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Statistical approach of elastic properties of continuous fiber composite

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ABSTRACT

This paper is an attempt to predict the elastic properties of plain-weave continuous fiber-reinforced composites by coupling data of microstructure analysis and mechanical tests with a stochastic and multi-scale finite element analysis. The difference of this study over the previous one relies in the fact that these microstructural data are used directly in the proposed procedure without any pre-processing. Thus, a random procedure is used to build the mesh of the representative volume element (RVE), the description of which is based on the mosaic model. The geometry of this RVE is described by a random choice of data provided by image analysis. Variables as the fiber modulus and the local fiber volume fraction are randomly assigned to each element of the mesh. Finally finite elements calculations are performed with the homogenization technique to obtain the macroscopic elastic properties.

The results show that geometry fluctuations of the RVE have a significant impact on the material macroscopic moduli. Furthermore, the method is more efficient to predict the mean values of the elastic moduli than the experimental dispersions (NB: the aim of this approach is to predict the scatter of elastic properties. An elastic homogenization procedure is sufficient to obtain numerically "mean" values). The results also show that the variations of the local fiber volume fraction have a small influence on the elastic properties because the mean value of the fiber volume fraction over the whole RVE varies very little from a draw to another. Finally, such a proposed method if it is fully automated could be very useful in preliminary design because cheaper than to perform experimental tests.

1. Introduction

The use of composite materials in structural applications has increased significantly in recent years and especially in the transport industry, thanks to their excellent specific properties that significantly reduce the gears weight. However, these materials have some weaknesses. Indeed, unlike most metals, continuous fiber composites have brittle characteristics and they show a large variability of their properties. This forces designers to consider very high safety factors, resulting in a loss of lightness. The ability to properly design light as possible components require a detail understanding of the statistical nature of the behavior of composite materials.

The dispersions of mechanical behavior of composites have two sources: those related to the intrinsic properties of the basic constituents such as differences of moduli and mechanical strength along the fibers; and those due to the molding process such as the variation of local volume fraction of fibers, the size and the spatial arrangement of the reinforcements. Many researchers worked earlier on statistical methods for predicting properties and uncertainties of composites. Among the oldest include Sun and Yamada [1] who worked on failure probability of composite laminates with random strength parameters, Baxevanakis et al. [2] which studied the fracture statistics of unidirectional composite, Lin [3] who studied reliability predictions of laminated composite plates with random system parameters, and more recently Shaw et al. [4] who worked on a reliability evaluation of fiber reinforced composite materials based on probabilistic micro and macro-mechanical analysis. However, most of these works focus on unidirectional composites. In these approaches, the dispersions related to the manufacturing process are not sufficiently taken into account since the local volume fraction of fiber and sometimes the ply thickness are the only statistical parameters related to the process which they consider. Another difficulty lies in the fact that the experimental data used by these authors for finite element calculations must be pre-processed, making their approach fairly heavy to implement on a real part.

In this study, we propose a very simple multi-scale statistical method for predicting elastic behavior and uncertainties of continuous fiber composite materials showing large dispersions. By

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introducing uncertainties at micro-scale (constituents) and meso-scale (yarn), macroscopic properties and dispersions can be deduced from homogenization calculations so that, these uncertainties can be propagated from micro to macro-level. Our method takes into account the main statistical manufacturing process parameters and experimental data (from image analysis and mechanical tests) are used directly in calculation without any pre-processing. Another novel aspect of the present work is the application to a woven composite.

2. Material and method

2.1. Material

The studied material is a plain weave E-glass/epoxy composite supplied by Hutchinson France with 95% and 3% to 5% of fibers respectively in longitudinal and transverse directions. This type of weave called quasi-uni directional (QUD) due to the very weak fiber volume fraction in the transverse direction. This material is a good example for illustrating our method since it is simultaneously close to unidirectional (UD) and fabrics. Glass fibers and epoxy resin properties as given by supplier are summarized in Table 1. Both are isotropic materials which can be characterized by only two parameters namely the young modulus (E) and the Poisson's ratio (ν). These raw materials are used for laminates manufacturing with a RTM process. The molded laminates are 4 mm thickness plates containing 10 plies all stacked in 0° direction. Thanks to the transparency of the matrix, an X-ray scan of the molded plate was possible as shown in Fig. 1. One can clearly notice the yarn misalignments leading to the yarn spacing dispersions.

2.2. Method

As mentioned earlier in the introduction, the proposed approach is simple, pragmatic and generic to be applied to other types of composites. It consists on experimentally measure the dispersions within the material at the microscopic level to predict the macroscopic behavior of laminates. The process will therefore include two stages. The first step deals with identifying all microscopic parameters that can influence the mechanical behavior of the laminate and have sufficient amount of experimental data to form a random Gaussian distribution. Then in a second phase, it will be question of using these experimental data in an automated procedure for finite element calculations of mechanical properties of the laminate. These calculations will be implemented on a representative volume element (RVE) using the homogenization method well described in [5–6].

One of the greatest advantages of our method is the use of experimental data without any pre-processing, which reduces the margin of error. Indeed, the usual approach consists in defining a statistical function linking the value of a variable to its probability of occurrence and then to use it to generate randomly the variable values necessary for calculations. With the proposed method, the random choice of variables is made directly from the experimental values and injected into the calculations. It leads to a minimization of the error and the operational time.

Table 1
Fiber and matrix characteristics of the studied material (data from the supplier).

	Type	E (MPa)	ν
Fiber	Glass E	79,000	0.22
Matrix	Epoxy	4000	0.35

3. Experimental procedure

3.1. Image analysis and definition of random variables

Image analysis is an effective technique in materials science to identify and quantitatively characterize the component of a microstructure. In this study, we focus beyond the local volume fraction of fibers, to all other microstructural variabilities which may affect the mechanical properties of the laminate. Thus, many pieces of plates are cut in longitudinal and transverse directions, then polished and observed under a scanning electron microscope (SEM). We chose the SEM because as can be seen in Fig. 1, epoxy matrix and the glass fibers are both transparent. So, the contrast obtained with an optical microscope was not satisfactory. SEM gives better results because with this technique, we have rather a chemical contrast, which is very suitable to our case since the mineral glass fibers are chemically very different from the organic matrix. We thus obtain very good images as shown in Fig. 4 with a good contrast which is essential to reliably quantify the different phases of the microstructure.

Referring to Figs. 2 and 3, there are a large number of parameters related to the manufacturing process and that may affect the mechanical properties of the material such as the local volume fraction of fibers, the size of longitudinal and transverse yarns (major axis of the ellipse), the longitudinal and transverse yarn spacing, and the stacking of the plies in phase or out of phase. To these parameters are added the intrinsic variabilities of constituents such as moduli and mechanical strength along single fiber. It is evident that we cannot consider all these variables in our study and a choice must be made to retain only those whose importance is proven and that we are able to quantify.

3.1.1. The local variations of the fiber volume fraction

Among the parameters influencing the mechanical behavior of the composites, the fiber volume fraction is by far the most important. It is thus necessary to measure it very carefully with the greatest possible precision. 120 large SEM images (1.5 × 1.2 mm) were performed with magnification ×100. Then, samples of size 1.1 × 0.8 mm and 200 × 200 μm are made at different locations of these raw images as shown in Fig. 4. Only one sample of 1200 × 800 μm per image can be performed against six for those of 200 × 200 μm. We obtain finally 120 samples of size 1.1 × 0.8 mm and 700 for 200 × 200 μm that allow us to calculate the local volume fraction of fibers. It should be noted that the selection of areas to be analyzed and calculations of fiber rat are managed automatically through a scripts implemented in Matlab software. The fiber rate distributions obtained are summarized in Fig. 5.

The results in Fig. 5 show that we have normal distributions of fiber rate that are well approximated by Gaussian functions. For the two sizes of samples, the average fiber volume fraction is approximately 52%, which is in agreement with the experimental values obtained by pyrolysis. Thus, hundred images of size 1.1 × 0.8 mm give the same mean value as 700 images of size 200 × 200 μm. This is quite logical since by increasing the size of the samples, we reduce the scatter. In the following, we will use only the distribution obtained with 200 × 200 μm samples which give us a better Gaussian fit. The measured values are stored in a text file and will be used as input data for finite elements calculations.

3.1.2. The longitudinal yarn size and the longitudinal yarn spacing variations

Referring to the results of Figs. 2 and 3, the longitudinal and transverse yarns have elliptical shapes and therefore characterized by two characteristic values: the major axis and the minor axis. By