Composites: Part B 58 (2014) 318–327

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Mechanical properties of hybrid composites using finite element method based micromechanics

Sayan Banerjee *, Bhavani V. Sankar

Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32608-6250, USA

ARTICLE INFO

Article history:
Received 18 April 2013
Received in revised form 16 September 2013
Accepted 25 October 2013
Available online 7 November 2013

Keywords:
A. Hybrid
B. Mechanical properties
C. Finite element analysis (FEA)
C. Micro-mechanics

ABSTRACT

A micromechanical analysis of the representative volume element of a unidirectional hybrid composite is performed using finite element method. The fibers are assumed to be circular and packed in a hexagonal array. The effects of volume fractions of the two different fibers used and also their relative locations within the unit cell are studied. Analytical results are obtained for all the elastic constants. Modified Halpin–Tsai equations are proposed for predicting the transverse and shear moduli of hybrid composites. Variability in mechanical properties due to different locations of the two fibers for the same volume fractions was studied. It is found that the variability in elastic constants and longitudinal strength properties was negligible. However, there was significant variability in the transverse strength properties. The results for hybrid composites are compared with single fiber composites.

1. Introduction

Hybrid composites contain more than one type of fiber in a single matrix material. In principle, several different fiber types may be incorporated into a hybrid, but it is more likely that a combination of only two types of fibers would be most beneficial [1]. They have been developed as a logical sequel to conventional composites containing one fiber. Hybrid composites have unique features that can be used to meet various design requirements in a more economical way than conventional composites. This is because expensive fibers like graphite and boron can be partially replaced by less expensive fibers such as glass and Kevlar [2]. Some of the specific advantages of hybrid composites over conventional composites include balanced effective properties, reduced weight and/or cost, with improvement in fatigue and impact properties [1].

Experimental techniques can be employed to understand the effects of various fibers, their volume fractions and matrix properties in hybrid composites. However, these experiments require fabrication of various composites which are time consuming and cost prohibitive. Advances in computational micromechanics allow us to study the various hybrid systems by using finite element simulations and it is the goal of this paper.

Hybrid composites have been studied for more than 30 years. Numerous experimental works have been conducted to study the effect of hybridization on the effective properties of the composite [3–11]. The mechanical properties of hybrid short fiber composites can be evaluated using the rule of hybrid mixtures (RoHM) equation, which is widely used to predict the strength and modulus of hybrid composites [3]. It is shown however, that RoHM works best for longitudinal modulus of the hybrid composites. Since, elastic constants of a composite are volume averaged over the constituent microphases, the overall stiffness for a given fiber volume fraction is not affected much by the variability in fiber location. The strength values on the other hand are not only functions of strength of the constituents; they are also very much dependent on the fiber/matrix interaction and interface quality. In tensile test, any minor (microscopic) imperfection on the specimen may lead to stress build-up and failure could not be predicted directly by RoHM equations [12].

The computational model presented in this paper considers random fiber location inside a representative volume element for a given volume fraction ratio of fibers, in this case, carbon and glass. The variability in fiber location seems to have considerable effect on the transverse strength of the hybrid composites. For the transverse stiffness and shear moduli, a semi-empirical relation similar to Halpin–Tsai equations has been derived. Direct Micromechanics Method (DMM) is used for predicting strength, which is based on first element failure method; although conservative, it provides a good estimate for failure initiation [13].

1.1. Model for hybrid composite

The fiber orientation depends on processing conditions and may vary from random in-plane and partially aligned to approximately

* Corresponding author. Tel.: +1 6175849862.
E-mail addresses: sbanerjee@ufl.edu (S. Banerjee), sankar@ufl.edu (B.V. Sankar).

1359-8368/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2013.10.065

uniaxial [1]. The fiber packing arrangement, for most composites, is random in nature, so that the properties are approximately same in any direction perpendicular to the fiber (i.e. properties along the 2-direction and 3-direction are same, and is invariant with rotations about the 1-axis), resulting in transverse isotropy [14]. For this paper, it is assumed that the fibers are arranged in a hexagonal pattern and the epoxy matrix fills up the remaining space in the representative volume element (RVE). Hexagonal pattern was selected because it can more accurately represent transverse isotropy as compared to a square arrangement. The RVE consists of 50 fibers. Multiple fibers were selected to allow randomization of fiber location. Hybrid composites are created by varying the number of fibers of carbon and glass to obtain hybrid composites of different volume fractions.

A cross section of a hybrid composite of polypropylene reinforced with short glass and carbon fibers is shown in Fig. 1 [3]. The black circles represent glass fibers (V_{fg} 6.25%) and the white circles represent carbon fibers (V_{fc} 18.75%). In order to represent such an arrangement, we consider the schematic of the RVE as shown in Fig. 2. Green and red represent two different fiber materials, while the matrix is shown in white. Also, it is assumed that the radii of the fibers are the same and only the count of carbon and glass fibers vary. This gives us much more flexibility in creating the finite element mesh. Although, this RVE architecture is a lot simplistic and entails some basic assumptions like same size and location of the fibers and absence of voids but there is still a lot to earn from the parameters that have been used.

The properties of the composite are independent of the 1-direction, hence a 2D analysis is performed. We have assumed here that the fibers remain unidirectional with no fiber undulation and waviness. An overall fiber volume fraction of 60% is assumed for all the composites analyzed in this paper. The proportions of the reinforcements have been varied to obtain five hybrid composites, keeping the total volume fraction of reinforcement phases constant. The volume fraction of any particular reinforcement, say A, was determined by the relation

$$V_{fA} = 0.6\left(\frac{N_A}{N_T}\right) \quad (1)$$

where N is the number of fibers of reinforcement A and N_T is the total number of fibers. (see Table 1).

2. Analysis for elastic constants

The RVE of the composite is analyzed using commercially available finite element software (ABAQUS/CAE 6.9-2). The composite is assumed to be under a state of uniform strain at the macroscopic level called macroscale strains or macrostrains, and the corresponding stresses are called macrostresses. However, the microstresses, which are the actual stresses inside the RVE can have a spatial variation. The macrostresses are average stress required to produce a given state of macro-deformations, and they can be computed using finite element method. The macrostresses and macrostrain follow the relation

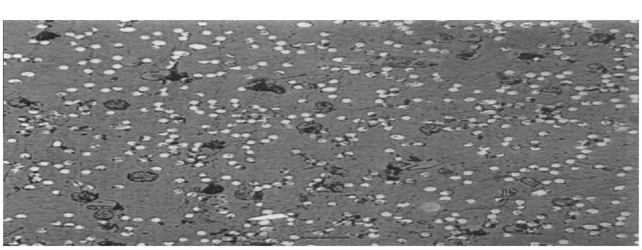

Fig. 1. Cross sectional area of a composite with V_{fc} 18.75% and V_{fg} (glass) = 6.25% [3].

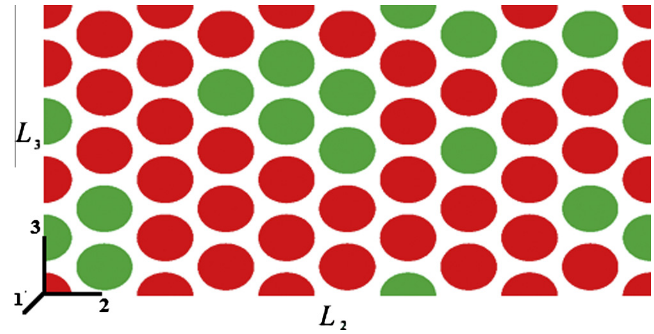

Fig. 2. RVE for Hybrid composite. fibers of two different reinforcements have different colors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Specimen numbering for the Hybrid Composites.

Specimen	V_{fc}	V_{fg}	V_f
H1	0.54	0.06	0.6
H2	0.42	0.18	0.6
H3	0.3	0.3	0.6
H4	0.18	0.42	0.6
H5	0.06	0.54	0.6

$$\{\sigma^M\} = [C]\{\varepsilon^M\} \quad (2)$$

where $[C]$ is the elastic constant of the homogenized composite, also known as the stiffness matrix. In this method, the RVE is subjected to six independent macrostrains. For each applied non-zero macrostrain, it is also subjected to periodic boundary conditions such that all other macrostrains are zero. The six cases are: Case 1: $\varepsilon_{11}^M = 1$; Case 2: $\varepsilon_{22}^M = 1$; Case 3: $\varepsilon_{33}^M = 1$; Case 4: $\gamma_{12}^M = 1$; Case 5: $\gamma_{13}^M = 1$; Case 6: $\gamma_{23}^M = 1$ [15], where the subscripts 1, 2, 3 are parallel to the material principal directions, as shown in Fig. 3, and the superscript M stands for macrostress or macrostrain.

2.1. Finite element analysis

For case 1, 2 and 4, a mixture of three and four-node plane strain elements, CPE3/CPE4 and for case 3, a mixture of three and four node generalized plane strain elements, CPEG3/CPEG4 were used. For cases 5 and 6 (longitudinal shear), three and four node shell elements were used, because out of plane displacements have to be applied for this case. Periodic boundary conditions (PBC) were applied on opposite faces of the RVE which are described in Table 2. Appropriate constraints on the RVE depend on the loading condition and have been determined by symmetry and periodicity conditions in [16]. For each strain case, six microstresses were calculated, three normal and three shear stresses in the 1-2-3 directions, in each element in the finite element model and volume averaged to find the macrostress for the RVE. The finite element model used is shown in Fig. 3, which contains 27,000 elements. The $[C]$ matrix can be inverted to obtain the compliance matrix or $[S]$ matrix, from which the elastic constants can be computed using the following relation

$$[C]^{-1} = [S] = \begin{bmatrix} \frac{1}{E_1} & \frac{-\nu_{12}}{E_1} & \frac{-\nu_{13}}{E_1} & 0 & 0 & 0 \\ \frac{-\nu_{21}}{E_2} & \frac{1}{E_2} & \frac{-\nu_{23}}{E_2} & 0 & 0 & 0 \\ \frac{-\nu_{31}}{E_3} & \frac{-\nu_{32}}{E_3} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad (3)$$