Composites Science and Technology 72 (2012) 269–277

Contents lists available at SciVerse ScienceDirect

Composites Science and Technology

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

A generic approach to constitutive modelling of composite delamination under mixed-mode loading conditions

Irene Guiamatsia *, Giang D. Nguyen

The University of Sydney, School of Civil Engineering, Sydney, NSW 2006, Australia

ARTICLE INFO

Article history:
Received 29 August 2011
Received in revised form 27 October 2011
Accepted 11 November 2011
Available online 25 November 2011

Keywords:
A. Polymer–matrix composites
B. Delamination
B. Plastic deformation
C. Damage mechanics
Cohesive model

ABSTRACT

A generic approach to constitutive modelling of composite delamination under mixed mode loading conditions is developed. The proposed approach is thermodynamically consistent and takes into account two major dissipative mechanisms in composite delamination: debonding (creation of new surfaces) and plastic/frictional deformation (plastic deformation of resin and/or friction between crack surfaces). The coupling between these two mechanisms, experimentally observed at the macro scales through the stiffness reduction and permanent crack openings, is usually not considered in depth in many cohesive models in the literature. All model parameters are shown to be identifiable and measurable from experiments. The model prediction of mixed-mode delamination is in good agreement with benchmarked mixed-mode bending experiments. It is further shown that accounting for all major dissipative mechanisms in the modelling of delamination is the key to the accurate prediction of both resistance and damage of the interface.

1. Introduction

In fibre-reinforced polymer composites, the interfacial region between plies of different orientations is particularly vulnerable to damage, due to the increased likelihood of voids and defects. Because of the geometrical constraint of stiff fibres in adjacent plies, delaminating cracks are constrained to evolve within the resin-rich interface which typically has very little resistance to fracture growth. Consequently, this mode of failure can easily lead to catastrophic loss of the structural integrity of a laminated composite component. Therefore, it is crucial, in the modelling of delamination, to accurately predict both the resistance and damage induced delamination of the interfacial region.

Experimental evidence [1,2] shows that the nature of delamination, including the associated energy loss, is strongly dependent on the fracture properties of the polymeric resin. Thermoset epoxies, preferred in the early days due to their superior manufacturing and in-service properties, are gradually being replaced by thermoplastic or particulate-enhanced resins, which offer higher fracture toughness thanks to substantial plastic deformation. Large permanent crack openings, a testimony of frictional/plastic dissipation at the crack faces, have been witnessed in experiments presented by Fan [3] on mixed-mode bending (MMB) tests and Rikards et al. [4] on double-cantilever beam (DCB) tests on composite laminates with fibre surface treatment. Not only is the plastic/frictional dissipation concomitant to the actual damage process, as noted by Carlsson et al. [5] for the End-Notched Flexure (ENF) test, but it may also exist *a posteriori*, should the newly created crack surfaces happen to come into contact. The need to consider the irreversible permanent deformation provides a rationale for the development of an improved interface constitutive model that is capable of handling both (i) mixed-mode loading conditions, and (ii) the coupling between debonding and plastic dissipation or friction that is witnessed experimentally.

In the literature, cohesive zone models have been widely used for the prediction of interfacial behaviour of laminated composites [10–19]. The combination of both strength and fracture criteria in these models give them advantages over models based on linear elastic fracture mechanics or virtual crack closure technique (e.g. [6,7]). The issue of mode interaction under mixed-mode loading has been treated with such strategies as a fully coupled interface stiffness matrix [12] or equivalent mixed-mode interface separation [13]. Furthermore, to handle the variable mode ratio that occurs in realistic loading situations, Turon et al. [14] proposed a strategy akin to switching between constitutive laws that are computed, *a priori*, under conditions of fixed-mode mixity. Although having gained in popularity to the extent of being considered as "standard models" for composite delamination, most existing cohesive models in the literature are based on damage theory and do not take into account the plastic/frictional dissipation. This treatment is appropriate only if this dissipative mechanism is negligible compared to the release of energy due to the creation of new surface areas, which is not always the case. It has been recently

* Corresponding author. Tel.: +61 2 9351 2134; fax: +61 2 9351 3343.
E-mail addresses: irene.guiamatsia@sydney.edu.au, irene.guiamatsia@utoronto.ca (I. Guiamatsia).

0266-3538/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2011.11.012

shown [8] that overlooking the plastic/frictional dissipation, even in pure mode I, leads to inaccurate prediction of the damage state, even when the structure's resistance can be well predicted. It is therefore rational to question the capability of damage-based cohesive models in predicting interfacial damage.

In the context of delamination modelling, there are not many cohesive models possessing coupling behaviour between damage and plasticity. In fact, Schipperen and De Borst [30] suggested, by comparing a pure damage model to two coupled damage/plasticity models (isotropic and orthotropic hardening), that pure damage models are computationally more efficient and just as accurate in terms of predicting the extent of delamination. It will be shown that, because friction and fracture are both dissipative mechanisms contributing to the interface damage process, a numerical model for delamination can only have true predictive capabilities if those physical mechanisms are adequately accounted for. For instance, Tvergaard and Hutchinson [32] proposed a traction separation law where the post-peak regime consisted of a region of pure plastic yielding followed by softening. More recently, Kolluri [22] followed the same principle by introducing a parameter, called the plastic limit, defining the boundary between pure plastic dissipation and pure damage dissipation. Su et al. [31] presented a formulation with separate yield functions for the normal and shear failure modes and a mixed-mode coupling parameter linking only the two plastic dissipations but resulting in a non-smooth yield surface that could cause numerical difficulties. The reader is also referred to Scheider [21] for a more extensive review of the literature on cohesive models. Existing coupled damage/plasticity models primarily aim to reproduce a particular form of the traction versus separation response that may be observed experimentally. Hence, the most common strategies are either to make use of phenomenological functions to fit the interface constitutive response, or enhancing classical plasticity models with stiffness reduction to capture the unloading response. Although these approaches (e.g. in [22]) are able to successfully produce the observed permanent deformation and stiffness reduction, the coupling parameter is usually not easy to identify, let alone calibrate. This is because the connection between the dissipative mechanisms represented by damage and plasticity remains unclear in those coupled models.

In this study, the development of cohesive zone models is approached from a different angle underpinned by physically based concepts and fundamentals. The formulation of a new class of cohesive models is put in a thermodynamic framework featuring strong coupling between different dissipative mechanisms [9]. The resulting constitutive models are thermodynamically consistent and possess contributions from damage and plastic/frictional mechanisms. Emphasis is put on establishing links between the coupled dissipative processes and a measurable quantity: the ratio between the damage dissipation and the total fracture energy. The mode interaction is adequately dealt with, thanks to the use of an explicitly defined dissipation potential. The proposed approach allows different experimentally observed strength and fracture criteria to be incorporated to guide the model predictive capability in mixed mode loading conditions.

The paper is organised as follows. First a general framework for the development of cohesive models featuring coupling between normal and shear modes, as well as between damage and plasticity, is presented. A cohesive model is derived from the general formulation using typical strength and fracture criteria in the literature. Its behaviour is then assessed in pure and variable mode loading conditions. The parameter identification shows that it is able to calibrate all parameters from experiments. This model was implemented in the finite element package ABAQUS/Explicit [23] and used for the prediction of failure in mixed-mode delamination benchmarks available in the literature. The importance of accounting for all major dissipative mechanisms in the constitutive modelling and its consequence in the correct prediction of both resistance and impact-induced delamination is addressed in the simulation of an impact test.

2. A thermo-mechanical formulation

The thermodynamic formulation is based on earlier developments [8,9], where further details can be found. The following expression for the Helmholtz energy potential is proposed:

$$\Psi = \frac{1}{2}(1-D)\left[T_n\left(u_n^e\right)^2 + T_s\left(u_s^e\right)^2\right] + \frac{1}{2}DT_n\left\langle -u_n^e\right\rangle^2 \tag{1}$$

where D is a scalar variable representing the interface damage; u is the interfacial separation, connected to the elastic $\left(u_n^e\right)$ and permanent $\left(u_n^p\right)$ parts through the incremental relationship: $\delta u = \delta u^e + \delta u^p$; T_n and T_s are the initial normal and shear stiffnesses of the interface, respectively. The Macauley brackets $\langle\cdot\rangle$ are introduced in the normal direction in order to prevent interpenetration of the crack faces. The interface normal (t_n) and shear (t_s) tractions, and damage energy (χ) are derived from the energy potential as:

$$t_n = \frac{\partial\Psi}{\partial u_n^e} = (1-D)T_n u_n^e - DT_n\left\langle -u_n^e\right\rangle \tag{2}$$

$$t_s = \frac{\partial\Psi}{\partial u_s^e} = (1-D)T_s u_s^e \tag{3}$$

$$\chi = -\frac{\partial\Psi}{\partial D} = \chi_n + \chi_s \tag{4}$$

It can be seen from Eq. (2) that $sgn(t_n) = sgn\left(u_n^e\right)$. The damage energies associated with mode I (χ_n) and II (χ_s) in Eq. (4) can be expressed in terms of elastic strains or stresses and damage as:

$$\chi_n = \frac{1}{2}T_n\left(\left(u_n^e\right)^2 - \left\langle -u_n^e\right\rangle^2\right) = \begin{cases} \frac{t_n^2}{2(1-D)^2T_n}, & t_n > 0 \\ 0, & t_n \leqslant 0 \end{cases} \tag{5}$$

$$\chi_s = \frac{1}{2}T_s\left(u_s^e\right)^2 = \frac{t_s^2}{2(1-D)^2T_s} \tag{6}$$

For a strong coupling between damage and plasticity, the dissipation potential is taken of the form:

$$\Phi = \sqrt{\phi_D^2 + \phi_{np}^2 + \phi_{sp}^2} \tag{7}$$

where the contributions to the dissipation potential from damage ϕ_D and plasticity in normal (ϕ_{np}) and shear (ϕ_{sp}) modes are respectively assumed of the forms:

$$\phi_D = \frac{\sqrt{F(k,D)}\chi\delta D}{cos\alpha}; \quad \phi_{np} = \frac{\sqrt{F(k,D)}t_n\delta u_n^p}{sin\alpha\sqrt{(1-k)\chi}};$$
$$\phi_{sp} = \frac{\sqrt{F(k,D)}t_s\delta u_s^p}{sin\alpha\sqrt{k\chi}} \tag{8}$$

In the above expressions, the mixed-mode ratio k is defined as the ratio between the mode II dissipation and the total dissipation; $F(k,D)$ is a function controlling the damage evolution and α is a parameter governing the coupling between damage and plasticity. The forms and roles of $F(k,D)$ and α will be discussed in the next sections. The stresses and damage energy are given as derivatives of the explicitly defined dissipation potential:

$$\chi = \frac{\partial\Phi}{\partial\delta D} = \frac{\partial\Phi}{\partial\phi_D}\frac{\partial\phi_D}{\partial\delta D} = \frac{\phi_D}{\sqrt{\phi_D^2 + \phi_{np}^2 + \phi_{sp}^2}}\frac{\partial\phi_D}{\partial\delta D} \tag{9}$$

$$t_n = \frac{\partial\Phi}{\partial\delta u_n^p} = \frac{\partial\Phi}{\partial\phi_{np}}\frac{\partial\phi_{np}}{\partial\delta u_n^p} = \frac{\phi_{np}}{\sqrt{\phi_D^2 + \phi_{np}^2 + \phi_{sp}^2}}\frac{\partial\phi_{np}}{\partial\delta u_n^p} \tag{10}$$