Fall 11-11-2015

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NATURE'S TOUGH COMPOSITES: A LOOK INTO BIOLOGICAL FIBROUS ARCHITECTURES

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Over a period of hundreds of millions of years, numerous examples of biological organisms have evolved light-weight, strong, and tough composite materials in order to adapt to ecological pressures and thrive in their specific niches. These composite structures consist of fiber-reinforced materials with different architectures including lamellar, cellular and helicoidal motifs. This lamellar motif is a common design utilized by a variety of distantly related organisms from mollusks to plants (e.g., queen conch and bamboo). The strength of the structures are dependent on the orientation of the reinforcing fibers. The fiber-matrix interface increases the toughness of the composite through crack deflection and crack bending. Another motif, the helicoidal structure, is found in a broad range of structures within organisms, and has provided a platform for superior damage mitigation. Here, we describe two biological structures consisting of the helicoidal architecture.

The diabolical ironclad beetle (*Phloeodes diabolicus*) has been reported to be both crush and penetration resistant. We investigated the elytra (forewing), which consists of a hierarchical arrangement of uni-directional alpha-chitin fiber sheets assembled in a helicoidal arrangement. Structure-function analysis using microscopy, spectroscopy as well as mechanical testing reveals new details into the mechanisms of energy absorption upon compression. A combination of motifs, that is the lamellar and helicoidal designs, are found in the mineralized raptorial appendages of smashing Stomatopods, The peacock mantis shrimp (*Odontodactylus scyllarus*) uses its harmer-like dactyl club to smash through the tough exoskeletal structures of mollusks, crustaceans, and other shelled marine organisms with incredible force (1500N) and speed (23 m/s). The success of the dactyl club's mechanical response, namely its resistance to catastrophic failure from repeated high-energy impacts, lies in its multi-regional and hierarchical composite architecture. This natural material features a compliant inner layer featuring helicoidal and lamellar arrangements of alpha-chitin fibrils mineralized by amorphous forms of calcium carbonate and calcium phosphate. An enamel-like surface region that allows for momentum transfer to prey caps this soft core. We describe ultrastructure-mechanical property relationships of this outer "impact" region using high-resolution electron microscopy, *in-situ* nano-mechanical testing and finite element modeling. Here, we highlight a number of fracture-mitigation strategies that yield toughness to an already stiff and hard biomaterial. Utilizing these design strategies, we have fabricated helicoidal carbon fiber-epoxy panels that show a greater resistance to damage from impact when compared to similar panels with a quasi-isotropic fiber arrangement.