

## Project Summary

**Overview:** Structural biomaterials (SBs), such as bone and shells, consist of a ceramic and an organic phase mixed together in intricate 3D patterns over a range of length scales. Despite the fact that SBs are predominantly composed of brittle ceramics they display extraordinary toughness. This toughness enhancement is believed to be a consequence of the intricate 3D arrangement of their constituent phases. However, several important questions remain, such as: (q.1) if specific architectural motifs are the key, then what are they and what are the precise mechanisms through which they enhance toughness? and (q.2) is it critical that the architecture be spread over several length scales, i.e., is hierarchy always important? The SBs fail through the evolution of complex crack patterns, in which the cracks are repeatedly trapped, deflected and split by the SBs' densely distributed ceramic-matrix interfaces. Therefore, the PI's overarching objective is to answer questions such as q.1–2 by developing a new phase field fracture theory (PFT) that would enable the simulation of the SBs' failure behaviors.

Phase field theory is an alternate theory of brittle fracture, and the simulation tools based on it have tremendous computational advantages. Notably, they can handle topology changes (crack branching, merging, etc.) easily with no additional difficulty in 3D. Currently, however, the application of PFT tools is critically limited due to the issue of crack broadening. The proposal discusses a systematic strategy for eliminating the issue of crack broadening. The PI will evaluate the success of the new PFT by comparing its predictions with carefully planned experimental measurements. In line with the overarching research objective, the PI will use the new PFT tools to uncover new toughening mechanisms in a prototypical SB architectural motif.

**Intellectual Merit:** The fact that the relationship between a SB's mechanical design and its toughness is not well-understood indicates that SBs hide a wealth of undiscovered material toughening mechanisms, and mechanics principles. By providing a way to “see” inside a material as it fails, the proposed PFT tools will allow one to discover, investigate, and understand new, small-scale architecture related mechanisms that give rise to toughness enhancement. The discovered new mechanisms would bring new mechanics principles to light.

Understanding the mechanics and physics of fracture is of great scientific and engineering importance. Phase field theory of fracture, and the variational fracture theory (VFT) on which it is based, show tremendous potential for revitalizing fracture mechanics by opening up completely new paradigms for understanding and modeling fracture phenomena. Though mathematically and computationally advanced, the PFT and VFT have been developed through a minimal inclusion of mechanics principles and fracture physics. Through incorporating more mechanics and physical principles in PFT, the proposed research would rectify some of its key shortcoming and place it on a strong theoretical mechanics foundation. This would provide the solid mechanics community with a new alternative strategy for attacking long outstanding problems in fracture mechanics that are of fundamental scientific importance, such as the effect of disorder in fragmentation. Solving the identified issue of broadening would dramatically improve the simulation capability of PFT-based computational tools. Thus, the proposed research would endow PFT with the potential to galvanize revolutionary developments in the computational design of high-toughness materials and enable the resolution of a number of key problems where understanding the evolution of complex fracture patterns is critical.

**Broader Impacts:** The PI plans to integrate the proposed research with a wide range of educational outreach activities. (i) The PI will collaborate with the Sci-Toons initiative at Brown to create educational videos related to bio-inspired engineering that are designed to reach a broad audience. The Sci-Toons videos use engaging storytelling to allow the general public to develop a greater understanding and appreciation of science. Through the use of “jargon free” language these videos also create new opportunities for dialogue between STEM and non-STEM majors. (ii) The PI and his students will collaborate with the SPIRA camp at Brown, which focuses on empowering high school age girls to pursue education in STEM fields. Specifically, the PI will use his research on bio-inspired materials to showcase some of the exciting new opportunities that await the next generation of engineers. The PI will expose the students to core concepts in mechanics and the design of structural materials through activities such as the “Soft landing: better materials for tomorrow's helmets and cars” egg drop competition and the hands on exploration of different materials' microscopic architectures. The proposed activities are designed to bolster public awareness of exciting new developments in bio-inspired engineering, and to specifically focus on motivating female high school students to pursue careers in science and engineering.