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Validation of a Representative Volume Element for unidirectional fiber-reinforced composites: Case of a monotonic traction in its cross section

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ABSTRACT

Based on a Finite Elements Analysis homogenization technique which uses a Representative Volume Element with a random distribution of the fibers, this article presents the adequate characteristics to obtain a mesoscopic model which predicts the mechanical behavior of a unidirectional glass fiber-reinforced polymer composite under monotonic transverse traction. A parametric study is made and finally an appropriate model was chosen to present the comparison between experimental and numerical results. The mesh and the RVE size/fibers size ratio are the most sensitives attributes. Considering the numerical model is in the framework of elasticity and elasto-plasticity, it is in good agreement with the macroscopic response. To improve the accuracy of the model, a further study accounting the interface and damage phenomenons as matrix cracking and fiber/matrix debonding is suggested.

1. Introduction

The multiscale material modeling is a commonly used technique to study the behavior of heterogeneous structures as it allows to simplify the problem by considering a sub-volume of a whole, without affecting the accuracy of the results [1–4]. In a numerical approach, this method reduces in a considerable way the simulation time which explains the emerging phenomena of computational micro and mesomechanics.

Solving this kind of continuum mechanics problems implies the use of a strategy: Finite Elements Method/Analysis (FEM/FEA), boundary elements, finite differences, finite volumes, among others [5]. The FEM/FEA is the most widely used method and therefor the one considered in the present study.

When choosing the homogenization technique based on FEA, the mechanical behavior of heterogeneous materials is often described by using Representative Volume Elements [6,7]. Since the RVE must be the smallest representation required to obtain by statistical averaging, the same mechanical properties as those at a macroscale [8], it is extremely important to study all the parameters that could affect its behavior.

Different types of RVE have been presented by several authors, for instance, Gonzalez and Llorca [9], considered a few 2D square RVE with a random and homogeneous dispersion of 30 and 70 circular monosized 5 μm fibers. Vaughan [10] examined an RVE containing 80 fibers with a diameter of 6.6 μm randomly distributed using a Nearest Neighbor Algorithm. Yang [11] studied an RVE with a volume fraction of 50% – 60% which fiber distribution was generated by a Random Sequential Algorithm while Ismail [12] developed an RVE with 28 monosized fibers of radius 3.3 μm, starting with a squared packed arrangement and applying a random velocity to obtain a realistic distribution of the fibers.

Furthermore, single fiber, double inclusion, squared distribution and random dispersion fibers RVEs were analyzed by Bouhala [13], for the cases of multifiber composites approximately 50 fibers were accounted with 0.4 mm and 0.488 mm as fibers radius. More recently, Herraez [14], studied different RVEs containing periodic and random dispersion of 42 fibers with a diameter of 7.19 μm comparing them to 80 fibers models to ensure an appropriate choice of the RVEs size.

In addition to the RVEs representing unidirectional composites, Toulemonde [15] and Huang [16] studied glass beads reinforced composites by considering two-dimensional and cubic RVE models respectively and Catapano [17] add to these kind of materials a random dispersion of air bubbles. El Moumen [18] generated three-dimensional RVEs with ellipsoidal and spherical particles by Poisson process. In agreement with the authors cited above, we are persuaded that an RVE model is an optimal solution to resolve the computational cost problem generated when considering the composite material at a macroscale. Indeed, previous works [19,20] confirm that using the real dimensions of the samples for FE calculations leads to a high simulation time. Therefore, the aim of this work is to find the appropriate characteristics of an

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RVE to correctly simulate the mechanical behavior of a polymeric-matrix reinforced with glass unidirectional fibers. Several models were generated using a random distribution for the fibers, periodic and symmetrical boundary conditions were studied and finally a suitable model was chosen to present the comparison between experimental and numerical results, based on a monotonic traction submitted in the composites transverse section.

2. Experimental approach

2.1. Materials and testing methods

The material used is an unidirectional composite laminate based on an epoxy-amine matrix reinforced with 54% volume fraction of commercial sizing glass fibers. The specimens are rectangular parallelepipeds measuring $250 \times 25 \times 2\ \mathrm{mm}^3$ cut with a diamond saw in the composites transverse direction. Moreover, bulk resin samples with the same dimensions are also considered.

The mechanical behavior of the bulk resin and the unidirectional composite are determined by a tensile test in transverse mode performed on a MTS DY35 universal tensile equipment. Tabs of $50 \times 25 \times 2\ \mathrm{mm}^3$ were bonded to the ends of the specimens to prevent gripping damage. A constant cross-head speed of 1 mm/min was used according to the standard NF EN ISO 527-5 for the composites and NF EN ISO 527-2 for the bulk resin.

The strains were measured by a contact extensometer with an initial length of 25 mm and 50% of maximum extension. For each material five samples were tested to quantify their dispersion. The force–displacement curves were analyzed with the MTS TestWorks 4 software to obtain the stress–strain curves reported in Fig. 1. As shown, the composite has a more brittle behavior than the bulk resin due to the presence of the fibers. From the linear part of the results, the Young modulus were defined, obtaining 2.7 GPa and 8 GPa for the bulk resin and the composite respectively.

3. Numerical approach

Nowadays, several numerical models to study the mechanical behavior of unidirectional composites have been proposed, nevertheless complex strategies are evoked making difficult for the industry to implement them. In this particular section, our aim is to establish a simple and fast methodology in order to provide a feasible procedure for industrial solutions.

3.1. 2D model

To generate the models used in the FEM simulation, a Phyton script was executed in ABAQUS creating the 2D composite's geometry previously defined by an ad hoc code developed in MATLAB.

The objective of the MATLAB algorithm, was to obtain a text file with the appropriate data to define several circles randomly distributed and embedded in a square. To do so, three input parameters need to be indicated: the expected RVE size L, the fiber's volume fraction V_f and the fibers diameter d.

In order to make a simple approach, the RVE edges do not intercept any of the circles, meaning the interval for the random generation is reduced in order to considered the fiber radius. As the function to trigger this numbers was *rand()* which is based on a uniform distribution, we assure that each value has the same probability to appear [21].

The number of fibers N is calculated using the input parameters, and two vectors containing the coordinates of the circles centers are progressively filled respecting the non-overlapping condition until the number of fibers is reached, this happens when $i = N$ (Fig. 2). First of all, two random numbers are generated and added to each list (x_1, y_1), then two other random values (x, y) are originated and accepted in the list as the next coordinates only if they respect the condition expressed in Eq. (1) which means the minimum distance between them is a diameter of each fiber. Coordinates (x, y) will be regenerated until the condition is achieved.

$$\sqrt{(x - x_i)^2 + (y - y_i)^2} \geq d \qquad 1 < i \leq N \tag{1}$$

Phyton reads the text file and calls two existing functions, *rectangle()* and *CircleByCenterPerimeter()* which define the geometry of the RVE. Finally, to obtain the part model in Abaqus, the script must be executed. In brief, the procedure is schematized in Fig. 2.

3.2. Finite Element Analysis

A parametric study was made in order to choose the characteristics of an appropriate computational model. For that purpose, the convergence of the macroscopic elastic properties are studied by dividing the calculated Young modulus at the top of the RVE (where the load is applied) by a chosen reference Young modulus

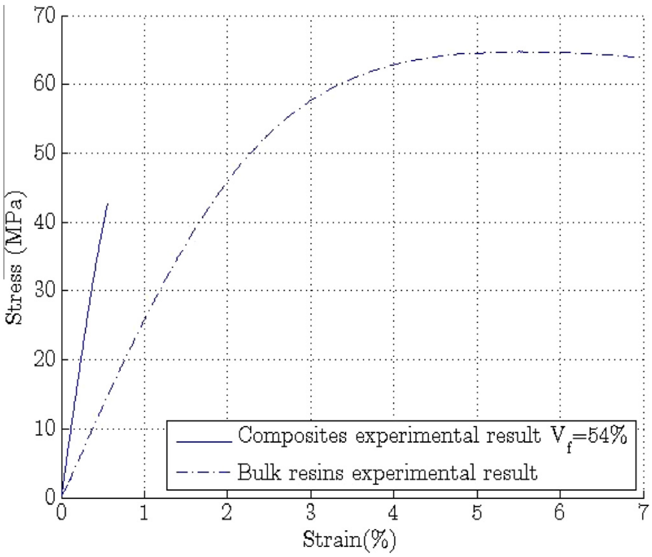

Fig. 1. Experimental tensile tests results of the composite and bulk resin samples.

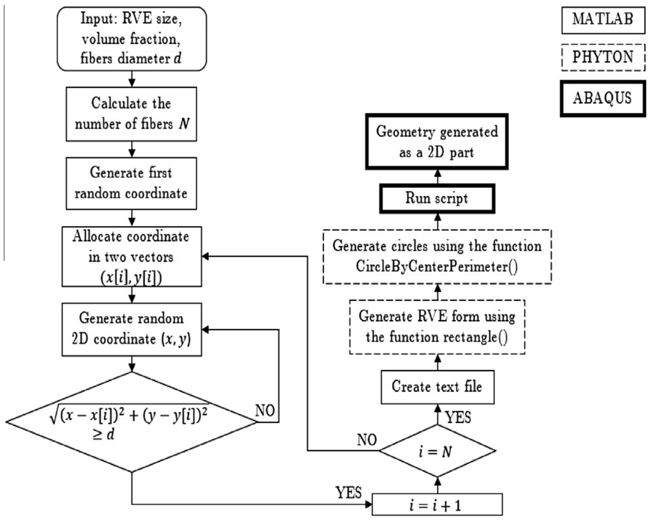

Fig. 2. Numerical process to obtain the RVE with random distributed fibers.