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Micromechanics model for particulate composites

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Abstract

The elastic and elastoplastic response of particulate composite materials is described in terms of a micromechanics model, based on previous works. This model initially proposed to determine the elastic stiffness of various types of composites, is now combined with the self-consistent model for plastic deformation. Through this analysis, the macroscopic properties of heterogeneous materials are linked with their microstructural parameters. Constitutive laws for plastic deformation are written for both material structures, i.e. matrix and inclusions. The proposed model was successfully applied on tensile experimental results for metal matrix particulate composites and polymer/nanosilica composite materials.

Keywords: Particulate composites; Plasticity; Micromechanics; Nanocomposites

1. Introduction

A lot of micromechanical models have been proposed to predict the elastic constants of composite materials (Halpin, 1969; Mori and Tanaka, 1973; Christensen and Lo, 1979; Chen and Cheng, 1996; Hu and Weng, 2000; Zheng and Du, 2001). These models are related with parameters such as filler volumefraction, filler/matrix stiffness ratio, particle aspect ratio, filler orientation (Ponte-Castaneda, 1991; Hori and Nemat-Nasser, 1993; Zheng and Du, 2001). It has been shown that the localization relation is determined by embedding one single isolated pattern into a reference material. The pattern is usually chosen to be a double ellipsoidal type, i.e. an ellipsoidal inhomogeneity is surrounded by another ellipsoidal cell. The outer cell characterizes local inhomogeneity distribution (Ponte-Castaneda, 1991; Hori and Nemat-Nasser, 1993; Hu and Weng, 2000). When the reference material is selected to be the unknown composite, a generalized self-consistent estimation is obtained. If matrix is taken as the reference material, the Mori-Tanaka method, double inclusion model, Ponte Castaneda model and effective self-consistent method can be recovered by choosing the orientation and shape of double cells. In the above-mentioned methods (apart from self-consistent methods) the localization relation is derived considering one isolated pattern, ignoring the influence of the other patterns. However, this can be a problem, if high filler concentrations are examined, as shown by (Ju and Chen, 1994; Ma et al., 2004).

This fact was taken into account in a work by (Ma et al., 2004), where these models are generalized

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for finite particle concentration, by considering many pattern interaction. In the same work, an analytical micromechanical model is proposed, for predicting the elastoplastic behaviour of an anisotropic composite with finite particle concentration, while an ellipsoidal distribution of particles introduced by (Ponte-Castaneda and Willis, 1995) is conserved for modelling the overall anisotropic behaviour of composites.

Apart from conventional composite materials, polymer nanocomposites, being a novel class of composite materials, exhibit a dramatic improvement in stiffness, strength and thermal properties, over those of pure polymers or conventional composite materials. This enhancement results from the fact that nanocomposites have much larger surface area per unit volume, since one of the constituents has dimensions in the range between 1 and 100 nm.

There is a large number of works dealing with material synthesis and characterization of polymer nanocomposites, but the fundamental mechanisms for mechanical property improvement are not yet completely defined (Hotta and Paul, 2004; Huang et al., 2004, 2003; Hua et al., 2005). Researchers have recently applied some of these models to access the thermal–mechanical properties of polymer nanocomposites (Nam et al., 2001; van Es et al., 2001; Brune and Bicerano, 2002; Yoon et al., 2002). In a recent work by (Sheng et al., 2004), the composite material stiffness dependence on plate like filler content is presented. A detailed analysis of the hierarchical nature of the underlying structure of polymer/nanoclay composites is also presented.

In the present work, micromechanics model based on (Eshelby theory, 1957; Mori and Tanaka, 1973; Chen and Cheng, 1996), will be applied to determine the elastic stiffness tensor of polymer nanocomposites. Further, this model combined with the self-consistent model of (Budiansky and Wu, 1962) for plastic deformation, will be used to predict the elastoplastic behaviour of particulate composites. Through this analysis, the macroscopic properties of heterogeneous materials are linked with their microstructural parameters. A kinematic description proposed by (Rubin, 1994a,b) will be applied to separate elastic and plastic deformation for both material structures: matrix and inclusions. Corresponding constitutive laws for plastic deformation will be written in respect to Rubin's analysis. The proposed model will be applied on experimental results for metal matrix particulate composites, performed in a work by (Yang et al., 1991), and on experimental data of polymer/nanosilica composites by Kontou and Niaounakis (2006).

2. Micromechanics model

Assuming that the composite materials, studied in this work, are composed of a continuous isotropic matrix and discrete isotropic spherical inhomogeneities, the overall stiffness tensor of this system, will be calculated and the elastic–elastoplastic behaviour will be formulated. The estimation of the stiffness tensor is based on previous works by (Taya and Chou, 1981; Chen and Cheng, 1996). Their works deal with the effective moduli of composites containing misoriented fibers and both are based on the (Eshelby, 1957; Mori and Tanaka, 1973). (Chen and Cheng, 1996) have extensively studied the effective elastic moduli of planar orientation distribution and transversely isotropic distribution of fibers. The interaction among fibers at different orientations was included in their analysis by adopting the mean stress concept of (Mori and Tanaka, 1973) together with eigenstrain idea of (Eshelby, 1957). The prediction of the effective moduli of fiber-reinforced thermoplastics (FRTP) was then possible. By extending this analysis, they have calculated the effective moduli tensor for spherical particles, acting as reinforcing agents, according to the following procedure.

When an infinite elastic body is subjected to a uniform stress field $\boldsymbol{\sigma}_0$ the corresponding uniform strain $\boldsymbol{\varepsilon}_0$ is

$$\boldsymbol{\varepsilon}_0 = \mathbf{C}_{\mathrm{m}}^{-1} \bullet \boldsymbol{\sigma}_0 \tag{1}$$

where $\mathbf{C}_{\mathrm{m}}$ is the elastic modulus tensor of the isotropic matrix. When there are ellipsoidal inclusions present in the matrix, a perturbed stress field is induced. Then the average stress field into the matrix is given by

$$\boldsymbol{\sigma}_{\mathrm{m}} = \boldsymbol{\sigma}_0 + \bar{\boldsymbol{\sigma}} = C_{\mathrm{m}} \bullet (\boldsymbol{\varepsilon}_0 + \bar{\boldsymbol{\varepsilon}}) \tag{2}$$

where $\bar{\boldsymbol{\sigma}}$ is the volumetric average of the perturbed stress field, and $\bar{\boldsymbol{\varepsilon}}$ is the perturbed strain field. If all inhomogeneities are aligned in one direction, according to (Taya and Mura, 1981), and the fact that the disturbed stress must be zero when it is integrated in the total volume, the following two expressions are extracted: