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Numerical investigation on the loading-delamination-unloading behavior of adhesive joints

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ABSTRACT

An elastic-plastic interface model at finite deformations is utilized to investigate the irreversible delamination behavior of adhesive joints subjected to loading-delamination-unloading. The interface model accounts for the irreversible delamination in the fracture process zone induced by the localized plastic deformation and damage. The interfacial parameters in the cohesive model are obtained by fitting the available experimental data. Results suggest that the cohesive model can capture the irreversible delamination failure behavior observed in adhesively bonded joints during a loading-unloading cycle. The overall nonlinear response is dominated by the cohesive strength and initial damage displacement jump. Further, we also investigate the effect of the ductile mechanisms for the bulk layer on the competition between the plastic deformation of the bulk layer and the delamination of the interface. It is observed that the degradation of unloading stiffness is attributed to the inelastic behavior of the interface.

1. Introduction

Interfacial delamination is identified as one of the most common types of failure mechanisms in a wide range of composite materials and structures due to their relatively weak interlaminar strengths. It usually occurs during the manufacturing process and the application of thermo-mechanical loading, and displays geometric discontinuities and large-scale inelastic deformations in composite laminates. Delamination can cause a loss of the load bearing capacity and stiffness degradation, leading to irreversible change of microstructure in composites. Substantial experimental efforts recently have been devoted to investigating test methods for mode II interlaminar fracture of carbon fiber reinforced composites [1], acoustic emission analysis in mode I loading of fiber reinforced composites [2], a Lamb wave based technique and a noncontact laser ultrasonic wavefield imaging technique for delamination and debonding detection and visualization [3,4]. Among them, the double cantilever beam (DCB) test is widely used as a popular test for the evaluation of the mode I fracture energy due to the ease of specimen preparation and equipment. Recently, Coronado et al. [5] experimentally investigated the influence of temperature on the process of DCB delamination under static and fatigue loadings. Blaysat et al. [6] presented a procedure for the identification of spatial interfacial traction profiles of peel loaded DCB samples. In their test, the recorded load-displacement curve is the key information for evaluating the bonding quality and the fracture toughness at the interface.

Analytical and numerical models have also been developed to capture the delamination and damage behaviors in composite materials and structures. Instead of defining an initial crack and assuming predefined progression of a crack, the delamination process can be characterized by cohesive zone models (CZMs) [7]. These cohesive models are further improved and applied for the fiber reinforced composites and adhesive joints, including the process of material separation in adhesively bonded joints during fatigue crack growth [8,9], delamination propagation in adhesively bonded joints and composite laminates [10–17]. Nevertheless, most of the literatures are involved in studying the loading behavior of the fiber reinforced composites and adhesive joints, while very few experimental efforts focus on the unloading behavior [18,19]. However, the unloading behavior is also important to understand the damage and fatigue mechanism induced delamination in composites and adhesive joints, especially for the irreversible change at interface during unloading.

Hence, the objective of the present study is utilizing the elastic-plastic cohesive formulation developed by Xu et al. [20,21] to capture the irreversible delamination response of adhesively-bonded

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components induced by the localized plastic deformation and ensuing damage accumulation during a loading-unloading cycle. Firstly, a parametric study to investigate cohesive material parameters on the load-displacement response of the DCB test is carried out and compared with the available experimental data in literature. Then, the obtained cohesive material parameters are utilized to predict the irreversible delamination of adhesive joints induced by the localized plastic deformation and damage at interface. Moreover, the effects of the ductile mechanisms for the bulk layer are elucidated to demonstrate the competition between the plastic deformation of the bulk layer and the inelastic interface delamination.

2. Governing equations

A finite strain analysis including strong discontinuities is carried out using a framework based on the standard continuum description that accounts for the irreversible crack initiation and propagation in adhesively-bonded components during the loading-unloading conditions. In this framework, large strain finite element computation is employed to address such issue of the inelastic constitutive behavior, where volumetric constitutive relations are given for the bulk layers, and a surface constitutive relation is adopted for the interface.

Within a principle of virtual work, cracks in adhesively-bonded components can be viewed as discontinuities which can be characterized by the presence of the cohesive zone along parts of its length as shown in Fig. 1. Hence, the principle of virtual work considering a crack can be described through a virtual (arbitrary) incremental displacement field $\delta\mathbf{u}$ and integrating over the total region Ω_0 with body forces neglected,

$$\int_{\Omega_0} J\boldsymbol{\sigma}\mathbf{F}^{-T} : (\delta\mathbf{u}\otimes\nabla)d\Omega_0 + \int_{\Gamma_c} \mathbf{t}\cdot\delta[\![\mathbf{u}]\!]d\Gamma - \int_{\Gamma_e} \tilde{\mathbf{t}}\cdot\delta\mathbf{u}d\Gamma = 0, \tag{1}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\mathbf{F}$ is the deformation gradient tensor, J is the Jacobian defined as $J = \det(\mathbf{F})$, $[\![\mathbf{u}]\!] = \mathbf{u}^+ - \mathbf{u}^-$ is the displacement jump vector across the cohesive surfaces, the surface tractions $\mathbf{t}$ are work-conjugate to the displacement jump $[\![\mathbf{u}]\!]$ across the cohesive surfaces, and $\tilde{\mathbf{t}}$ denotes the traction vector on the external surface Γ_e.

3. Finite-strain constitutive models

3.1. The irreversible traction-separation law for the interface

To characterize the observed irreversible behaviors of the ductile interface in adhesively-bonded components during loading-delamination-unloading, we utilize the irreversible elastic-plastic cohesive zone model [20,21]. In this model, the 'ductile' interface undergoes complex deformation and demonstrates a highly nonlinear traction-separation relation as shown in Fig. 2, resulting in the irreversible behavior induced by the plastic deformation and damage. Moreover, the 'plastic' unloading is described by the unloading stiffness $\mathbf{K}$ (equal to the initial stiffness) and the residual displacement jump δ_p, while the 'damage' unloading is characterized by reducing the interfacial unloading stiffness $\mathbf{K}$ to $(1 - D)\mathbf{K}$ and the residual displacement jump δ_p'.

Following the previous work [20,21], a thermodynamically consistent free energy potential per unit surface area with no hardening/softening is expressed as

$$\psi = \frac{1}{2}(\boldsymbol{\delta} - \boldsymbol{\delta}^p)\cdot\mathbf{K}\cdot(\boldsymbol{\delta} - \boldsymbol{\delta}^p), \tag{2}$$

where $\boldsymbol{\delta}^p$ denotes the plastic irrecoverable portion of $\boldsymbol{\delta}$ as $\boldsymbol{\delta}^p = \boldsymbol{\delta} - \boldsymbol{\delta}^e$, and $\mathbf{K}$ denotes the interface elastic stiffness tensor which can be written in terms of the stiffness K_n in the normal direction and K_t in the tangential direction as

$$\mathbf{K} = K_n\mathbf{n}\otimes\mathbf{n} + K_t(\mathbf{1} - \mathbf{n}\otimes\mathbf{n}), \tag{3}$$

where $\mathbf{1}$ denotes the second order identity tensor.

Further, the local traction $\mathbf{t}$ can be derived by differentiating the free energy potential ψ with respect to the elastic displacement jump $\boldsymbol{\delta}^e$,

$$\mathbf{t} = \frac{\partial\psi}{\partial\boldsymbol{\delta}^e} = \mathbf{K}\cdot(\boldsymbol{\delta} - \boldsymbol{\delta}^p). \tag{4}$$

The cohesive traction $\mathbf{t}$ can be additively decomposed as

$$\mathbf{t}_n = (\mathbf{n}\otimes\mathbf{n})\mathbf{t} = t_n\mathbf{n}, \quad \mathbf{t}_t = (\mathbf{1} - \mathbf{n}\otimes\mathbf{n})\mathbf{t}, \tag{5}$$

where $\mathbf{t}_n$ and $\mathbf{t}_t$ are the normal and tangential traction vectors.

The yield function φ is given by

$$\varphi = \bar{t} + \mu\langle t_n\rangle - t_y, \tag{6}$$

where $\bar{t}$ is the effective tangential traction, $\bar{t} = \sqrt{\mathbf{t}_t\cdot\mathbf{t}_t}$, $\langle\cdot\rangle$ is the McCauley bracket defined as $\langle x\rangle = \frac{1}{2}(x + |x|)$, t_y represents the critical cohesive strength, and μ is the friction coefficient.

The following cohesive plastic flow rule is given by

$$\dot{\boldsymbol{\delta}}^p = \dot{\gamma}\mathbf{n}_{flow}, \tag{7}$$

where $\dot{\gamma}$ is the plastic multiplier, and $\mathbf{n}_{flow}$ is the unit flow vector defined in terms of the cohesive plastic yield function φ as

$$\mathbf{n}_{flow} = \frac{\partial\varphi}{\partial\mathbf{t}}\left(\left|\frac{\partial\varphi}{\partial\mathbf{t}}\right|\right)^{-1} = \frac{1}{\sqrt{1+\mu^2}}\left(\frac{\mathbf{t}_t}{\bar{t}} + \mu\mathbf{n}\right). \tag{8}$$

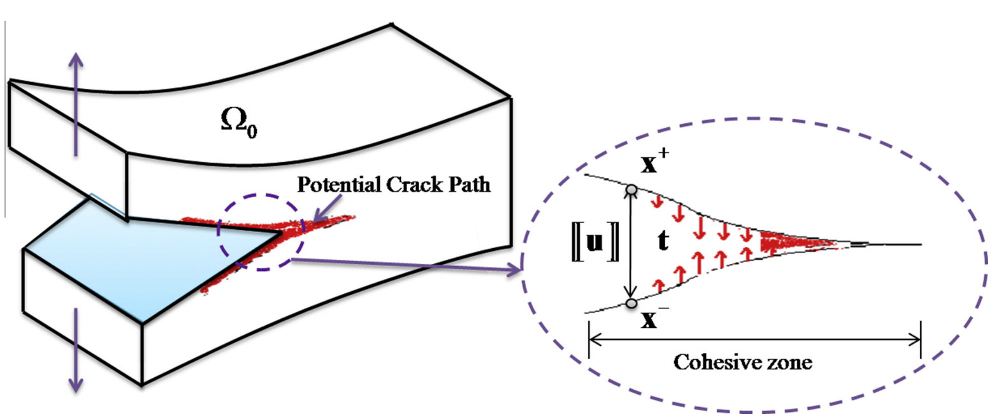

Fig. 1. Interface cracking in adhesively-bonded components with cohesive zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)