# ABSTRACT

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Nature has been adopted several techniques to survive over the past billion years of evolutions. Geometrically patterned interfaces seem to be a common motif in Nature. In particular, architecture plays a crucial role in increasing the strength, toughness, and damage tolerance among different species. For instance, alligator, turtle, armadillo, sea urchin, ammonite, Ironclad beetle, and boxfish are among species included patterned interfaces inside their structure. Here, the role of shape, geometry, and microstructure of both interlocking and non-interlocking patterned interfaces bio-inspired from Nature is investigated in enhancing the mechanical properties under multiaxial loading conditions.

The role of non-interlocking patterned interfaces is studied under remote mode-I loading condition. In particular, the role of the shape of the opening crack behind the crack tip is investigated as the crack propagates along the non-interlocking patterned interfaces. The shape of the interface behind the crack tip for different amplitude-to-wavelength aspect ratios with two analytical models is studied and compared with finite element simulations through the J-integral method. Additionally, the role of the material length scale is explored by investigating the relationship between the geometrical characteristic lengths and the emerging material length scale using a finite-element-based cohesive zone model. The results suggest that geometrical toughening is influenced by a size effect, but it is bounded between two extreme conditions.

The role of interlocking patterned interfaces is investigated for both boxfish carapace and Ironclad beetle cuticle. These two species are selected due to their extraordinary performance against attack and compression loads which are fatal to the other species. The boxfish carapace (Lactoria cornuta) contains hexagonal dermal scutes, a combination of the brittle hexagonal plate (hydroxyapatite) on top of a very compliant (collagen) material. While the mineral plates are separated by patterned sutures (triangular patterns), there is no interphase material connecting them. Instead, the connection between mineralized plates is done through the collagen base which is different from

other naturally occurring sutures (e.g., sutures in turtle, alligator, armadillo). The protective role of the boxfish scute architecture in controlling the crack directions is investigated by employing analytical, numerical, and experimental tools for different geometrical and material parameters. Further analysis revealed that this architecture helps to arrest the cracks inside the sutures area. Additionally, the results confirmed that both architecture and material properties play a key role in controlling the cracks direction inside the brittle plates.

Beetles are a subclass of arthropod dating back over 300 million years. The complex cuticle microstructure found within the exoskeleton (elytra) of this specially adapted insect results in extremely high compressive resistance, far beyond any other beetle identified to date. Elytra consists of separated parts connected using dovetail-joints blades and contains a hierarchical assembly of alpha-chitin fibers embedded within a proteinaceous matrix that provides both strength and toughness. The architecture of the suture region of the elytra, modified for terrestrial living, has a unique architecture consisting of specially modified interlocking blades, whose elliptical geometry, laminated microstructure and frictional interfacial features, enhance mechanical properties such as toughness and load resistance. The presence of microstructure inside the interlocking joints results in delamination inside blades and thus, develops a new competing mechanism that is different from pull out or fractures. By using a combination of finite element analysis, experimental methods (i.e., optical and electron microscopy, computed tomography, and mechanical testing), and 3D printing prototype technique, the unique adaptations, novel architectural design features and interfacial structures are revealed within the exoskeleton of Ironclad beetle.  This model system represents a tough, resistance biological material that exemplifies a departure from other types of beetles and can be inspired for future engineering applications.