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Linking the equation of state for fiber-reinforced composites to those of the individual fiber and matrix constituents

Alexander J. Carpenter[a]*, Sidney Chocron[a], Charles E. Anderson, Jr.[b]

[a]*Engineering Dynamics Department, Southwest Research Institute, 6220 Culebra Rd. San Antonio, TX 78238, U.S.A.*
[b]*CEA Consulting, 7818 Mary Carolyn, San Antonio, TX 78240, U.S.A.*

Abstract

A new approach for modeling fiber-reinforced composites in numerical computations was recently developed to relate the average stresses and strains within the composite to the stresses and strains within the individual fibers and matrix constituents. In the initial implementation of this approach, it was assumed that the fibers and matrix both obey Hooke's law, which implies that the two materials each have a constant sound speed. This assumption is accurate at slower-rates, but it cannot capture the increase in shock speeds characteristic of materials subjected to large strains at very fast strain rates. To increase the accuracy of the model in this regime, Hooke's law was modified such that the elastic moduli of the fibers and matrix depend on volumetric strain, as described by the Mie-Gruneisen equation of state. This allows the composite model to reproduce both the approximate magnitude and orientation dependence of the average shock speed in the composite without average material properties for the composite. Instead, only material constants for the individual fibers and matrix are needed.

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1. Introduction

Modeling fiber-reinforced composites under high-rate impact conditions is not always straightforward, as the constitutive behavior is strongly dependent on fiber orientation and various damage mechanisms affect the response

* Corresponding author. Tel.: +1-210-522-2621 ; fax: +1-210-522-6290 .
E-mail address: alexander.carpenter@swri.org

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[1-3]. One promising method for modeling these materials at the continuum level, which allows for fast-running computations, is to numerically divide an element representing multiple composite laminae into individual laminae with different orientations within the element's material model. Each lamina can then be further separated into the individual fiber and matrix components. The average stresses and strains at each of these scales are related through simple rules of mixtures based on the relative geometry of the constituents and laminae. Because the stresses and strains are known at each level, it is straightforward to implement multiple failure mechanisms. Adjustment of the element's response once damage has occurred is achieved simply by modifying the appropriate mixture rules. This approach was implemented as a continuum composite material model in the dynamic finite element hydrocode LS-DYNA, and initial studies utilizing this model [4, 5] indicate that it can reproduce a variety of slow-rate mechanical tests and ordnance-velocity ballistic impacts of various composite materials. One advantage of the model is that most of the required input parameters are properties of the individual fiber and matrix constituents, which minimizes the number of material tests required from the full composite.

The current implementation of the above approach possesses one significant downside with regards to predictions in the hypervelocity regime. The full stress-strain response of the individual fiber and matrix constituents is governed by the appropriate form of Hooke's law (fibers are transverse isotropic, matrix is fully isotropic). This assumption results in a constant bulk modulus for each constituent, which is appropriate for low-rate to ordnance-velocity impacts, but leads to decreased accuracy as impact speeds increase, which leads to faster strain rates within the materials. In reality, the resistance of materials to volumetric straining can increase significantly as the material is compressed. Equations of state such as Mie-Grüneisen have been developed to reflect this behavior for individual materials.

In this study, the stiffness tensors governing elastic deformation of the fibers and matrix were modified to account for the increase in stiffness predicted by the Mie-Grüneisen equation of state (EOS). The additional properties required by this model modification are equation of state parameters for the fiber and matrix materials. However, when combined with the rules of mixtures already implemented in the model, this allows the model to predict the volumetric response of the full composite at very fast rates without requiring equation of state parameters for the composite as a whole. The model's predictions were compared to high-speed plate impact data obtained directly from tests of multilayer composite materials to show that the model naturally reproduces both the orientation dependence and magnitude of the measured shock response.

Nomenclature

P	hydrostatic pressure, calculated from stress tensor as $(\sigma_{11}+\sigma_{22}+\sigma_{33})/3$
ε	compressive volumetric strain, $1-\rho_0/\rho$ or calculated from strain tensor as $-\varepsilon_{11}-\varepsilon_{22}-\varepsilon_{33}$
ρ	material mass density (ρ_0 is initial material density at $\varepsilon = 0$)
c_0	initial bulk sound speed within a material
s	slope of shock Hugoniot in u_s-u_p plane
Γ_0	Grüneisen gamma
U	internal energy within material per unit volume
u_s	shock speed
u_p	particle speed
C_{ij}	ij-component of material stiffness matrix
E	Young's modulus
ν	Poisson's ratio
V_f	Volume fraction of fibers within composite