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Bioinspired Architectured Materials with Interpenetrating Phases

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We study biological materials to seek inspiration from nature how to design synthetic architectured materials with superior properties for various engineering applications [1]. Plants and animals have evolved over billions of years to become very efficient in utilizing materials for their desired functions.

In this paper, we first provide a brief overview on biological materials and discuss on how the knowledge of biological materials can be used to design novel synthetic architectured materials with superior properties. Examples of desired material characteristics include high stiffness, strength and fracture toughness, high impact resistance, and light weight. Then, we present several examples of biological and bioinspired materials with various architectures with search for optimized properties.

First, we focus on two-phase architectured material systems and investigate the effect of geometry of phases on their composite's mechanical response. To explore the effects of the geometric arrangement, initially simplified two-phase periodic composite models are developed with a 1:1 volume ratio of each phase. The models include (1) a composite with two discontinuous phases, (2) a composite with one continuous and one discontinuous phase (matrix-inclusion composite), and (3) a composite with two interpenetrating phases (bi-continuous, composite). For each model, stiff and soft phases are also alternated, so that the total of six geometric arrangements are explored. Initially, material properties of phases are assumed to be linear elastic and isotropic, for simplicity. Then, constitutive laws are expanded to include nonlinear elasticity and plasticity. The analysis is done computationally using a finite element software Abaqus and experimentally by 3D printing these structures and testing them in compression. First, we study single unit cells of such periodic geometries under applied periodic boundary conditions to predict effective elastic moduli of those six models. Results demonstrate that for composites with linear elastic components, the composite with a stiff continuous phase and soft inclusions has the highest stiffness while a composite with two discontinuous phases has the lowest stiffness. The interpenetrating composites have similar stiffnesses that are slightly lower than the effective stiffness of the composite with a stiff continuous phase with soft inclusions. Then, we change the geometry by keeping a sample size constant and while increasing a number of unit cells and apply mixed boundary conditions, as in an experimental setting. We find that as the unit cell size decreases, the stiffness and strength of composites decrease. Good agreement is found between computational and experimental results.

This project on composites with interpenetrating phases was inspired by our recent experimental observations on bone showing that bone at the nanoscale is a composite with interpenetrating phases [2]. Bone is a biocomposite made of soft and deformable organic phase (mainly collagen) and a stiff but brittle mineral phase (hydroxyapatite). By assigning properties of collagen and hydroxyapatite in the interpenetrating composite models described above, we find that the stiffness is about 36 GPa. These results agree closely with measurements done on micropillars of bone [3]. We also present report on our results on more realistic representations of the bone ultrastructure involving two interpenetrating phases, based on transmission electron microscopy images. These findings contribute to new understanding of bone as most of the existing models in the bone literature assume that minerals are discretly arrranged in a collagen matrix.

Also, we report on synthetic composite materials with more complex interpenetrating geometries such as those based on triply periodic minimal surfaces (TPMS) [4]. Various architectures of TPMS are explored to identify optimal geometries. Results are compared graphically with other composite materials by using Ashby diagrams.

Secondly, we employ topology optimization methods which enable the computation of optimal designs for a given set of boundary conditions, and use additive manufacturing to 3D print these materials. Most additive manufacturing processes have utilized comparatively simple materials. Recently, devices that are capable of additively manufacturing more complex materials, such as short fiber and particulate composites, have begun to reach the market. The addition of this new capability greatly expands the design space. While previous efforts were able to optimize on the macroscale, there is now the opportunity to optimize on both the macroscale and microscale. This work focuses on the impact that various microstructural variables have on the macroscale optimization. Two microstructure cases are investigated: ellipsoidal inclusions and short fibers. For each case, a number of variables, such as orientation, shape, and material properties are investigated. This investigation is completed in two steps. First, the stiffness tensor of the specified microstructure is computed via the homogenization method. Second, several canonical design problems are topologically optimized using the stiffness tensor as the material parameter. The results are then evaluated by comparing the compliance of the final designs. This allows for the identification of key trends in the relationship between the effectiveness of the final macroscale design and the microstructural variables.

Acknowledgments

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