Composites Part B 87 (2016) 263–273

Contents lists available at ScienceDirect

Composites Part B

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

Probabilistic strength based matrix crack evolution in multi-directional composite laminates

N. Jagannathan [a, b], S. Gururaja [b, *], C.M. Manjunatha [a]

[a] Structural Technologies Division, CSIR-National Aerospace Laboratories, Bangalore, 560017, India
[b] Department of Aerospace Engineering, Indian Institute of Science, Bangalore, 560012, India

ARTICLE INFO

Article history:
Received 30 March 2015
Received in revised form
24 August 2015
Accepted 27 September 2015
Available online 3 November 2015

Keywords:
A. Polymer-matrix composites (PMCs)
B. Damage tolerance
C. Analytical modelling
Matrix cracking

ABSTRACT

Matrix cracking is the first and most dominant mode of damage in laminated polymer composites resulting in significant stiffness degradation. In the past, matrix cracking has been quantified using crack density evolution with loading and correlating the crack densities with stiffness degradation of the laminate. In the present study, an analytical framework for matrix crack evolution for a general Multi-Directional (MD) symmetric laminate has been proposed using oblique coordinate based shear-lag analysis coupled with a probabilistic strength approach. The statistical parameters have been estimated from a master laminate. The ply-by-ply crack density evolution has also been simulated. The crack density evolution and associated stiffness degradation predictions have been compared to existing experimental values. The stiffness degradation trends closely match with experimental data and stiffness values estimated from current approach are conservative.

1. Introduction

The use of Fiber Reinforced Polymer (FRP) composites for structural load bearing applications has increased in recent times. Approximately 50% by weight of the recent Boeing 787 airframe is made from FRPs [1]. Over the next few decades, these materials are likely to replace conventional materials due to their high specific strength, stiffness, corrosion resistance, easy formability and much greater fatigue life [2]. During service, composite structures are subjected to time varying events of loading, environment degradation, damage events such as bird impact, runway debris, hailstorm, etc., acting individually or sometimes in combination. Due to the inherent inhomogeneity and distinctly anisotropic nature, FRPs exhibit a multitude of damage mechanisms such as matrix cracking, interfacial fiber-matrix debonding, fiber breaks, delamination, fiber micro-buckling etc. under static and fatigue loading. Damage typically starts very early during loading and evolves steadily [3,4]. Matrix cracking happens to be the most dominant mode of damage to first appear in the laminate [4,5]. Typically, matrix cracks initiates in the lamina making the maximum off-axis angle with the loading direction. When the laminate is viewed in thickness direction, the matrix cracks appear transverse to the loading direction and propagate along the fiber direction of the off-axis ply (as shown in Fig. 1 (a)). As the static loading increases or as the number of cycles increase in case of fatigue, the matrix crack density (i.e., the number of matrix cracks per unit length) attains a saturation state called Characteristic Damage State (CDS) [6]. Since matrix crack evolution in composite laminates is accompanied by stiffness degradation, it becomes important to model this phenomenon.

Experimental investigation of crack initiation and evolution is mostly limited to cross-ply or Quasi-Isotropic (QI) laminates [7–11]. Notable observations from experimental studies on matrix cracking are as follows:

1. During matrix cracking, there occurs a continuous loss of stiffness, stress redistribution and reduction in stress concentration. Other damage modes such as delamination are also triggered when it attains CDS [3,4].
2. Matrix cracks form instantaneously through the laminate width along the fiber direction and are referred to as tunneling cracks. However, more complex cracking like partial cracking has been observed in plies adjacent to 90° ply [9,10].
3. The applied far field strain magnitude causing matrix crack initiation in a particular off-axis ply increases with decrease in ply thickness as well as with increase in neighboring ply

* Corresponding author.
E-mail address: suhasini@aero.iisc.ernet.in (S. Gururaja).

http://dx.doi.org/10.1016/j.compositesb.2015.09.050
1359-8368/

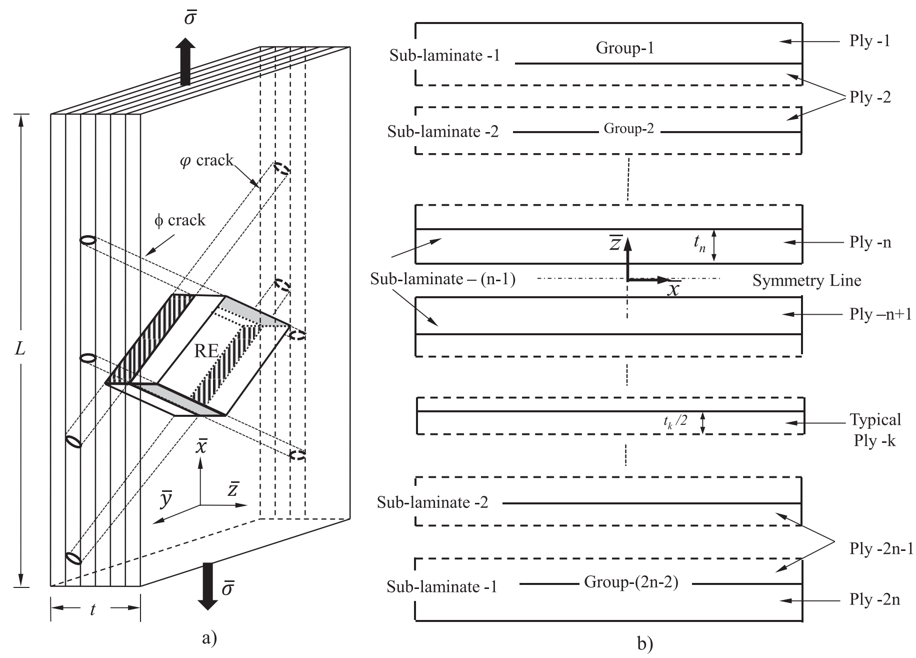

Fig. 1. Matrix cracking in MD-laminate. a) Representative element, b) Sub-laminate concept.

thickness [12–16]. In other words, the neighboring plies provide a 'constraint' effect and matrix cracking initiation becomes dependent on the location of the ply under consideration with respect to the overall stacking sequence of plies. Thus, matrix crack initiation strain for surface plies are found to be lower than for plies located in between other plies.

4. Saturation matrix crack density at CDS decreases with increase in the ply thickness or with increase in constraint ply thickness [11].
5. The matrix crack initiation strain is higher for plies with off-axis angle less than 90° and curved crack paths are also observed [17,18].
6. For MD-laminate containing plies with off-axis angle less than 45°, the laminate fails before any matrix cracks form in that ply and offers limited contribution to overall stiffness reduction of the laminate [8,19].

Over the last three decades, numerous matrix crack initiation and evolution models have been developed to predict matrix crack density evolution under a given loading scenario. Starting with basic 1-D shear lag analysis extended for crack evolution [20–22], 2-D stress analysis using variational method [23] and finite fracture mechanics [24] have been used to simulate matrix cracking in cross-ply laminates. 3-D stress analysis using plane strain assumptions [25] and probabilistic energy based criteria have also been successfully used for matrix crack predictions [26,27]. In addition to these approaches, concept of damage mechanics has been used [28,29]. Crack Opening Displacement (COD) based concepts have also been looked at [30] and crack evolution has been calculated using change in strain energy. Statistical strength based models have also been used to predict crack density evolution [31–36].

Most of the models described here are able to predict matrix crack evolution for simple cross-ply laminates using some form of strength based or energy based criterion and cannot be extended to the more general and more relevant MD-laminates. In MD-laminates, due to the presence of multiple off-axis plies oriented at different angles to the loading direction, the matrix crack evolution is also different in each ply. Few authors have attempted to provide a framework for matrix crack evolution in MD-laminates based on synergistic damage mechanics [19], energy based approach complimented with analytical stress analysis [37,38], 2-D Finite Element Analysis (FEA) with damage constitutive model [39] and more recently, the micro-mechanics based damage model for stiffness reduction with energy based damage evolution [40]. A majority of the approaches described so far employ an energy based criterion for matrix crack initiation and evolution. In-plane uniaxial loading has been considered in most models described here. Recently, crack evolution models under bi-axial loading have been developed [41]. Though statistical strength based theories have been promising in predicting the crack evolution in cross-ply laminates [31–36], no attempt has been made to extend the same to MD-laminates. In this work, a probabilistic strength based framework for matrix crack density evolution and associated stiffness reduction for a symmetric MD-laminate has been presented using oblique coordinate system based stress analysis [36,42,43]. The corresponding stiffness degradation have also been modeled and compared with the available experimental observations in the literature.

2. Matrix crack evolution model

This section describes the methodology adopted to predict matrix crack evolution in a symmetric MD-laminate under in-plane loading. The salient concepts adopted in this study have been listed below.

2.1. Geometry and co-ordinate system

A $2n$ ply symmetric MD-laminate has been considered in this study. A typical k^{th} ply in the MD-laminate has a thickness t_k and length L as depicted in Fig. 1(b). As mentioned in the earlier section, matrix cracks develop along the fiber direction and the crack spacing in any off-axis layer is defined as the distance between two