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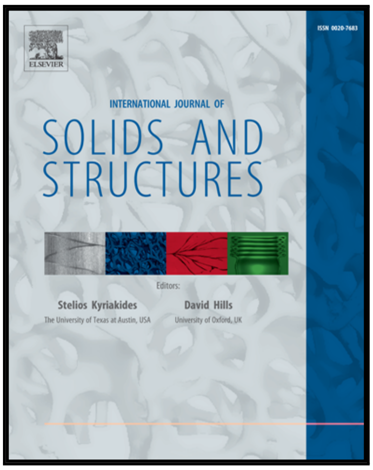

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Micromechanics of Composite Materials Governed by Vector Constitutive Laws

Brett A. Bednarcyk[1], Jacob Aboudi[2], and Steven M. Arnold[1]

[1]NASA Glenn Research Center, Cleveland, Ohio, U.S.A., Brett.A.Bednarcyk@nasa.gov, (216)433-2012, (216) 433-8300 fax
[2]Tel Aviv University, Tel Aviv, Israel

Abstract

The high-fidelity generalized method of cells micromechanics theory has been extended for the prediction of the effective property tensor and the corresponding local field distributions for composites whose constituents are governed by vector constitutive laws. As shown, the shear analogy, which can predict effective transverse properties, is not valid in the general three-dimensional case. Consequently, a general derivation is presented that is applicable to both continuously and discontinuously reinforced composites with arbitrary vector constitutive laws and periodic microstructures. Results are given for thermal and electric problems, effective properties and local field distributions, ordered and random microstructures, as well as complex geometries including woven composites. Comparisons of the theory's predictions are made to test data, numerical analysis, and classical expressions from the literature. Further, classical methods cannot provide the local field distributions in the composite, and it is demonstrated that, as the percolation threshold is approached, their predictions are increasingly unreliable.

1. Introduction

Physical phenomena such as heat conduction, diffusion, electric permittivity, magnetic permeability, and electric conductivity are governed by first-order tensor (vector) constitutive laws. These constitutive laws relate two field vectors via a second-order property tensor (e.g., Fourier's law of heat conduction). In composites, the constituent materials are governed by these vector laws, whereas the composite macroscopic behavior is governed by an effective constitutive law of the same form. There has been much effort targeted towards predicting the effective second-order property tensor of composite materials for the above physical phenomena. Expressions for composite effective thermal conductivities, based on various micromechanical analyses, have been derived, see for example Christensen (1979) and references cited there. Furthermore, expressions for the effective thermal conductivities of composites derived by Maxwell, Rayleigh, Bruggeman, as well as others, were recently summarized by Pietrak and Wisniewski (2015). Many other such expressions have been reported and applied in the literature, c.f. Hamilton and Crosser (1962), Springer and Tsai (1967), Kumar et al. (2011), Dinulovic and Rasua (2009), Avila et al. (2015). Likewise, the Mori-Tanaka (1973) method was employed by Hatta and Taya (1985) and Nan et al. (1997) for the prediction of effective conductivities. These methods, however, while predicting effective properties, cannot provide the local field distributions. These local field distributions are important as they provide insight into the influence of microstructure on material performance (e.g., effective properties) and are a key factor in the design of fit-for-purpose materials consistent with an integrated computational materials engineering (ICME) paradigm. For example, local hot spots (e.g., temperature spikes) within a given material microstructure are likely zones of increased chemical or environmental reactivity and/or failure locations, thus suggesting the tailoring of the microstructure to minimize such spikes. As mentioned by Pietrak and Wisniewski (2015), expressions derived for any one of the physical phenomena governed by vector constitutive laws are applicable to the other types simply by substituting the correct composite constituent property types in the expressions, as