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Prediction and experimental validation of composite strength by applying modified micromechanics for composites containing multiple distinct heterogeneities

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ABSTRACT

The mechanical properties, such as strength and stiffness, of epoxy-based composites containing MWCNTs were experimentally and theoretically investigated. The classical analytic homogenization approach, called the Mori-Tanaka model, was firstly modified and reported to predict strength properties for composites containing multiple heterogeneities. In the modified Mori-Tanaka micromechanical strength modeling, the composites were considered as a two-phase simple model, as well as multiple heterogeneity case. The values obtained here were compared to experimentally measured data. The specimens reinforced with heterogeneities such as multi-walled carbon nanotubes (MWCNTs) were mainly fabricated and tested to measure the strength and stiffness of epoxy-based composites. When comparing the experimentally measured data of those composites with the predicted values obtained from the modified micromechanics models, it was confirmed that the developed approach successfully captures the effect of different types of heterogeneity on the resulting strength and stiffness of composites containing different geometrized nanofillers.

1. Introduction

Polymer matrix-based composites (PMCs) containing reinforcements, such as carbon nanotubes (CNTs), carbon nanofibers, disk-shaped graphites, and metal spheres are of interests due to their unique electrical, thermal, and mechanical properties. Most significantly, CNTs are considered to be ideal candidates for improving mechanical properties of PMCs [1,2]. With 5.0 wt % of multi-walled nanotubes (MWNTs), shear strength for epoxy-based composites was increased by 45.6% compared to that of neat epoxy matrix [3]. Improved elastic moduli, yield strength, and toughness of PMCs were reported when various CNTs were used [4–6]. In addition, CNTs can be used to improve the inter-laminar shear strength of carbon and glass fiber-reinforced composites by applying fiber surface treatment [7–9].

An accurate prediction of the mechanical behavior of PMCs is crucial to design their use in composite fields. Halpin-Tsai method is popular and widely used for estimating the mechanical properties of the composites [10–12]. This method, however, can only predict the mechanical properties of composites which contain simple geometrized fillers by employing an exponential shape factor, as well as three-dimensionally oriented case. The classical Mori-Tanaka micromechanical method is also used to predict the mechanical, thermal and electrical properties of PMCs [13–22]. Composites often contain multiple heterogeneities such as well-dispersed reinforcements, agglomerated reinforcements, interphase between fillers and a matrix, defects, etc. In order to capture the real behavior of composites to estimate the effective properties, these multiple heterogeneities should be considered to investigate the effect of reinforcement dispersion, orientations, and perturbation of each heterogeneity. Classical micromechanics modeling, unfortunately, cannot capture the perturbation effect of multiple heterogeneities in a matrix. Previous studies related to analytic approaches were limited to the two-phase composites, which contains only single heterogeneity without other different phases in a matrix.

In this study, the Mori-Tanaka micromechanical modeling was modified to predict mechanical properties for composites containing multiple heterogeneities. In the modified Mori-Tanaka micromechanical strength modeling, the composites were

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considered as a two-phase simple model, as well as multiple heterogeneity case, which is for composites containing multiple different geometrized nanofillers. The objective of this approach was mainly to predict composite strength values in this study, and compare those with existing experimental data. The specimens reinforced with heterogeneities such as MWCNTs were mainly fabricated and tested to measure experimental data.

2. Micromechanics modeling approach

Mori-Tanaka micromechanical approach has been mainly used to estimate effective heterogeneous material properties, particularly for composites containing low volume fractions of reinforcements in elastic resins. Such approaches are based upon the Eshelby solution [24] for the stress and strain field due to an ellipsoidal inclusion in an infinite domain subjected to uniform far-field loading (*cf.*, Mura, 1991; Nemat-Nasser and Hori, 1993) [25,26]. This approach can be extended to predict the mechanical [13–16] and thermal properties [18–21], as well as electrical conductivities [22,23] for composites containing multiple heterogeneities. This micromechanical scheme can be also used to estimate the composite strength by averaging stress and strain fields, and their assumptions as described in the following in the next section.

2.1. Mori-Tanaka method for two phase composites

The Mori-Tanaka method (MTM) assumes that a single ellipsoidal heterogeneity is embedded into a matrix domain, whose strain field has been perturbed by other heterogeneities in the system. The MTM uses the continuum averaged stress and strain fields to predict effective material properties [27,28]. The average stresses in the matrix, $\langle\boldsymbol{\sigma}\rangle_{\mathrm{M}}+\boldsymbol{\sigma}_{\mathrm{A}}$, and in the heterogeneity, $\langle\boldsymbol{\sigma}\rangle_{\Omega}+\boldsymbol{\sigma}_{\mathrm{A}}$, are derived based on the equivalent inclusion method with the applied stress, $\boldsymbol{\sigma}_{\mathrm{A}}$. The strength of composites containing heterogeneities is dominated by the weakest constituent in the point of the average stress fields. Thus, the fracture propagation initiates when the average stress field in the constituent reaches its ultimate strength. Based on an ellipsoidal heterogeneity idealization as shown in Fig. 1a, the total stress in the heterogeneity for a composite with matrix (0), inhomogeneity (1), can be expressed as

$$\boldsymbol{\sigma}_{\mathrm{A}}+\langle\boldsymbol{\sigma}\rangle_{\Omega}=\boldsymbol{L}^{(0)}:\left\{\boldsymbol{L}^{(0)^{-1}}:(\boldsymbol{\sigma}_{\mathrm{A}}+\langle\boldsymbol{\sigma}\rangle_{\mathrm{M}})+\boldsymbol{S}^{(1)}:\langle\boldsymbol{\varepsilon}^{*}\rangle-\langle\boldsymbol{\varepsilon}^{*}\rangle\right\} \tag{1}$$

where $\boldsymbol{L}^{(0)}$ is the 4th rank elastic stiffness tensor for the matrix, $\boldsymbol{L}^{(1)}$ is the 4th rank elastic stiffness tensor for the heterogeneity. Here a colon "**:**" is used to denote the tensor double dot product. $\boldsymbol{S}^{(1)}$ is the 4th rank Eshelby tensor for the heterogeneity, $\langle\boldsymbol{\varepsilon}^{*}\rangle$ is the fictitious misfit eigenstrain for the heterogeneity effect. The Eshelby tensor is a function of the geometry of the heterogeneity and Poisson's ratio of the matrix. Since the strain and stress fields are uniform in Ω as shown in Fig. 1, the average stress for the homogeneity and the matrix are given as

$$\langle\boldsymbol{\sigma}\rangle_{\Omega}=\boldsymbol{L}^{(0)}:\left\{\boldsymbol{\varepsilon}^{\infty}+\left(\boldsymbol{S}^{(1)}-\boldsymbol{I}\right):\boldsymbol{\varepsilon}^{*}\right\} \tag{2}$$

$$\langle\boldsymbol{\sigma}\rangle_{\mathrm{M}}=\boldsymbol{L}^{(0)}:\boldsymbol{\varepsilon}^{\infty} \tag{3}$$

where $\boldsymbol{\varepsilon}^{\infty}$ is the given farfield strains, and $\boldsymbol{I}$ is the 4th rank identity tensor. The average total stress in the matrix and in the heterogeneity can be expressed as a function of heterogeneity volume fraction (c_1), and the applied stress ($\boldsymbol{\sigma}_{\mathrm{A}}$) in different form as

$$\boldsymbol{\sigma}_{\mathrm{A}}+\langle\boldsymbol{\sigma}\rangle_{\mathrm{M}}=\left\lfloor\boldsymbol{I}-\boldsymbol{c}_1\boldsymbol{L}^{(0)}:\left(\boldsymbol{S}^{(1)}-\boldsymbol{I}\right):\boldsymbol{\alpha}^{-1}:\left(\boldsymbol{L}^{(0)}-\boldsymbol{L}^{(1)}\right):\boldsymbol{L}^{(0)^{-1}}\right\rfloor:\boldsymbol{\sigma}_{\mathrm{A}} \tag{4}$$

and

$$\boldsymbol{\sigma}_{\mathrm{A}}+\langle\boldsymbol{\sigma}\rangle_{\Omega}=\left\lfloor(1-\boldsymbol{c}_1)\boldsymbol{L}^{(0)}:\left(\boldsymbol{S}^{(1)}-\boldsymbol{I}\right):\boldsymbol{\alpha}^{-1}:\left(\boldsymbol{L}^{(0)}-\boldsymbol{L}^{(1)}\right):\boldsymbol{L}^{(0)^{-1}}+\boldsymbol{I}\right\rfloor:\boldsymbol{\sigma}_{\mathrm{A}} \tag{5}$$

with

$$\boldsymbol{\alpha}=(\boldsymbol{1}-\boldsymbol{c}_1)\left(\boldsymbol{L}^{(1)}-\boldsymbol{L}^{(0)}\right):\boldsymbol{S}^{(1)}-\boldsymbol{c}_1\left(\boldsymbol{L}^{(0)}-\boldsymbol{L}^{(1)}\right)+\boldsymbol{L}^{(0)} \tag{6}$$

2.2. Modified Mori-Tanaka method for multiphase composites

The MTM can be directly applied to a multiphase composite case. The modified MTM (M-MTM) may be used to estimate the average stress and strain fields, and strength in the matrix and in the multiple heterogeneities for composites containing several multiple ellipsoidal inclusions which can be various different geometrized fillers. If a finite ellipsoidal subregion V is in the infinite domain, and then it contains several inclusions, Ω_α ($\boldsymbol{\alpha}=1, 2, \ldots, \mathrm{n}$). The average stress for composites can be expressed as follows:

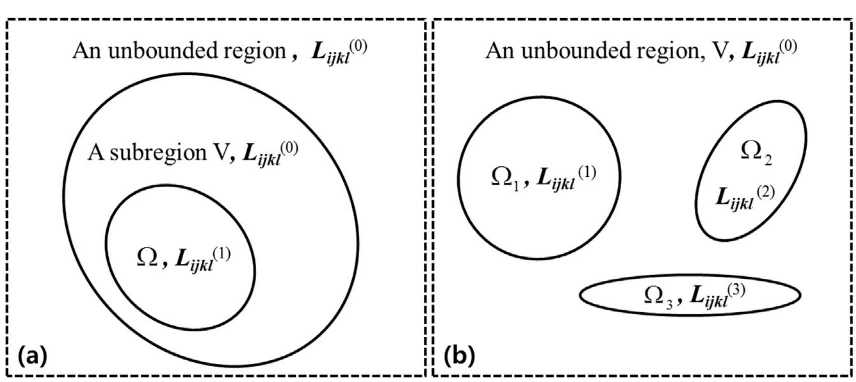

Fig. 1. Schematics of (a) a two-phase and (b) multiple heterogeneities inclusion methodology.