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A parametric study of the peel test

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Abstract

The force required to peel a film from a substrate is generally a complex function of geometry, the constitutive properties of the film and substrate, and the interfacial cohesive properties. In most analyses, the effects of the transverse shear force that is an integral aspect of almost any peel test are neglected, although they can be incorporated in an indirect fashion through models that invoke a root-rotation angle. In this study, a complete elastic solution that incorporates all the components contributing to crack-tip deformation, including bending moment, transverse shear force and axial force, is derived in a self-consistent way. In particular, it is shown that, for a strong interface that requires a reasonably large peel strain, the transverse shear results in a significant deviation of the phase angle from earlier analyses that neglected the shear term. The present analysis also links the transverse shear component to the root-rotation angle. A cohesive-zone analysis is presented for the peeling of an elastic–plastic film. In this analysis, the interface is modeled using cohesive elements, and the film is modeled by a full, two-dimensional, finite-element analysis. This analysis allows the full effects of bending, axial loading, and transverse shear to evolve, with no *a-priori* assumptions being made about their relative magnitudes. The numerical results show how the peel force depends on the film thickness. When the film is relatively thin, the peel force increases with an increase in thickness as the extent of plasticity increases. This increase in plasticity is associated with (i) an increase in the contribution of bending to the deformation at the crack tip, relative to the contribution of transverse shear, and (ii) an increase in the physical limits imposed by the dimensions of the film on the volume of any crack-tip plastic zone. When the film is relatively thick, elasticity dominates the deformation of the film, and small-scale yielding effects become important. The peel force is dictated by the toughness of the interface and by crack-tip plasticity (if any) induced by the cohesive stresses. Therefore, peel forces tend to minimum values for both thick and thin films. A maximum peel force is exhibited for films with an intermediate thickness.

Keywords: C. Peel test; D. Fracture; Elasto-plasticity

1. Introduction

Owing to its simplicity of concept and geometry, the peel test is popular for adhesion measurements. The geometry consists of a film bonded to a thick substrate, and the test proceeds by measuring the force required to pull the film off the substrate. This peel force is then related to the properties of the interface. Under some limiting conditions, the peel force is a direct measure of the interfacial toughness. However, more generally, the peel force is affected by the geometry, the constitutive properties of the film and substrate, and the cohesive properties of the interface. The geometrical terms include the peel angle, θ, and the film thickness, h (Fig. 1). If the film and substrate are both isotropic and elastic, then the relevant constitutive properties are the Young's moduli, E and E_s, and Poisson's ratio, ν and ν_s, of the film and substrate. The yield strength and hardening characteristics of the film enter the problem if there is plasticity. For the purposes of this paper, it was assumed that the substrate is very hard, so that yield did not occur at any scale within the substrate. The film was assumed to have a yield strength of σ_Y, with a power-law hardening relationship after yield, so that the true strain, $\tilde{\varepsilon}$,

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Nomenclature

E	Young's modulus of film
$\bar{E}$	$E/(1-\nu^2)$ in plane strain, and E in plane stress
E_s	Young's modulus of substrate
$\mathcal{G}$	energy-release rate
$\mathcal{G}_I$	mode-I component of energy-release rate
$\mathcal{G}_{II}$	mode-II component of energy-release rate
h	film thickness
M	bending moment (per unit width) acting at crack tip
n	power-law hardening exponent for film
N	axial (compressive) force (per unit width) acting at crack tip
P	force (per unit width) applied to film
P_f	peel force (per unit width) required to cause delamination
V	transverse shear force (per unit width) acting at crack tip
α	primary dimensionless modulus mismatch ratio
β	secondary dimensionless modulus mismatch ratio
Γ	mixed-mode interfacial toughness
Γ_I	mode-I component of interfacial toughness (area under mode-I traction-separation law)
Γ_{II}	mode-II component of interfacial toughness (area under mode-II traction-separation law)
θ	peel angle
ν	Poisson's ratio of film
ν_s	Poisson's ratio of substrate
$\hat{\sigma}$	mode-I cohesive strength of interface
σ_Y	yield strength of film
$\hat{\tau}$	mode-II cohesive strength of interface
ψ	phase angle

and true stress, $\tilde{\sigma}$ were related by

$$\tilde{\varepsilon} = \frac{\sigma_Y}{\bar{E}}\left(\frac{\tilde{\sigma}}{\sigma_Y}\right)^{1/n} \quad \text{for } \tilde{\sigma} \geqslant \sigma_Y, \qquad (1)$$

where n is the power-law hardening exponent, and $\bar{E} = E$ in plane stress, and $\bar{E} = E/(1-\nu^2)$ in plane strain.

The cohesive properties of the interface were assumed to be described by mode-I and mode-II traction-separation laws, and a mixed-mode failure criterion that couples them. In general, the important features of traction-separation laws are the mode-I toughness, Γ_I, the normal cohesive strength, $\hat{\sigma}$, the mode-II toughness, Γ_{II}, and the shear cohesive strength, $\hat{\tau}$.[1] Other details of the laws, such as the shape, generally seem to have a minor role on the fracture process; they affect details of the fracture, but not the fundamental conclusions that will be emphasized in this paper. For the purposes of this paper, a simple shape for the traction-separation laws was used, as illustrated in Fig. 2. These two laws were linked with a simple mixed-mode fracture criterion [1]

$$\frac{\mathcal{G}_I}{\Gamma_I} + \frac{\mathcal{G}_{II}}{\Gamma_{II}} = 1, \qquad (2)$$

where $\mathcal{G}_I$ and $\mathcal{G}_{II}$ are the mode-I and mode-II components of the energy-release rate, such that the total energy release rate is given by

$$\mathcal{G} = \mathcal{G}_I + \mathcal{G}_{II}. \qquad (3)$$

The mode-I and mode-II components of the energy-release rate are defined by

$$\mathcal{G}_I = \int_0^{\delta_n} \sigma \, d\delta_n \quad \text{and} \quad \mathcal{G}_{II} = \int_0^{\delta_t} \tau \, d\delta_t. \qquad (4)$$

The mode-I and mode-II toughness are defined by

$$\Gamma_I = \int_0^{\delta_{nc}} \sigma d\delta_n \quad \text{and} \quad \Gamma_{II} = \int_0^{\delta_{tc}} \tau \, d\delta_t, \qquad (5)$$

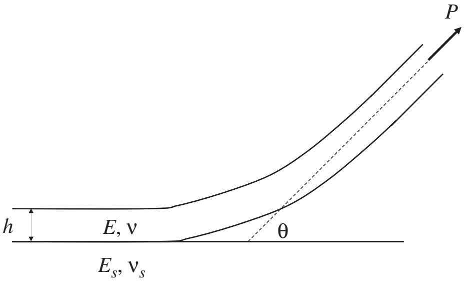

Fig. 1. A schematic illustration of the peel-test geometry. A film of thickness h, modulus E and Poisson's ratio ν is bonded to a substrate of modulus E_s and Poisson's ratio ν_s. A force P is applied to the remote end of the film at an angle θ to the plane of the interface between the film and substrate.

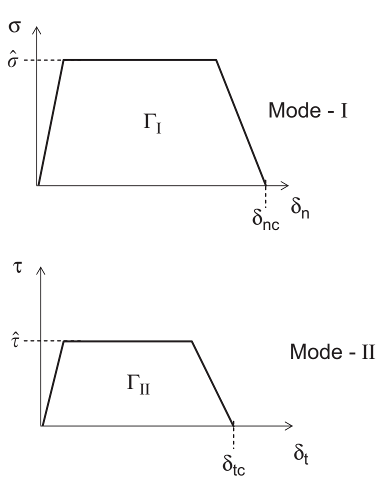

Fig. 2. Mode-I and mode-II traction-separation laws used for the cohesive-zone model in this paper.

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[1] Other parameters that can be used as possible characterizations of the cohesive properties of the interface include a critical root rotation, critical displacement or critical strain. These are essentially variations on a theme, and can be re-expressed in terms of the cohesive strength and toughness.