a
p	accumulated plastic strain
$\mathbf{P}$	first Piola Kirchhoff stress tensor
$\boldsymbol{t}$	tangential opening direction
$\bar{t}$	surface traction amplitude per unit deformed surface
t_k	thickness of a k by k-fiber cell
$\bar{t}_{\max}$	surface traction reached at maximum opening
$\bar{\boldsymbol{t}}$	surface traction per unit deformed surface
$\bar{\boldsymbol{t}}^-$	surface traction of the minus element
t^n	time at time step n
T	time interval
$\mathbf{T}$	surface traction per unit reference surface
$\boldsymbol{u}$	displacement field
$\boldsymbol{u}_a$	nodal displacements
$\boldsymbol{u}^{\text{m}}$	micro-displacement
$\boldsymbol{u}^{\text{M}}$	mesoscale opening
$\boldsymbol{u}^0_{\text{m}}$	compatibility displacement
$\bar{\boldsymbol{u}}$	prescribed displacement field
$\boldsymbol{w}_u$	trial functions
W_{ext}	work of external forces
W_{int}	work of internal forces
$\boldsymbol{x}_a$	nodal current position
$\boldsymbol{X}$	material position
$\boldsymbol{X}_a$	initial nodal position
α	Boolean changing at fracture onset
α_M	first Chung–Hulbert parameter

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