Mechanical behaviors of bio-inspired composite materials with functionally graded reinforcement orientation and architectural motifs

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Abstract

Naturally-occurring biological materials with stiff mineralized reinforcement embedded in a ductile matrix are commonly known to achieve excellent balance among stiffness, strength and ductility. Interestingly, nature offers a broad diversity of architectural motifs, exemplify the multitude of ways in which exceptional mechanical properties can be achieved. Such diversity is the source of bio-inspiration and its translation to synthetic material systems. In particular, the helicoid and the "brick and mortar" architectured materials are two key architectural motifs we are going to study and to synthesize new bio-inspired materials.

Due to geometry mismatch (misorientation) and incompatibilities of mechanical properties between fiber and matrix materials, it is acknowledged that misoriented stiff fibers would rotate in compliant matrix beneath uniaxial deformation. However, the role of fiber reorientation inside the flexible matrix of helicoid composites on their mechanical behaviors have not yet been extensively investigated. In the present project, fiber reorientation values of single misoriented laminae, mono-balanced laminates and helicoid architectures under uniaxial tensile are calculated and compared. In the present work, we introduce a Discontinuous Fiber Helicoid (DFH) composite inspired by both the helicoid microstructure in the cuticle of mantis shrimp and the nacreous architecture of the red abalone shell. We employ 3D printed specimens, analytical models and finite element models to analyze and quantify in-plane fiber reorientation in helicoid architectures with different geometrical features. We also introduce additional architectures, i.e., single unidirectional lamina and mono-balanced architectures, for comparison purposes. Compared with associated mono-balanced architectures, helicoid architectures exhibit less fiber reorientation values and lower values of strain stiffening. The explanation for this difference is addressed in terms of the measured in-plane deformation, due to uniaxial tensile of the laminae, correlated to lamina misorientation with respect to the loading direction and lay-up sequence.

Except for fiber, rod-like, reinforced laminate, platelet reinforced composite materials, "brick and mortar" architectures, are going to be discussed as well, since it can provide in-plane isotropic behavior on elastic modulus that helicoid architecture can offer as well, but with different

geometries of reinforcement. Previous “brick and mortar” models available in the literature have provided insightful information on how these structures promote certain mechanisms that lead to significant improvement in toughness without sacrificing strength. In this work, we present a detailed comparative analysis that looks at the three-dimensional geometries of the platelet-like and rod-like structures. However, most of these previous analyses have been focused on two-dimensional representations. We 3D print and test rod-like and tablet-like architectures and analyze the results employing a computational and analytical micromechanical model under a dimensional analysis framework. In particular, we focus on the stiffness, strength and toughness of the resulting structures. It is revealed that besides volume fraction and aspect ratio of reinforcement, the effective shear and tension area in the matrix governs the mechanical behavior as well. In turns, this leads to the conclusion that rod-like microstructures exhibit better performance than tablet-like microstructures when the architecture is subjected to uniaxial load. However, rod-like microstructures tend to be much weaker and brittle in the transverse direction. On the other hand, tablet-like architectures tend to be a much better choice for situations where biaxial load is expected.

Through varying the geometry of reinforcement and changing the orientation of reinforcement, different architectural motifs can promote in-plane mechanical properties, such as strain stiffening under uniaxial tensile, strength and toughness under biaxial tensile loading. On the other hand, the various out-of-plane orientation of the reinforcement leads to functionally graded effective indentation stiffness. The external layer of nacre shell is composed of calcite prisms with graded orientation from surface to interior. This orientation gradient leads to functionally graded Young’s modulus, which is confirmed to have higher fracture resistance than homogenous materials under mode I fracture loading act.

Similar as graded prism orientation in calcite layer of nacre, the helicoid architecture found in nature exhibits gradients on geometrical parameters as well. The pitch distance of helicoid architecture is found to be functionally graded through the thickness of biological materials, including the dactyl club of mantis shrimp and the fish scale of coelacanth. This can be partially explained by the long-term evolution and selection of living organisms to create high performance biological materials from limited physical, chemical and geometrical elements. This naturally “design” procedure can provide us a spectrum of design motifs on architectural materials.

In the present work, linear gradient on pitch distance of helicoid architectures, denoted functionally graded helicoid (FGH), is chose to be the initial pathway to understand the functionality of graded pitch distance. Three-point bending on short beam and low-velocity impact tests are employed in FEA to analyze the mechanical properties of composite materials simultaneously. Both static(three-point bending) and dynamic(low-velocity impact) tests reveal that FGH can provide multiple superior properties at the same time, such as peak load and toughness, while the helicoid architectures with smaller pitch angle or the helicoid architectures with larger pitch angle can only provide one competitive property at one time. Specifically, helicoid architectures with smaller pitch angle, such as 15°, show higher values on toughness, but less competitive peak load under static three-point bending tests, while helicoid architectures with larger pitch angle, larger than or equal to 22.5°, exhibit less value of toughness, but higher peak load. The explanation on this trend and the benefits of FGH is addressed by analyzing the transverse shear stresses distribution through the thickness in FEA, combined with analytical prediction. In low-velocity impact tests, the projected delamination area of helicoid architectures is observed to increase when the pitch angle is decreasing. Besides, laminates with specific pitch angles, such as 45°, classical quasi-isotropic laminate, 60°, specific angle ply, and 90°, cross-ply, are designed to compare with helicoid architectures and FGH.