Composite Structures 131 (2015) 425–432

Contents lists available at ScienceDirect

Composite Structures

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

A micropolar cohesive damage model for delamination of composites

Md.M. Rahaman [a], S.P. Deepu [a], D. Roy [a,*], J.N. Reddy [b]

[a] Computational Mechanics Lab, Department of Civil Engineering, Indian Institute of Science, Bangalore 560012, India
[b] Advanced Computational Mechanics Lab, Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843-3123, United States

ARTICLE INFO

Article history:
Available online 14 May 2015

Keywords:
Micro-rotations
Micropolar cohesive law
Length scales
Mesh-free methods

ABSTRACT

A micropolar cohesive damage model for delamination of composites is proposed. The main idea is to embed micropolarity, which brings an additional layer of kinematics through the micro-rotation degrees of freedom within a continuum model to account for the micro-structural effects during delamination. The resulting cohesive model, describing the modified traction separation law, includes micro-rotational jumps in addition to displacement jumps across the interface. The incorporation of micro-rotation requires the model to be supplemented with physically relevant material length scale parameters, whose effects during delamination of modes I and II are brought forth using numerical simulations appropriately supported by experimental evidences.

1. Introduction

Delamination is a commonly encountered mode of failure in laminated composite structures. Onset and propagation of delamination generally result in considerable reduction in the load carrying capacity, possibly triggering sudden structural collapse. Prediction of delamination initiation and its propagation have thus become topics of contemporary research interest, especially as composites are being extensively used in critically important aerospace structures and defense industries, among others. This has spawned a considerable literature that deals with theoretical modeling and experimental investigations, yielding a number of criteria for delamination initiation and propagation. However, only few of these are based on the physical mechanisms at the micro-structural level that cause inter-laminar fracture, even as one anticipates that an accurate prediction of delamination in real world applications should be woven around a physically consistent failure criterion. This is motivation enough for proposing a micromechanically founded delamination criterion incorporating intrinsic length scales and forms the aim of the present study.

A review of the literature reveals two existing approaches in modeling delamination. While the first one broadly works within the classical fracture mechanics setting, the second poses the problem as one in damage mechanics, softening plasticity, or a combination of the two [1]. The first approach, which employs classical fracture mechanics, uses stress-based criteria to predict delamination initiation [2,3], and techniques based on linear elastic fracture mechanics (LEFM) such as virtual crack closure technique (VCCT) [4–8], J-integral method [9], virtual crack extension [10], or stiffness derivative [11] to model delamination propagation. However, finite element (FE) implementations of the LEFM techniques are fraught with difficulties, especially as the simulation of delamination growth may require complex moving mesh techniques [12]. Also, the calculation of fracture parameters makes use of the nodal variables as well as the topological information from the nodes behind and ahead of the crack front, computations of which are extremely cumbersome when a progressive crack growth is involved [13]. Many of these difficulties may be readily overcome if recourse is taken to the framework of damage mechanics. The concept of cohesive zone modeling (CZM), [14–16] is the most widely used interface damage model for the numerical simulation of delamination. The CZM relates the traction and displacement jump occurring at the interface between two layers. This model facilitates the integration of both delamination initiation and propagation. Decohesion elements provide appropriate criteria for the initiation and propagation of delamination without the prior knowledge of the crack location and propagation direction, thereby predicting the non-self-similar delamination growth [17]. Although, The FE implementation using decohesion elements is quite straightforward [18–23], it allows for a mesh-independent representation of material softening only with a very refined mesh [24]. Moreover, the FE analysis faces convergence issues when the interfacial strength is higher [26].

Many of these limitations could be overcome if mesh-free shape functions are used in lieu of the conventional FE bases [27], as they enable the introduction of a numerical length scale through the radius of the kernel used in the integral function representation.

* Corresponding author.
E-mail address: royd@civil.iisc.ernet.in (D. Roy).

http://dx.doi.org/10.1016/j.compstruct.2015.05.026
0263-8223/

Useful though it is, such a model by itself does not include the intrinsic length scale parameter to reflect on the micromechanics of delamination. It would thus appear that there is a need to fall back on a lower scale cohesive zone modeling when the geometric length scale is smaller compared to the cohesive length scale [34]. Clearly, then, a more accurate prediction of delamination is not ensured by the mere deployment of mesh-free shape functions alongside the traditional CZM.

The objective of this work is to develop a physically consistent micropolar cohesive damage model that could be used to predict, possibly with enhanced accuracy, delamination initiation and propagation. The organization of the rest of the paper goes as follows. Section 2 briefly describes the micropolar elasticity theory used in this work and the construction of the micropolar cohesive model for delamination of composites. Equations of equilibrium and their discretization are presented in Section 3. This is followed by numerical illustrations and concluding remarks in Sections 4 and 5, respectively.

2. Micropolar model for delamination

2.1. Basic equations of micropolar elasticity

In a micropolar continuum, besides the usual displacement vector field u, an additional field of micro-rotation vector φ is introduced. This micro-rotation is different from macro-rotation, which is the curl of the displacement vector u. The introduction of micro-rotation results in an asymmetric strain tensor ε and a micro-curvature tensor κ (the latter also called the wryness tensor) given by (see [39])

$$\varepsilon_{ij} = \frac{\partial u_j}{\partial x_i} - e_{ijk}\varphi_k \tag{1}$$

$$\kappa_{ij} = \frac{\partial \varphi_j}{\partial x_i} \tag{2}$$

where e_{ijk} denote components of the third order permutation tensor. The strain tensor ε and the micro-curvature tensor κ are work conjugates to the asymmetric stress tensor σ and the couple stress tensor μ respectively; see [28–32,39] for a more detailed exposition. The constitutive equations for linear micropolar elasticity are given as

$$\sigma_{ij} = D_{ijkl}\varepsilon_{kl} \tag{3}$$

$$\mu_{ij} = \Psi_{ijkl}\kappa_{kl} \tag{4}$$

For materials like composites, which are of current interest, the constitutive tensors $\mathbf{D}$ and Ψ typically correspond to the anisotropic micropolar elasticity, an account of which may be found in Lesen [40]. It so happens that the anisotropy of composites modeled as a micropolar continuum may often be described as orthotropic for the conventional stress and isotropic for couple stress [38].

Delamination analysis may be performed based on a two-dimensional plane strain problem as suggested by Alfano and Crisfield [1]. Presently, the constitutive equations for the micropolar plane strain problem are chosen to be in the form:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \\ \sigma_{21} \\ \mu_{13} \\ \mu_{23} \end{bmatrix} = \begin{bmatrix} \frac{1-\nu_{32}\nu_{23}}{E_2E_3D_c} & \frac{\nu_{21}+\nu_{31}\nu_{23}}{E_2E_3D_c} & 0 & 0 & 0 & 0 \\ \frac{\nu_{12}+\nu_{13}\nu_{32}}{E_1E_3D_c} & \frac{1-\nu_{31}\nu_{13}}{E_1E_3D_c} & 0 & 0 & 0 & 0 \\ 0 & 0 & (G_{12}+G_m) & (G_{12}-G_m) & 0 & 0 \\ 0 & 0 & (G_{12}-G_m) & (G_{12}+G_m) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2Gl^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2Gl^2 \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \\ \varepsilon_{21} \\ \kappa_{13} \\ \kappa_{23} \end{bmatrix} \tag{5}$$

where

$$G = \frac{E_1}{2(1+\nu_{12})} \tag{6}$$

$$D_c = \frac{1-\nu_{12}\nu_{21}-\nu_{23}\nu_{32}-\nu_{13}\nu_{31}-2\nu_{21}\nu_{32}\nu_{13}}{E_1E_2E_3} \tag{7}$$

G_{12}, l and G_m are respectively the shear modulus, internal length scale parameter for the laminate and micropolar shear modulus, with ν_{ij} (i, j = 1, 2 and 3) denoting the Poisson's ratios. The symmetry of the constitutive matrix is ensured by using the reciprocal relations

$$\frac{E_{ij}}{\nu_i} = \frac{E_{ji}}{\nu_j} \quad \text{(no sum over } i \text{ and } j) \tag{8}$$

Note that a plane stress anisotropic micropolar model can be obtained by the following changes in Eq. (5).

$$\frac{1-\nu_{32}\nu_{23}}{E_2E_3D_c} \to \frac{E_1}{1-\nu_{12}\nu_{21}} \tag{9}$$

$$\frac{\nu_{21}+\nu_{31}\nu_{23}}{E_2E_3D_c} \to \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} \tag{10}$$

$$\frac{\nu_{12}+\nu_{13}\nu_{32}}{E_1E_3D_c} \to \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} \tag{11}$$

$$\frac{1-\nu_{31}\nu_{13}}{E_1E_3D_c} \to \frac{E_2}{1-\nu_{12}\nu_{21}} \tag{12}$$

The length scale parameter l in the constitutive model attempts at bridging the micro- mechanics with the macro-continuum by enabling the micro-rotation terms in the governing equations. One may observe that the rotational stiffness becomes smaller for smaller values of l with the stress tensor regaining its symmetric nature when G_m equals zero [30]. Thus one recovers the classical continuum as a limiting case of the micropolar theory.

2.2. Micropolar cohesive law

At the interface where delamination is known to initiate and propagate, the classical traction separation law provides for the relevant constitutive equations by relating the cohesive surface traction, τ to the displacement jump, Δ .This phenomenological model, also known as the cohesive law or the decohesion law, is popularly used to model the crack surfaces (see [13,24,17,34] for a state-of-the-art on CZM). Over a period of time, Dugdale [14], Needleman [34], Rice and Wang [43], Tvergaard [41], Tvergaard and Hutchinson [42], Xu and Needleman [46], Camacho and Ortiz [44], Geubelle and Baylor [47] et al. have proposed several versions of the CZM, which are tabulated in Chandra et al. [45].

Of interest here is a modified traction separation law that accommodates the micropolar continuum. Accordingly, in addition to the usual stress tractions and displacement jumps, couple-stress tractions and rotational jumps must also be considered. The resulting CZM, which incorporates material length scale parameters, is referred to as the micropolar cohesive zone model (MCZM). In the micropolar traction separation law, Eq. (13) relating the stress traction and the displacement jump is supplemented with Eq. (14), which relates the couple traction τ_θ with the rotation jump Δ_θ through the intrinsic cohesive surface length scale (l_c)

$$\tau_i = K_p(1-D)\Delta_i \quad i = n, t \tag{13}$$

$$\tau_\theta = K_p(1-D)l_c^2\Delta_\theta \tag{14}$$