Composites Part A 112 (2018) 290–298

Contents lists available at ScienceDirect

Composites Part A

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

Combining interface damage and friction in cohesive interface models using an energy based approach

Zhenmin Zou*, Marwah Hameed

School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Keywords:
Cohesive zone model
Interface element model
Interface damage and friction coupling
Interface stiffness dependence

ABSTRACT

Cohesive zone models coupling interface damage and friction have been developed in the literature and are available in the commercial finite element package ABAQUS to consider the enhancing effect of through-thickness compression on interfacial fracture resistance. It is revealed in this paper that these models are extremely dependent on interface stiffness, because interface stiffness reduction factor is used to combine damage and friction in these models. The interfacial constitutive law converges but only when the interface is extremely stiff and an unrealistic evolution of the interface damage is produced. A new approach is then developed which uses a cohesive energy related parameter to combine interface damage and friction. The behaviour of the new coupled model is independent of the interface stiffness once the interface is moderately stiff. The new and existing damage/friction coupled models have been employed to simulate the shear failure of a composite specimen and the predictions are compared against the experimental data in the literature. The new model produces converged results over a wide range of interface stiffness and the predictions match the experiments quite well, better than the existing models.

1. Introduction

Cohesive zone model is one of the most popular tools for simulating damage in composite structures, such as delamination [1,2], fibre/matrix debonding [3] and adhesive bonding joint failure [4]. In most of the existing cohesive zone models, the effect of through-thickness stress on damage initiation and growth is ignored when the interface is under compression. However, experiments have shown that through-thickness compression increases both the interlaminar shear strength [5] and mode II fracture energy [6]. Excluding this effect will produce an inaccurate prediction of interlaminar damage in composite structures. The direct effect of the through thickness compression is the contact/friction in the damaged interface area. Sitnikova et al. [7] simulated delamination in a laminate subjected to low velocity impact. It was revealed that friction in the delaminated area must be considered in order to capture the intact zone underneath the impactor as commonly observed in experiments.

Tvergaard [3] was the first to introduce friction into the cohesive zone model, but the frictional stress was included only when total decohesion had occurred. On the other hand, some researchers proposed to activate frictional stress in the cohesive zone model from the very beginning of the decohesion process [8]. To achieve a continuous and smooth transition from decohesion to a pure friction state explicitly, a predefined function was used to regulate the addition of frictional stress to the interface shear traction [9,10].

Effort has been made to include friction in cohesive zone model naturally. Based on a meso-mechanical approach, Alfano and Sacco [11] divided a representative elementary area of the interface into a damaged part and an integral part. The relative measure of the damaged area was defined as the damage parameter and friction was assumed to take place only in the damaged part. The classical rule of mixture was then used to combine the contributions from the integral and damaged parts, and so the constitutive law of the interface was established. A seamless transition from pure cohesive behaviour to a purely frictional one is achieved during the damaging process. Similar concept of interface damage/friction coupling has been adopted by the commercial finite element package ABAQUS. A surface-based cohesive contact model is available in ABAQUS [12] in which the cohesive traction separation behaviour is defined as a surface interaction property between a contact pair of surfaces.

Issues arose when the above damage/friction coupled cohesive models in [11,12] were employed to simulate interfacial damage in composites. Alfano and Sacco [11] conducted an interface stiffness sensitivity study when modelling a fibre push out test. The results are nearly independent of the stiffness but only for an extremely stiff interface. It is well known that the traditional cohesive zone model (i.e.

* Corresponding author.
E-mail address: z.zou@manchester.ac.uk (Z. Zou).

https://doi.org/10.1016/j.compositesa.2018.06.017
Received 6 April 2018; Received in revised form 31 May 2018; Accepted 10 June 2018
Available online 15 June 2018

those without damage-friction coupling) produces converged results once the interface stiffness is moderately high, not extremely high. The guidelines for choosing the interface stiffness is that it should be high enough to provide a sufficient connection but low enough to avoid the risk of numerical problem [13]. An excessively stiff interface will cause numerical ill condition. Using the surface-based cohesive model in ABAQUS, Zhang and Zhang [14] simulated delamination in a composite laminate. Their investigation showed that an input of a high friction coefficient, greater than 0.6, is required in order to match the prediction with the experiment, although friction coefficients of similar material measured in other experiment are less than 0.6 [15].

The interface damage/friction coupling method proposed in [11] has been increasingly employed in cohesive zone models by others [16–19]. More and more researchers have used the surface-based cohesive contact model in ABAQUS [12] to simulate damage in composite materials and structures [14,20–22]. There is an urgent need to address the issues encountered by this type of damage/friction coupling in cohesive zone models.

The present study aims to develop a new approach to combine damage and friction naturally in cohesive interface models, but avoid the drawback of the existing damage/friction coupled models in [11,12]. The behaviour of the cohesive zone model in [11] and the surface-based cohesive model in ABAQUS [12] are first analysed to identify the reason behind their extreme dependence on interface stiffness. A new method is then proposed to combine damage and friction in the cohesive model more properly. Finally, the new and existing coupled models are employed to simulate the shear failure of a composite specimen. Predictions are compared against the experimental data in the literature to demonstrate the success of the new method and the advantage of it over the existing approach in [11,12].

2. The existing damage/friction coupling method in cohesive zone models

Combining damage and friction in the cohesive zone model was first proposed by Alfano and Sacco [11]. For simplicity, only the formulation of the model under through-thickness compression is summarised and presented in this section. Based on a meso-mechanics method, a unit representative elementary area (REA) of the interface is partitioned into two parts, a damaged part of an area ω and an undamaged part of an area $(1-\omega)$ as shown in Fig. 1. Friction is assumed to only take place in the damaged part. The relationship between the tractions τ_i and separations δ_i $(i = 1, 2)$ of the interface is then expressed as

$$\tau_1 = k_1\delta_1 \tag{1a}$$

$$\tau_2 = (1-\omega)k_2\delta_2 + \omega\tau_f \tag{1b}$$

where subscripts 1 and 2 represent the normal and shear directions, respectively. k_i is the cohesive stiffness of the interface. τ_f is the frictional stress which is obtained by

$$\tau_f = k_2(\delta_2-\delta_s) \quad \text{if } k_2\ |\delta_2-\delta_s| + \mu\tau_1 < 0,\ \text{sticking occurs} \tag{2a}$$

$$\tau_f = -\mu\tau_1\frac{\delta_2-\delta_s}{|\delta_2-\delta_s|} \quad \text{if } k_2\ |\delta_2-\delta_s| + \mu\tau_1 \geqslant 0,\ \text{sliding takes place} \tag{2b}$$

where μ is the coefficient of friction and δ_s is a frictional sliding displacement. δ_s is zero initially and is updated in the following incremental form

$$d\delta_s = 0 \quad \text{when } k_2\ |\delta_2-\delta_s| + \mu\tau_1 < 0 \tag{3a}$$

$$d\delta_s = \left(|\delta_2-\delta_s| + \frac{\mu\tau_1}{k_2}\right)\times\frac{\delta_2-\delta_s}{|\delta_2-\delta_s|} \quad \text{when } k_2\ |\delta_2-\delta_s| + \mu\tau_1 > 0 \tag{3b}$$

The shear traction τ_2 on the interface in Eq. (1b) is the sum of the cohesive shear stress $\tilde{\tau}_2 = (1-\omega)k_2\delta_2$ and the contribution of frictional stress τ_f. Friction and cohesive damage are coupled by the term $\omega\tau_f$.

The damage parameter ω in the constitutive Eq. (1) defines the effective cohesive stiffness $(1-\omega)k_2$ of the interface. When the bilinear cohesive traction-separation law as shown in Fig. 1 is employed, the damage evolution law is expressed as

$$\omega = \max_{\text{history}}\tilde{\omega} \quad \text{and} \quad \tilde{\omega} = \max\left\{0,\ \min\left\{1,\ \frac{\delta_{2f}(\delta_2-\delta_{2o})}{\delta_2(\delta_{2f}-\delta_{2o})}\right\}\right\} \tag{4}$$

where δ_{2o} and δ_{2f} are separations at damage initiation and full damage, respectively. They are related to the interface shear strength τ_{2c} and mode II fracture energy G_{2c} as follows

$$\delta_{2o} = \tau_{2c}/k_2 \quad \text{and} \quad \delta_{2f} = 2G_{2c}/\tau_{2c} \tag{5}$$

It can be seen in Fig. 1 that the ratio between δ_{2o} and δ_{2f} defines the shape of the bilinear cohesive law. Because δ_{2o} depends on the initial stiffness k_2 of the interface, a method is proposed in the present paper to describe how stiff an interface is. The interface is considered as: (a) extremely stiff if $\delta_{2o}/\delta_{2f} \leqslant 0.001$; (b) stiff when $0.001 < \delta_{2o}/\delta_{2f} \leqslant 0.01$; (c) moderately stiff in the case of $0.01 < \delta_{2o}/\delta_{2f} \leqslant 0.05$; (d) weak if $0.05 < \delta_{2o}/\delta_{2f} \leqslant 0.25$; and (e) very weak when $0.25 < \delta_{2o}/\delta_{2f}$.

In the present work, the behaviour of the above damage/friction coupled interface model under through thickness compression was investigated, using the interface properties given in Table 1. Different values of the initial interface stiffness k_2 were attempted. A constant compressive through thickness stress τ_1 was assigned and the interface was loaded by increasing the shear separation δ_2 monotonically.

When friction is excluded (by setting $\mu = 0$), this interface model reproduces the bilinear traction–separation relationship shown in Fig. 2 as expected. It can be seen that changing interface stiffness k_2 only changes the separation δ_{2o} at damage initiation as indicated in Eq. (5). The two most important parameters of the cohesive zone model, peak shear traction and the area under the curve, remain unchanged. However, when friction is included ($\mu = 0.26$), k_2 has a significant effect on the behaviour of the interface. The increase of k_2 raises the shear traction during the entire interface damaging process. Both the peak shear traction and the area under the curve keep increasing as the interface becomes stiffer and stiffer. The curves converge when k_2 reaches extremely high values.

The damage parameter and shear stress during the damaging process ($\delta_{2o} \leq \delta_2 \leq \delta_{2f}$) can be derived from Eqs. (1), (4) and (5) as

$$\omega = \frac{1-\tau_{2c}/k_2\delta_2}{1-\tau_{2c}/k_2\delta_{2f}} \quad \text{and} \quad \tau_2 = \frac{\delta_{2f}-\delta_2}{\delta_{2f}-\delta_{2o}}\tau_{2c} + \omega\tau_f \tag{6}$$

Obviously, ω depends on the initial interface stiffness k_2. The dependence is significant as shown by the damage evolution curves in Fig. 3. A weak interface produces a steady damage evolution. For a moderately stiff interface, ω increases rapidly after damage initiation and then slows down gradually until it reaches unity. If a very stiff interface is used, ω climbs sharply to a value very close to unity, resulting in a flat line in most of the damaging process. The damage evolution curves converge when the interface is extremely stiff.

Since the contribution of the frictional stress to the shear stress on the interface is in proportion to ω, the shear stress-sliding separation curve becomes extremely sensitive to k_2. The converged shear stress takes an approximate form of $\tau_2 = (1-\delta_2/\delta_{2f})\,\tau_{2c} + \tau_f$.

A simple finite element model, consisting of two solid elements connected by a surface-based cohesive interface, was also created in ABAQUS to check the behaviour of the surface-based cohesive contact model in ABAQUS. Almost identical results to those presented above were obtained. There is no formulation available in the ABAQUS manual and how the model works is described in the manual as follows [12]. If the interface is under tension, only the cohesive behaviour is active. When the interface is under compression, the conventional pressure overclosure relationship governs the contact behaviour in the normal direction and the cohesive model makes no contribution to the normal stress. In the shear direction, the cohesive model is active and the friction model activates once cohesive damage initiates. The