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A micromechanical study of stress concentrations in composites

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ABSTRACT

Random and periodic representations of composite microstructures are inherently different both in terms of the resultant range of stresses that each phase carries as well as the total load over the entire volume comprising both matrix and fiber phases. In this study, an algorithm was developed to generate random representative volume elements (RVE) with varying volume fractions and minimum distances between fibers. The random microstructures were analyzed using finite element models (FEM) and the results compared to those for periodic microstructured RVEs in terms of the range of stress values, maximum stress, and homogenized stiffness values. Using a large number of random RVE analyses, a meaningful estimation for range and average maximum stress in the matrix phase was achieved. Results show that random microstructures exhibit a much larger range of stress values than periodic microstructures, resulting in an uneven distribution of load and distinct areas of high and low stress concentration in the matrix. It is shown that the maximum stress in the matrix phase, often responsible for failure initiation, is largely dependent on the random morphology, minimum distances between fibers, and volume fraction. Moreover, it is shown that the predicted overall load-carrying capacity of the matrix changes depending on the use of random or periodic microstructures.

1. Introduction

Micromechanical analysis can provide researchers with a range of information on the local and global properties of composite materials. Many studies in composite structural design and analysis are done at the macrostructural level using homogenized material properties, but there are a number of macrostructural behaviours that are governed by fiber/matrix interactions and properties at the microstructural (fiber) level [1,2]. A thorough understanding of composite fiber/matrix interactions and their underlying mechanisms is critical to understanding and predicting the macrostructural behaviour of these materials.

Fig. 1 shows two examples of typical periodic and random microstructures. Micromechanical analysis is traditionally performed on a periodic (or repeating) microstructure, where there are two types of periodic microstructures commonly referred to as hexagonal and square packed. The periodic microstructure assumption confines researchers to the study of global phenomena such as global effective properties, often leading to difficulties with the accurate prediction of material properties and associated behaviour under load. Because of the irregular nature of the fiber distribution within the composite cross section, a phenomenon such as failure that is highly dependent on local morphology can not be accurately studied using ordered cross sections based on the periodic microstructure assumption.

Real composite structural morphology is very different from the repeating microstructure model and there is therefore an error associated with the use of repeating microstructures for analysis, particularly in the context of non-linear problems [3]. Microstructural morphology of composites influences the magnitudes and the distribution of stresses at the microstructural scale and ultimately dictates the overall behavior of the composite material at the macrostructural level. For this reason, irregular or random microstructures based on real composite morphologies have been adopted for the evaluation of linear and non-linear properties of composites by several researchers [4–6]. Random microstructures have also been used in the computational design of novel fibers [7].

It should also be noted that analytical approaches such as the famous Mori-Tanaka method [8,9]] and self-consistent schemes have been successful at predicting the overall properties of composites. In addition, there exist homogenization methods that can compute second order moments of local stress [10,11]. However,

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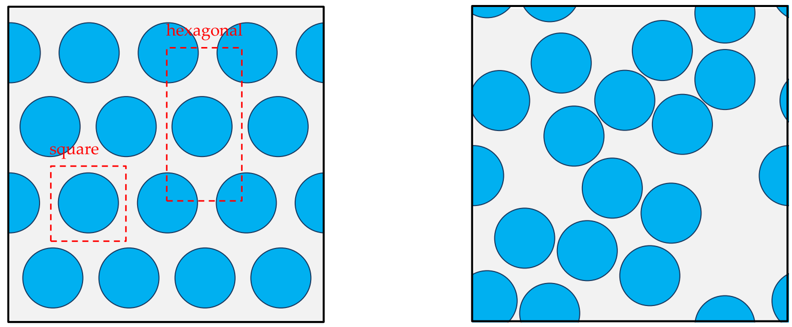

(a) Periodic microstructure (b) Random microstructure

Fig. 1. Two types of microstructures with the same number of fibers (and V_f) where (a) is a periodic or uniform microstructure and (b) is a random or nonuniform microstructure. Square and hexagonal packing (or unit cells) are shown in the periodic microstructure.

analytically predicting the range and distribution of stresses and strains, and the interactions between fibers or inclusion phase remains a challenge. In a recent study, it was shown that finite element analysis results of strain maps have a good agreement with experimental results acquired from digital image correlation (DIC) [12]. And with the computational advances of recent decades, it is affordable to analyze irregular or random microstructures and study local phenomena using finite element analysis. A significant challenge associated with the analysis of random microstructures is the generation of a representative volume element (RVE) that is a geometrical representation of the actual microstructure [13], meaning that the RVE must be statistically equivalent to a real microstructure [14,15]. A good geometrical representation requires that the size of the RVE be optimum; if the RVE is too small it cannot include the range of irregularities that affects stress distribution and if it is too large, it is computationally expensive.

Transverse matrix microcracking is often the first mode of failure in composite structures [16] and governs the fracture process [17,18]. The current study is focused on the transverse cross-section where the failure and fracture initiation is dominated by matrix properties and where the distribution of fibers dictates the stress concentrations and distributions in the matrix. Random microstructures are used to study the effects of morphology and fiber distribution on stress concentrations and the maximum stresses in the matrix phase of carbon-epoxy composites.

In this study, we show that the maximum stress in the matrix is largely dependent on the random morphology of the microstructure. First, the stresses in the matrix phase for periodic and random microstructures are analyzed with a new approach using an area percentage histogram. The histogram is a method to display the results for the entirety of the matrix phase for both types of microstructure. Secondly, it is shown that it is necessary to investigate a large number of random samples to ensure the inclusiveness of the analysis for maximum stress. This is because the maximum stress in the matrix phase depends on the specific random morphology and consequently, the results of analyses for maximum stress in random RVEs leads to a range of values rather than a singular value. These values then can be used in probabilistic design optimization of macro-scale structures [19] or reliability analysis, uncertainty modeling, and life prediction of composite parts [20–22].

The results show the range and frequency of the maximum stress values vary with different types of microstructures. It is shown that both the range of values as well as the maximum stress is strongly dependent on the minimum distance between fibers. Also, the modulus properties in the transverse direction change depending on the choice of microstructural representation due to the difference in the load-carrying behavior of the matrix in the random and periodic microstructures. It is shown that the matrix phase participates less in carrying the transverse load in random microstructures compared to periodic ones.

2. Microstructural representation

Although the word random implies no biased information, random microstructures follow rules such as the minimum distance between fibers. As soon as such a rule is added to a "random" phenomena it is no longer random, and perhaps a better term for these microstructures would be pseudo-random or irregular. For the purposes of this study, however, the term "random" is used to describe irregular microstructures and the term "periodic" for regular or repeating microstructures.

Several methods exist for the generation of random microstructures. These methods can be classified in two main categories; image-processing based and numerical generation. For the first method, an image from the cross section of the composite is acquired and the microstructure topology is generated numerically using image processing techniques [3,23–25]. This method requires several steps (image acquisition, image processing, etc) and can be computationally expensive if a large number of different random arrangements are to be studied.

The second category involves generating the random microstructures algorithmically. The primary challenge associated with these methods is to come up with an approach where the resulting microstructure is a statistically fair representation of the actual microstructure. Statistical functions such as the nearest fiber distance distribution function of virtual and actual microstructure can be compared to find a fair RVE or *Statistically Equivalent* RVE (SERVE) [14,26]. Random Sequential Absorption (RSA) is one of the methods used to generate random positions of fibers and particles [27,28], and has been shown to be statistically representative [29]. Another approach used by Gusev et al. [30,31] employs a Monte Carlo technique to generate random microstructures from perturbations of a regularly packed microstructure. A similar method based on the perturbation of regular microstructure is used in Ref. [32] to generate meso-scale random RVEs. Vaughan et al. [33] used statistical data from image processing of cross-sections to generate microstructures that are representative of actual samples. A method also is developed that starts from overlapping fibers, then by moving the fibers in several steps non-overlapping realistic RVEs were generated [34]. Another algorithm called Random Sequential Expansion (RSE) has been developed that can achieve