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Nonlinear mechanics of delamination in fiber-composite laminates: asymptotic solutions and computational results

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Abstract

A delamination in a composite laminate under mechanical loading involves an interface crack between dissimilar, anisotropic composite plies undergoing coupled I, II and III deformation modes. With the presence of high crack-tip local stresses, the effect of inherently nonlinear composite material constitutive properties on the delamination becomes an interest and important issue. In this paper, a nonlinear anisotropic laminate elasticity formulation is introduced to establish governing field equations for a delamination between dissimilar fiber-composite plies. In the context of nonlinear fracture mechanics, the dominant stress singularity and asymptotic solution structure are determined for a delamination in a composite laminate with nonlinear ply constitutive properties. A computational method is used to analyze the delamination field in a composite with complex lamination variables. Delamination energy release rates associated with individual modes are obtained for symmetric angle–ply composite laminates for illustration. Several case studies are conducted to compare the solutions for nonlinear delamination problems with those of corresponding linear interface-crack problems. Unique features of nonlinear composite delamination mechanics are presented, including the order of stress singularity, coupled tearing-mode contributions, and large delamination closure due to strong ply material anisotropy, discontinuity and Poisson's effect.

Keywords: B. Non-linear behaviour; C. Delamination; C. Computational simulation; Asymptotic stress

1. Introduction

Delamination, sometimes also called interlaminar cracking, is a unique and frequently encountered failure mode in advanced composites due to stress concentrations at geometric discontinuities and inherently weak interlaminar strength along the ply interface. The presence and growth of delamination may lead to performance and safety problems, such as stiffness reduction and structural integrity, in composite laminates. Reliable design and analyses of advanced composite structures require clear understanding of the fundamental nature of delamination and establishment of suitable criteria for evaluating delamination growth.

A delamination problem in fiber composites is complex in nature. It involves a highly anisotropic, laminate material system with interface discontinuities (or cracks) and high stress intensities. It is well-known that stresses in the vicinity of a crack tip in linear elastic isotropic and anisotropic solids exhibit, mathematically, a characteristic, inverse square-root singularity [1–4]. In fiber composites, strong anisotropic material nonlinearities [5,6], especially shear constitutive properties, are observed and they introduce additional complications to the crack problem. Before examining a delamination problem in the anisotropic, nonlinear fiber composite, it is appropriate to review first the established analytical solutions for crack problems in a power-law, isotropic material.

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The well-known asymptotic stresses and strains near the crack tip are first determined by Rice and Rosengren [7] and Hutchinson [8,9]. The order of the dominant stress singularity, depending on the hardening exponent, can be determined with a path-independent integral [10]. Angular distributions of stress and strain depend on loading modes and the hardening coefficient. Studies by Hayashi [11] and Pan and Shih [12] obtain asymptotic solutions for a power-law hardening solid with orthotropy in a plane-stress (or strain) condition. The stress singularity is found to depend only on the hardening exponent, not on the plastic orthotropy. However, angular variations of near-field stresses (and strains) do depend on the material orthotropy.

In fiber composites, the anisotropic nature of the material nonlinearity is significantly different from that of a monolithic isotropic material. In particular, composite shear properties are highly nonlinear whereas longitudinal and transverse responses remain linear [5]. Proper formulation of nonlinear constitutive equations becomes the first important step in addressing a composite delamination problem. Several attempts have been made on developing nonlinear constitutive models [13–15] for fiber composites. For example, Hahn and Tsai [13] use a complementary energy density function approach, based on a polynomial basis, to derive a two-dimensional nonlinear model. Three-dimensional nonlinear constitutive relationships for general fiber composites however, have not been fully established in the literature. Inherent coupling of in-plane and transverse deformations in a fiber composite laminate leads to significant complexities due to simultaneous presence of mode-I, II and III deformations in the delamination problem.

In the realm of solid mechanics, a delamination problem may be viewed as an interface crack between dissimilar, highly anisotropic composite laminates subject to general loading. Asymptotic solutions for an interfacial crack between dissimilar isotropic materials have been obtained in several studies [16–19]. An oscillatory stress singularity has been noted, leading to controversial and inadmissible results [18,19]. The issue is addressed [20] by considering surface contact along the interface crack. The study of a delamination between dissimilar, anisotropic linear elastic composites [21–23] indicates that oscillatory characteristics similar to that of an interface crack between dissimilar isotropic solids exist. Furthermore, delamination in composite laminates has been shown [23], in fracture-mechanics terms, to be dominated by coupled mode-I, II and III deformations with a complex crack-tip stress field. Approximate solutions based on the energy release concept are also proposed [24] and details of the near-field variables may not be needed.

It should be mentioned that the delamination problems in fiber composites have also been investigated with a different approach, using continuum damage mechanics of composite materials [25,26]. Meso-mechanics has been introduced [27,28] to address intraply damage and delamination in a composite laminate. The delamination is modeled [28,29] with an interlaminar interface in the composite laminate, and associated computational methods [28,30,31] are developed for evaluating the effects of delaminations on composite laminate behavior and failure.

In this paper, the delamination problem is studied in the context of nonlinear, anisotropic laminate elasticity with interlaminar cracks between dissimilar, anisotropic fiber composite plies. The objectives of this paper are to: (1) establish 3D nonlinear constitutive equations for fiber composites; (2) determine the dominant delamination stress singularity in a nonlinear composite laminate; (3) investigate the effect of nonlinear constitutive equations on the delamination crack-tip asymptotic field, and (4) study the effects of composite lamination variables on delamination fields and associated energy release rates.

2. 3D nonlinear constitutive equations for fiber composite

Consider a composite material with a fiber orientation ϕ, where ϕ is the angle measured counterclockwise from the positive X_3-axis to the fiber direction L (Fig. 1). Introducing the strain energy density function, $W(e_{ij})$, for the composite, one can obtain the stress–strain relationship from

$$\sigma_{ij} = \frac{\partial W}{\partial e_{ij}}, \tag{1}$$

where σ_{ij} and e_{ij} are stress and strain tensors. The complementary energy density function W^* is expressed as $W^* = \sigma_{ij}e_{ij} - W$. For convenience, contracted notations are used for stresses and strains with $[\sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6] = [\sigma_{11}, \sigma_{22}, \sigma_{33}, \sigma_{23}, \sigma_{13}, \sigma_{12}]$ and $[e_1, e_2, e_3, e_4, e_5,$

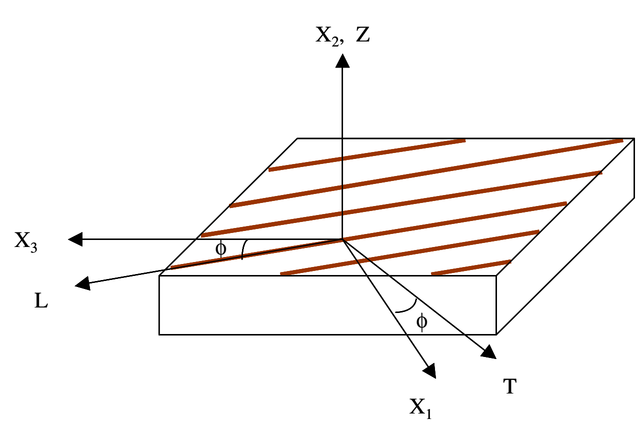

Fig. 1. Coordinates and notations for a fiber composite material.