Impact of Hydroxyapatite Morphology on the Fracture Behavior of Lamellar Bone: A Phase-Field Modeling Approach

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Abstract

Lamellar bone, the basic building block of bone, exhibits a remarkable combination of stiffness and toughness, which emerges from the interaction of hydroxyapatite (HA) polycrystals and organic phases. While many computational studies have explored the effective properties of lamellar bone, they often model HA either as platelets (1) or grains (2) without fully investigating the implications of these morphologies on fracture behavior. This study employs a phase-field damage modeling approach within a 2D finite element framework to evaluate the influence of HA morphology and size on the fracture properties of lamellar bone. Two Representative Volume Element (RVE) configurations were analyzed: one with platelet-based minerals (100–200 nm) and another with granular-based minerals (10–15 nm). Both configurations incorporated mineralized collagen fibrils (MCFs) modeled as anisotropic elastic materials with a diameter of 50 nm and a physiological volume fraction of 50%, and their interactions with HA were mediated by non-collagenous proteins using a semi-cohesive fracture profile. The platelet-based configuration demonstrated superior mechanical performance in terms of stiffness, strength, and toughness, with MCFs acting as effective crack propagation barriers. In contrast, granular configurations exhibited lower fracture resistance due to their lower aspect ratio. The study further revealed that higher mineral aspect ratios in the loading direction enhance stiffness and load-bearing capacity, leading to increased tissue strength.

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