

THE USE OF COHESIVE ZONE MODEL TO SIMULATE THE BLISTER TEST ON AN ELASTIC-PLASTIC FILM BONDED TO A RIGID SUBSTRATE

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Abstract

A finite element simulation of a blister test of a film bonded to a substrate and subject to plane strain condition is performed. The film is taken to be ductile, while the substrate is assumed to be rigid. In the formulation, the interface adjoining the thin film and substrate is assumed to be the only site where cracking may occur. A traction separation law, with two major parameters: adhesion energy, Γ_0 and interface strength, $\hat{\sigma}$, is introduced to simulate the adhesive and failure behaviors of the interface between the film and the substrate. The effects of the adhesion properties: Γ_0 and $\hat{\sigma}$, geometry and material properties of the film on the onset and growth of interface delamination are investigated. We suggest a method to extract the adhesion energy, Γ_0 and the interface strength, $\hat{\sigma}$, independently of how much the film deforms plastically, by fitting the predicted results of our model to experimental data.

Introduction

The blister test is widely used to measure the adhesive fracture toughness. External pressure applied on a film, initially bonded to a substrate, causes delamination at the interface. The crack propagates along the interface as the external pressure is increased. In the experiment, the pressure, the central deflection and/or the debonded length are measured. Various types of blister tests have already been suggested. For example, the one dimensional blister test corresponds to the case where a pressure is applied through a long rectangular window introduced in the substrate. In this case, plane-strain condition prevails. If instead a circular hole is introduced in the substrate, axisymmetric conditions are obtained corresponding to a different "axisymmetric" test. Other types of blister tests are described in Williams [1], such as shaft loaded (point loaded), island and constraint blister test. Williams [1] describes analytical solutions developed for these various geometries for materials that deform elastically. If plastic deformation also takes place, the analytical solutions predict much lower value as the plastic dissipation energy in the film is not accounted for.

In this paper a finite element analysis of a blister test under plane strain condition is presented. We assume that the thin film exhibits plastic deformation and is bonded to a rigid substrate. We employ a traction separation law at the interface between the film and the rigid substrate to describe the delamination process. This model characterizes the adhesion properties at the interface, including adhesive fracture toughness and interfacial strength. The effect of material properties, geometry and interfacial properties on the onset and propagation of the crack along the interface is studied.

Problem Formulation

We adopt the traction separation relation introduced by Needleman [2], to describe the fracture process along a plane of crack growth, and further developed by Tvergaards and Hutchinson [3], see Fig. 1. The maximum strength, in Fig. 1, is the adhesion strength $\hat{\sigma}$, whereas the adhesion energy, Γ_0 , is the area under the curve. The quantities, λ_1 and λ_2 are shape parameters. The continuum properties of the materials are such that the film follows the finite plastic-strain J_2 flow theory under plane strain conditions. We only focus on cases of a soft film on a hard substrate. For simplicity, the substrate is assumed to be rigid.

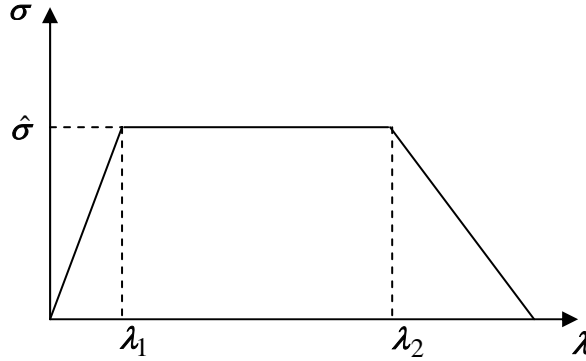


FIGURE 1: Traction separation law.

Although the pressure can be readily measured experimentally, the interpretation of its behavior with the various parameters is not always straightforward. A more convenient quantity must have an energy form so an analysis based on energy concepts is possible. The product of the pressure with the central deflection, H , is generally proportional to the energy release rate [1] and therefore appropriate for our analysis. Dimensional analysis shows that the product of the pressure with the central deflection, pH , are functions of the following dimensionless parameters:

$$pH = F \left[\frac{\Delta a}{R_0}, \frac{t}{R_0}, \frac{\hat{\sigma}}{\sigma_y}, \Gamma_0, \frac{\sigma_y}{E}, N \right] \quad (2)$$

Finite element model

The finite element calculations are carried out using the finite element code ABAQUS. The substrate is simulated as a rigid surface. Due to symmetry only half of the film is modeled. A uniform pressure is applied to the de-bonded strip of the film. A user subroutine is embedded in ABAQUS to describe the traction separation law ahead of the interfacial crack. Another task of the subroutine is to apply the same magnitude of the pressure to the new de-bonded area of the film upon separation. The mesh is very refined in the vicinity of the crack tip to carefully catch the behavior of crack advance with increasing pressure. The smallest element size, denoted Δ_0 , is $\Delta_0 = 0.025R_0$.

Parametric Studies

Before presenting the effect of the individual parameters separately, we first compare the finite element results against available analytical solutions. We consider an approximate

analytical solution for a two dimensional strip loaded with a uniform pressure. Williams [1] presented two solutions depending on whether the film is taken as a flexible membrane or sustain bending. For small angle and in the case the film behaves as a flexible membrane, the energy release rate is given by:

$$\frac{G}{pH} = \frac{7}{6} \quad (3)$$

where p represent the uniform pressure and H is the maximum (central) deflection of the film. The bending solution for this case is:

$$\frac{G}{pH} = \frac{4}{3} \quad (4)$$

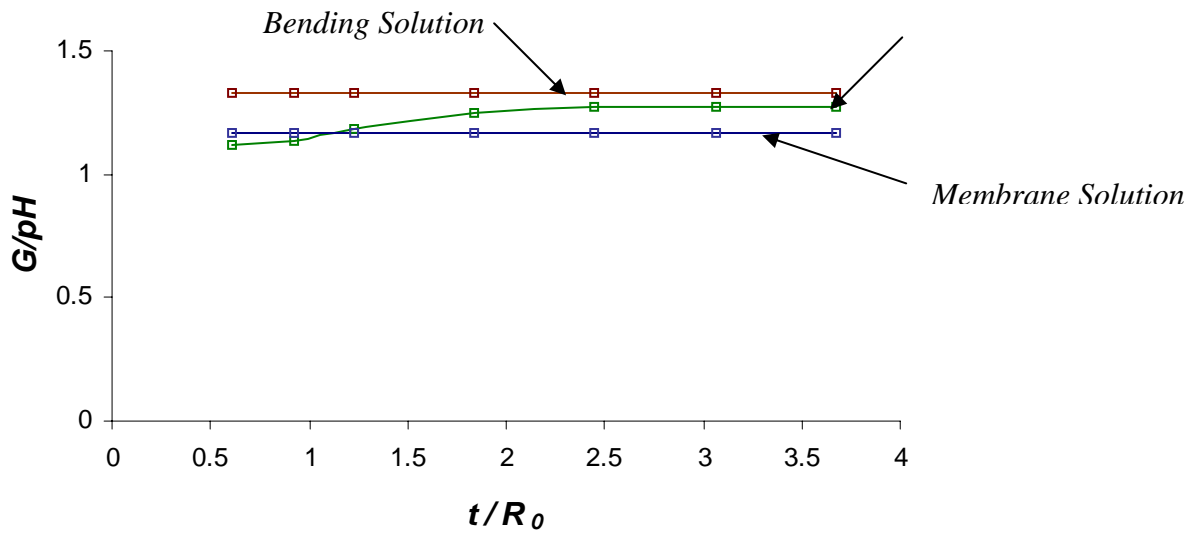


FIGURE 2: Comparison of analytical and FEM solution for the elastic case.

Finite element calculations are carried out for elastic films with different thicknesses. Fig. 2 shows the normalized energy release rate G/pH versus thickness, for the “membrane”, “bending” approximate analytical solutions and the finite element solution. Quite obvious the finite element solution predicts well the elastic solution for the “membrane” and “bending” cases. For example, at the extreme “membrane case” the finite element results are 3 - 4% lower than the analytical solution, while it is lower by less than 5% for the “bending” case. However, the analytical solution present an upper bound for both the ‘membrane’ and “bending” case. This is presumably due to the differences in boundary conditions and the assumptions undertaken in the analytical solutions. Furthermore, there is a transition from “membrane” to “bending” solution as the thickness increases. Thus, we have shown that our finite element model can well predict the solution for an elastic thin film bonded on a rigid substrate. In the following, we present the finite element results for an elastic-plastic film bonded to a rigid substrate. Note that, in equation (3) and (4), the energy release rate is independent from the material properties of the material and is proportional to the product of pressure with central deflection, pH . In the rest of the paper we study the dependence of the latter quantity on the various influencing parameters as it has an energy form and is related to the energy release rate.

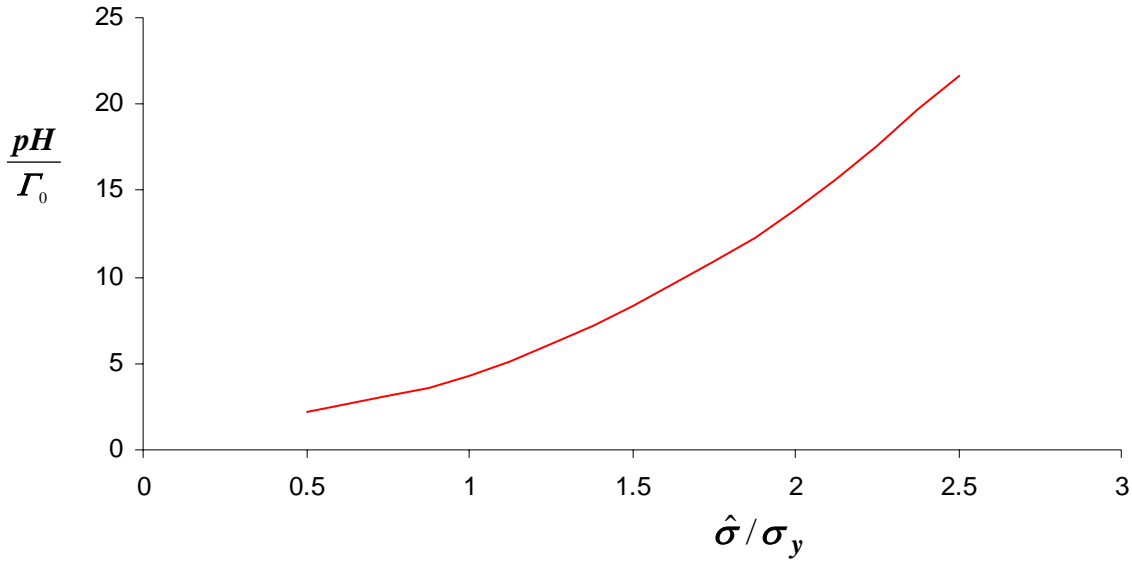


FIGURE 3: Dependence of the product of pressure and central deflection, pH , on $\hat{\sigma}/\sigma_y$.

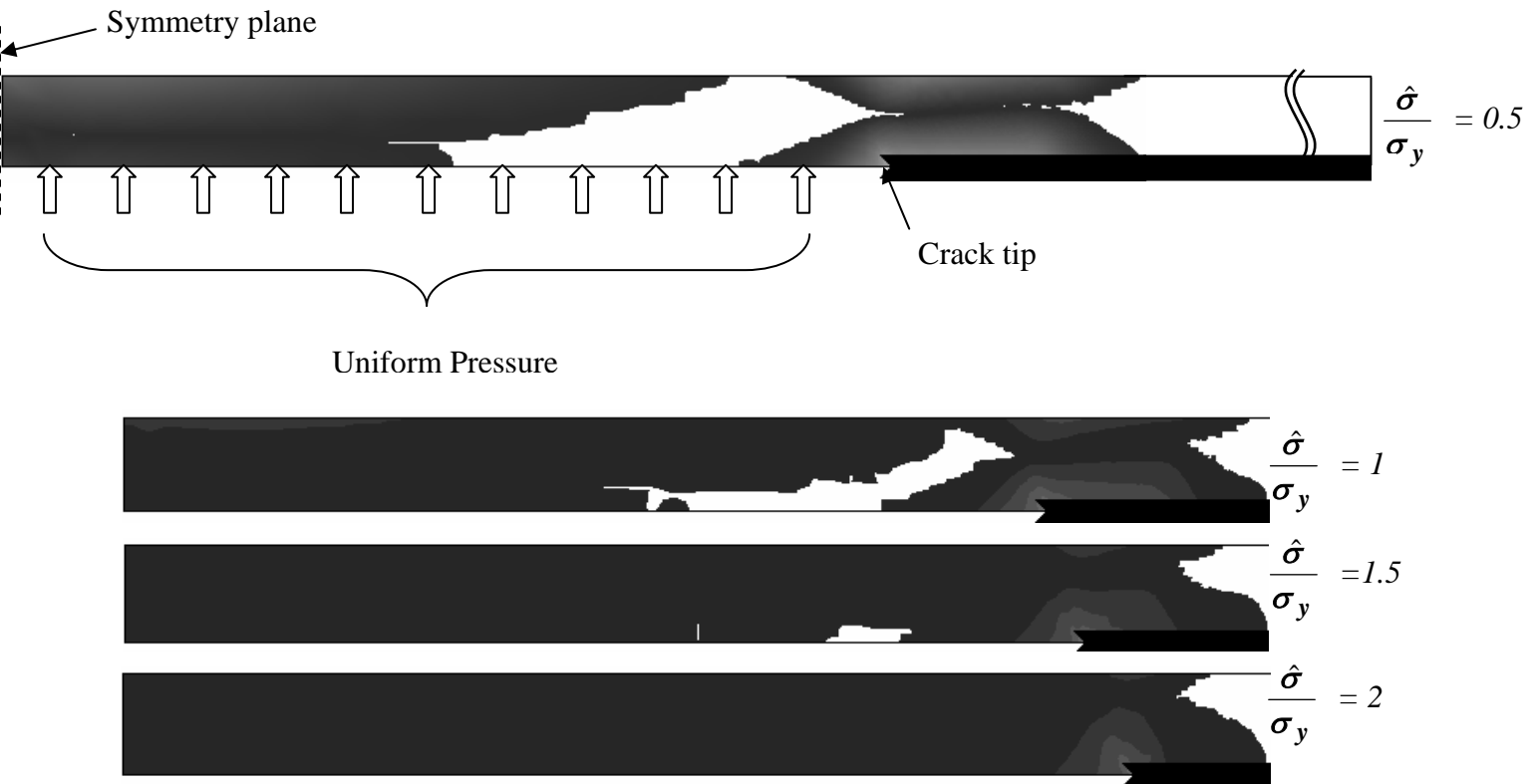


FIGURE 4: Plastic zone profiles for different values of $\hat{\sigma}/\sigma_y$.

Effect of the adhesion strength $\hat{\sigma}$:

The dependence of pH , the product of the pressure with the central deflection on the adhesion strength is displayed in Fig. 3. The general trend is that pH increases with increasing interfacial strength. As shown, there is steady increase of pH with increasing interfacial strength. Moreover, the rate of increase also increases. Fig. 4 shows the plastic zone

developed at the “unstable” pressure for different interfacial strengths. It does reflect the trend of pH , i.e. it increases with increasing interfacial strength.

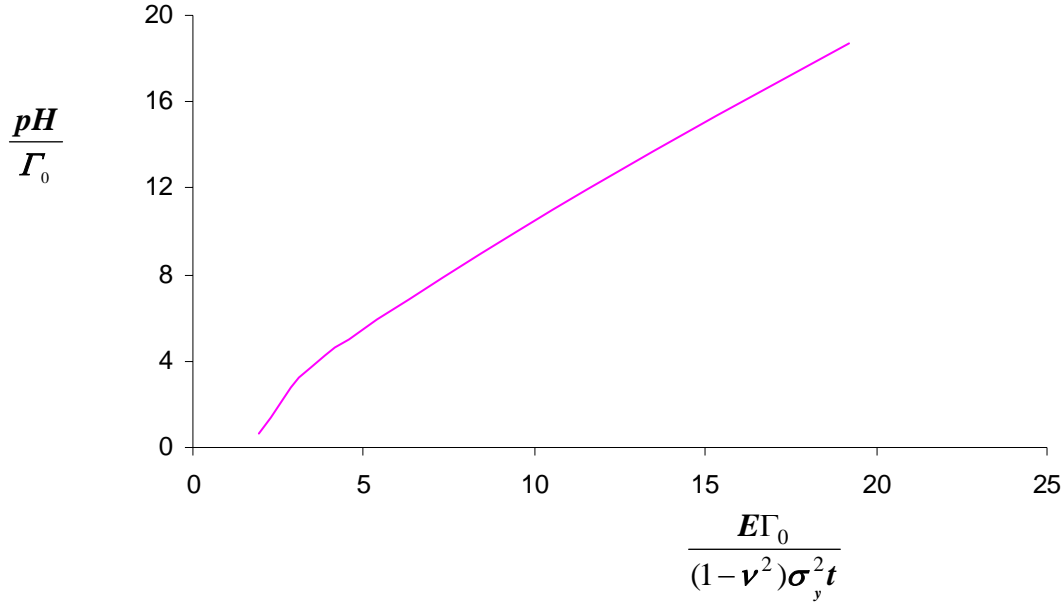


FIGURE 5: Dependence of the product of pressure and central deflection, pH , on adhesion energy.

Effect of Adhesion energy Γ_0 :

The effect of adhesion energy on pH is shown in Fig 5. The variation of adhesion energy is brought about by varying the critical normal displacement δ_n . As shown, pH increases linearly with increasing adhesion energy. Our results are consistent with those in Tvergaard and Hutchinson [3], Tvergaard and Hutchinson [4], Tvergaard and Hutchinson [5], Liu *et al.* [6]. In the latter references, a linear dependence of the steady state toughness on the adhesion energy is demonstrated.

Effect of N :

The dependence of pH on the strain-hardening coefficient is illustrated in Fig. 6. As would be expected, pH decreases as N increases. The same finding was reported elsewhere [3, 6]; Strain hardening increases the traction ahead of the crack tip and makes it easy to attain the peak stress. As the strain hardening increases, pH decreases to a value slightly lower than the adhesion energy, Γ_0 , as the material becomes progressively elastic- the plastic dissipation energy diminishes.

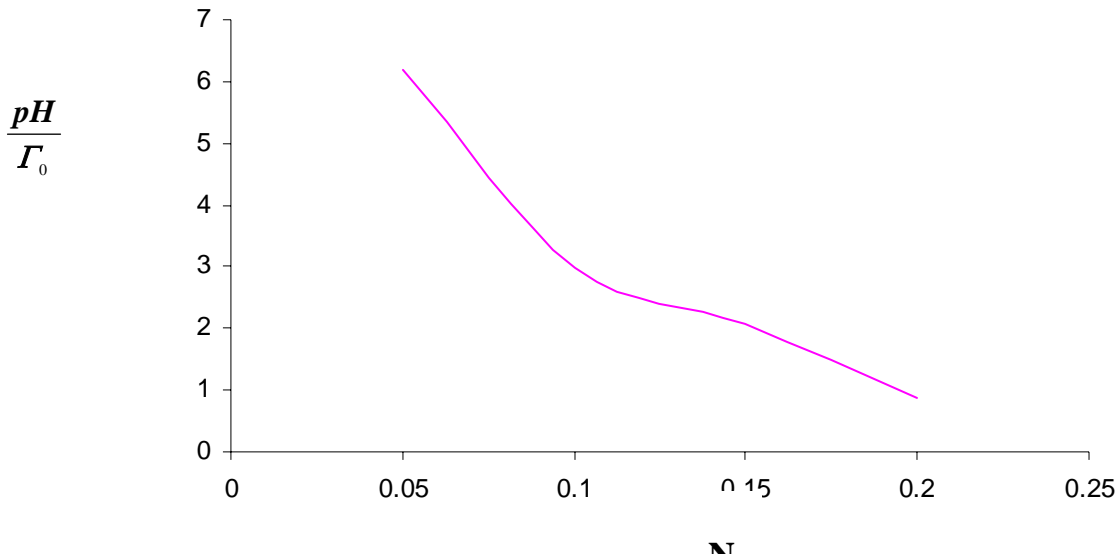


FIGURE 6: Dependence of the product of pressure and central deflection, pH , on strain-hardening exponent.

Effect of the elastic modulus, E :

The general trend that pH increases with increasing elastic modulus is readily seen in Fig. 7. With holding the yield stress fixed, reducing the elastic modulus implies increasing the ratio of yield stress to elastic modulus σ_y/E , which promotes plastic flow localization. Such instability is expected to cause a reduction in $\hat{\sigma}/\sigma_y$ [3]. In the latter reference the most important influence on toughness due to an increase in σ_y/E was attributed to the reduction in $\hat{\sigma}/\sigma_y$. In this case the toughness is reduced.

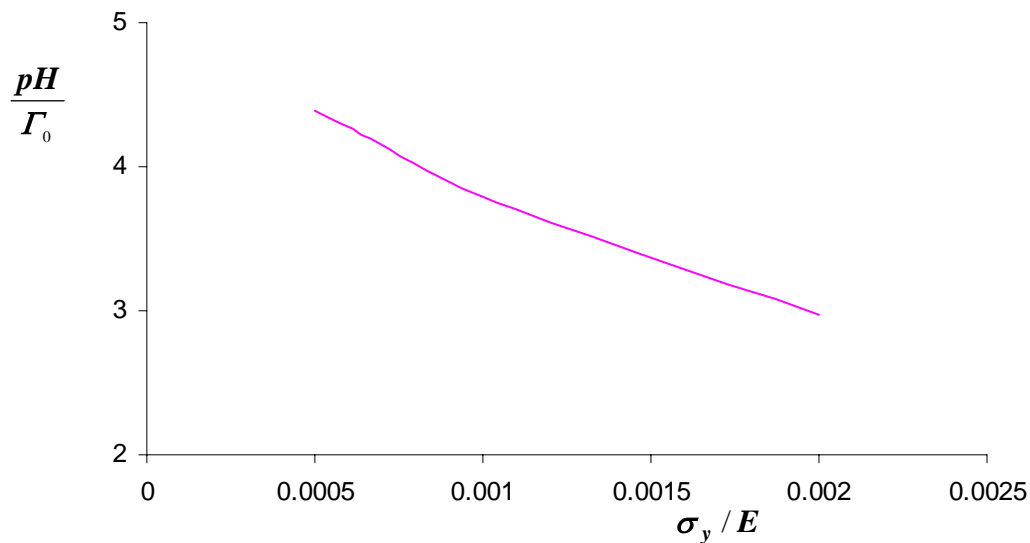


FIGURE 7: Dependence of the product of pressure and central deflection, pH , on σ_y/E .

In [6] a similar trend was attributed to mode mixity at the crack tip. Since we choose the substrate to be rigid, increasing the elastic modulus of the film leads to an increase in elastic

mismatch. It is well known that mode mixity affect the toughness quite significantly, particularly when the contribution of mode two energy release rate to the toughness is considerable. We calculate the ratio δ_n / δ_t at the crack tip as a rough estimate of the trend of mode mixity. The result shown in Fig. 8 indicates that mode mixity effect is more significant with increasing elastic modulus.

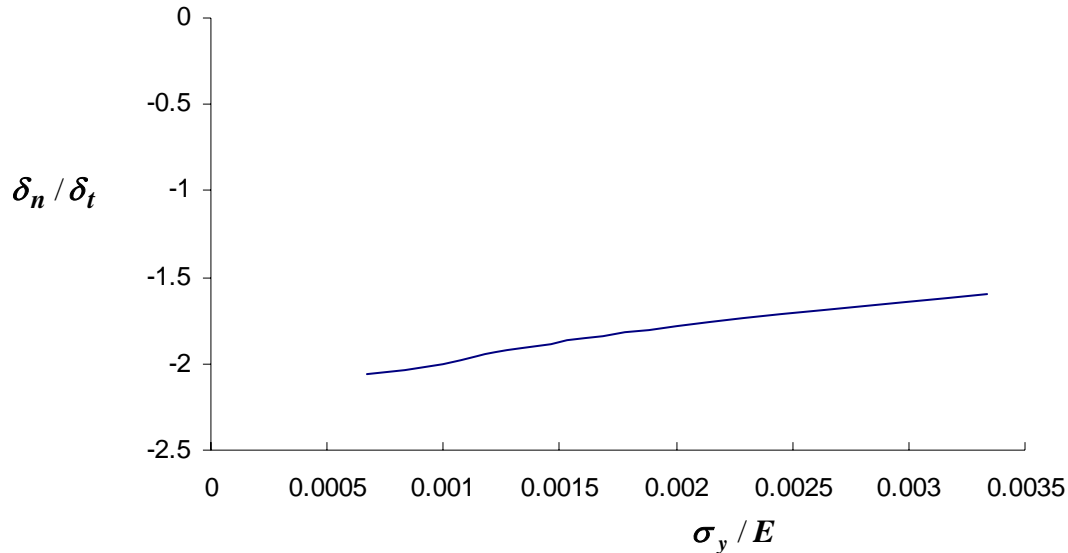


FIGURE 8: Variation of δ_n / δ_t with σ_y / E .

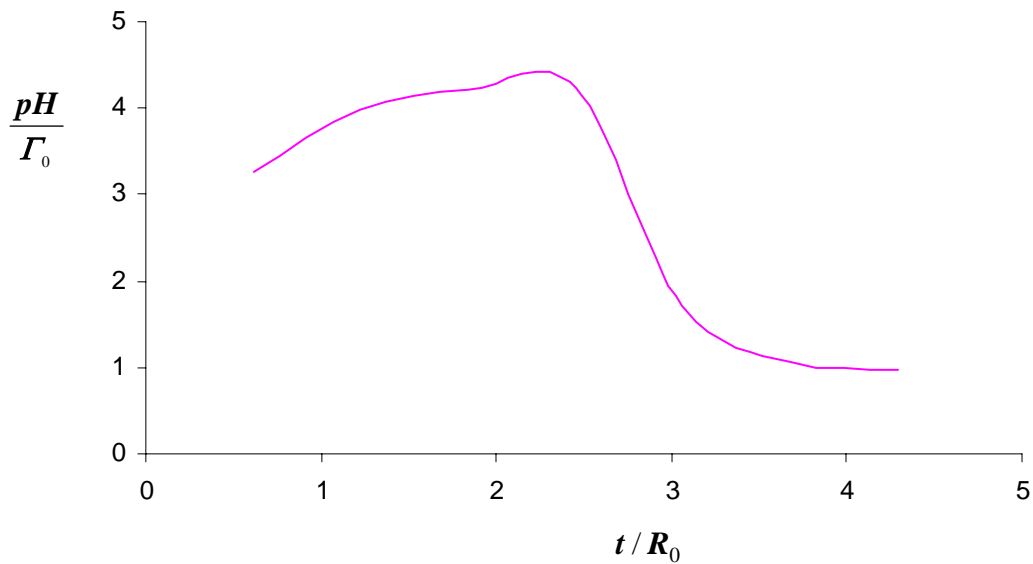


FIGURE 9: Dependence of the product of pressure and central deflection, pH , on thickness.

Effect of the thickness, t :

The product of the pressure with the central deflection, as shown in Fig. 9, increases with thickness to reach a maximum value at a critical thickness and reduces to nearly the value of

the adhesion energy; that is just slightly above the elastic limit ($pH/G = 0.75$). Analysis of the plastic zone profile shows that as the thickness increases there is an increase of the plastic zone size followed by a reduction for large thicknesses. This agrees well with the trend shown in Fig. 8. That is, although the pressure increases monotonically with the thickness, the central deflection, H , decreases progressively and for large thicknesses the product of the pressure with the central deflection, pH , reduces significantly. This can be related to the plastic zone constraint applied by the surrounding material, which is more significant for large thicknesses.

Discussion

Interface fracture resistance is well characterized by only two parameters: Adhesion energy Γ_0 and interface strength $\hat{\sigma}$. A good evaluation of the adhesion quality of an interface is, therefore, readily attained through few tests and computations. In particular, performing a test on a very thick film is very useful. Fig. 9 shows that pH approaches the elastic limit, given by equation (4), as the thickness becomes very large. Since the material is nearly elastic the energy release rate should correspond to the adhesion energy. Once the adhesion energy is determined a second test is performed with the actual film thickness. The applied pressure and the central deflection are measured. The adhesion strength is now readily determined by using the results presented in this paper. With reference to Fig. 3, which shows the dependence pH on the adhesion strength $\hat{\sigma}/\sigma_y$, the measured pressure is compared against those plotted in the figure, and the corresponding value for the adhesion strength $\hat{\sigma}$ is extracted.

Conclusion

The interface fracture resistance of an elastic-plastic film bonded on a rigid substrate is studied through modeling a blister test subject to the plane strain condition. The adhesion quality is established by determining the dependence of the product of the pressure with the central deflection on geometry and material properties of the film and the interface adhesion parameters. We suggest that a combination of modeling and two experimental tests are sufficient to determine the intrinsic interface toughness: the adhesion energy Γ_0 and the interface strength $\hat{\sigma}$.

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