Composite Structures 152 (2016) 617–625

Contents lists available at ScienceDirect

Composite Structures

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

Effects of triangle-shape fiber on the transverse mechanical properties of unidirectional carbon fiber reinforced plastics

Lei Yang [a], Xin Liu [a,*], Zhanjun Wu [a], Rongguo Wang [b]

[a] State Key Laboratory of Structural Analysis for Industrial Equipment, School of Aeronautics and Astronautics, Dalian University of Technology, Dalian 116024, PR China
[b] National Key Laboratory of Science and Technology on Advanced Composites in Special Environments, Harbin Institute of Technology, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 14 December 2015
Revised 5 May 2016
Accepted 23 May 2016
Available online 24 May 2016

Keywords:
Carbon fiber reinforced plastics (CFRPs)
Transverse mechanical properties
Triangle-shape fiber
Finite element method (FEM)
Representative volume element (RVE)

ABSTRACT

In this paper, the transverse mechanical properties of triangle-shape carbon fiber reinforced plastic (TCFRP) were studied by numerical micromechanical approach, compared with the traditional round-shape carbon fiber reinforced plastic (RCFRP), to reveal the effect of triangle-shape fiber on the transverse mechanical properties of CFRP and its intrinsic mechanisms. The simulation results indicate the fiber shape can affect both the microscopic deformation and damage behavior of the composites. The triangle-shape fibers provide more restriction to the deformation of matrix than round-shape fibers do, resulting in higher stiffness of the composites; the triangle-shape fiber can improve both the transverse tension and compression strength of the composites with respect to round-shape fiber. These numerical findings are backed by experimental results. Thus, with both good wave-absorbing performance, and excellent mechanical properties that are as good as or even better than RCFRPs, the TCFRPs can serve as very promising structural and functional materials.

1. Introduction

Over the past few decades carbon fiber reinforced plastics (CFRPs) have been increasingly used in aerospace [1] and other industries [2] for their high specific stiffness, high specific strength, and outstanding designability. The physical and mechanical properties of CFRP are dependent largely on the fiber content, the fiber orientation, and the cross-section shape of fibers [3]. Generally, the cross-section shape of the reinforcing fibers in composites is round-shape. However, from the viewpoint of structural mechanics, it is recognized that non-round-shape fiber will be better than round-shape fiber in mechanical properties of CFRPs, because the non-round-shape carbon fibers have higher specific surface area than the conventional round-shape carbon fibers (RCFs). The larger area in the surface contacting with the matrix can increase the interfacial bonding force, consequently improve the mechanical properties of the composites [4]. Besides, in some fields, non-round-shape carbon fiber reinforced composites may be better choice for their special properties. For example, for composites reinforced by triangle-shape carbon fibers (TCFs), the TCFs in the composites can reflect incidence microwave many times as its microstructure can work like anechoic chamber [5], contributing to higher absorbing ratio of electro-magnetic wave.

However, up to date, there are only a limited number of studies on the non-round-shape carbon fibers and their composites. Park et al. [6–8] studied the mechanical properties of various shapes of carbon fibers reinforced cement composites. They found that C-shape carbon fiber reinforced cement composites showed higher tensile and flexural strength than round-shape and any other shape carbon fibers reinforced composites. Xu et al. [9,10] conducted a comprehensive experimental study to identify the differences of the kidney section carbon fibers and circular section carbon fibers in the surface characteristics of fibers and mechanical properties of composites. It was revealed that the kidney fibers with larger specific surface area have a better adsorption characteristic and higher impregnating performance compared with the circular fibers. Pakravan et al. [11] studied the influence of acrylic fibers shape on the flexural behavior of cement composite. It was found that by increasing the fibers' shape factor, both flexural strength and toughness of the composite increased.

In the previous work, the authors [4] manufactured the triangle-shape carbon fiber reinforced plastics (TCFRPs) and round-shape carbon fiber reinforced plastics (RCFRPs), as shown in Fig. 1, and their flexural properties were experimentally investigated. It was found that the TCFRPs showed higher flexural strength and flexural modulus than RCFRPs, and the tensile

* Corresponding author.
E-mail address: liuxindlut@dlut.edu.cn (X. Liu).

http://dx.doi.org/10.1016/j.compstruct.2016.05.065
0263-8223/

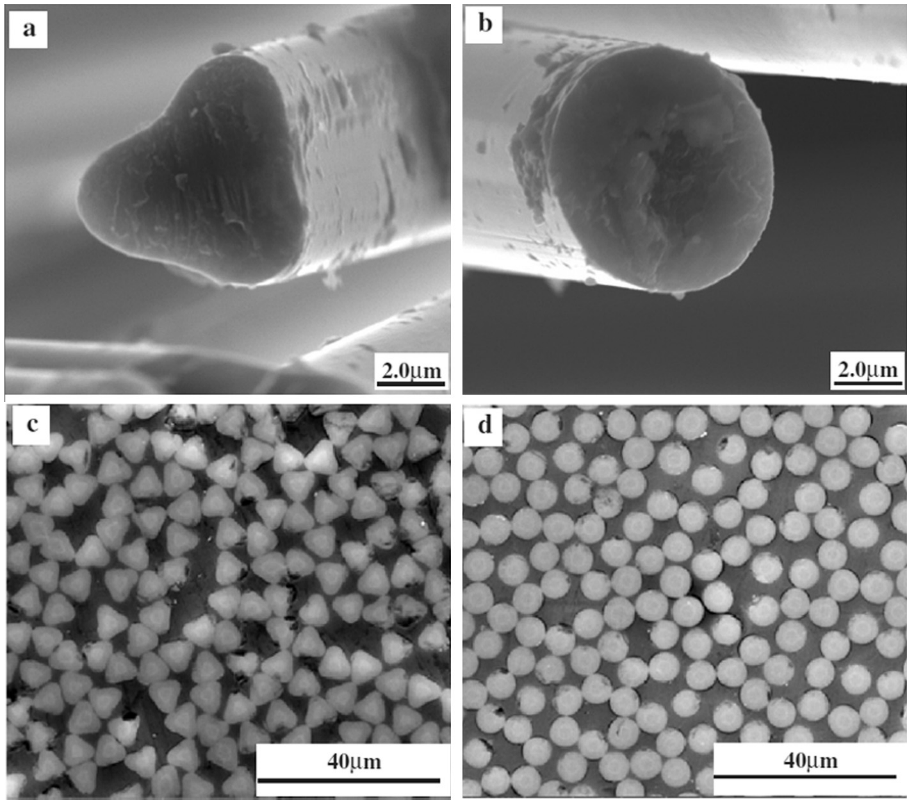

Fig. 1. SEM micrographs of triangle and round shape carbon fibers and their composites: (a) TCF, (b) RCF, (c) TCFRP, (d) RCFRP.

strength and tensile modulus did not reduce. To the best knowledge of the authors, there is no other study on the mechanical properties of TCFRPs. Besides, all the existing investigations as mentioned above about non-round-shape carbon fiber reinforced composites were based on experimental methods.

In order to thoroughly understand the effect of fiber shape on the mechanical properties of CFRPs, a micromechanics approach based on numerical method is a good choice to reveal the intrinsic mechanisms of this effect. Many researchers have presented various micromechanics approaches [12–17]. The authors [18] previously developed a micromechanical model for fiber reinforced plastics, which can precisely simulate the mechanical and damage behavior of unidirectional fiber-reinforced polymer composites. In this study, this model is used to simulate the micromechanical and damage behavior of unidirectional TCFRPs and RCFRPs subjected to transverse tension and compression loads. The simulated elastic properties, damage behavior and strength of TCFRPs and RCFRPs are compared, and simulation results are also compared with experimental results, so as to determine the effects of triangle-shape fiber on the transverse mechanical properties of CFRPs.

2. Modeling strategies

2.1. FEM model

To perform micromechanical analysis of composites, a representative volume element (RVE) of the microstructure large enough to possess the same properties with the macroscopic material should be generated. From Fig. 1 it can be seen that the fibers are randomly embedded in the matrix, which should be taken into account in the RVE of composites. From the figure it can also be seen that the section of triangle fiber is not an exact triangle, but with fillet at each vertex. These fillets were naturally formed during the manufacture process of the fibers, thus should be retained in the RVE.

The random distribution of fibers in the RVE is generated by the random sequential expansion (RSE) algorithm [19] developed by the authors. Shown in Fig. 2 are the generated RVEs of TCFRP and RCFRP. Each RVE contains 30 fibers [20], with fiber volume fraction of 50%. For RCFRP, the radius of the round-shape fibers is 5 μm; for TCFRP, the side length of the triangle-shape fibers is 10 μm, and the fillet radius is 1.6 μm. Five separate RVEs with different fiber distributions are generated for both TCFRP (TCF-1–TCF-5) and RCFRP (RCF-1–RCF-5) to take into account the effect of microscopic configuration.

The modeling and simulation platform of this study is the FEM package ABAQUS. The fibers and matrix are meshed with 4-node bilinear plane strain quadrilateral, reduced integration elements. As the interface between fibers and matrix can have significant influence on the properties of the composites, a layer of 4-node two-dimensional cohesive elements with very small thickness (0.01 μm) are introduced between each fiber and the surrounding matrix to simulate the interfacial debonding. Taking the RVE of TCF-1 as an example, shown in Fig. 3 is the finite element discretization of TCF-1.

Periodic boundary conditions are applied to the RVEs to ensure a macroscopically uniform stress/displacement field, which are expressed as follows:

$$\mathbf{u}_R - \mathbf{u}_{RB} = \mathbf{u}_L - \mathbf{u}_{LB} \tag{1}$$

$$\mathbf{u}_T - \mathbf{u}_{LT} = \mathbf{u}_B - \mathbf{u}_{LB} \tag{2}$$

where $\mathbf{u}$ is the displacement vector of any node on the boundary, and subscripts L, R, B and T refer to the left, right, bottom and top edges, while subscripts with two letters correspond to the vertexes of the RVE. These relations between displacements are included in