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Enhanced composite damping through engineered interfaces

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ABSTRACT

The damping properties of unidirectional, laminated, and woven composites have been predicted using a multiscale implementation of the High-Fidelity Generalized Method of Cells micromechanics theory. This model considers periodic repeating unit cell geometries on both the global and local scales and utilizes the constituent material specific damping coefficients, mechanical properties, and local fields, along with the strain energy approach, to determine effective directional specific damping coefficients of the composite. In addition to comparisons of the HFGMC predictions with results from the literature, the effect of a degraded fiber/matrix interface was examined parametrically. A significant finding was that strong maxima exist in the predicted composite damping coefficients as a function of degree of interfacial mechanical degradation. This suggests that drastic improvements in damping in composites can be achieved by properly engineering the fiber/matrix interface. The multiscale HFGMC simulations presented illustrate that the decrease in composite mechanical properties caused by such an engineered interface can be minimized when implemented within a technologically relevant laminate, while still maintaining an extreme improvement in the laminate damping properties.

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1. Introduction

Material damping is important in the design of structures as it limits vibration amplitudes, increases fatigue life, and affects impact resistance. This is particularly true for composite materials, which are currently used extensively in applications that experience frequent dynamic loading. Furthermore, the damping capacity of composites can be significantly greater than that of standard engineering materials, as described in the recent review paper by Treviso et al., (2015). Like other performance parameters of composites (e.g., stiffness, strength, density) the effective damping capacity of composite materials are dependent on not only the damping properties of the constituent materials, but also microstructural details such as fiber volume fraction, fiber orientation, ply stack up, fiber packing array, and weave pattern in woven composites. Therefore, like other performance parameters, composite damping capacity can be engineered.

The damping phenomenon in composite materials has been modeled using linear viscoelastic models, employing the correspondence principal to obtain the storage and loss moduli, and by the strain energy approach (see Treviso et al., (2015) and the references cited therein). In the present investigation, a multiscale micromechanical method for predicting composite damping capacities, based on the strain energy approach, is presented. This approach establishes the stored and dissipated elastic energy within the composite constituents, which are used to determine the specific damping capacities of the composite in the various directions. An early example of this approach was presented by Ungar and Kerwin, (1962). Adams and Bacon, (1973), Ni and Adams, (1984), and Adams and Maheri, (2003) employed the strain energy approach to examine damping of composite laminated plates and beams. Saravanos and Chamis, (1990) presented simplified closed-form equations for composite specific damping capacities resulting from various mixture rules. Kaliske and Rothert, (1995) predicted the specific damping capacities of composites by employing the micromechanical method of cells with the strain energy approach (Aboudi, 1991), showing good agreement with test data. Chandra et al. (2002) compared the damping predictions of various micromechanical models, including strain energy approach applied to the finite element method. Tsai and Chi, (2008) utilized the generalized method of cells to predict the composite specific damping capacities, demonstrating good agreement with finite element predictions based on the strain energy approach. In addition, the investigation of El Mahi et al., (2008) employed the strain energy approach in conjunction with the finite element method to examine damping in composite laminates, showing good agreement with measured results. Of course, by attributing all damping in a

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composite to the dissipated energy in the constituent materials, the strain energy approach does not explicitly account for certain in situ damping mechanisms that could be present, such as matrix cracking, interfacial debonding, and free motion of the phases.

Finegan and Gibson, (2000) investigated the damping properties of a composite composed of epoxy matrix reinforced by copper wires, with a high damping interface. The results of elasticity, finite element, and mechanics of materials approaches were compared to experimental damping measurements as a function of the interface and fiber volume fractions.

The multiscale micromechanical method presented herein is based on the High-Fidelity Generalized Method of Cells (HFGMC) micromechanics theory Aboudi et al., (2013) in combination with the aforementioned strain energy approach for the modeling of damping. The triply-periodic High-Fidelity Generalized Method of Cells is first enhanced to enable coupled multiscale analysis, wherein both the local (fiber/matrix/interface constituent) and global (laminate/woven) scales are synergistically linked. The HFGMC method determines the strain (or stress) concentration tensors, which are used to establish the macroscopic constitutive equations of the composite, and also to provide the local stress and strain fields throughout the composite. This enables the prediction of not only effective composite properties, but also the strain energy distributions (and thus specific damping coefficients) in response to given external loading. The present multiscale HFGMC implementation considers an arbitrary number of local repeating unit cells (RUCs), which consist of the composite constituent materials (e.g., fiber, matrix, and interface). These local RUCs are then arranged in a global RUC, whose mechanical and damping properties represents that of the multiscale composite material.

This multiscale HFGMC model is applied to predict the specific damping coefficients of unidirectional, laminated, and woven polymer matrix composites with and without degraded fiber-matrix interfaces. Herein these interfaces are treated as a *distinct third phase* separating the fiber and the matrix, with its own variable damping and mechanical properties. It should be noted that the present investigation utilizes a two scale analysis, but the methodology could be generalized to admit an arbitrary number of scales, as has been done in the case of the Multiscale Generalized Method of Cells (Aboudi et al., 2013, Liu et al., 2011, Liu and Arnold, 2013, Bednarcyk et al., 2015).

2. Multiscale High-Fidelity Generalized Method of Cells

In order to model the effect of damping in composite materials that involve multiple microstructural scales (e.g., laminates, woven composites), the High-Fidelity Generalized Method of Cells (HFGMC) micromechanical model has been implemented in a two-scale framework. These two scales are referred to as global and local, see Fig. 1. The global scale (Fig. 1b) represents a repeating unit cell of a periodic composite material, whose constituents may be themselves periodic composite materials. Thus, the local scale (Fig. 1c) represents the RUCs present within the global scale constituents. Obviously, coordinate transformations are required when passing tensor quantities from one scale to the other.

2.1. Global scale analysis

The HFGMC theory, which has been fully described by Aboudi et al. (2013), considers a composite material with triply-periodic microstructure, Fig. 2(a), wherein periodicity conditions are enforced in all three Cartesian coordinate directions. The global repeating unit cell (RUC), Fig. 1(b), defined with respect to local coordinates (Y_1, Y_2, Y_3), is divided into N_A, N_B, and N_Γ global subcells in the Y_1, Y_2, and Y_3 directions, respectively. Each global subcell is labeled by the indices ($AB\Gamma$) with $A=1, \ldots, N_A$, $B=1, \ldots, N_B$ and $\Gamma=1, \ldots, N_\Gamma$, and may contain a distinct homogeneous material or a composite material. The dimensions of the RUC are D, H, and L, whereas the dimensions of global subcell ($AB\Gamma$) in the Y_1, Y_2, and Y_3 directions are denoted by D_A, H_B, and L_Γ, respectively. A coordinate system ($\bar{Y}_2^{(A)}, \bar{Y}_2^{(B)}, \bar{Y}_3^{(\Gamma)}$) is introduced in each subcell whose origin is located at its center.

2.1.1. Global scale mechanical analysis

The global subcell nonlinear elastic constitutive equation of the anisotropic material is given in an incremental form by,

$$\Delta\sigma_{ij}^{(AB\Gamma)} = C_{ijkl}^{(AB\Gamma)}\,\Delta\varepsilon_{kl}^{(AB\Gamma)} \tag{1}$$

where $\Delta\sigma_{ij}^{(AB\Gamma)}$, $\Delta\varepsilon_{kl}^{(AB\Gamma)}$, and $C_{ijkl}^{(AB\Gamma)}$ are the components of the stress increment, strain increment, and instantaneous (tangent) stiffness tensors of global subcell ($AB\Gamma$), respectively.

The basic assumption in HFGMC is that the increment of the displacement vector $\Delta U_i^{(AB\Gamma)}$ in each global subcell is represented as a second-order expansion in terms of its coordinates ($\bar{Y}_1^{(A)}, \bar{Y}_2^{(B)}, \bar{Y}_3^{(\Gamma)}$), as follows,

$$\begin{aligned}
\Delta U_i^{(AB\Gamma)} = {} & \Delta\bar{\varepsilon}_{ij}\,X_j + \Delta W_{i(000)}^{(AB\Gamma)} + \bar{Y}_1^{(A)}\Delta W_{i(100)}^{(AB\Gamma)} + \bar{Y}_2^{(B)}\Delta W_{i(010)}^{(AB\Gamma)} \\
& + \bar{Y}_3^{(\Gamma)}\Delta W_{i(001)}^{(AB\Gamma)} + \frac{1}{2}\left(3\bar{Y}_1^{(A)2} - \frac{D_A^2}{4}\right)\Delta W_{i(200)}^{(AB\Gamma)} \\
& + \frac{1}{2}\left(3\bar{Y}_2^{(B)2} - \frac{H_B^2}{4}\right)\Delta W_{i(020)}^{(AB\Gamma)} \\
& + \frac{1}{2}\left(3\bar{Y}_3^{(\Gamma)2} - \frac{L_\Gamma^2}{4}\right)\Delta W_{i(002)}^{(AB\Gamma)}
\end{aligned} \tag{2}$$

where $\Delta\bar{\varepsilon}_{ij}$ are the applied (external) average strain increments, and the unknown terms $\Delta W_{i(lmn)}^{(AB\Gamma)}$ must be determined from the fulfillment of the equilibrium conditions, the periodic boundary conditions, and the interfacial continuity conditions of displacements and tractions between global subcells. The periodic boundary conditions ensure that the increments of displacement and traction at opposite surfaces of the global RUC are identical. A principal ingredient in the HFGMC micromechanical analysis is that all these conditions are imposed in the average (integral) sense.

As a result of the imposition of these conditions, a linear system of algebraic equations is obtained, which can be represented in the following form:

$$\mathbf{K}\ \Delta\mathbf{V} = \Delta\mathbf{F} \tag{3}$$

where the matrix $\mathbf{K}$ contains information on the global geometry and instantaneous properties of the materials (or composites) within the individual subcells ($AB\Gamma$), and the displacement vector increment, $\Delta\mathbf{V}$, contains the unknown displacement coefficients $\Delta W_{i(lmn)}^{(AB\Gamma)}$, which appear on the right-hand side of Eq. (2). The vector $\Delta\mathbf{F}$ contains information on the applied average strain increments $\Delta\bar{\varepsilon}_{ij}$. The solution of Eq. (3) enables the establishment of the following localization relation which expresses the average strain increments $\Delta\bar{\varepsilon}_{ij}^{(AB\Gamma)}$ in the global subcell ($AB\Gamma$) to the externally applied average strain increments $\Delta\bar{\varepsilon}_{ij}$ in the form,

$$\Delta\bar{\varepsilon}_{ij}^{(AB\Gamma)} = A_{ijkl}^{(AB\Gamma)}\,\Delta\bar{\varepsilon}_{kl} \tag{4}$$

where $A_{ijkl}^{(AB\Gamma)}$ are the instantaneous global strain concentration tensor components, of the subcell ($AB\Gamma$).

The final form of the effective incremental constitutive law of the multi-phase composite, which relates the average stress increments $\Delta\bar{\sigma}_{ij}$ and strain increments $\Delta\bar{\varepsilon}_{kl}$, is established as follows:

$$\Delta\bar{\sigma}_{ij} = C_{ijkl}^{*}\ \Delta\bar{\varepsilon}_{kl} \tag{5}$$