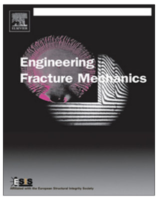
Engineering Fracture Mechanics 169 (2017) 189–200

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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



Damage onset modeling in woven composites based on a coupled stress and energy criterion

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ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 10 October 2016
Accepted 15 November 2016
Available online 24 November 2016

Keywords:
Polymer matrix composites
Finite element analysis
Crack initiation

ABSTRACT

The crack onset configuration at damage onset in a four-layer plain weave glass fiber/epoxy matrix composite is studied at the mesoscopic scale using a coupled criterion based on both a stress and an energy condition. The possible crack shapes are selected based on optical microscope observations of damage mechanisms on a specimen edge during a tensile test. The crack location, length and orientation, the decohesion length and the strain at damage onset are determined. The damage onset strain is underestimated compared to the experimental value determined by acoustic emission if only a stress criterion is considered. The coupled stress and energy criterion leads to a more reasonable estimate of strain at damage onset.

1. Introduction

Textile composites are increasingly used for aeronautical and automotive advanced structural applications. An advantage of woven composites is the large variety of the fiber reinforcements, whose architecture can be varied throughout the structure. Therefore, fewer assembly operations are required compared to classical laminated composite structures, which reduces both production costs and the number of weak points in the structure.

Woven composites offer a high potential for material design, which can be optimized using design tools able to describe the evolution of the mechanical behavior from damage onset to final failure of the materials. Macroscopic phenomenological models have been developed for the prediction of damage evolution and failure in 2D [1,2] and 3D [3–7] textile composites. However, expensive and time consuming experimental identifications of the model parameters are required. Moreover, these parameters have to be re-identified each time the fiber architecture or the constituents change. The number of tests may be reduced by using more predictive models at the mesoscopic scale, which take into account the fiber reinforcement architecture.

Different meso-scale approaches have been used to model the evolution of the material behavior with growing damage [8–12]. An analytical model using a damage mosaic laminate model was proposed by Gao et al. [8]. It allows the calculation of the effective Young's modulus of the damaged composite. However, yarn undulation, which has a significant influence on the damage location [11,13], is not described by such a model. In most published studies, a Finite Element (FE) approach based on continuum damage mechanics (CDM) is used (*e.g.*, [9,11,14]). It consists in detecting damaged elements using a

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http://dx.doi.org/10.1016/j.engfracmech.2016.11.021
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Nomenclature

Energy criterion

ΔW_k	change in kinetic energy
ΔW	change in potential energy
$W(0)$	potential energy of the undamaged state
$W(d)$	potential energy of the cracked state
G^c	critical energy release rate
ΔS	crack surface
h	specimen thickness
E^{eq}	equivalent elastic modulus
$A(d)$	normalized incremental energy release rate

Stress criterion

f	stress based failure criterion
f_c	criterion for transverse cracking
f_d	criterion for decohesions
Y_t	transverse ply strength
Z_t	out-of-plane ply strength
S_{12}^R	in-plane shear strength
S_{13}^R, S_{23}^R	out-of-plane shear strengths
p_{12}, p_{13}, p_{23}	shape parameters
Y_c	transverse compressive ply strength

Crack shape

$d = (d_1, \ldots, d_n)$	parameters describing the crack shape
(x, y)	coordinates of the crack center
(x_c, y_c, z_c)	coordinates of the crack center localized using the stress criterion
$(x*, y*)$	crack location at damage onset determined using the energy criterion
d_c	crack length
d_s^*	crack length at damage onset for a crack localized using the stress criterion
d_c^*	crack length at damage onset determined using the energy criterion
θ	crack orientation
θ^*	crack orientation at damage onset
μ	decohesion length
$\mu*$	decohesion length at damage onset

Strains

ϵ_e	strain measured experimentally
ϵ_e^c	strain at damage onset determined experimentally
ϵ	applied global strain
ϵ_{energy}	strain calculated using the energy criterion
ϵ_{energy}^c	strain at damage onset calculated using the energy criterion
ϵ_{energy}^s	strain at damage onset for a crack localized using the stress criterion
ϵ_s	strain at damage onset obtained using the stress criterion only

Material properties

E_m	Young's modulus of the matrix
ν_m	Poisson's ratio of the matrix
E_f	Young's modulus of the fibers
ν_f	Poisson's ratio of the fibers
E_l	longitudinal Young's modulus of the yarns
E_t	transverse Young's modulus of the yarns
ν_{tt}, ν_{lt}	Poisson's ratios of the yarns
G_{lt}	shear modulus of the yarns

stress based failure criterion and reducing the local stiffness of these damaged elements with increasing loading. An advantage of this method is the ease of implementation in FE codes. However, erroneous damage propagation directions can be predicted with these models [14,15]. Moreover, regularization methods [16,17] are required in order to avoid damage pattern dependence on FE mesh, which leads to a non-local damage zone. In this case, a very small mesh size compared to the