Journal of the Mechanics and Physics of Solids 116 (2018) 17–32

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

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

Predicting the mixed-mode I/II spatial damage propagation along 3D-printed soft interfacial layer via a hyperelastic softening model

Lei Liu, Yaning Li*

Department of Mechanical Engineering, University of New Hampshire, Durham, NH 03824, USA

A R T I C L E I N F O

Article history:
Received 20 October 2017
Revised 11 January 2018
Accepted 20 March 2018
Available online 22 March 2018

Keywords:
Hyperelastic
Suture
3D printing
Damage propagation
Mixed-mode, Stress triaxiality

A B S T R A C T

A methodology was developed to use a hyperelastic softening model to predict the constitutive behavior and the spatial damage propagation of nonlinear materials with damage-induced softening under mixed-mode loading. A user subroutine (ABAQUS/VUMAT) was developed for numerical implementation of the model. 3D-printed wavy soft rubbery interfacial layer was used as a material system to verify and validate the methodology. The Arruda – Boyce hyperelastic model is incorporated with the softening model to capture the nonlinear pre-and post- damage behavior of the interfacial layer under mixed Mode I/II loads. To characterize model parameters of the 3D-printed rubbery interfacial layer, a series of scarf-joint specimens were designed, which enabled systematic variation of stress triaxiality via a single geometric parameter, the slant angle. It was found that the important model parameter *m* is exponentially related to the stress triaxiality. Compact tension specimens of the sinusoidal wavy interfacial layer with different waviness were designed and fabricated via multi-material 3D printing. Finite element (FE) simulations were conducted to predict the spatial damage propagation of the material within the wavy interfacial layer. Compact tension experiments were performed to verify the model prediction. The results show that the model developed is able to accurately predict the damage propagation of the 3D-printed rubbery interfacial layer under complicated stress-state without pre-defined failure criteria.

1. Introduction

Adhesive interfacial layers are ubiquitous in both engineering and natural material systems. They are essential in governing the mechanical behaviors of these materials. For example, interfacial layers are key mechanical features in engineering laminated composites (Herrera-Franco and Drzal, 1992; Sela and Ishai, 1989), metal matrix composites (Ibrahim et al., 1991) and ceramic matrix composites (Srivastava, 2011; Naslain, 1998), and in many biological material systems, such as the nacre layer of the sea shells (Barthelat and Espinosa, 2007), the suture layers in human skulls (Jaslow, 1990; Liu et al., 2017), the turtle carapace (Krauss et al., 2009), the pelvic girdle of a stickleback (Song et al., 2010), and the seed coat of a common millet (*Panicum miliaceum*) (Hasseldine et al., 2017). In the literature, interface morphology was identified as an important factor to influence fracture and crack propagation of adhesive interfaces (Zavattieri et al., 2007; Zavattieri et al., 2008; Cordisco et al., 2012; Li et al., 2012; Cordisco et al., 2014; Cordisco et al., 2016). Recently, a wavy interface morphology was

---

* Corresponding author.
E-mail address: yaning.li@unh.edu (Y. Li).

https://doi.org/10.1016/j.jmps.2018.03.016
0022-5096/© 2018 Elsevier Ltd. All rights reserved.

proved to enable effective load transmission under in-plane mixed Mode I/II loading (Li et al., 2011, 2012, 2013). This research suggested that the strength and toughness of the adhesive interfacial layer can be enhanced by tuning the interface morphology.

Traditionally, desired interface morphologies can be achieved by etching, laser ablation, and hot wire electrical discharge machining (WEDM) etc. (Zavattieri et al., 2008; Cordisco et al., 2016; Malik and Barthelat, 2016). However, with these traditional manufacturing methods, the variation and resolution of the morphological pattern is limited, and the mechanical performance of the wavy adhesive interfacial layer is largely influenced by the quality of the interfacial bonding. With the rapid development of 3D printing technology, these limitations are being removed. Recently, high-quality biomimetic composite suture specimens with complicated wavy interface patterns were directly fabricated via a multi-material 3D printer (Lin et al., 2014a, 2014b), providing a promising tool to advance this topic in the field. Along with this new development, new challenges appear in modeling the damage initiation and evolution of 3D printed soft adhesive interfacial layer.

Practical approaches to evaluating material failure under mixed-mode loading include (1) a cohesive zone model (CZM), (2) a damage mechanics model, and (3) a virtual internal bond (VIB) model. The concept of cohesive zone was first proposed by Dugdale (1960) and Barenblatt (1962). Conceptually, a CZM captures interface fracture via defining its traction-separation behavior. Widely-used traction-separation laws include polynomial (Needleman, 1987), exponential (Xu and Needleman, 1993), trapezoidal (Tvergaard and Hutchinson, 1992) and bilinear (Camacho and Ortiz, 1996). Remmers et al. (2003) proposed cohesive segments model to simulate the initiation and nucleation of coexisting cracks without assuming crack propagation path. Sun and Liew (2017) incorporated the cohesive segments model into an element-free framework to study the thermal-mechanical failure behavior of materials. A multi-scale approach (Hori and Nemat-Nasser, 1999; McDowell, 2010) was developed to relate the micro-structure and the macroscopic level failure behavior. For example, Toro et al. (2016) presented a two-scale formulation to account for the nucleation of cohesive cracks in the micro-scale domain. The cohesive zone model has been applied to simulate the crack initiation and propagation of a sinusoidal interface under Mode I loading (Zavattier et al., 2007; Zavattier et al., 2008; Cordisco et al., 2012; Li et al., 2012; Cordisco et al., 2014; Cordisco et al., 2016). However, in a CZM for in-plane problem, the traction-separation behavior only considers tension in the normal (σ_{nn}), shear in tangential (σ_{nt}) direction; for adhesive joints with certain interfacial layer thicknesses, the damage propagation of material under a complicated stress state cannot be fully captured. Particularly, the stress component (σ_{tt}) along the tangential direction of the interfacial layer, which is not considered in CZM, may significantly influence the stress-state of the material and therefore, the damage initiation and evolution of the interfacial layer.

In a damage mechanics modeling approach, the full 3D stress state is modeled as progressive failure for a continuum (Kachanov, 1986; Lippmann and Lemaitre, 1996), and both damage initiation and damage propagation of the material are determined by the stress state (Rice and Tracey, 1969). Damage mechanics models have been used widely in predicting failure of composite materials (Hashin and Rotem, 1973; Talreja, 1985; Ellyin and El-Kadi, 1990; Maire and Chaboche, 1997), and the ductile failure of metals (Johnson and Cook, 1985; Bao and Wierzbicki, 2004; Bai and Wierzbicki, 2008, 2010; Li and Wierzbicki, 2010). Both the CZM and the damage mechanics models require a pre-defined criterion for damage initiation and evolution.

The virtual internal bond model (VIB), which was first proposed by Gao and Klein (1998), conceptually has the advantage of simulating material failure without pre-assuming any failure criteria (Gao and Klein, 1998). In the VIB model, the material is assumed to consist of micro particles/atoms connected by a randomly distributed network of cohesive bonds (Gao and Klein, 1998). The strength and softening of each cohesive bond is determined by a potential prescribed between atoms/particles, such as the Cauchy potential (Milstein, 1980). The cohesive behavior between atoms/particles could be incorporated into the constitutive model of a material at the macro scale through the Cauchy-Born rule (Born and Huang, 1956). By extending the concept of VIB model to macro scale, based on the concept of continuum damage mechanics (CDM), Volokh (2007, 2010) developed a strain energy density based model to capture the damage-induced softening of hyperelastic materials. To remedy the pathological mesh sensitivity of the bulk failure models, Volokh (2017) proposed a new promising solution which enables prediction of failure localization by considering the law of mass balance in the fracture process.

Typically, mixed-mode I/II failure criteria can be calibrated via many different experimental approaches, such as mixed-mode bending (MMB) tests, Arcan tests, and scarf joint experiments. The mixed-mode bending test was first introduced by Crews and Reeder (Crews and Reeder, 1988; Reeder and Crews, 1990). For the MMB test, the combination of Mode I and Mode II was limited by the testing apparatus, and the stress field is very complicated. The Arcan test (Arcan et al., 1978) was first designed to study the strength of laminae in fiber-reinforced composites in plane-stress condition. Later, the Arcan test was modified to study the mixed-mode fracture behavior of adhesive bonds (Pang and Seetoh, 1997; De and Narasimhan, 1998). Bascom and Oroshnik (1978) developed scarf-joint specimens to study the mixed-mode fracture energy of an adhesive layer under different bond angles. Conceptually, both the scarf joint specimen and Arcan test for the adhesive layers could provide different combinations of Mode I and Mode II loads by simply varying the slant angle of the specimen/fixture. Compared with scarf-joint specimens, Arcan tests can reach a relatively uniform stress with little stress concentration, but it is limited by the design of the fixture, and experiments can be performed only under certain slant angles. Also, during loading, Arcan test specimens always experience a certain level of rotation, sometimes non-negligible horizontal forces are generated. The experimental procedure of the scarf joint specimens is more straightforward; no special fixture is needed to perform the experiment. However, the traditional scarf joint specimens could not be used for simple shear, and the notorious stress concentration at the free edge of the specimens makes the strength obtained from the scarf joint experiments consistently lower than the real strength of the material. In the present investigation, scarf joint