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Nature 's tough composites: A look into biological fibrous architectures

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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 lightweight, 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.