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Debonding of confined elastomeric layer using cohesive zone model

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ABSTRACT

Wavy or undulatory debonding is often observed when a confined/sandwiched elastomeric layer is pulled off from a stiff adherend. Here we analyze this debonding phenomenon using a cohesive zone model (CZM). Using stability analysis of linear equations governing plane strain quasi-static deformations of an elastomer, we find (i) a non-dimensional number relating the elastomer layer thickness, h, the long term Young's modulus, E_∞, of the interlayer material, the peak traction, T_c, in the CZM bilinear traction-separation (TS) relation, and the fracture energy, $\mathcal{G}_c$, of the interface between the adherend and the elastomer layer, and (ii) the critical value of this number that provides a necessary condition for undulations to occur during debonding. For the elastomer modeled as a linear viscoelastic material with the shear modulus given by a Prony series and a rate-independent bilinear TS relation in the CZM, the stability analysis predicts that a necessary condition for a wavy solution is that $T_c^2 h/\mathcal{G}_c E_\infty$ exceed 4.15. This is supported by numerically solving governing equations by the finite element method (FEM). Lastly, we use the FEM to study three-dimensional deformations of the peeling (induced by an edge displacement) of a flexible plate from a thin elastomeric layer perfectly bonded to a rigid substrate. These simulations predict progressive debonding with a fingerlike front for sufficiently confined interlayers when the TS parameters satisfy a constraint similar to that found from the stability analysis of the plane strain problem.

1. Introduction

Systems consisting of a soft elastic or viscoelastic layer confined between two stiff substrates occur in numerous industrial applications. One example is manufacturing of bio-implants, which may involve mechanically demolding a soft polymer layer sandwiched between two relatively stiff molds [1]. A frequently observed phenomenon is the occurrence of contact undulations when a stiff layer is separated from the soft layer under tensile tractions. Classical examples include the formation of ripples when a contactor approaches an elastic film bonded to a fixed base [2–4], and wavy debonds in peel [5] and probe tack tests [6–8]. Experimentally, the characteristic spacing, λ, between two adjacent undulation peaks has been found [2,9] to scale linearly ($\lambda \approx 3-4h$) with the thickness h of the confined interlayer while being independent of the interfacial adhesion properties. The linear stability analyses and energy arguments [10–13] have been used to show that undulations result from the competition between the strain energy of the system acting as a stabilizing influence, and the energy associated with the interfacial forces (such as van der Waals forces) acting as a destabilizing influence. These approaches give a threshold value of the interaction energy for the onset of instability. For example, it was shown [10,14] that the condition $\frac{A}{6\pi d^4} \geq \frac{2E}{3h}$ is necessary for the onset of contact instabilities when a rigid contactor is gradually brought close to an elastic film of thickness h and Young's modulus E, where A is the effective Hamaker constant for van der Waals interactions and d the gap between the contactor and the film at the onset of instabilities. Other examples include [15] morphological changes in an elastic film caused by an applied electric field. Combined experimental and linear stability approaches have helped identify a threshold value of the effective voltage as a function of the film stiffness.

As debonding ensues at the interface between an adhesive and an adherend, multiple nonlinear processes such as cavitation and fibrillation may occur at the debonding site. These involve different length scales and contribute to the overall energy dissipation during the creation of the two new surfaces. In a cohesive zone model (CZM) [16,17], the collective influences of these small-scale mechanisms are lumped together into a traction-separation (TS) relation. In this approach the adjoining points on the two sides of an interface are conceived to be connected by a spring of zero length that begins softening with extension (separation) after reaching a critical extension and subsequently breaks upon

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Nomenclature

Symbols

A	Hamaker constant for van der Waals interaction
$\mathbf{B}$	Left Cauchy-Green tensor
d	Distance between an elastic film and an approaching contactor
$\overline{d}$	Damage variable
D	Bending rigidity of the flexible plate
E	Young's modulus of the elastomeric interlayer
h	Thickness of the elastomeric interlayer
i	$=\sqrt{-1}$
K	Slope of the rising part of the straight line in the bilinear traction-separation law
k	Wavenumber of the x- dependent part of the perturbation to the stream function and the hydrostatic pressure.
m	Ratio of the modulus of the spring in the spring-dashpot link to the long-time modulus for the 1-term Prony series
p	Hydrostatic pressure not related to strains for incompressible materials
R	Reaction force on the rigid adherend
T	Normal traction at the interface
t	Time
u, v, w	Displacement components along x,y and z directions, respectively
x, y, z	Axes of the rectangular Cartesian coordinate system when the index i of the system x_i has values 1, 2 and 3, respectively
α	Magnitude of the slope of the falling part of the straight line portion of the bilinear traction-separation relation
Δ	Applied vertical displacement to the upper adherend
δ	Displacement jump at the interface, also called the contact opening
λ	Dominant wavelength of debonding undulation
μ	Shear modulus of the elastomeric interlayer
ψ	Stream function introduced to define displacement components u and w
ω	Growth rate of a perturbation
a_1, a_2	Material constants in the constitutive equation used to model finite strain viscoelasticity
a_T	Shift factor relating the relaxation time at temperature T to that at the reference temperature
C_1, C_2	Constants in the Williams- Landel-Ferry (WLF) equation for a_T
$E_\infty(=3\mu_\infty)$	Long term Young's modulus ($=3\times$long-term shear modulus) of the viscoelastic material
$E_0(=3\mu_0)$	Instantaneous Young's modulus($=3\times$instantaneous shear modulus) of the viscoelastic material
F_t	Deformation gradient
$\mathcal{G}_c$	Fracture energy of the interface
g_R	Relaxation function normalized by the instantaneous modulus of the viscoelastic material
$K_{softening}$	$=T_c{}^2/\mathcal{G}_c$
$K_{elastic}$	$=E_\infty/h$
l_{finger}	Length of a finger
p^{nh}	Non-homogeneous perturbation to the hydrostatic pressure
T_c	Peak value of the normal traction at the interface
x_i	Axes of the rectangular Cartesian coordinate system
δ_c	Critical displacement jump when damage initiates
δ_f	Displacement jump at the initiation of debonding/separation
ε_{ij}	Components of the infinitesimal strain tensor
μ_i	Shear modulus of the i^{th} term in the generalized Maxwell model used to define the relaxation function of the viscoelastic model.
μ_R	Relaxation function for the elastomeric interlayer when modeled as a linear viscoelastic material
σ_{ij}	Components of the stress tensor
τ_i	Characteristic relaxation time of the i^{th} element of the generalized Maxwell model
ϕ_{c1}	The lower limit of ϕ for debonding instability
ϕ_{c2}	The value of ϕ beyond which region III sets in
ψ^{nh}	Non-homogeneous perturbation of the stream function
$\tilde{A}$	Area of the interlayer initially bonded to the rigid adherend
$\tilde{p}$	z-dependent part of the hydrostatic pressure perturbation
$\tilde{T}$	Temperature
$\tilde{T}_{REF}$	Reference temperature
$\frac{\partial}{\partial x_i}$	Partial derivative (with respect to x_i) operator
$\overline{x}$	Distance along the x axis normalized by the half width of the rigid adherend
$\dot{\Delta}$	Rate of the applied vertical displacement to the upper adherend
$\overline{\delta}$	Contact opening normalized by δ_f
$\tilde{\psi}$	z-dependent part of the stream function perturbation
$\tilde{\omega}$	The growth rate ω normalized by $1/\tau_1$