Journal of the Mechanics and Physics of Solids 59 (2011) 1355–1373

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

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

High-fidelity simulations of multiple fracture processes in a laminated composite in tension

X.J. Fang [a], Z.Q. Zhou [a], B.N. Cox [b], Q.D. Yang [a,*]

[a] Department of Mechanical and Aerospace Engineering, University of Miami, Coral Gables, FL 33124, USA
[b] Teledyne Scientific Co LLC, Thousand Oaks, CA 91360, USA

ARTICLE INFO

Article history:
Received 14 June 2010
Received in revised form
8 March 2011
Accepted 3 April 2011
Available online 14 April 2011

Keywords:
Fracture
Fiber-reinforced composite material
Finite elements

ABSTRACT

The augmented finite element method (A-FEM) is used to study the fundamental composite failure problem of delamination and associated damage events spreading from a stress concentrator during tensile loading. The solution exploits the ability of A-FEM to account for coupled multiple crack types that are not predetermined in shape or number. The nonlinear processes of each fracture mode are represented by a cohesive model, which provides a unified description of crack initiation and propagation and can also describe crack coalescence and bifurcation. The study problem is an orthogonal double-notched tension specimen, in which delaminations interact with transverse ply cracks, intra-ply splitting cracks, non-localized fine-scale matrix shear deformation, and fiber breaks. Cohesive laws and constitutive laws for matrix shear deformation are calibrated using literature data from independent tests. The calibrated simulations are mesh independent and correctly reproduce all qualitative aspects of the coupled damage evolution processes. They also correctly predict delamination sizes and shapes, the density of transverse ply cracks, the growth rate of splitting cracks, softening of the global stress–strain curve, and the ultimate strength. A sensitivity analysis relates variability in cohesive law parameters to predicted deviance in engineering properties. Given the known variability in cohesive law parameters, the predicted deviance in ultimate strength agrees with that in experimental data. The importance of including the interactions between different crack systems and non-localized shear deformation is demonstrated by suppressing the presence of separate mechanisms; the predicted delamination shapes, splitting crack growth rate, and the stress–displacement relationship fall into significant error.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Despite extensive research on composite materials, predicting their progressive failure remains a challenging task due to the complexity of the interactions among multiple damage processes. For laminated composites, the damage processes include transverse matrix cracking, fiber rupture (in tension) or kinking (in compression), splitting between fiber and matrix; interlaminar delamination and fine-scale nonlinear shear deformation (Yang and Cox, 2005). Experimentally it has been widely observed that the intra-ply and inter-ply damage modes interact with each other to form complex 3D crack networks. Fig. 1(a) shows the multiple damage modes in a double-notched tension specimen with a symmetric $[0/90]_s$ ply

* Corresponding author. Tel.: +1 305 284 3221; fax: +1 305 284 2580.
E-mail address: qdyang@miami.edu (Q.D. Yang).

0022-5096/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jmps.2011.04.007

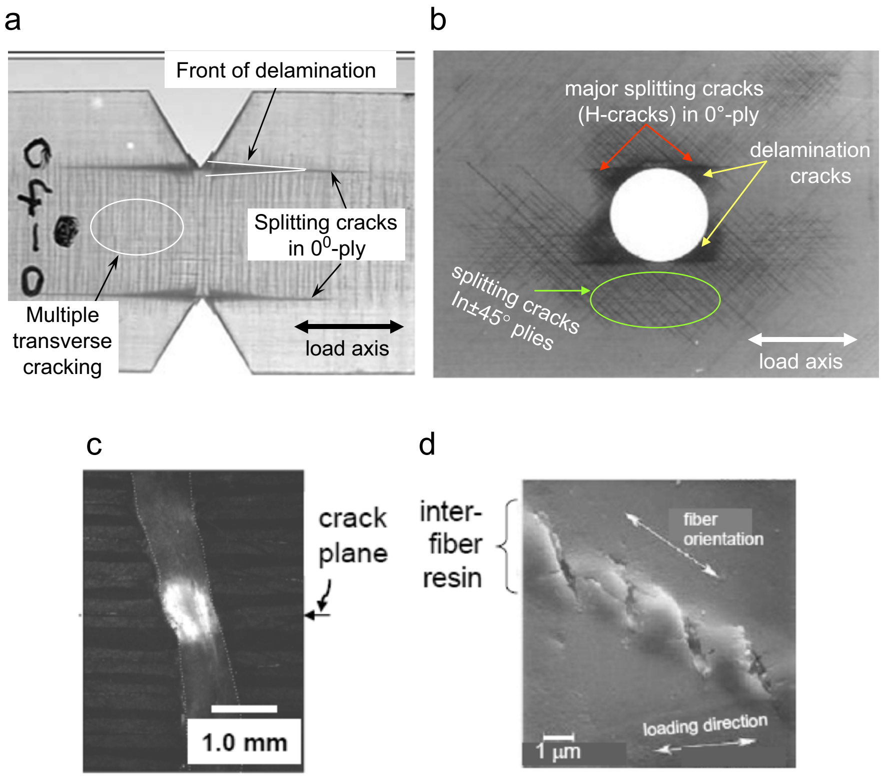

Fig. 1. (a, b) X-ray radiography reveals damage mechanisms viewed through the ply stack in (a) a double-notch tension specimen with symmetric orthogonal ply stack $[0/90]_s$ (Hallet and Wisnom, 2006b), and (b) a quasi-isotropic laminate $[-45/+45/90/0]_s$ with a circular open hole under tensile loading (Case and Reifsnider, 1999). (c) polarized light micrograph shows distributed damage in a fibrous stitch that has been sheared by a mode II delamination crack (Cox et al., 2008). (d) Scanning electron micrograph of en echelon cracking between two fibers in a carbon–epoxy composite loaded in off-axis tension (Cox et al., 1994).

stack. Dominant splitting cracks in the 0°-ply appear as sharply defined horizontal lines and eventually span the specimen. Transverse cracks proliferate in the 90°-ply during load increase. In addition, the major splitting cracks are accompanied by wedge-shaped delaminations between the plies (areas of shadow around the splitting cracks). Fig. 1(b) shows the multiple cracking features in a quasi-isotropic laminate ($[-45/+45/90/0]_s$) with a central open hole. The splitting cracks are shorter and the delaminations are lobe-shaped and transverse cracking occurs predominantly in the $\pm 45°$ plies. The intra-ply cracks, i.e., the splitting cracks in the 90°-ply and off-axis cracks in $\pm 45°$ plies are distributed differently in space in different plies, and show evidence of coupling with delaminations at inter-ply interfaces (in the dark-lobed regions).

As well as the crack systems visible in Fig. 1, fine-scale shear deformation has also been observed occasionally within individual plies by microscopic examination (Spearing, 2010). This deformation arises under shear loading. It is continuously distributed, rather than discrete, over spatial scales much smaller than the spacing of any of the crack systems shown in Fig. 1 (the most closely spaced being the transverse ply cracks, with spacing ~1 mm to order of magnitude) and is therefore a distinct mechanism. While not always examined in full detail, the distributed shear deformation is likely to consist at the fiber scale of fibrillar crazing or arrays of microcracks, whose lengths typically span the distance between neighboring fibers, i.e., 1 μm to order of magnitude. Examples appear in old experimental studies: Fig. 1c shows fine-scale damage distributed throughout the section of a fibrous reinforcing stitch that has been sheared by a mode II delamination crack; Fig. 1d shows an array of microcracks between two off-axis fibers in a carbon/epoxy composite loaded in tension. In both cases, shear damage arises from μm-scale phenomena. Several authors have concluded that including shear nonlinearity of the ply material is necessary to achieve good correlation between simulations and experiments, especially for predicting splitting crack growth accurately (Wisnom and Chang, 2000; Cox and Yang, 2006; Hallett and Wisnom, 2006a).

Thus the total damage system in a polymer composite subject to arbitrary stress states comprises multiple crack types and possibly fine-scale distributed shear damage. Accounting for the strong interactions among these multiple damage mechanisms in an accurate and computationally efficient scheme remains a difficult task.

Traditionally, the intra-ply and inter-ply damage processes have been treated separately with different theories. Delamination problems have been analyzed using either linear elastic fracture mechanics methods (e.g., (Pagano and Schoeppner, 2000; Galessgen et al., 2002; Tay, 2003)) or cohesive interface models (Shahwan and Waas, 1997; Wisnom

Download English Version:

https://daneshyari.com/en/article/796737

Download Persian Version:

https://daneshyari.com/article/796737

Daneshyari.com