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MULTI-SCALE MODELLING OF DAMAGE PROGRESSION IN FRC LAMINATES – APPLICATIONS OF DEM

DONGMIN YANG*,†, YONG SHENG*, JIANQIAO YE* and YUANQIANG TAN†

* School of Civil Engineering, University of Leeds, LS2 9JT, Leeds, UK
Email: d.yang@leeds.ac.uk
y.sheng@leeds.ac.uk
j.ye@leeds.ac.uk

† School of Mechanical Engineering, Xiangtan University, 411105, Hunan, China
Email: tanyq@xtu.edu.cn

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Abstract. As a natural progress of the research in the area of modeling damage at microscopic scales, a discrete element method (DEM) has been proposed to simulate the damage progression in FRC laminates. DEM has been used to study the interfacial debonding, transverse cracking, delamination, and transverse cracking and delamination in FRC laminates. The purpose of this research is not only to validate the application of DEM in terms of its advantages in the simulation of damage progression and the prediction of cracking density and stiffness reduction, but also to highlight the potential of DEM in the future research application for composite damage mechanism, composite material design and optimization.

1 INTRODUCTION

Due to its superior properties, such as high strength, high stiffness and light weight, FRC has been widely used in engineering applications, particularly aerospace engineering, mainly as a replacement of conventional metals. Composite materials have shown excellent performances in the application of jet-engine by significantly increasing the thrust-to-weight ratios, compared with the traditional metal alloys. Fiber reinforced composite can fail in many different modes depending on the external loading conditions. For the prediction of composite failure strength and the purpose of composite product design, understanding of matrix, fiber and interface failure mechanisms is essential. These failure modes include *fiber breakage*, *matrix cracking, debonding, delamination* and eventually *catastrophic failure* [1]. The damage process of fiber reinforced composite is quite complicated because of the above damage types and more importantly the interaction between each other, especially under complicated loading conditions, for instance, triaxial loading or impact loading. Therefore it is necessary to treat the damage initiation and propagation in a progressive manner in a numerical model for composite damaging. The analysis and prediction of the progressive damage of composite is very challenging, but critical for the design and optimization of composite components for special applications.

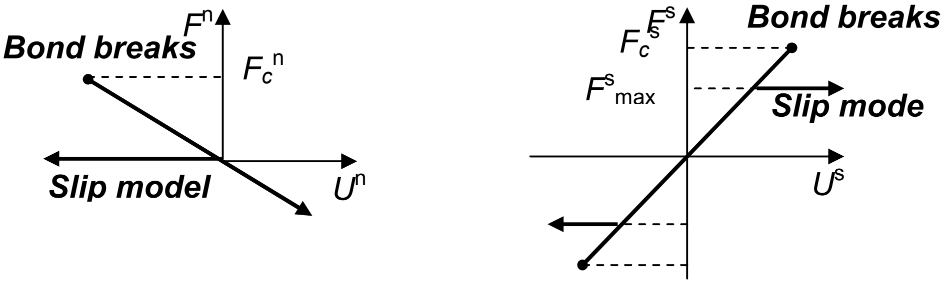
To improve the understandings of damaging process in the fiber reinforced composite multi-ply laminates subject to static axial loads, a novel modeling methodology, Discrete Element Method (DEM) is presented to provide the advanced predictive capability and a computational tool that enables engineers to gain the insights of failure evolutions inside the material from microscale to macroscale so that designs can be optimized to enhance the damage tolerance of composite material.

2 DEM CONSTITUTIVE MODELS FOR COMPOSITE

DEM allows particles to be bonded together at contacts and to be separated when the bond strength or energy is exceeded. Therefore it can simulate the motion of individual particles and also the behavior of bulk material which is formed by assembling many particles through bonds at contacts with specific constitutive laws. In a DEM model of bulk material, elementary micro scale particles are assembled to form the bulk material with macroscopic continuum behavior determined only by the interaction of particles [2, 3]. Unlike the traditional solution using the strain and stress relations, contact properties are the predominant parameters in a DEM solution, combined with size and shape of the particles. Subject to external loading, when the strength or the fracture energy of a bond between particles is exceeded, flow and disaggregation of the particle assembly occur and the bond starts to break. Consequently, cracks form naturally at micro scale. Hence, damage modes and their interaction emanate as the process of debonding of particles. The way that DEM discretizes the material domain gives the most significant advantage over the traditional continuum mechanics based methodologies, as the difficulties encountered by the traditional methods, such as dynamic material behavior of composites, crack tip singularities and crack formulation criteria can all be avoided due to the naturally discontinuous representation for the microstructure of composite materials via particle assemblies in DEM.

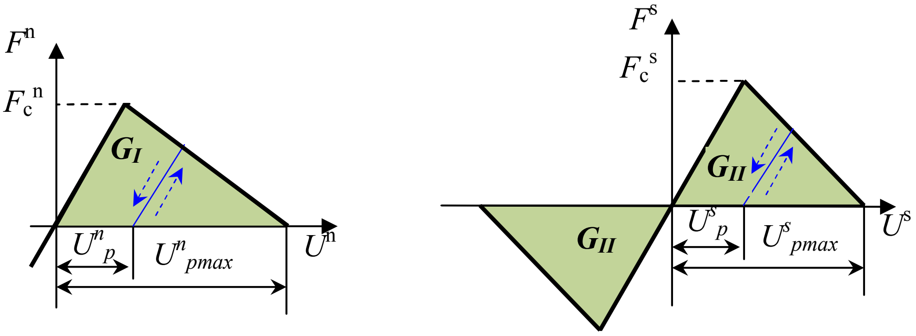
Solid materials are usually modeled by DEM through adding a bond at the contact of two contacting particles. Bonds in DEM can be envisioned as a kind of glue joining the two contacting particles. There are two intrinsic bonds, contact bond and parallel bond in PFC2D [4] that is a popular commercial code of DEM and is used as the simulation platform of this research. A parallel bond can be regarded as a set of elastic springs with constant normal and shear stiffness, uniformly distributed over either a circular or rectangular cross-section lying on the contact plane and centered at the contact point [3]. Parallel bond can transmit both forces and moments, and will be used in this paper to describe the linear elasticity of fiber and elastic matrix. The parallel bond has a linear elastic behavior, as shown in Fig.1. The bond breaks when the contact force exceeds its strength [5, 6].

As suggested in [7, 8] that the interface between two composite plies is adhesive, there exist residual interfacial traction forces, even when the two plies are detached but before they are entirely separated. Therefore alternative contact models have been proposed by DEM users to account for the complex interfacial behaviour by considering more complicated constitutive laws. The contact softening model was proposed for this purpose based on the contact bond model [3, 9]. The concept of contact softening model (illustrated in Fig.2) is similar to the cohesive zone model (CZM) in the continuum mechanics [10, 11]. The only difference between these two models is the unloading and reloading curves after yielding.



(a) *normal behavior* (b) *shear behavior*

Fig.1 Constitutive behavior of the parallel bond at contact



(a) normal behaviour *(b) shear behaviour*

Fig.2 Constitutive behavior of contact softening model

The contact softening model describes the behavior of contact bonds in elastic, and represents plastic deformation by linearly softening the bond after the contact force reaches the bond strength. In both tensile and shear situations, the bond strength decreased to zero when the plastic displacement reaches the maximum plastic displacement $U_{p\max}$ which is related to the fracture energy release rate G. The interfacial crack may behavior as mode I, mode II or mix mode according to the stress field at the crack tip. In order to simulate the three fracture modes in DEM, the maximum plastic displacement $U_{p\max}$ was kept constant, while the bond normal and shear strengths were defined individually. Hence, in a two dimensional system, the fracture energy release rate for mode I and mode II are, respectively:

$$G_I = \frac{1}{2}\cdot \sigma_{nmax}\cdot U_{pmax} \tag{1}$$

$$G_{II} = \frac{1}{2}\cdot \sigma_{smax}\cdot U_{pmax} \tag{2}$$

The fracture energy release rate for mix mode can be calculated as:

$$G = \frac{1}{2}\cdot \sigma_n \cdot U_p^n + \frac{1}{2}\cdot \sigma_s \cdot U_p^s = \frac{1}{2}\cdot \sigma_n \cdot \sum\left|\Delta U_p^n\right| + \frac{1}{2}\cdot \sigma_s \cdot \sum\left|\Delta U_p^s\right| \tag{3}$$

σ_n and σ_s are the normal and shear stresses of the bond when yield occurs. For the mixed mode, the fracture energy release rate is somewhere between the rates of two single fracture modes.

3 MODELLING RESULTS AND DISCUSSIONS

The damage behavior of DEM model depends on bond properties and particle size which have to be calibrated through virtual tension (or compression) tests as well as convergence tests before being used in the final models of composite. Details of model calibration are referred to our previous work in [5, 12-14], while only a summary of the DEM applications in modelling of composite damage progression, which covers matrix cracking, interfaical debonding, delamination as well as transverse cracking, is presented here.

The DEM modelling started with the simulation of material failure process in the microbond test of single fiber reinforced composites to investigate how the matrix cracks initiates and propagates to cause the fiber/matrix interfaical debonding, as shown in Fig.3. The plastic deformation and the cracking of the matrix were simulated by introducing the contact softening model. The initiation and propagation of interfacial debonding were captured naturally by the DEM simulation. Vises with two different vise angles were used in the simulations. It was found that the vise angle had effects on the material damage process [5].

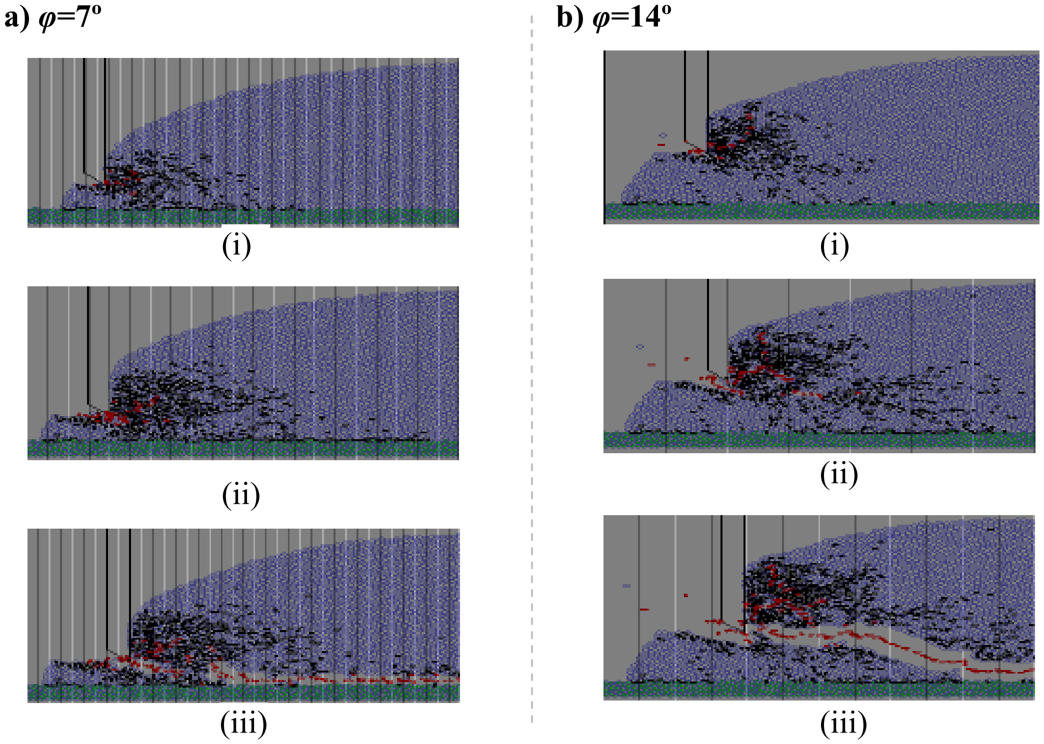
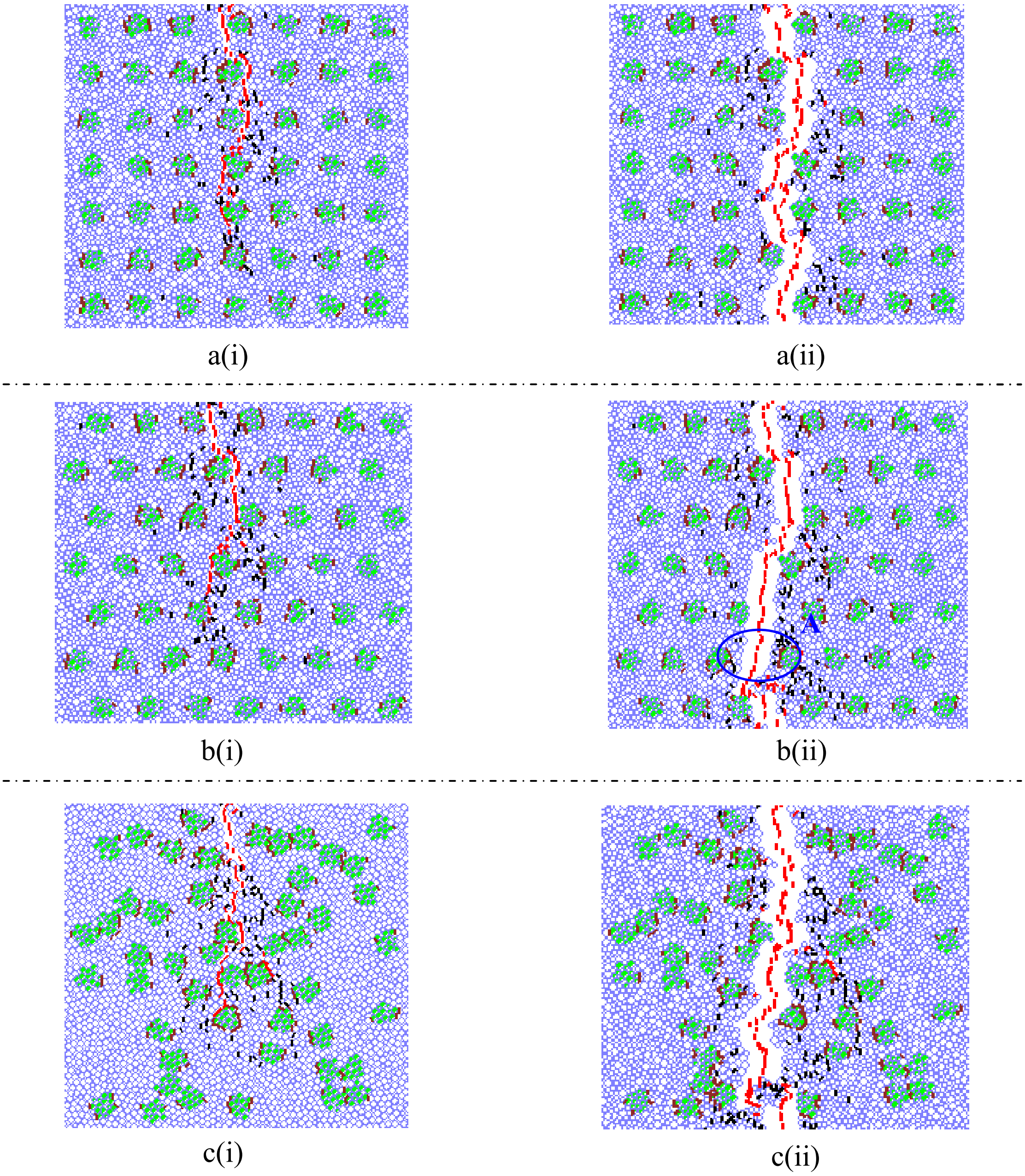


Fig.3 DEM simulation of micrbond test at different vise angle φ: (a) $\varphi=7^{\circ}$, and (b) $\varphi=14^{\circ}$.

(Black dot indicates the bond has started to yield, and red dot indicates the final failure.)

DEM was then employed to simulate transverse cracking in composite laminae, due to its intrinsic advantages in modeling microscopic damage and fracturing in multiphased materials. Three types of fiber distributions, i.e., rectangular, hexagonal and random distributions, have been simulated to study the effect of fiber distribution on the transverse cracking, as illustrated in Fig.4. The initiation as well as dynamic propagation of transverse cracking has been captured by the DEM model, showing good agreement to the experimental observations. Furthermore, the DEM simulations have provided unique insights of the microscopic cracking and damage in forms of matrix plastic deformation and fiber/matrix interface yielding. The effect of fiber volume fraction was also studied by using different fractions in the DEM modeling for randomly distributed fibers [14].



a(i) a(ii)

b(i) b(ii)

c(i) c(ii)

Fig.4 DEM dynamic simulation of transverse cracking in laminae

(‘a’, ‘b’ and ‘c’ represent rectangular, hexagonal and random distribution of fibers, respectively; Red, black and brown lines describe transverse cracking, matrix plastic deformation and interface yield, respectively.)

This work has further led to the findings that the distribution and volume fraction of fibers not only affect the transverse cracking path, but also the mechanical behaviors of the material through the populations of the residual matrix plastic deformation and fiber/matrix interfacial yielding.

To simulate initiation and propagation of delamination in anisotropic fiber reinforced composite laminates, a DEM model was developed by constructing a hexagonal arrangement of particle elements where contacts between particles were represented by parallel bonds with particular normal and shear properties. The contact softening model was introduced to count for the residual interfacial tractions. DCB, ELS and FRMM tests were simulated by the developed DEM model. Schematic in Fig.5 demonstrates a DEM model of DCB test in terms of crack evolution. Numerical results of loading curves were compared and found agreed very well with results from other numerical methods and experimental investigations. It has been confirmed that the present DEM model can simulate composite delamination accurately in all three fracturing modes with the capture of crack extension and plastic zone (see Fig.6) by which the complexity of dealing with the singularity at crack tips and the closing of existing cracks were all avoided [13].

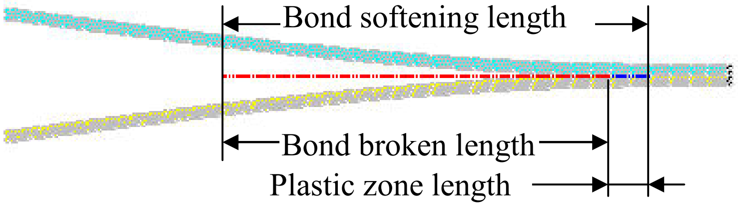


Fig. 5 Schematic of damage propagation in DEM modelling of DCB test

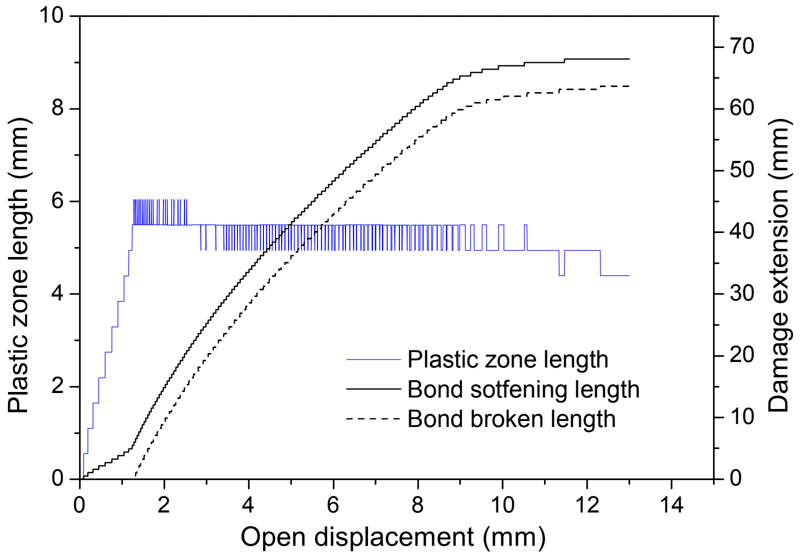
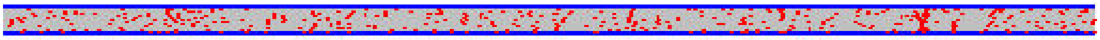


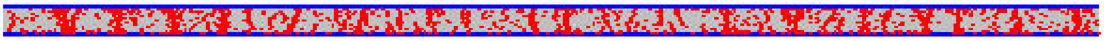
Fig.6 Plastic zone and damage extension in DCB test

The initiation and propagation of transverse cracking as well as interfacial delamination in cross-ply laminates under uniaxial loading was eventually modelled by DEM. The 90° and 0°

plies were respectively treated as isotropic and orthotropic materials whose elastic properties were accounted by adopting the parallel bond model at the contacts of the discrete particles. The interface between the 90º and 0º plies was represented by a contact softening model. The developed DEM model was validated by comparing the stresses distribution in a representative element of cross-ply laminate with the results obtained from the analytical methods. As an application of the developed DEM model, the transverse cracking and interfacial delamination in both $[0^\circ_1/90^\circ_n]_s$ and $[90^\circ_n/0^\circ_1]_s$ cross-ply laminates under transverse loading were analyzed by comparing the calculated crack density with the experimental data and other numerical predications. The modelling result of $[0^\circ_1/90^\circ_3]_s$ cross-ply laminate was selected and shown in Fig.7 as an example. The comparisons shown that the DEM model is capable of not only modeling the damage in laminates at microscopic particle level, but also capturing both the transverse cracking and delamination phenomenon, and predicting crack density as well as stiffness reduction quantitatively at macroscopic level [15].



(a) σ_c=64.38MPa



(b) σ_c=110.4MPa

(c) σ_c=294.3MPa (without interfacial delamination)

(d) σ_c=294.3MPa (with interfacial delamination)

Fig.7 Dynamic initiation and propagation of transverse cracking and/or delamination in $[0^\circ_1/90^\circ_3]_s$ cross-ply laminate.

(Particles with blue and gray colors indicate 0˚ and 90˚ plies, respectively. Red short lines are micro-cracks in 90˚ ply, and black short lines indicate interfacial delamination.)

4 CONLUSIONS

DEM has been used in the modelling of interfacial debonding, transverse cracking, delamination, and transverse cracking and delamination in FRC laminates. The outcome of this research has validated the application of DEM in composite laminates in terms of its advantages in the modeling of damage progression and the prediction of cracking density and stiffness reduction, and also proved the potential of DEM in the future research of composite material design and optimization.

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