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# A bending-to-stretching analysis of the blister test in the presence of tensile residual stress

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**Abstract**

The adhesion of films and coatings to rigid substrates is often measured using blister geometries, which are loaded either by an applied pressure or a central shaft. The measurement will be affected if there are residual stresses that make a contribution to the energy release rate. This effect is investigated using analytical solutions based on the principle of virtual displacements. A geometrically nonlinear finite element analysis is conducted for comparison. Furthermore, the relationships among strain energy release rate, load, deflection, and fracture radius are discussed in detail. Both analytical solutions and numerical results reveal that uniform tensile residual stresses reduce a specimen's deflection if it experiences plate behavior under small loads. However, this effect becomes negligible when membrane stresses induced by the loading become dominant.


*Keywords:* Blister test; Thin film; Residual stress; Delamination; Bending; Stretching; Adhesion; Fracture mechanics; Coating

## 1. Introduction

Blister tests are often used for measuring interfacial fracture energy between a coating film and the substrate (Dannenberg, 1961; Williams, 1969). A thin film bonded to a substrate may be debonded by applying

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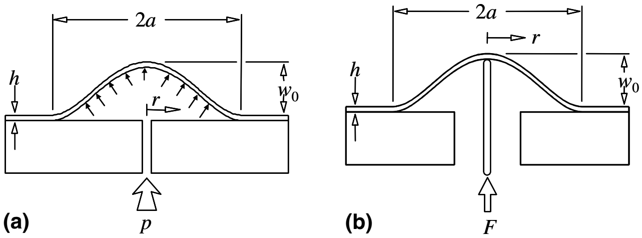


Fig. 1. Schematics of the loading configurations for (a) pressurized blister, (b) shaft-loaded blister (after Wan et al. (2003)).

either a hydrostatic pressure or a central load, as shown in Fig. 1. The deformation mode in a blister film experiences a transition from bending, when subjected to very small loads, to stretching under high loads. In a bending analysis, the in-plane stresses in the specimen are ignored, while bending rigidity is not considered during stretching analysis. A load–deflection curve is linear for a bending plate, but cubic for a stretching membrane. Besides the conventional circular, unconstrained geometry, several alternative blister configurations have been proposed to measure the adhesion energy between thin films and rigid substrates (Chang et al., 1989; Dillard and Bao, 1991; Wan, 2002; Sun et al., 2004). The following review focuses on two standard blister geometries, which will be analyzed in detail later in the paper.

The most conventional blister geometry uses pressure to load a specimen. Bennett et al. (1974) investigated the effect of specimen thickness on the elastic analysis of a pressurized blister, and conducted finite element analysis (FEA) for verification. The analysis of blisters for thin films gained much attention. Hinkley (1983) reported an approximate solution of the pressurized blister without residual stress based on the assumption of a spherical cap for a loaded blister, but gave the wrong solution for the strain energy release rate. Voorthuyzen and Bergveld (1984) solved numerically the von Karman equation for a pressurized blistering film with residual stress. Gent and Lewandowski (1987) later corrected the solution for energy release rate by using a similar method. Allen and Senturia (1988) gave equations for both the load–defection relationship and strain energy release rate for both circular and square specimens with constant residual stress. Lin and Senturia (1990) and Sizemore et al. (1995) experimentally verified their elastic model for thin flexible film and applied a perturbation of bending moment for thick films. Small and Nix (1992) conducted finite element analysis to compare the accuracy of the analytical solutions based on different deflection profiles. Cotterell and Chen (1997) studied the transition from bending to stretching of a blister geometry using Hencky's series solution, and gave a polynomial expression for the strain energy release rate. Using the assumption of a uniform and isotropic membrane stress, Arjun and Wan (2005) gave an approximate analytical solution for a pressurized blister without residual stress, and demonstrated the transition from bending to stretching with increasing load. Recently, still based on the assumption of uniform and isotropic in-pane stresses, Wan et al. (2003) obtained an approximate analytical solution for a clamped circular film in the presence of uniform residual tension (Arjun and Wan, 2005). Jensen and Thouless (1993) analyzed both tensile and compressive residual stresses in a blister specimen for both small linear displacement limit (pure bending) and large nonlinear membrane-type limit (pure stretching). Sheplak and Dugundji (1998) investigated the transition from bending to stretching of a circular plate's deflection with initial stretching using a finite difference technique, and found that tensile residual stress delayed the transition from bending to stretching.

An alternate way of applying load to a blister is by using a rigid shaft to displace the center of the debonding film. Malyshev and Salganik (1965) studied the response of a penny-shape debond by treating the coating as a bending plate. Jensen (1991) and Thouless and Jensen (1994) reported strain energy release rates for a point loaded blister with and without residual stress. Williams (1997) reviewed the strain energy release rate of peel and blister test for flexible films under both applied pressure and a point load. Wan and