International Journal of Solids and Structures 47 (2010) 901–911

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

In-plane fracture of laminated fiber reinforced composites with varying fracture resistance: Experimental observations and numerical crack propagation simulations

Siva Shankar Rudraraju [a,b], Amit Salvi [b], Krishna Garikipati [a], Anthony M. Waas [a,b,*]

[a] University of Michigan, Department of Mechanical Engineering, 2350 Hayward Street, Ann Arbor, MI 48109, USA
[b] University of Michigan, Department of Aerospace Engineering, FXB Building, 1320 Beal Avenue, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 2 June 2009
Received in revised form 19 November 2009
Available online 23 December 2009

Keywords:
In-plane
Through-the-thickness
Fracture
Toughness
Fiber composite
VMCM
Cohesive
Micromechanics
Bridging zone

ABSTRACT

A series of experimental results on the in-plane fracture of a fiber reinforced laminated composite panel is analyzed using the variational multiscale cohesive method (VMCM). The VMCM results demonstrate the influence of specimen geometry and load distribution on the propagation of large scale bridging cracks in the fiber reinforced panel. Experimentally observed variation in fracture resistance is substantiated numerically by comparing the experimental and VMCM load–displacement responses of geometrically scaled single edge-notch three point bend (SETB) specimens. The results elucidate the size dependence of the traction-separation relationship for this class of materials even in moderately large specimens, contrary to the conventional understanding of it being a material property. The existence of a "free bridging zone" (different from the conventional "full bridging zone") is recognized, and its influence on the evolving fracture resistance is discussed. The numerical simulations and ensuing bridging zone evolution analysis demonstrates the versatility of VMCM in objectively simulating progressive crack propagation, compared against conventional numerical schemes like traditional cohesive zone modeling, which require a priori knowledge of the crack path.

1. Introduction

Laminated fiber reinforced composites are finding increased use as structural materials in a variety of aerospace and other industrial applications. An appealing property of these composites is their high specific strength (strength per unit weight). Even though a strong case can be made for using composite structural parts in several areas of a load bearing structure, the requirement to demonstrate structural integrity and damage tolerance (SIDT) necessitates a fundamental understanding of the mechanical response, damage tolerance and damage growth of a load bearing composite structure. While several investigations have addressed damage growth in the form of delamination crack growth, relatively little has been done to understand damage propagation when a crack, or damage in the form of a crack that has severed all laminae of a laminate, is present in a composite structure. The influence of such wide area damage on the load bearing ability of a homogeneous and isotropic material has received considerable attention in the past; however, a similar effort at understanding issues in a non-homogeneous and macroscopically orthotropic structure is still a problem that requires resolution. Because of the different length scales associated with the microstructure of a composite material and the resulting composite structure, a multitude of failure mechanisms can be simultaneously operative, leading to a very complex damage progression in a composite structure. A sharp, through the thickness crack can be present in these composites initially, but, as soon as local damage (this can be in the form of matrix micro-cracking) accumulates, crack blunting and distributed damage occurs across the highly stressed areas around the initial crack tip. As this initial crack starts to grow, a damaged zone of material (bridging zone) evolves in the wake of the instantaneous crack tip. Thus, unlike in monolithic materials (such as metals), there is no well-defined "crack" that can be identified. Instead, a diffused zone of damage is seen to advance. This distributed damage results in additional resistance to advancing damage growth, largely contributed by fiber bridging and pullout in the crack wake . This enhanced fracture resistance is desirable and is a major contributor to the increased toughness of these laminated composites (Cooper, 1970; Aveston et al., 1971; Aveston and Kelly, 1973; Cox, 1991).

Analytical models based on linear elastic fracture mechanics (LEFM) have been developed and implemented within finite element codes to study a variety of fracture problems. LEFM based approaches have proven to be effective in predicting crack initiation and subsequent growth in cases where material nonlinearity is negligible, and process zones are small (Hertzberg, 1983; Xie and Biggers, 2006a,b; Xie et al., 2004, 2005). However, in heterogeneous materials, like laminated fiber composites, the process zone

* Corresponding author. Address: University of Michigan, Department of Aerospace Engineering, FXB Building, 1320 Beal Avenue, Ann Arbor, MI 48109, USA.
E-mail address: dcw@umich.edu (A.M. Waas).

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doi:10.1016/j.ijsolstr.2009.12.006

size may be larger than any characteristic problem length scale, and thereby, the basic tenets of LEFM cease to hold (Xie et al., 2006). Several mechanisms may contribute to this situation. Micro-cracking, fiber bridging, coalescence of voids and other microstructural mechanisms can give rise to a process zone that is considerably larger than that permitted for the application of LEFM models. Furthermore, the material nonlinearity that is induced by these mechanisms leads to a relief of the singular fields that would otherwise persist in a strict LEFM setting of an elastic material. A new length scale, l^*, emerges that is related to a characteristic elastic modulus E, fracture toughness Γ and cohesive strength, σ_c, defined as, $l^{*2} = \frac{E\Gamma}{\sigma_c^2}$. If l^* is larger than any characteristic length scale in the problem, then, cohesive zone models (CZM) become an indispensable tool for analysis (Pietruszczak and Mroz, 1981; Ungsuwarungsri and Knauss, 1987; Tvergaard and Hutchinson, 1992; Schellekens and Borst, 1993; Xu and Needleman, 1994; Camacho and Ortiz, 1996).

In order to implement a CZM in its simplest form, two fracture parameters are required: a fracture toughness (or energy) and a cohesive strength. Both parameters can be experimentally determined by coupon level tests, and are subsequently used as material properties for prediction of crack growth in other structural configurations. In CZM, an existing crack starts to grow when the crack tip stresses reach the cohesive strength, and evolves according to the energy available in the deformed system to create additional cracked surface. Based on these two parameters, a cohesive traction-separation law is assumed in numerical simulations of crack growth. This micromechanical law relates the evolution of crack face tractions with the crack face opening displacement, and numerically manifests the resistance offered to crack advancement within the cohesive zone. This two parameter dependent evolution, unlike the solely fracture toughness based LEFM schemes, better represents the physics of crack growth in materials with significant process zones, and it has been widely used in many numerical implementations, like the discrete cohesive zone method (DCZM) (Xie and Waas, 2006; Xie et al., 2006). However, all implementations of CZM methodology require a priori knowledge of the "intended" crack path. This prevents CZM from being applied to a wide range of problems involving arbitrary crack path evolution. Conventional finite element based implementations of CZM (Nguyen et al., 2001) constrain the crack path evolution to element interfaces, as standard finite elements lack the ability to represent cracks within the element domain. This restriction places a limitation on those problems for which the crack path direction is not known a priori.

In addition to the above drawbacks of CZM models, recent work by Jin and Sun (2005, 2006), has addressed some basic issues pertaining to the reconciliation of LEFM and CZM. In particular, two issues have been considered; (1) when CZM is used, the placement of CZM elements along the intended crack path can lead to an alteration of the stiffness of the original body that is to be studied, and, (2) the traction-separation laws used for traditional CZM modeling, which start with a vanishing traction at vanishing separation, may be in conflict with the presence of an intense stress field that was present in the original body that is being modeled.

To order to address these basic issues and to circumvent the numerical restrictions on unrestricted and objective simulation of crack propagation in materials, a micromechanics based, mesh independent numerical technique for simulating crack propagation is essential. Standard finite elements fail to accomplish this task as they lack the ability to capture the discontinuous displacement modes involved in crack propagation problems. However, in recent years finite elements with discontinuities (enhanced finite elements) have gained increasing interest in modeling material failure, due to their ability to capture the specific kinematics of a displacement discontinuity (like cracks) through additional discontinuous deformation modes. In discontinuous displacement enhanced finite elements, the crack path is present inside the elements, unlike cohesive zone methods which are restricted to crack propagation along element interfaces. The ability of the enhanced finite element to encompass a crack path, leads to objective simulation of crack propagation without mesh bias. Depending on the support of the enriching discontinuous displacement modes, the enhanced finite elements are popularly classified as element enrichment methods (Armero and Garikipati, 1996; Garikipati and Hughes, 1998; Jirasek, 2000; Borja and Regueiro, 2000; Oliver and Huespe, 2004; Mosler and Meschke, 2004; Gasser and Holzapfel, 2003) and nodal enrichment methods (XFEM, Belytschko et al., 2001; Belytschko et al., 2003; Moes et al., 2000; Wells and Sluys, 2001). Interested readers are referred to Oliver et al. (2006), for detailed discussion and comparison of these methods. Though these enhanced methods provide a general numerical framework for simulation of crack evolution, the actual micromechanics implementation which incorporates the physics of crack formation is wide open. In this context, we present the Variation Multiscale Cohesive Method (VMCM), which is an enhanced finite element method containing elemental displacement field enrichment, naturally arising out of the variational multiscale formulation presented in Garikipati and Hughes (1998) and Garikipati (2002), seamlessly embedding the cohesive nature of crack path evolution. In this paper, the VMCM method advanced by the authors is briefly presented, and it is used to study through the thickness crack propagation in fiber reinforced laminated panels. A more detailed presentation of VMCM is available in other related studies by the authors (Garikipati, 2002; Rudraraju et al., 2008), where the method is referred to as the variational multiscale method (VMM).

Table 1
Lamina and laminate properties of carbon fiber/epoxy $[-45/0/+45/90]_{6s}$ laminated fiber reinforced composite.

Laminate	Lamina
E_{xx}: 51.5 GPa	E_{11}: 141 GPa
E_{yy}: 51.5 GPa	E_{22}: 6.7 GPa
G_{xy}: 19.4 GPa	G_{12}: 3.2 GPa
ν_{xy}: 0.32	ν_{12}: 0.33

The paper is organized as follows: in Section 2, the application of VMCM to study crack propagation is motivated through a discussion of experimental results in scaled SETB specimens, loaded to failure. Section 3 presents the details of VMCM implementation using the finite element method. Simulations of SETB tests with varying specimen size are provided in Section 4. Comparison of experimental results, against the predictions of VMCM are discussed in Section 5, while concluding remarks are presented in Section 6.

2. Motivation

The primary motivation for the current work is the experimentally observed scaling in the in-plane fracture resistance,[1] with increase in specimen size of single edge-notch three point bend (SETB) specimen, subjected to primarily Mode-I crack tip conditions. The material used in all the experiments herein is a carbon fiber/epoxy

[1] Traditionally, fracture resistance is defined in terms of the energy released per unit area of crack surface formation. But, unlike in most monolithic materials, there is no well-defined "crack" that can be identified in a laminated fiber composite panel, where a crack like feature propagates severing all laminae of the laminate. Then, by unit area of crack surface, we mean unit area of completely failed (both matrix and fiber failure) surface along the crack like diffused zone of damage. The usage of the term "fracture toughness" is resisted, to avoid confusion with the traditional LEFM approach, where it is often regarded as a material property.