Composites Part B 102 (2016) 9–28

Contents lists available at ScienceDirect

Composites Part B

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

A DEM model for visualising damage evolution and predicting failure envelope of composite laminae under biaxial loads

Yaser Ismail [a], Dongmin Yang [b,*], Jianqiao Ye [a,**]

[a] Department of Engineering, Lancaster University, Lancaster, LA1 4YR, UK
[b] School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, UK

ARTICLE INFO

Article history:
Received 21 March 2016
Received in revised form
11 June 2016
Accepted 4 July 2016
Available online 7 July 2016

Keywords:
FRP
Damage evolution
Failure criterion
DEM
Micromechanical modelling

ABSTRACT

A two dimensional particle model based on the discrete element method (DEM) is developed for micromechanical modelling of fibre reinforced polymer (FRP) composite laminae under biaxial transverse loads. Random fibre distribution within a representative volume element (RVE) is considered for the micromechanical DEM simulations. In addition to predicting the stress-strain curves of the RVEs subjected to transverse compression and transverse shear stresses against the experimental testing results and other numerical modelling results, the DEM model is also able to capture the initiation and propagation of all micro damage events. Fibre distribution is found to more significantly influence the ultimate failure of composite laminae under transverse shear, while it has much less effect on the failure under transverse compression. The failure envelope of composite laminae under biaxial transverse compression and transverse shear is predicted and compared with Hashin and Puck failure criteria, showing a reasonable agreement. The predicted failure envelope is correlated with the damage evolution and the quantitative analysis of failure events, which improves the understanding of the failure mechanisms.

1. Introduction

Fibre reinforced polymer (FRP) composite laminates have been widely used over the past thirty years in aerospace industries mainly due to their high stiffness-weight and strength-weight ratios. However, there is yet a universal model or approach to accurately predict the failure strength of FRP composite laminates under biaxial or triaxial loads in real applications [1]. A large amount of experimental tests need to be carried out to obtain the failure strength of FRP composite laminates which is usually designed to be much larger than the required strength under real loading conditions. This means that in many cases the FRP composites are over safely designed and their advantages of light weight and design flexibility have not been maximised. In addition, the experimental tests are affected by the testing environment and the results are very diverse, especially when materials are subjected to a system of loads including transverse load that is very difficult to carry out. Therefore, an accurate and universal approach for predicting the strength of FRP composite laminates is always highly demanded.

Generally, five different failure mechanisms could occur in composite laminates and they depend mainly on the loading conditions and directions [2]. Fibre fracture and localised fibre buckling occur when tension and compression are, respectively, applied along the fibre direction. Tensile load applied in the direction perpendicular to the fibres results in either fibre/matrix debonding or matrix cracking. Delamination takes place between plies and has to be considered in order to predict the laminate behaviour precisely. There are a few theoretical failure criteria available for predicting failure modes separately as well as the failure envelope of composite lamina/laminates under different loading conditions. Among them, there are several well-known physically-based phenomenological failure criteria [3–6] that have the capability to predict the failure envelope and also provide information on failure modes of composite lamina/laminates under certain loading conditions [1]. In particular, Puck's failure criterion is one of the better criteria adopted in the World Wide Failure Exercise (WWFE) for predicting composite laminate failure. However, these criteria contain several non-physical parameters that need to be obtained from specific and challenging experimental tests. It has been shown

* Corresponding author.
** Corresponding author.
E-mail addresses: d.yang@leeds.ac.uk (D. Yang), j.ye2@lancaster.ac.uk (J. Ye).

http://dx.doi.org/10.1016/j.compositesb.2016.07.004
1359-8368/

in WWFE that the predictions of failure strength under some loading conditions (in particular biaxial and triaxial loads) by existing failure criteria are not accurate enough. One of the main reasons is that these criteria have not considered the effects of heterogeneous material microstructure and the interaction as well as progression between different failure modes. Theoretically it is not straightforward to dynamically correlate different failure modes during the failure process as the random and heterogeneous microstructure of composite lamina/laminates are hardly to be considered. Micromechanics analysis is very useful for studying the mechanical behaviour of FRP composite laminates and understanding their damage process and failure strength. Within the framework of micromechanical modelling, the macroscopic properties are obtained through a representative volume element (RVE) of the material microstructure. Unlike the conventional homogenisation techniques, micromechanical modelling can take into account the details of geometry and fibre distribution to compute the stresses and strains in each material constituents, which leads to more accurate predictions of damage initiation and propagation and failure strength [7].

Two different approaches have been widely employed for numerical micromechanical modelling. The first approach assumes that the fibres are periodically distributed and uses a unit cell consisting of one or two fibres for the modelling. For example, Paris et al. [8], used a single fibre unit cell to study the fibre/matrix debonding of a glass-epoxy composite. Ha et al. [9], determined the failure envelope of a composite lamina under biaxial loads by modelling a unit cells of square and hexagonal fibre arrangements. The second approach uses a RVE in which several dozens of fibres are distributed randomly. Intensive studies have been carried out using this method to understand the effects of RVE size, position of fibres and internal distance between fibres on the elastic properties as well as the strength of FRP composite laminae. For instance, Trias et al. [10], concluded that the minimum size of carbon fibre reinforced polymer with a volume fraction of 50% is $\delta = L/r_f = 50$, where L is the side of the RVE and r_f is the fibre radius. Yang [11] found that inter-fibre spacing has a significant impact on the transverse tensile and compressive strength of composites, especially when thermal residual stress is taken into account.

Apart from FEM modelling, discrete element method (DEM) has been recently introduced to model the damage evolution in composites. For instance, the crack propagation and stress-strain curves of composite materials under transverse tensile loading was simulated by DEM in Refs. [12,13]. It was concluded that DEM has advantages of tracing the crack path within the microstructures in addition to predicting the final failure strength. Yang et al. [14,15], also investigated the transverse cracks and delamination in cross-ply laminates and predicted the crack density using two dimensional DEM. With the increasing of computer power and the lowering of the cost, DEM has become more beneficial than traditional numerical approaches in studying damage initiation and crack propagation at microscopic scale. For instance, Maheo et al. [16], used three dimensional DEM to model the damage of a composite material under uniaxial tension. Although the model assumed a periodic distribution of fibres and used only one fibre, it has demonstrated the potential of DEM for modelling the failure process as well as failure strength under real uniaxial loads in three dimensions.

Despite of the massive research efforts recently devoted to investigating the failure behaviour of composite laminates under shear loading [17–22], the damage mechanisms and failure theory are still not fully understood. Therefore this paper aims to extend our previous work on DEM modelling of composite materials from uniaxial loading to biaxial loading. Two dimensional DEM is used to visualise the damage mechanisms and to predict the stress-strain curves as well failure strength of composite lamina under three different types of loads, *i.e.*, transverse compression, transverse shear and biaxial loads. The stress-strain curves obtained in this paper have advantages over those from traditional numerical models as the microscopic damage at different loading levels can be clearly visualised. The failure envelope of MY750 matrix reinforced by E-glass fibres under both transverse normal and shear loads is also predicted by DEM and compared with Puck [5] and Hashin [3] failure criteria.

2. The discrete element method (DEM) and its contact models

In two dimensional DEM, circular elements (or particles) are used to discretise the material domain, as shown in Fig. 1. Each particle in DEM has mass and its motion is governed by the Newton's Second Law. The particles can be rigid or deformable, and interact with each other through contacts. To represent the mechanical behaviour of a bulk material, a bonding model is usually employed to bond two rigid particles at the contact. A few bonding models have been reported in literatures to numerically achieve the desired material properties. For instance, André et al. [23], developed a cohesive beam model which later was used by Ref. [16] to predict the damage of a composite material. In this study, however, the parallel bond model developed in Ref. [24] is adopted. The parallel bond can be described as a finite-sized piece of cementitious material deposited between two contacting particles, and can be envisioned as a set of elastic springs uniformly distributed over its cross-section. When two particles are bonded by a parallel bond the overall behaviour the contact is a result of particle-particle overlap (grain-based part) and parallel bond (cement-based part), as shown in Fig. 1.

The grain-based part is represented by a linear contact model that can be described as a pair of springs at the contact (one in the normal direction and the other one in the shear direction). The inter-particle force, F, acting at the contact point represents the action between elements A and B and may be decomposed into a normal force F^n and a shear force F^s. These forces are related to the relative displacements through normal and shear stiffness k^n and k^s as follows:

$$F^n = k^n u^n \tag{1}$$

$$\Delta F^s = -k^s \Delta u^s \tag{2}$$

where u^n and Δu^s are the overlap and incremental tangential displacement, respectively; k is the resultant contact stiffness calculated by:

$$k^n = \frac{k_n^{(A)} k_n^{(B)}}{k_n^{(A)} + k_n^{(B)}} \tag{3}$$

$$k^s = \frac{k_s^{(A)} k_s^{(B)}}{k_s^{(A)} + k_s^{(B)}} \tag{4}$$

where $k_n^{(A)}$ and $k_n^{(\boldsymbol{B})}$ are the normal stiffness, and $k_s^{(A)}$ and $k_s^{(B)}$ are the shear stiffness of particles A and B, respectively.

The force $\overline{F}$ and moment $\overline{M}$ associated with cement-based part are calculated by:

$$\Delta \overline{F}^n = \overline{k}^n A \Delta u^n \tag{5}$$