Geomechanics for Energy and the Environment 4 (2015) 4–28

Contents lists available at ScienceDirect

Geomechanics for Energy and the Environment

journal homepage: www.elsevier.com/locate/gete

Analysis of delamination and damage growth in joined bi-layer systems

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HIGHLIGHTS

- The paper presents analytical solution of the delamination process in a bi-layer plate using the cohesive zone model.
- The effect of elastic moduli and softening moduli on the delamination process has been clarified.
- It was shown that the limit load value is related to fracture energy and stiffness moduli of adhering plates.
- The scale effect is analytically expressed.

ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form 7 October 2015
Accepted 7 October 2015
Available online 17 October 2015

Keywords:
Delamination
Cohesive zone
Shear lag
Damage process

ABSTRACT

The analysis of mechanical response of joined bi- or multi-layer systems is a typical problem for both geomechanics and composite technology. The elastic or visco-elastic layers interact through joining interfaces transferring stress state between layers and assuring structure integrity. The typical damage modes are related to progressive delamination at bonding interfaces, affected by distributed layer cracking. The present work is aimed to provide an analytical study of the stress state in a bi-layer system and of the progressive delamination process. The cohesive zone model is applied to simulate the interface response with shear stresses related to displacement discontinuities and to the specific fracture energies in shear mode. The following specific issues are discussed: delamination mode growth with the related critical and post-critical response of evaluation length of the process zone, scale effect of the critical stress. The analysis results can be applied to clarify the effect of material parameters on the damage process and to discuss experimental testing of epoxy joined ceramic elements, with specification of the connection strength, related to both the critical interface stress and the specific fracture energy.

1. Introduction

Coating layers are usually deposited on boundary surfaces of structural elements in order to improve their mechanical response, such as wear, corrosion or fatigue resistance. Due to mismatch of the thermo-mechanical properties of film–substrate systems the residual stresses are generated both in the initial and loaded states. The damage and failure in layered structures or coatings on substrate constitutes the most important class of problems for this type of composite materials. In most cases the delamination at interface and layer cracking are the main modes of degradation of structure performance. An extensive research has been conducted in the last period in this area, with application of different approaches generally based on the fracture mechanics models or on Cohesive Zone Model (CZM) approach. In the case of surface cracking the small cracks can nucleate from a surface defect but for low load they do not channel through the film. Thus, as a result, small cracks remain stable

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http://dx.doi.org/10.1016/j.gete.2015.10.001

and can be tolerable for many applications. However, for higher stresses within the coating one observes a channeling process with a network of cracks surrounding islands of the intact film.[1] Upon reaching coating/substrate interface several failure mechanisms can follow: cracks enter the substrate material and stabilize at a certain depth.[2–4] They can also deviate and propagate along the coating/substrate interface resulting in a subsequent debonding of the protective film.[5,6] The substrate spalling is another intriguing phenomenon: the crack enters the substrate and selects a path at a certain depth parallel to the interface. This type of failure is common for brittle substrates.[7,8] The cracks arrested on the coating/substrate interface have been observed, also when cracks tend to interface under perpendicularly applied axial strain.[9–12] Then new cracks may appear during loading with initially increased crack density to stabilize at a fixed value, unaffected by further loading. This mode of failure is known as a segmentation or multiple cracking of thin films. The fundamental mode of failure, when the load causes the separation of the layers by generated interface cracks, is delamination directly associated with the fracture toughness.

The fracture mechanics models are usually based on Linear Elastic Fracture Mechanics (LEFM) and energy criteria, namely on the potential energy release rate as the generalized driving force specifying progressive crack growth at its critical value. In Ref. [10,13,14] the energy release rate has been derived in a closed form by applying the variational approach in crack analysis of coated and multilayer systems. In the analysis of segmentation cracking, Hu and Evans[15] assumed the constant shear stress value at the interface, corresponding to ductile response. The similar elastic-perfectly plastic model for the interface was applied by Timm et al.[16] to predict the crack spacing within asphalt pavements. A considerable efforts have been devoted to develop fracture mechanics of interfacial cracking. Hutchinson and Suo[17] provided an extensive study of the singular stress regime and of cracking modes along the interface combined with layer cracking. As the compliance discontinuity occurs, it affects the driving force and induces the local shear stresses at the crack tip. Due to the elastic mismatch the interface or near interface crack experiences both tensile and shear modes (Modes I and II) even if the remote loading corresponds to Mode I. Generally, the crack growth near or at the interface has been shown to depend on the relative strength of coating and substrate or the strength of interfacial bond relative to the strength of adjacent layers. Numerous studies have also been devoted to the fatigue failure of coated layers and correlation between the ability of cracks to traverse an interface undeflected and the bond strength of the interface.[18–22] Suresh and Sugimara successfully predicted the crack growth toward the interface in ductile-bimaterial systems by accounting for the constraint of plastic slip mechanisms ahead of the crack tip and adapted this approach to the analysis for crack growth in a system with brittle coatings.[23–26]

The LEFM solutions for interface cracks exhibit singular oscillatory behavior of stress field in the crack tip zone, generating some difficulties in crack growth modeling. An useful alternative to LEFM is the shear lag (SL) or the cohesive zone model (CZM). The shear lag approach has been frequently applied in the analysis of stress transfer through the interfacial shear stress in composite or bonded materials. The interface tractions τ_n, σ_n are then assumed to be related to displacement jumps u_t, u_n. The elastic analysis of rivet connected elements using this methods was initiated by Volkersen[27] in 1938 and later by Cox[28] in a simple one dimensional model of analysis of stress transfer between a matrix and a fiber assuming the linear elastic relation between shear stress and tangential slip. The subsequent treatments by Hedgepeth[29] and Kelly and Tyson[30] were devoted to composite analysis assuming elastic or elastic–plastic interaction models. The cohesive zone models (CZM) first proposed by Dugdale[31] and Barrenblatt[32] were addressed to analyze the localized damage or plastic flow in the front of crack tip. Next they have been developed to become an effective numerical tool for the analysis of crack initiation and growth, also for study of interfacial fracture of composites. In the literature, numerous proposals for the non-linear interaction between interface tractions and displacement jumps have been presented for the cohesive elements, such as trapezoidal,[33] perfectly plastic,[34] polynomial and exponential rules.[35,36] However, the most common and useful is the bilinear model, accounting for elastic and softening deformation stages preceding final failure. The cohesive zone models implemented in FEM have been widely exploited for specification of critical loads of bonded joints.[37,38] The interface problems and delamination failure were numerically analyzed in Ref. [39–42]. The comparative analysis of several cohesive models in predicting the onset of cracking and failure loads was presented in Ref. [42].

The analytical solutions for the cohesive zone models have been presented in several papers. The analytical treatment is important for the analysis of effect of material and geometric parameters on failure loads and their modes. The analytical solution of beam debonding form rigid substrate under normal load was presented by Williams and Hadivinia.[43] The problem of fiber pull-out for the assumed cohesive model was analytically treated by Schreyer and Peffer.[44] The delamination process under compressive normal load was treated by Mroz and Bialas,[45] next by Bialas and Mroz[46,47] indicating differing tangential deformation response due to coupling of delamination and sliding friction effects. The numerical treatment of cracking of surface coating layer in flexural mode was experimentally and numerically treated by Bialas et al.[48] Crack patterns in thin layers under temperature loading were studied analytically by Bialas and Mroz[48,49] presenting stress analysis and applying the total energy minimization method for prediction of crack pattern. The analytical solutions for specific cases of delamination process in a bi-material structure were presented by Ivanova et al.[50] and Nikolova et al.[51]

The objective of the present work is to provide the analytical treatment of the delamination process in a bilinear structure for the assumed linear elastic and linear damage relation between interface shear stress, τ_I and displacement jump u_I. The analytical solutions provide the insight into the initiation and growth of the damage