Finite Element-Based Methodology for Studying Crack Propagation at the Microstructural Length-Scale in Cortical Bone

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Introduction At the microstructural length-scale, experimental observations have identified relationships between crack propagation and microstructural features in cortical bone [1]. Microstructural components, such as interstitial bone, osteons, and cement lines, have different mechanical properties and/or composition [2,3], and this heterogeneity likely determines the behavior of propagating microcracks. Finite element (FE) modeling of the microstructural features, coupled with explicit representations of cracks, will enhance our understanding of the role of variations in mechanical properties, fracture toughness, and porosity in microcrack growth. This study introduces and explores a modeling methodology that can be used to study the relationships between damage propagation and the geometry and material properties of microstructural features.

Methods An efficient model generation code to quickly create FE models including cylindrical representations of microstructural features, such as osteons, osteonal lamellae, cement lines, and porous spaces, was developed using MATLAB [4]. For each model, unique geometry, material, and location information can be specified. The code writes a script, which is then processed using Abaqus [5] to generate the desired FE model.

Using experimental data [2,6,7], two models were created with 5.5% porosity, isotropic linear elastic material properties (elastic modulus of 25 GPa for the interstitial bone), a Poisson's ratio of 0.3, inner osteon diameters of 58.8 µm, and outer osteon diameters of 246.8 µm. Models 1 and 2 had osteon tissue moduli of 25 GPa and 20 GPa, respectively. A uniform displacement was applied to the top face of each model and other boundary conditions were applied (Fig. 1).

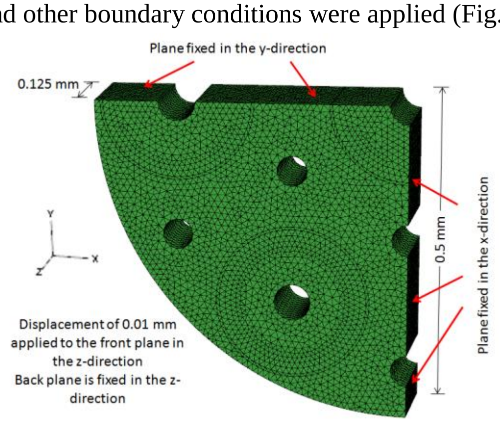

Fig. 1. FE geometry model used for study.

FRANC3D/NG (FE fracture modeling program developed in-house) was used to insert a crack into each model and re-mesh, and FE analyses were then performed using Abaqus. Using FRANC3D/NG, crack opening displacement (COD) values were obtained and stress intensity factors (SIFs) were calculated (assuming that linear elastic fracture mechanics (LEFM) was applicable). Crack growth was based on a user defined criterion: $\Delta a_i = \Delta a_{mean}\left(\frac{K_I^i}{K_{mean}}\right)^n$, where for each crack growth step, Δa_i represents the crack growth at a crack front point, n = 1, Δa_{mean} was user specified, K_I^i was the mode I SIF calculated for each crack front point, and K_{mean} was the mean of the mode I SIFs. This criterion allowed for an exploration of the overall methodology.

After the cracks were propagated one step in each model, 8 additional analysis/crack propagation steps were performed. The resulting crack fronts were then compared across models.

Results The cracks were successfully grown in each of the two different models (Fig. 2). The crack front in Model 2 diverged from the front in Model 1 after entering the low modulus region of the osteon (Fig 2b).

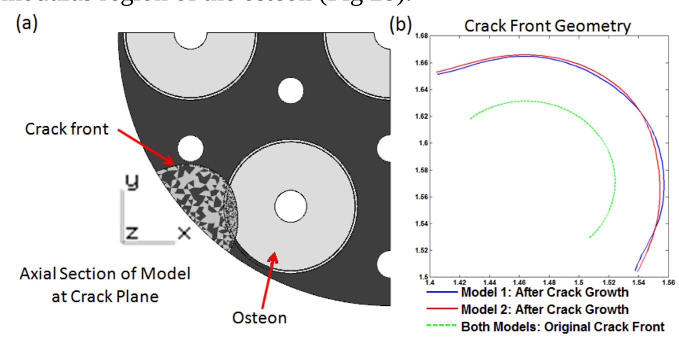

Fig. 2. After 9 crack growth steps: (a) Schematic of crack in the 2 material model. (b) Plot showing crack front locations.

Discussion The variations between the crack fronts (Fig. 2b) were as expected for the modulus combinations used and the chosen crack growth propagation criterion. The utility of our methodology for studying crack propagation in different microstructures was successfully demonstrated.

Further, in concert with experimental data, this modeling methodology can be used to explore and develop different crack propagation criteria that are specifically suitable to bone at the microstructural length-scale. Crack growth in bone may not be accurately predicted using LEFM concepts, and user-defined criteria focusing on COD values (and including critical values), that can be used when LEFM is not applicable, can easily be incorporated into the methodology allowing for great flexibility when modeling crack propagation in future studies.

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