Mechanics of Materials 91 (2015) 64–75

Contents lists available at ScienceDirect

Mechanics of Materials

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

Mixed-mode translaminar fracture of woven composites using a heterogeneous spring network

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ARTICLE INFO

Article history:
Received 19 April 2015
Received in revised form 24 July 2015
Available online 3 August 2015

Keywords:
Spring network model
Fracture simulation
Glass/epoxy plain weave composite
Intra-laminar fracture

ABSTRACT

A statistical approach is taken to model the complex fracture process involved in the mode-I and mixed-mode translaminar growth of a macroscopic crack in a representative woven composite material. A two dimensional rectangular elastic spring network with nearest and next-nearest neighbour interactions was used to discretise a typical fracture specimen. An arrangement of rigid truss elements was introduced at the top and bottom edges of the network to model the displacement boundary conditions realistically. Heterogeneous properties of the woven composites were incorporated in the model by defining four types of regions composed of different combinations of hard and soft bonds. Among the model parameters, the ratio between the modulus of hard and soft bonds was found to have minimal effect on the fracture process as well as the macroscopic response. However, the ratio between the mean failure threshold strains is shown to be critical in simulating nucleation of damage at multiple sites around the initial crack plane resulting in large process zones and higher dissipation of energy during crack growth that is typical of composite materials as reported in existing literature.

1. Introduction

Steadily increasing use of composite materials in primary structural applications demands damage tolerant design approach to ensure optimum as well as safe utilisation of these materials. To exploit the superior mechanical performance of fiber reinforced composite material systems and the associated cost benefits, there has been a focused effort towards developing a comprehensive understanding of the dominant failure modes: inter-laminar fracture caused primarily due to matrix cracking leading to delamination (Alif et al., 1998; Nikbakht and Choupani, 2009) and intra-laminar (or translaminar) fracture which involves both matrix cracking and significant fiber breakage (Rami and Rani, 2003; Laffan et al., 2012). Development of models that can realistically reproduce the characteristic features of the fracture behaviour of these material systems are, therefore, critical for their design.

Mode-I fracture properties of composite materials systems have been characterised using standard fracture specimens, such as, Double Cantilever Beam (DCB), Compact Tension (CT), etc. For mode-I translaminar fracture, a combination of CT and ECT fracture specimen was found to be most suitable in terms of extent of stable crack growth that was achievable, efficient use of material and ease of data reduction for characterisation of fracture properties (Laffan et al., 2012). In mode-I translaminar fracture, fiber orientation angle also influences the fracture process. As the fiber orientation angle changes from 0° to 90°, the fracture toughness increases and the fiber breakage becomes the dominant mode of failure, rather than the matrix cracking. In case of a symmetric cross-ply laminate, 90° plies

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http://dx.doi.org/10.1016/j.mechmat.2015.07.013
0167-6636/

dominate the fracture process compared to 0°, where fiber breakage is the primary mode of failure (Jose et al., 2001).

In characterisation of effect of mode-mixity on fracture properties and failure mechanisms, introduction of mode-II component was shown to greatly affect the delamination at the interface of 0/90 plies and the associated damage zone in CFRP cross-ply laminates (Laffan et al., 2013). The crack growth takes place due to the initiation of fiber fracture at the delamination fronts, followed by the fracture of bundles of fibers. In a recent study on translaminar mixed-mode fracture of plain weave glass/epoxy composite, Boyina et al. (2014) showed that under conditions of higher mode-mixity, the macroscopic response prior to final failure is highly non-linear in spite of the inherent brittleness of the constituents. From the corresponding micrographs of mid-thickness plane of fractured specimens it was established that the fracture process under conditions of higher mixity had significantly higher fiber–matrix debonding along the transverse fibers which resulted in gradual dissipation of energy prior to final failure due to fiber breakage along the crack path. Using different data reduction techniques, such as compliance method (Laffan et al., 2013; Boyina et al., 2014), virtual crack closure method (Rizov, 2013), the effect of mixity on energy release rate has been shown to result in increased resistance to continued growth of a crack-like defect. While these studies provide an insight into the failure mechanisms and characterise the fracture properties in terms of effective energy release rate, the properties are specific to loading configurations and therefore have little predictive power.

The mechanical as well as fracture properties of complex brittle materials, such as composite materials, are known to be statistically distributed (Lawn and Wilshaw, 1975; Jan et al., 2002; Alava et al., 2006). The fracture process in them involves formation of micro-cracks at multiple sites, their interaction and growth leading to final failure which is hard to model using classical fracture mechanics theory or using standard finite element method. Statistical models that represent continuum by a lattices of particles connected to each other by a network of springs, incorporate the statistically distributed nature of the properties into the spring behaviour and are able to provide an insight into the effect of disorder on the fracture behaviour of heterogeneous material systems (Alava et al., 2006). Overall statistical features of brittle failure of heterogeneous systems in absence of a pre-existing macroscopic crack, such as effect of residual stress on transition from brittle to non-brittle macroscopic response are well reproduced using a spring network with random initial spring length (Curtin and Scher, 1990). Similarly, by using a spring network with random failure threshold, the decay in distribution of avalanche size being a power law and damage initiating randomly under application of macroscopic strain initially but the growth of damage becoming highly correlated resulting in formation of a well defined macroscopic crack can also be simulated (Ray, 2006). Extended to composite materials, the effect of disorder, represented by a fraction of softer springs in the network having the same failure threshold stress, is shown to result in decrease in the load bearing capacity of the composite material (Moukarzel and Duxbury, 1994). Interestingly in presence of an initial macroscopic crack, a similar disorder has been shown to result in an increase in overall load bearing capacity (Urabe and Takesue, 2010). In these studies, simulations for various combinations of heterogeneity, however, have been performed for assumed material behaviour and there has been little emphasis on quantitative validation with experimental data. As a result, the effectiveness of statistical models in reproducing experimental data has remained largely untested and procedures to find the required model parameters, unidentified.

Can a predictive model based on disordered spring network be developed that is able to model mode-I and mixed mode loading configurations and incorporate the effects of complex mechanisms involved in the fracture process of a woven roving mat reinforced epoxy matrix during the growth of a macroscopic defect? In this paper, numerical analysis is carried out on the mixed-mode fracture behaviour of plain weave glass/epoxy composites using a random spring-network model and the results are benchmarked with the experimental findings of Boyina et al. (2014). The fracture specimen is modelled as a 2-dimensional rectangular spring network with nearest and next-nearest neighbour interactions, and the fixtures are replicated with the rigid truss members. Complex heterogeneous properties of the woven composite are incorporated by defining four types of regions, which are in turn composed of soft or hard bonds. The key model parameters influencing the fracture properties are identified as: the modulus ratio between the soft and hard bonds, failure threshold of the hard bonds, the ratio of failure threshold and the relative proportion of different regions. Simulations are carried out to determine the influence of these parameters on the fracture behaviour and to identify the suitable combination of these parameters which produces near experimental behaviour.

2. Spring network model for mixed-mode fracture of heterogeneous materials

2.1. Spring network model

The complex fracture process in glass–epoxy woven composite material under conditions of higher mixity exhibits significant non-linear macroscopic response in spite of the constituents being brittle (Boyina et al., 2014). Microscopically, the crack path was shown to depend on the local micro-structure and the damage process to involve significant fiber–matrix debonding along transverse fibers before final failure due to fiber breakage. In the present study, to simulate the complex fracture process involved in the growth of a crack, a rectangular domain within the modified compact test specimen used by Boyina et al. (2014) is first identified and then discretised using a 2 -dimensional square lattice as shown in Fig. 1(a) and (b) respectively. Lattice size of the rectangular domain representing the MCT specimen is taken to be 45×60, similar to the lattice size reported by Urabe and Takesue (2010). The representative unit of the domain is a square lattice as shown in Fig. 1(c). Where each lattice