Composite Structures 134 (2015) 740–749

Contents lists available at ScienceDirect

Composite Structures

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

A 3D microstructure based resistor network model for the electrical resistivity of unidirectional carbon composites

Hong Yu [a,b], Dirk Heider [a,c,*], Suresh Advani [a,b]

[a] Center for Composite Materials, University of Delaware, United States
[b] Department of Mechanical Engineering, University of Delaware, United States
[c] Department of Electrical & Computer Engineering, University of Delaware, United States

ARTICLE INFO

Article history:
Available online 5 September 2015

Keywords:
CFRP
Electrical resistivity
Resistor network
Microstructure

ABSTRACT

Continuous carbon fiber reinforced polymers (CFRP) exhibit high anisotropy in electrical resistivity. Fiber conductivity and fiber volume fraction governs the resistivity along the fiber direction while the role of fiber undulation and spacing need to be explored when determining electrical properties perpendicular to the fiber direction. A 3D resistor network model is formulated to predict the electrical conductivity of unidirectional (UD) single layer CFRP as a function of the electrical material properties and microstructural parameters such as fiber spacing and waviness. The sensitivity study reveals that fiber waviness is the key factor determining the electrical resistivity of UD CFRP in the transverse direction. Predictions using the proposed model are in good agreement to reported experimental data.

1. Introduction

During the past few decades, carbon fiber reinforced polymers (CFRP) have been widely used in aerospace, automotive and other industries due to its high strength to weight ratio and excellent corrosion resistance. Recently, applications that exploit the electrical property of CFRP have been investigated such as carbon fiber assisted heating during composites structure manufacturing [1,2], self-sensing of damage of composite structures [3–6], integrated electromagnetic shielding [7–11], and lightning strike protection of composite structures [12–14]. Good understanding of the electrical properties of CFRP is the key to the success of these applications.

Electrical properties of the constituent material of the CFRP differ by several orders of magnitude. Carbon fiber itself is a good conductor with electrical resistivity in the range of 10^{-5} Ωm [15–18]. In contrast, the polymer matrix can be regarded as a good insulator with electrical resistivity ranging from 10^{10} Ωm to 10^{20} Ωm [12]. Thus, CFRP conductivity along the fibers is governed by the continuous conduction mechanism along the fibers while electrical properties in the other directions are influenced by the shortest conduction path of connected fibers in the width or thickness direction.

Microstructure based modeling and analysis has been used to study the mechanical behavior [19,20] and thermal conduction [21] of unidirectional fiber reinforced composites. The common modeling approach assumes that the fibers are straight parallel cylinders and create the fiber spacing information from the cross section of a composite specimen to represent the microstructure. A more detailed study of the microstructure was performed by Gutowski and Dillon [22] which relaxed the assumption of straight fibers, and introduced a parameter that quantified multiple contact points along its length with the neighboring fibers due to the fiber waviness. The waviness resulted in electrical contacts between neighboring fibers creating a continuous conductive path, which governs the electrical conduction in transverse direction.

In this work 2D micromechanics models of electrical conductivity of composites are reviewed. A two-step scheme for generating the 3D microstructure of CFRP is introduced. The microstructure describing the relationship between neighboring fibers including distances between contact points and their waviness is used to build an equivalent electrical resistor network model. A contact resistance term is integrated into the model to represent the resistance between fiber contact points. The model predicts electrical resistivity as a function of fiber volume fraction, intrinsic carbon fiber properties, fiber waviness and applied pressure during processing of such composites. A sensitivity study is conducted to identify the key factors that influence the electrical resistivity of CFRP.

* Corresponding author at: Center for Composite Materials, University of Delaware, United States. Tel.: +1 302 831 8898.

E-mail address: heider@udel.edu (D. Heider).

http://dx.doi.org/10.1016/j.compstruct.2015.08.131
0263-8223/

2. Electrical conduction mechanisms of CFRP

2.1. Review of existing models for electrical conduction of unidirectional CFRP

The longitudinal electrical resistivity of single carbon fiber or carbon fiber tow has been reported by carbon fiber manufacturers [15–18] or previous researchers [23,24] and for most PAN fibers is in the range of 10^{-5} Ωm. To our knowledge, the transverse electrical resistivity/conductivity of dry fiber tow hasn't been reported. The conventional rule-of-mixture (ROM) model is accurate in describing the composite conductivity along the fiber direction but fails to describe the electrical properties in the transverse direction.

Continuum models have been widely used to consider the microstructure of composites in the study of thermal conduction and micromechanics of composite materials [19–21]. It is common practice to use a 2D continuum medium model to study the transport of heat in composite materials. However, when it comes to electrical conduction in carbon fiber composites, the 2D model fails due to the large orders of magnitude difference between the electrical conductivity of carbon fibers and the polymer matrix. The polymer matrix in such a composite system can be regarded as an insulator and doesn't contribute to the electrical conduction in composites.

Resistor network model has also been adopted and modified by previous researchers to study the thermal and electrical conduction behavior of composites. Self-sensing of damage of composites has been achieved [3–5,25,26] mainly based on the change of longitudinal electrical resistance of composites after structural damage, while the through-thickness resistivity is not the focus.

Huang et al. [25] proposed the concept of "electrical ineffective length" and used a resistor network model incorporating mechanical loading to model the change of longitudinal electrical resistance of unidirectional CFRP under loading in the fiber length direction. Hexagonal packing order of carbon fibers was assumed in their model. Since it is believed that longitudinal electrical resistance is more useful in self-sensing of composite structural damage, this model doesn't consider the through-thickness electrical resistivity of CFRP, which may be important in other situations such as composite panels subject to lightning strike and characterization of electromagnetic shielding property of CFRP.

Xia et al. [4] adopted a similar approach to model transverse conduction behavior of CFRP as well as longitudinal resistance. Hexagonal and square packing arrangements were assumed in their model. Random fiber–fiber contacts were introduced and compared with uniform fiber–fiber contact distributions. While assumption of ideal periodic packing arrangement simplifies the calculations, it cannot address the impact of random fiber distribution on the property. Also, in this model, fiber–fiber contact resistance is not considered. Similar to Park's model, the electrical ineffective length is back calculated by fitting the model results with the experimental data, making it less effective in predicting resistivity of composites.

Many of these resistor network models have been developed to relate electrical resistance change to mechanical loading in composite structures. Evolving fiber breakage under loading is believed to be the major factor contributing to electrical resistance change. However, the underlying mechanisms of electrical behavior of composites without mechanical loading where fiber breakage is not involved have received much less attention.

Finite element method (FEM) has been adopted by researchers to study the orthotropic electrical conduction behavior of composites, especially for extreme conditions where Joule heating of composites needs to be considered. Todoroki et al. [3,26] applied FEA to study the effect of measured orthotropic electric conductance on delamination. Ogasawara et al. [27] studied the coupled thermal–electrical behavior of CFRP exposed to simulated lightning current using FEM. In these FE models, bulk properties of composites are used without considering the microstructure of composites. Due to the complexity of the composite microstructure, it is impractical to model the composite microstructure in full detail with FEM.

While conventional models can provide general information of electrical and mechanical interaction of CFRP, they are unable to accurately predict the effective electrical properties that are inherently dependent on the microstructure. It follows that an accurate prediction of macroscopic electrical conduction behavior can only be accomplished by capturing the microstructure of the material as a basis for the model. Another advantage of a microstructure-based model is that multi-physics simulation such as thermo-electric-mechanical interactions can be addressed at the local scale.

Modeling of electrical conductivity in through-thickness direction must take into consideration the contact between fibers, fiber waviness, and intrinsic single fiber property. Of these mechanisms, the contact between fibers is quite important because it influences continuous electrical conduction path in the through-thickness direction and thus dictates the overall electrical conductivity of CFRP in the through-thickness direction. Clearly, other mechanisms such as fiber breakage and sizing of fibers can also be important, although limited number of numerical studies [29]have modeled the effects of mechanical breakage of single fibers within a tow and the surface treatment of carbon fibers on the overall electrical conductivity of carbon fiber tow.

2.2. Electrical conduction mechanism in longitudinal direction

Since the electrical conductivity of typical polymer matrix systems are 10–20 orders smaller than that of carbon fibers, polymer matrix can be regarded as insulators. The single layer UD CFRP is therefore comparable to a carbon fiber tow in terms of electrical conduction. The highly anisotropic behavior of the electrical conductivity of unidirectional CFRP is due to different conduction mechanisms in transverse and along the fiber direction.

Along the fiber direction, the current flows through the fibers and the carbon fiber tow can be regarded as resistors in parallel. The resistivity of the unidirectional carbon fiber tow depends on the intrinsic resistivity of the fibers and on the fiber volume fraction. The longitudinal electrical conductivity of CFRP with fiber volume fraction of v_f can be calculated by the rule of mixture:

$$\sigma_L = \sigma_{fiber} * v_f \tag{1}$$

2.3. Electrical conduction mechanism in transverse direction

In carbon fiber reinforced polymer composites, undulating carbon fibers lead to electrical contacts between fibers. It's noted by Park et al. [28] that the random fiber-to-fiber contacts contribute to transverse electrical conduction and explains the anisotropy of electrical conductivity. Fiber-to-fiber contacts create the continuous electrical conduction path, contributing to overall electrical conductivity, as illustrated in Fig. 1. Applied pressure and elastic modulus of fibers can affect the fiber waviness during the fabrication process and thus influence electrical resistivity of carbon fiber tow. Although this mechanism has been mentioned by other researchers when commenting on their data qualitatively, there is no quantitative model built based on this mechanism.

The loading applied in the through-thickness direction during processing impacts the overall microstructure and contact point geometry. First, the through-thickness loading influences electrical resistivity by changing the fiber volume fraction and thus