Closed-form estimates of the homogenized elastic properties for bio-inspired staggered composites

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Abstract

Several biological materials, such as nacre, spider silk and bone, have evolved their nano- and micro-structure in order to optimize their load-bearing capabilities in response to various external stimuli. In many cases, exceptional mechanical properties are achieved, combining strength, stiffness, and toughness in a way that often exceeds those of most commonly used engineering materials. This remarkable performance can be attributed to their highly organized microscale structure, characterized by a staggered arrangement of platelet-like elements embedded within a compliant matrix.

Inspired by these highly performing natural materials, bio-mimetic staggered composites have recently attracted significant attention, with early manufacturing attempts made possible by advancements in multi-material 3D printing technologies. Moreover, the growing interest in staggered composites has driven the development of various analytical formulations that attempt to describe the mechanical behavior of these class of materials. However, the majority of the existing formulations focus primarily on determining the stiffness along the staggering direction, leaving the other equivalent elastic properties underexplored. Moreover, notable discrepancies often arise when comparing the available analytical estimates with established numerical results or experimental measurements.

This work tries to overcome these limitations by proposing simple yet effective closed-form expressions for the complete set of equivalent elastic constants characterizing the mechanical response of staggered composites. A micromechanical variational formulation is used, considering six independent loading scenarios: three axial tests along the mutually orthogonal axes of orthotropy, and three shear tests in the planes orthogonal to these directions. By imposing stationary conditions of the (microscale) total potential energy over a class of quasi-compatible strain fields describing the dominant microscale kinematics, a consistent approximation of the equilibrium solution at the representative volume element (RVE) level is established. The overall equivalent constitutive response naturally follows from the Hill-Mandel homogenization conditions. The soundness and accuracy of the proposed formulation is assessed through comparisons between the theoretical estimates of the equivalent elastic constants and their counterparts obtained via a computational homogenization procedure.

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