International Journal of Solids and Structures 82 (2016) 111–124

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

On the parametric sensitivity of cohesive zone models for high-cycle fatigue delamination of composites

Stephen Jimenez, Ravindra Duddu*

Department of Civil and Environmental Engineering, Vanderbilt University, 400 24th Avenue South, 267 Jacobs Hall; Nashville, TN 37212, United States

ARTICLE INFO

Article history:
Received 15 June 2015
Revised 15 September 2015
Available online 10 November 2015

Keywords:
High-cycle fatigue
Cohesive zone model
Damage mechanics
Mixed mode delamination
Composite materials

ABSTRACT

This article investigates the sensitivity of cohesive zone models (CZMs) for high-cycle fatigue delamination in relation to constituent static parameters, namely, the cohesive strength and stiffness, whose values are frequently calibrated by curve fitting or selected for convenience without any physical basis. After reviewing the damage mechanics formulation of mixed-mode CZMs for static (monotonic) loading in bilinear, exponential, and polynomial cohesive laws, the source of uncertainty arising from the calibration or selection of static parameters is remarked. The formulation of the CZMs for high-cycle fatigue loading using interface separation, strain, and strain energy release rate (SERR) based fatigue damage rate functions is discussed. Several numerical studies are conducted to explore the sensitivity of CZMs for fatigue delamination in relation to static cohesive parameters and to the shape of the cohesive law under mode I and mixed-mode loading. The performance of the CZMs is also investigated for additive and non-additive decomposition of total damage into its static and fatigue components, and for constrained and unconstrained damage update strategies in the vicinity of the crack tip. Numerical studies illustrate that a CZM employing the separation or strain based fatigue damage rate function is highly sensitive to phenomenological cohesive strength and stiffness parameters, whereas a CZM employing the SERR based damage rate function is minimally sensitive to the same static parameters. While the shape of the static cohesive law does not affect fatigue crack growth rate predictions, studies show that cohesive laws with higher-order smoothness can better describe linear Paris regime behavior. The main conclusion of this article is that incorporating a SERR based fatigue damage rate function into a CZM with higher-order smoothness leads to a more robust approach for simulating high-cycle fatigue delamination of laminated composite materials.

1. Introduction

1.1. Preamble

As the design of composite structures is increasingly dictated by lighter weight and better performance requirements, the prediction of long term performance degradation of laminated composite materials using accurate progressive damage accumulation models is becoming ever more important. In the past two decades, the cohesive zone model (CZM) has been extensively used to model and simulate the progressive growth of delamination and debonding in composites within the framework of the finite element method (FEM) because it does not require remeshing as the crack propagates. A variety of CZMs have been developed in the literature for monotonic loading scenarios featuring bilinear, trapezoidal, polynomial, or exponential shapes (van den Bosch et al., 2006). More recently, CZMs have been developed to investigate high-cycle fatigue debonding and delamination growth, which are the dominant modes of failure for subcritical cyclic loading in laminated composite structures (Mi et al., 1998). A more detailed literature review of the CZMs for monotonic (static) and cyclic (fatigue) loading is given in the following Section 1.2. It is important to note that the CZM is essentially a damage mechanics approach for simulating fracture (Alfano and Crisfield, 2001) and is phenomenological in nature. Although many of the CZM parameters have a physical interpretation, they are actually calibrated by fitting the model results to experimental data. Consequently, the viability of CZMs as reliable and accurate progressive damage accumulation models rests on the use and development of cohesive laws that are minimally sensitive to phenomenological parameters. To this end, this study investigates the effect of the shape, strength and stiffness parameters of static cohesive laws on delamination crack growth rate under high-cycle fatigue loading.

The significance of static cohesive parameters (e.g., initial stiffness and cohesive strength) has already been investigated for monotonic

---

* Corresponding author. fax.: +1-615-343-4891.
E-mail address: ravindra.duddu@vanderbilt.edu (R. Duddu).

http://dx.doi.org/10.1016/j.ijsolstr.2015.10.015

(static) loading cases, and several studies reported that the shape of the cohesive law has little effect on global load-displacement behavior so long as the critical fracture energy is held constant (Gustafson and Waas, 2009; Valoroso and Champaney, 2006). However, there are some static loading studies where numerical results are sensitive to the CZM parameters, particularly the cohesive strength (i.e., maximum traction) and the shape of the damage-softening regime (Chandra et al., 2002; de Borst, 2003). For high-cycle fatigue loading, the approach has generally been to decompose damage into static and fatigue components and employ power-law functions to describe fatigue damage accumulation over large numbers of cycles (de Moura and Gonçalves, 2014; Harper and Hallett, 2010; Jimenez et al., 2014; Khoramishad et al., 2010; Robinson et al., 2005). Typically, the power law function is defined based on either the interface separation or the strain energy release rate (SERR) by introducing two new parameters, namely, the damage coefficient and exponent. These two model parameters are then calibrated by matching numerical results to the experimental data in the Paris regime, wherein the crack growth rate with respect to loading cycles $\mathrm{d}a/\mathrm{d}N$ varies linearly with the strain energy release rate ΔG or the stress intensity factor ΔK when plotted on a log-log scale (Paris and Erdogan, 1963; Paris et al., 1961). A key point is that the interaction between static and fatigue damage under cyclic loading introduces a non-physical dependence of fatigue crack growth rate on static model parameters of cohesive stiffness and cohesive strength, which are usually taken as penalty parameters under monotonic loading cases (Pascoe et al., 2013). Additionally, the crack growth rate predictions are affected by the lack of smoothness of cohesive law (e.g. bilinear shape with C^0 continuity) due to the abrupt change from linear elastic behavior to damage-induced softening behavior. Moreover, the power law fatigue damage functions based on interface separation and SERR exhibit different parametric sensitivities depending on the numerical implementation. To the best of the authors' knowledge, there exist no prior investigations that assess the sensitivity of crack growth rate results to CZM parameters for high-cycle fatigue loading of laminated composites.

The main contribution of this article is with respect to the assessment of the sensitivity of interface separation and SERR based fatigue damage model predictions to static cohesive stiffness and strength parameters and to the shape (smoothness) of the cohesive law. The second contribution is the investigation of the additive and non-additive decompositions for combining static and fatigue damage components during cyclic loading, along with a sensitivity study between constrained and unconstrained damage update algorithms at the crack tip. The main conclusion of this article is that the SERR based fatigue damage function leads to a more reliable formulation for predicting delamination crack growth under high-cycle fatigue loading.

1.2. Literature review

The various approaches for numerical simulation of delamination can be classified into linear elastic fracture mechanics (LEFM) approaches and continuum damage mechanics (CDM) approaches. The cohesive zone model (CZM), developed by Hillerborg et al. (1976) using the concept of a bounded stress field within the vicinity of a crack tip (Barenblatt, 1962; Dugdale, 1960) can be recast into the CDM approach (Alfano and Crisfield, 2001). In the CZM, cohesive elements are placed along potential crack interfaces and their constitutive behavior is defined by a traction-separation ($T-\delta$) law. Typically, the cohesive element is assumed to have zero thickness and the crack interface separation δ is calculated from the relative displacement of its nodes once the interface begins to open. The $T-\delta$ function generally features an initial elastic regime followed by a softening regime that can take a variety of shapes. Although the bilinear cohesive law is the simplest and also the most commonly employed $T-\delta$ law, other prominent formulations incorporate the exponential functions (Xu and Needleman, 1994) and polynomial functions (Park et al., 2009) which were derived from thermodynamically based energy potentials. In early studies, CZMs were used to investigate crack growth under monotonic loading (Mi et al., 1998; Robinson et al., 2000; Schellenkens and de Borst, 1993; Yang and Ravi-Chandar, 1998) and were not designed with an inelastic (irreversible) response to separation. Later, CZMs were formulated for non-monotonic loading by incorporating loading history dependent state variables to account for the irreversibility of damage accumulation in the material behind the crack tip (Alfano and Crisfield, 2001; Foulk et al., 2000; Park et al., 2009). For example, Foulk et al. (2000) developed cohesive laws with a response dependent on the maximum separation during loading history; whereas, Alfano and Crisfield (2001) and Yang et al. (2001) presented CZM formulations by incorporating an irreversible damage variable, D_{s}, to represent interface degradation and permanently weaken the cohesive element. In general, following the damage mechanics framework the $T-\delta$ law can be written as Alfano and Crisfield (2001),

$$T = (1 - D_{\mathrm{s}})K^0\delta, \tag{1}$$

where K^0 is the initial (undamaged) cohesive stiffness, and the scalar internal state variable $D_{\mathrm{s}} \in [0, 1]$ controlling the shape of the softening regime. To ensure the irreversibility of damage, the condition $\dot{D}_{\mathrm{s}} \geq 0$ is imposed.

For monotonic (static) loading, at least two strength parameters are required to define the $T-\delta$ law, namely, the critical fracture energy G_{C} and cohesive strength $T_{\max}$, and additional shape and stiffness parameters are specified depending on the assumed shape of the cohesive law (Xu and Needleman, 1994). Under pure mode I (normal separation) and mode II (tangent separation) conditions, the corresponding critical fracture energies are usually denoted by G_{IC} and G_{IIC}, and the corresponding cohesive strengths are denoted by $\sigma_{\max}$ and $\tau_{\max}$, respectively. Since, in reality, debonding and delamination failures take place under variable mode-mix ratios with both normal and tangent separations, the mixed-mode behavior is conveniently described in terms of mode I and mode II parameters through an interaction criterion (Jiang et al., 2007). The mode I critical fracture energy G_{IC} (or critical SERR) is a material property that can be determined experimentally through a double-cantilever beam (DCB) test, and there is relatively little uncertainty in its value (Gustafson and Waas, 2009). Oftentimes, G_{IC} is the only known cohesive parameter of a material (Diehl, 2008). The standard procedure for retrieving G_{IIC} is the end notched flexure (ENF) test; however, the accuracy of this test is disputed (O'Brien, 1998; Pascoe et al., 2013).

Cohesive strength parameters $\sigma_{\max}$ and $\tau_{\max}$ are the maximum tractions that the interface can sustain without damage in the normal and tangential directions, respectively. The value of $\sigma_{\max}$ may be calibrated through various experiments (Gustafson and Waas, 2009), however there is no standard procedure for this measurement. Ferracin et al. (2003) suggested a combined numerical and experimental approach for determining $\sigma_{\max}$ by conducting a wedge-peel test and comparing the deformation of adherent arms to simulation results where a CZM is applied along the adhesive fracture process zone. Some authors regard $\sigma_{\max}$ as an adjustable penalty parameter because in many cases it does not heavily influence global load-displacement results, so long as a sufficiently large value is chosen (Turon et al., 2007; Xie et al., 2006). The value of $\tau_{\max}$ can be determined from a single lap joint (SLJ) test, however, care must be taken to account for uncertainty of G_{IC} and G_{IIC} which can significantly affect the calibrated result (Gustafson and Waas, 2009). The other stiffness and strength related parameters K_{n}^0, $\delta_{\mathrm{n}}^{\mathrm{c}}$, and $\delta_{\mathrm{n}}^{\mathrm{u}}$ are usually dependent on G_{IC} and $\sigma_{\max}$; likewise, K_{t}^0, $\delta_{\mathrm{t}}^{\mathrm{c}}$, and $\delta_{\mathrm{t}}^{\mathrm{u}}$ are usually dependent on G_{IIC} and $\tau_{\max}$, where the subscripts n and t denote the normal (mode I) and tangential (mode II) components, respectively. Lee et al. (2010) proposed an iterative nonlinear optimization scheme to calibrate $\sigma_{\max}$, $\tau_{\max}$, K_{n}^0, and K_{t}^0 from experimental data, provided that