SHORT FIBER REINFORCED COMPOSITE MATERIALS MECHANICAL PERFORMANCE ANALYSIS

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ABSTRACT

This paper present a method for generating RVE analyses of random short fiber reinforced composite materials. An embedded element technique is used to simplify mesh generation for the matrix material. Compared with a more conventional unstructured mesh, this method saves times and ensures calculation accuracy. However, embedded element technique was sensitive to the meshing size, higher fiber volume fractions required finer meshes. Using control variable method to study the effect of some parameters of the fiber to the mechanical performance of composite material, such as fiber volume fraction, fiber length, fiber orientation. The effect of fiber length plays a larger role to the mechanical performance of composite material than other parameter.

1 Introduction

Nowadays, short fiber reinforced composite materials are used widely in engineering fields. To expand the use of this kind of composite, it requires accurate material characterization.

In the short fiber reinforced composite materials, the fiber distribute randomly in the matrix material. Although the aspect ratio of the short fiber is large, it is difficult to achieve completely in the matrix unidirectional arrangement [1]. For the research of the mechanical model and the constitutive relation of this kind of composite materials, it often simplifies by a homogenization procedure or orientation averaging [2]. In order to better characterize the influence from the microscopic stress and strain state to the macroscopic mechanical properties, it is necessary to build the numerical model of the short fiber reinforced composite materials, and to use the numerical method for the simulation and the calculation.

Finite Element Analysis (FEA) is widely used to model the response of randomly distributed fiber composites [3]. FEA methods developed for particle reinforced composites have been modified to model slender fiber inclusions, but generating realistic fiber architectures still remains a challenge. High volume fractions are difficult to achieve for fibers with large aspect ratios and distorted finite element meshes can occur at local fiber contact points [4 - 7].

In this paper, a modified random adsorption algorithm is used to generate planar 2D fiber architectures. Using the embedded element techniqu, the translational degrees of freedom of each beam element are eliminated, becoming constrained to the interpolated values of the corresponding degrees of freedom of the matrix element, thus embedding saves time in mesh generation and it has a small error[8].

Then it is important to study the influence of the parameters of the fiber to the overall elastic properties. Because it can also better predict to the mechanical properties of the short fiber reinforced composite materials.

2 Finite element modelling

Planar 2D fiber architectures have been generated by a modified random sequential adsorption algorithm by language python. For each fiber bundle, random numbers within upper and lower bounds of the RVE are generated for the x and y coordinates of the center of mass. Another random number is used to generate a fiber orientation about the center of mass. This can be completely random. In this model, intersection of fibers are ignored. To compare with the model which can not ignore the intersection of fibers, therefore no limitation is imposed on the fiber volume fraction.

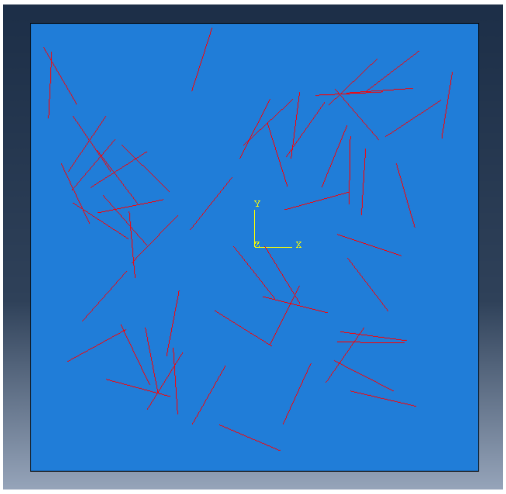

Figure 1 RVE generation

In ABAQUS, we use 1D beam elements to represent fiber bundles. For each beam, it is assumed to have a circular cross-section, where the effective diameter is assigned as a function of the filament count and tow volume fraction (V_{tow}). There is a relation between the target volume fraction of the laminate (V_f) and the volume of deposited fiber bundles (V'_f).

$$V'_f = \frac{V_f}{V_{tow}} \tag{1}$$

The matrix material is modelled using a regular array of 2D, plane stress continuum elements. L.T. Harper has been determined the critical size of the RVE for discontinuous fiber architectures, therefore the model of RVE is $20\mathrm{mm} \times 20\mathrm{mm}$ [9]. Beam elements are fixed to the solid elements using the Embedded Element technique, a type of multi-point constraint within ABAQUS/Standard. The translational degrees of freedom of each beam element are eliminated when it is embedded, becoming constrained to the interpolated values of the corresponding degrees of freedom of the matrix element. Embedding eliminates the need for a complex meshing algorithm to pair the coincident nodes and hence saves time in mesh generation.

Many researchers have proved that the embedded element technique is much simpler than the TIE command which is used to constrain the fibers to the matrix at coincident nodes in the irregular meshed model. It can save time in mesh generation and calculation, and the error between them is negligibly small, less than 1% [3].

Material properties used for all subsequent Finite Element Analyses are listed in Table 1.

Fiber tow mondulus	144000(MPa)
Fiber Poisson's ratio	0.3
Matrix mondulus	3350(Mpa)
Matrix Poisson's ratio	0.38
Fiber tow size	24000
Tow volume fraction	60(%)
Filament dimeter	7(μm)
Effective tow diameter	1.4(mm)
RVE thickness	3.5(mm)

Table 1: Parameters used in the FE model.

3 Boundary conditions for 2D model

Effective material properties of each random fiber architecture have been approximated by applying periodic boundary conditions, assuming translational symmetries in the x and y directions and ignoring traction conditions.

According to[10], the periods of translation in the x and y direction are a_i and b_j respectively, where *a* is the length of the cell, *b* is the width, and *i* and *j* are the number of periods. The cell is subjected to a set of macroscopic strains, which are introduced as three extra degrees of freedom at three individual dummy nodes in ABAQUS/Standard.

The translational symmetries in the x-direction for boundaries x=0 and x=a (i=1 and j=0) are :

$$\begin{gathered} U_{x=a} - U_{x=0} = a\varepsilon_x^0 \\ V_{x=a} - V_{x=0} = 0 \end{gathered} \tag{2}$$

The translational symmetries in the y-direction for boundaries x=0 and x=b (i=0 and j=1) are :

$$\begin{gathered} U_{y=b} - U_{y=0} = b\gamma_{xy}^0 \\ V_{y=b} - V_{y=0} = b \end{gathered} \tag{3}$$

To construct the equivalent homogeneous medium representing the microscopically heterogeneous one, one can define the macroscopic stress and macroscopic strain over the volume of the RVE

$$\tilde{\sigma} = \frac{1}{abt}\int \sigma dV \tag{4}$$

Where t is the RVE thickness.

$$\tilde{\varepsilon} = \frac{1}{abt}\int \varepsilon dV \tag{5}$$

The effective elastic constant can thus be defined as

$$\tilde{\sigma} = \tilde{C}\tilde{\varepsilon} \tag{6}$$

4 Mesh sensitivity

Using the embedded element technique, it should consider the sensitivity of the density of the finite element mesh. It supposes that the matrix edge length is same to fiber element length for all models, ranging from 2mm down to 0.05mm. The same random seed was specified in the RVE generator to produce identical fiber architectures on repeat runs of the model. The model of RVE is 20mm × 20mm. The material properties used for all finite element model are listed in Table 1.

From Fig 2. , it show that the average RVE modulus is converge with the increase of the number of elements. For higher fiber volume fractions, it will take longer to converge, and when the number of elements is too small, the error is much bigger. The reason why a greater number of embedded beam elements share the same matrix elements at higher volume fractions.

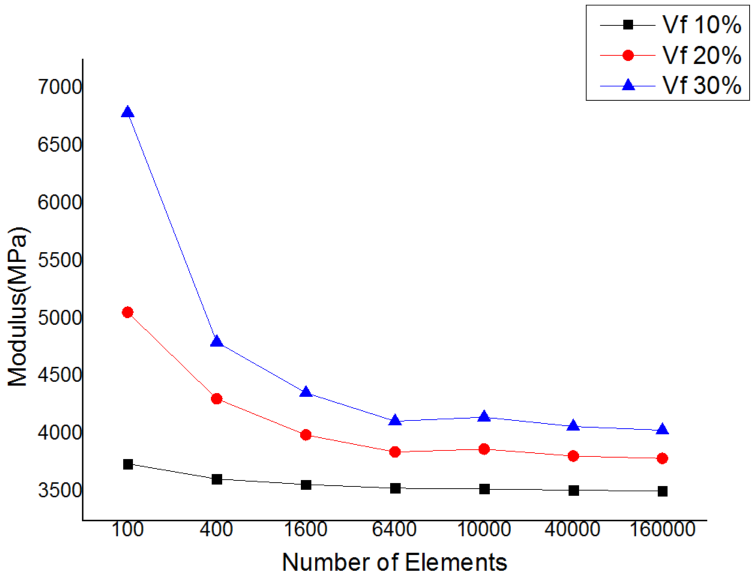

Figure 2: Effect of mesh density for three different fiber volume fraction

The error for the average RVE modulus between an element length of 0.1mm and 0.05mm is less than 1% in all cases: 0.2% for 10% vf, 0.5% for 20% vf and 0.8% for 30% vf. Therefore an element length of 0.1mm has been used for all subsequent model.

5 Discussion

In this part, we will discuss the effect from the parameters of fiber to the mechanical behavior of the short fiber reinforced composite material under uniaxial tensile condition(direction of x axis and direction of y axis). The first one is the effect of fiber volume fraction. The second one is the effect of the length of fiber, it is also the effect of the aspect ratio of fiber. The last one is the orientation of fiber, because fibers distribute randomly in this kind of composite material.

5.1 Effect of fiber volume fraction

When we study the effect of fiber volume fraction to the mechanical behavior, we fix others parameters of fibers, such as, the length of fiber is 2.5mm, the orientation of fiber distributes randomly. And we change the volume fraction of fiber from 5% to 30%.

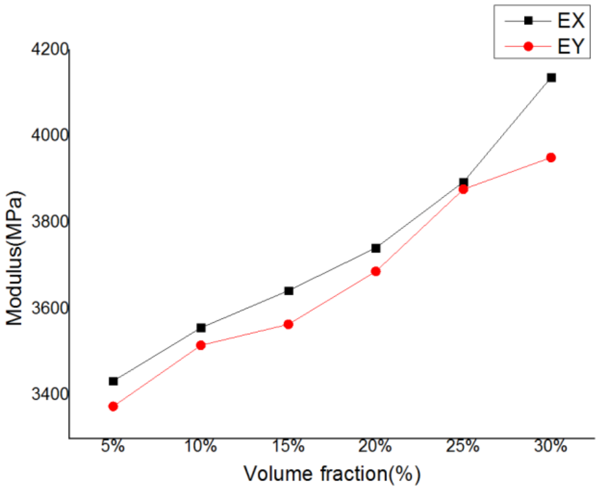

Figure 3: Effect of fiber volume fraction to the modulus of composite material

From Fig 3., it show that the fiber volume fraction influence the average RVE modulus under uniaxial tensile condition. When the volume fraction augment, EX increase about 20.5% and EY increase about 17.1% from 5% vf to 30% vf. With the fiber volume fraction augment, there are more fibers distribute in the matrix material, fibers can bear more tension than matrix, hence the ability to sustain tension of the composite material augment also.

5.2 Effect of the length of fiber

To study the effect of the length of fiber to the mechanical performance of composite material, we fix the fiber volume fraction(30%). The length of fiber change from 2.5mm to 10mm, and the fibers distribute uniaxially (*x*-axis) in the matrix material.

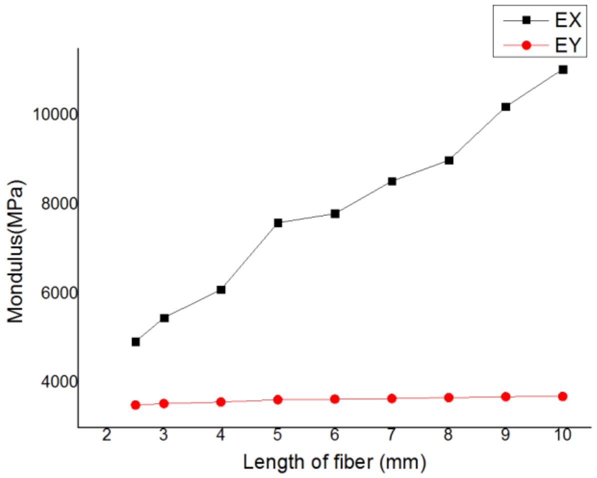

Figure 4: Effect fiber length to the modulus of composite material

From Fig 4., it show that the fiber length influence the average RVE modulus under uniaxial tensile condition. When the fiber length augment, EX increase about 123.9% and EY increase about 5.5% from 2.5mm to 10mm. Compare with the effect of the volume fraction, the fiber length plays a larger role to the mechanical performance of composite material. With the increase of fiber length, the number of fiber bundles will decrease, but the longer fiber can bear bigger tension than the shorter fiber.

5.3 Effect of the orientation of fiber

When we study the influence from the orientation of fiber to the mechanical performance of composite material, we fix the fiber length (2.5mm) and the fiber volume fraction(10%). Then we change the angle between the fiber orientation and x-axis from 0° to 90°. The position of fiber is random, but the orientation of fiber is limited.

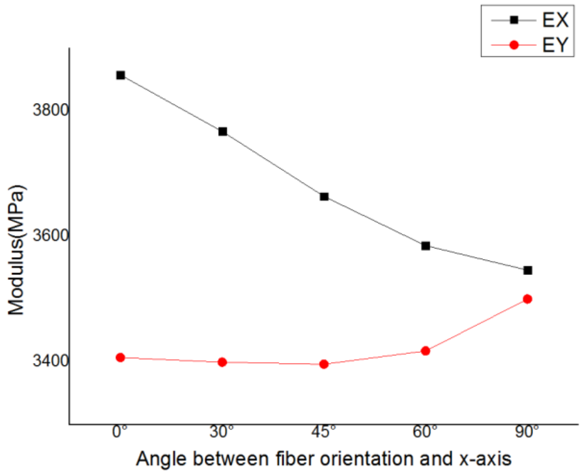

Figure 5: Effect of fiber orientation to the modulus of composite material

From Fig 5., it show that the fiber orientation influence the average RVE modulus under uniaxial tensile condition. When the angle augment, EX decrease about 8.1% and EY increase about 2.7% from 0° to 90°. Compare with the effect of the volume fraction and the effect of the length, the fiber orientation has less influence to the mechanical performance of composite material. When the angle is equal to 0°, fibers distribute uniaxially, therefore composite material can bear more tension in the direction of x-axis, but it bears less tension in the direction of y-axis.

6 Conclusion

When we built the model of the short fiber reinforced composite material, the RVE is constructed of layers, and we suppose that there are not any fibers distribute out of plane. We ignore the cross-sectional area of fiber, hence using one-dimensional element to represent the fiber. There are three random numbers to determine the position and orientation for each bundle of fiber. Mesh refinement studies indicated that the embedded element method was sensitive to the number of fibre bundles within the RVE model. Higher fiber volume fractions required finer meshes. The optimum element length is 0.1mm for a fiber volume fraction less than 30%.

Under uniaxial tensile condition, some parameters of fiber influence the mechanical behavior of the short fiber reinforced composite material. Using control variable method, we found that fiber volume fraction, fiber length and fiber orientation influence the RVE average modulus. When the fiber volume fraction augment, the modulus in x-direction and y-direction all augment. The effect of fiber length is same, but it plays a larger role to the mechanical performance of composite material. For the orientation of fiber, when the angle between the fiber orientation and x-axis increases, the modulus in x-direction also increases, but the modulus in y-direction decreases. Compare with the effect of the volume fraction and the effect of the length, the fiber orientation has less influence to the mechanical performance of composite material. Therefore when fiber volume fraction and fiber length augment, the mechanical properties of the short fiber reinforced composite material will enhance.

In this paper, we suppose that the constitutive relation of fiber and matrix material is linear elastic relation. In the future, we will change the constitutive relation of fiber and matrix material to study the mechanical properties.

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