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3D particle models for composite laminates with anisotropic elasticity

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ABSTRACT

This paper presents an assessment of three different particle based approaches for 3D modelling of fibre reinforced polymer (FRP) composite laminates with anisotropic elasticity, namely 3D Discrete Lattice model, 3D Hexagonal Close Packing model and Extended 2D Hexagonal and Square Packing model. These approaches are compared and evaluated against experimental results using a 0° ply lamina case. It has been confirmed that the Extended 2D Hexagonal and Square modelling approach in Discrete Element Method (DEM) is capable of modelling 3D composite laminates with better efficiency. Angle-ply lamina and two different laminates are modelled with the chosen particle approach. Good agreements between DEM, Finite Element and theoretical results prove the capability of this developed DEM approach for modelling the elastic behaviour of general FRP composite lamina and laminates.

1. Introduction

Glass fibre and carbon fibre reinforced polymer composite laminates, i.e. GFRP and CFRP, have been widely used in aerospace, mechanical and civil engineering mainly due to their high stiffness-weight ratios. In addition, with proper design and optimization of the layer-up, desired modulus and strength in different directions of the laminates can be achieved. However, due to the complexity of the microstructure of FRP composite laminates, the onset of damage does not cause instantaneous failure of the entire structure. There exists a progressive process from the damage initiation to final structural collapse [1]. Thus it is much more challenging to predict the strength of a FRP composite laminate than that of conventional homogenous materials and structures. Understanding of the failure mechanisms as well as developing accurate and universal failure criteria for predicting the ultimate strength of FRP composite laminates, particularly under triaxial loads, is therefore of significant importance. There are a number of failure criteria being developed and some of them have been implemented in finite element software packages, for instance, Hashin failure criteria [2] in ABAQUS and Tsai-Wu failure criterion [3] in ANSYS. Recently, the second World Wide Failure Exercise (WWFE-II) of assessing some existing failure criteria for FRP composite laminates has shown satisfactory performance of each criterion to various degrees, however, it was concluded from WWFE-II that '*no one model contains all what is required to produce a robust and reliable tool for designers*' [4]. There are also considerable variations in the accuracy of the predictions by these criteria. One of the main reasons for this is that some of those failure criteria are not capable of dealing with the damage progression after the occurrence of first failure. It is recognised from the exercise that failure criteria capable of distinguishing various failure modes and their interactions would be more potent to be adopted by the industry. This poses a big challenge on experimental tests to obtain valid results for calibrating the predictions of damage progression from the failure criteria. While it is already mentioned in the WWFE-II exercise that lacking of test data, particularly under high hydrostatic pressure, has resulted in incomplete failure envelope for benchmarking the failure criteria. The monitoring and visualization of in-situ damage progression during mechanical tests is no doubt very difficult to produce valid data. More recently, the third World-Wide Failure Exercise (WWFE-III) was conducted to highlight the degree of maturity of twelve internationally recognised approaches (some of them are different from the criteria mentioned in WWFE-II) considering their capabilities of detecting the various damages within the composite materials when subjected to multi-axial loading [5–7]. Thirteen cases were adopted to test the cracking and failure propagation arising from ply thickness, lay-up sequence, size effects and various loading conditions of unidirectional and multi-directional GFRP and CFRP composite laminates. It was found that any two models cannot give identical predictions for any of the 13 test cases. In few cases, the ratio between the highest and lowest predictions can reach a factor of 20. Still, progressive cracking or damage cannot be predicted by any of the model for a lamina under the shear and transverse loading [7]. Meanwhile, there was still a lack of agreement between these tested models when it comes to the effects of ply thickness, lay-up sequence and delamination driven by the matrix

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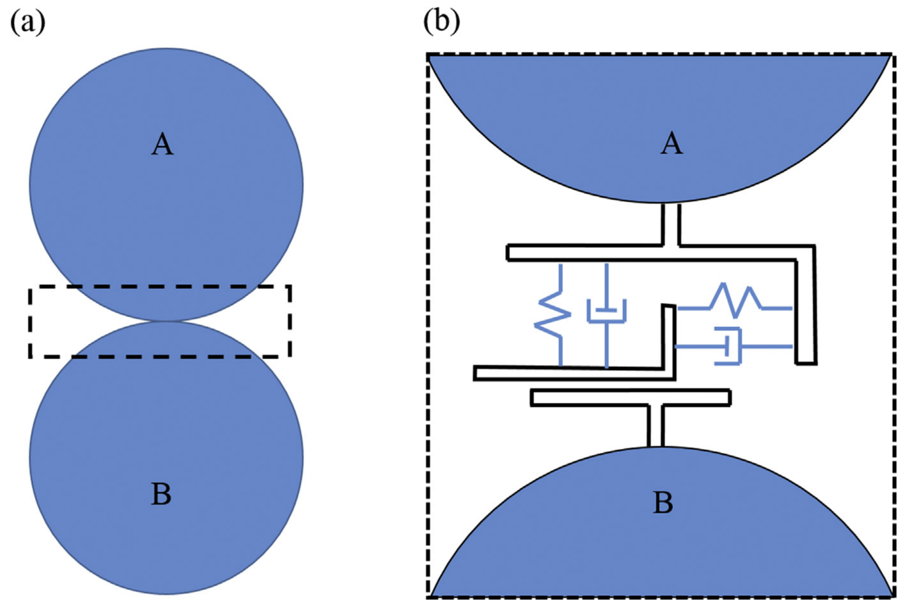

Fig. 1. Representation of a contact between two particle elements in 3D DEM: (a) two particles in contact and (b) the physical elements of the contact.

cracking, etc. Recently, a big step forward to improve the understanding of the crack initiation in FRP composite laminates has been made by using synchrotron-radiation computed tomography (SRCT) to acquire high-resolution, in-situ images of cracks for more accurate measurement of the location, shape and size of small cracks in the order of 1 μm [8,9]. This promising in-situ testing technology can provide more quantitative validations for numerical models in terms of damage progression from one type of failure to another.

For a long time, numerical modelling of damage progression in FRP composite laminates has been reported using Finite Element Method (FEM) [10–14], Boundary Element Method (BEM) [15–18] as well as Discrete Element Method (DEM) [19–22]. The FEM and BEM methods are based on continuum mechanics and are capable of accurately predicting stress distribution as well as crack initiation, but the crack propagation and intersection is always challenging to deal with by these methods. The DEM is based on discontinuous mechanics and uses discrete particles that are bonded together to represent the continuity of FRP composite materials. As the particles only interact with the neighbouring particles through contacts and bonds, fracture events are accounted for at the local level by the breakage of bonds. This gives an advantage to DEM when modelling the damage progression. However, DEM employs explicit time integration scheme to track the motion of individual particles and their interaction, thus it is relatively more expensive in terms of computational efficiency, in particular when the detailed material microstructures are considered. In addition, when particles are randomly packed, it is not straightforward, if possible, to determine the microscale bond and particle properties in order to represent the elasticity and failure strength of the target material. Trial and error tests are usually required to calibrate the bond and particle properties through virtual mechanical tests, e.g. compressive test and Brazilian test, etc. Also large number of particles are required for any random packing model to represent the anisotropy of composite. Therefore, to improve the computation efficiency in some cases, the particles are packed in a regular form, e.g. hexagonal or square in 2D and face-centred cubic or hexagonal in 3D. In principal a theoretical formula can be derived to correlate the particle and bond stiffness (i.e. micro stiffness) with real material elastic stiffness (i.e. macro stiffness). Based on average strain energy method, formulations for both isotropic and anisotropic materials in 2D and isotropic materials in 3D have been derived and employed in various studies [23–26]. In the previous works from the authors, based on the theoretic formula for bonded particles in a hexagonal packing, 2D DEM model of cross-ply composite laminates have been developed to investigate the damage progression of transverse cracking and delamination [1,21]. However, in practice many FRP composite laminates are angle-ply laminates in which not all layers are placed either in 0 or 90°. Therefore a 3D DEM model should be developed to model the damage progression in angle-ply FRP composite laminates, and a rigorous formula for describing the relationship between micro and macro stiffness is required. For a DEM model of a composite with single or a few carbon fibres which are orthotropic, a formula is also required to determine the bond stiffness of particles. In view of these constraints on 3D DEM models and to enhance the capability of DEM in modelling damage progression, a theoretical relationship between the bond stiffness in 3D DEM models and the real material stiffness is required.

The present study aims to develop 3D DEM modelling approaches to represent the anisotropic elasticity of the composite materials. Three different approaches have been tested and the most appropriate approach for the general anisotropic composites has been identified and recommended. 3D discrete lattice approach, 3D Hexagonal Close Packing (HCP) approach and extended 2D Hexagonal and Square Packing approach are considered and evaluated. The following sections of this paper are organized as bellow: the background of theory and formulation for DEM and these three approaches are presented in Section 2. The three DEM models of the 0° ply composite lamina are described in Section 3, in which the comparison and evaluation are made. In Section 4, typical angle-ply laminae and two composite laminates were built with the chosen model and validated against the theoretical and FEM results. Finally, conclusions and recommendations are made in Section 5.

2. 3D DEM theory and microplane theory

2.1. 3D DEM theory

In the DEM, the interaction between the contacting particles is treated as a dynamic process and the stress and deformation of the whole particles assembly are obtained from the averaged force and displacement of each individual particle. The contact which connects the two particles can be physically represented through springs, friction resistance and damp absorber, as shown in Fig. 1 [27].

The dynamic behaviour of particles in DEM is completed through