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A promising way to model cracks in composite using Discrete Element Method

L. Maheo [a,b,*], F. Dau [c], D. André [c], J.L. Charles [c], I. Iordanoff [c]

[a] Univ. Bretagne Sud, LIMATB, F-56100 Lorient, France
[b] Ecoles Saint-Cyr Coetquidan, CREC, F-56380 Guer, France
[c] Arts et Metiers ParisTech, laboratoire I2M, dpt. DuMAS, UMR CNRS 5295, F-33405 Talence, France

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ABSTRACT

In this article, the Discrete Element Method (DEM) is taking advantage for the damage modeling of a composite material. At this stage of work, a Representative Elementary Volume (REV) of an unidirectional composite material modeled in 3D is considered to prove the relevance of the approach. The interest to introduce the Discrete Elements (DE) on the scale of constituents (fiber and matrix) is to be able to report local mechanisms of degradation such as the matrix micro-fissuring, the fiber/matrix debonding and the break of fiber, appropriate to this type of material. The short-term objective is to use this DEM modeling to treat locally the damages induced by an impact loading associated with a conventional Finite Element modeling beyond the damaged zone. First, the geometrical modelings of the fiber and the matrix are presented. The phase of calibration of the DE model intrinsic parameters governing the fiber and matrix behavior and the fiber/matrix interface is afterward retailed. At this stage, each constituent is assumed to be brittle elastic. Then, simulations of longitudinal and transversal tensions but also of in plane and out of plane shearing are performed on the REV using DEM. The results are discussed and compared with those known for the literature. The capacity of the present DEM to capture the crack paths is particularly highlighted.

1. Introduction

The increasing market of composite in the aeronautical sector in particular imposes statutory requirements for the safety of the properties and the persons. Concerning the composite material, a major industrial stake is to propose a structural material performing against impacts such as falls of tools during the maintenance, tire debris projections or hail storm. Faced with the need to strongly reduce experiments for the benefit of numerical simulations, the issue is then to develop digital models always more efficient. Then, the trend is to favor multiscale approaches allowing a dialogue between a local damaged zone and the global behavior of the considered structure. Some authors consider the multiscale approach by global/local iterative calculations performed on the whole structure (macroscopic scale) and more locally around the process zones (microscopic scale). The most common methods consist of returning the structures effects (macro scale) to a fine model (micro scale) using adaptive boundary conditions (downward methods) [1,2] and reinjecting a corrective load (multi-grid and decomposition methods) [3,4] or degraded homogenized properties [5] from the local scale to the global scale. Others authors propose a multiscale method for micro–macro failure of composites computing an equivalent discontinuity at macro scale [6].

Others attempt to finalize modelings in which models intended to report at the same time local and global effects using coupling techniques (sticking methods). Within this framework, a direct coupling approach is proposed by the authors of the present study. It consists of introducing locally the Discrete Elements Method, DEM, initially developed by [7] and adapted to the degradation of a continuous medium when cracking or fragmentations appear [8] and coupling it with a more conventional continuous method beyond the process zone. So, the works [9] presents the Discrete Elements Method (DEM) coupled with the Constrained Natural Element Method (CNEM) using Arlequin technique[10]. More recently, this coupling was taken advantage to treat the case of a laser impact on glass [11]. In order to generally deal with the case of impact on composite target, the originality of this work is to propose a 3D modeling using DE for a composite medium. The case of an UD cell is considered at the moment but an extension to UD ply and composite textile is also planned.

* Corresponding author at: Ecoles Saint-Cyr Coetquidan, CREC, F-56381 Guer, France. Tel.: +33 290 404 049.

E-mail address: laurent.maheo@univ-ubs.fr (L. Maheo).

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Until now, the use of DEM to model composites is almost restricted to a 2D domain with studies on the damage observed in a fold UD [12–14] during debonding tests [15–17]. The DEM turns out to be an excellent tool to identify qualitatively the initiation and the distribution of fiber/matrix interfacial debonding [16] and to quantitatively determine the degraded mechanical properties; the degradation of the Young modulus can be related to the density of cracks inside the material [12]. Thanks to growing computing powers, works on the use of the DEM in a 3D domain for homogeneous materials as silica [18] or heterogeneous as the concrete [19] is now possible. Shiu et al. [19] shows in particular the capabilities of the method to predict the depth of penetration of missiles according to their shape. More recently, Aghazadeh Mohandesi et al. [20] used the DEM to prove its capability to describe the behavior of a sand PET composite under compressive loadings and with different temperature conditions.

Our objective is thus to introduce the DEM developed in the laboratory [21] to prove its capability and its relevance to treat the cracks propagation at the microscopic scale. The case of an UD is considered in this work through a Representative Elementary Volume (REV) constituted by a fiber flooded in a cube of resin. The geometrical modeling of the fiber and the matrix is first presented). The filling technique is particularly described. The mechanical modeling of the continuous media constituted by the fiber and the matrix is then handled. It consists of the introduction and calibration of mechanical links to report a brittle elastic behavior. Cohesive beams developed in [26,27] stand for these links. The calibration step to identify beam parameters at microscopic scale is detailed for each constituent (fiber and matrix) and for the interface (fiber/matrix). Numerical tests to validate the REV behavior are then presented. Longitudinal and transversal tractions, and in plane and out of plane shearing are performed on the REV. The parametric simulations qualitatively and quantitatively show the relevance of the present DE model.

Comparisons are also made between two criteria implemented for the failure process. Some conclusions and perspectives conclude this work.

2. Geometrical modeling of the heterogeneous media

2.1. General considerations

The geometrical modeling of the fiber and the matrix is guided by the following requirements and assumptions: (i) use the simplest DE shape, (ii) adopt a compatible DE size with the scale of mechanisms to observe, (iii) adopt a radius distribution to get a correct representation of the continuous medium (compaction and isotropy), and (iv) use a sufficient number of DE to ensure the macroscopic results non sensitivity to the discretization.

In the present DEM, the formulation is naturally in explicit dynamics. The DE geometry associated with the density carries the kinetic information whereas the links connecting the centers of adjacent DE pilot the behavior, see Section 3.1. For efficiency reasons, the implementation and treatment are performed using spherical DE. More complex geometries could be however envisaged by the use of Voronoï cells [22,23]. The size of spheres is varying according to a Gaussian distribution. It is chosen in such a way to be able to analyze the mechanisms of degradation at the scale they occur; the matrix micro-cracking, the fiber/matrix debonding and the failure of fibers are the interesting mechanisms. Their number and their size have also to allow a good geometrical representation of the fiber/matrix interface.

Practically, building the continuous medium (fiber or matrix) consists of placing at one time a set of DE whose radius has been beforehand chosen according to the required distribution. This stuffing operation is followed by a phase of relaxation to get the best cohesion of the isotropic continuous. The last is governed by two criteria: an optimal rate of compaction (ratio between the volume of spherical DE and the enveloping volume) of 6.3 and a minimal number of coordination (number of contacts by DE) of 6 [26].

Even if the objective at this stage is not to study the degradation of the fiber, its modeling uses the same distribution (casting) of DE as the matrix. This choice allows: (i) to avoid prohibitive filling times due to significant differences of size and (ii) to get a sufficient fine representation of both the media (fiber and matrix) and the interface.

At this stage, being able to represent damage mechanisms at the fiber scale does not present any interest except for the final failure but this will be useful in the future when intra tow fissuring will be considered.

2.2. Representative Elementary Volume (REV)

A cubic domain is considered as the Representative Elementary Volume (REV). It is made of a cylindrical carbon fiber flooded in an epoxy matrix. Results are widely available in the literature [24] for such a REV. It also corresponds to a will to avoid too prohibitive times of simulations. The main objective at this stage is to prove the interest of the present DEM for the modeling of the damage mechanisms in composite. In parallel to this work, one can precise developments are performed in the laboratory to model cells containing several fibers randomly distributed within a Statistical Elementary Volume (SEV) such as those considered in [25]. The way of parallel computing is explored.

For the present REV, the fiber is assumed to be of a cylindrical shape. Its diameter is such as the volume rate of fiber is of the order of 51.3%. This corresponds to an arbitrary fixed value. The length of the cell in the fiber direction results from an analysis of sensibility [25]. The Fig. 1(a) presents the elementary volume by distinguishing the cylindrical volume of the fiber of that cubic of the matrix.

2.3. DEM modeling of the REV: the filling technic

The filling of the REV by the discrete elements has to enable a correct representation of the continuums (fiber and matrix). The filling operation is challenged by the following objectives: (i) to reach a rate of compaction for modeling correctly the continuums [26], (ii) to insure the media isotropy [26] (the carbon fiber anisotropy is not yet considered but envisaged in future works), (iii) to preserve a definition of the geometry in the interface fiber/matrix as precise as possible.

The most effective one consists into two steps. The first stage consists in filling the whole volume of the cubic cell by aiming at the rate of compaction of reference of 6.3 [26] without distinction of the volumes of the fiber and the matrix. This filling makes in two operations:

- A first operation of random trial in the space of the possible positions is realized insuring the geometrical strict condition of not overlapping of DE.
- The second operation consists in introducing a set of DE by forcing their overlapping in the restricted volume of REV. DEM calculations are then performed to release internal energy until obtaining the desired rate of compression.

The second stage simply consists in differentiating DE belonging to the fiber of those belonging to the matrix, so as to obtain the volume rate of fiber wished (desired), that is 51.3% (Fig. 1(b)). The distinction of fiber DE of those of the matrix is simply made by locating the position of the DE centers close to the interface represented by a perfect cylindrical envelope. So, the centers of DE located in the envelope will be allocated to the fiber whereas those situated out-