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Micro-crack propagation on a biomimetic bone like composite material studied with the extended finite element method

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Abstract

Cortical bone contributes to about 80% of the weight of the human skeleton. Along its other properties, cortical bone presents a high resistance to fracture propagation. With this paper the authors aim to model this material using the Extended Finite Element Method (X-FEM) and to understand the mechanism that allow this material to have such a property. A numerical model was developed, considering a biomimetic bone like composite material, modelling the primary anatomical and functional unit of cortical bone, the osteon, as a fiber, the interstitial lamellae as the matrix, and the cement line between them. Different properties were considered for all the above mention materials, and their influence on the micro-crack propagation was studied. The cracks introduced and their geometry allowed the authors to understand why the cracks are arresting their propagation, and why is this material so resistant to crack propagation. The results are presented using the calculated stress intensity factors, for different material and geometries, and also using several brittle fracture crack propagation examples calculated using X-FEM.

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1. Introduction

The human cortical bone is a very complex material and its properties are directly related with the cellular structures that characterize this living tissue. Nevertheless Mohsin et al. (2006) have shown that bone can be represented as an composite material and that although the discontinuities in its microstructure provide stress concentrations points in order to crack initiation to occur, they also provide barriers for crack propagation. Vashishth et al. (2000) have experimentally tested the bone brittle crack propagation resistance, and have concluded that the

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cortical bone crack propagation occurs via the formation of a micro-crack zone which subsequently develops into a wake. Understanding this phenomenon will allow not only to understand why the cortical bone so resistant to crack propagation, but also will enable us to develop new biomaterials based on a biomimetic approach.

Najafi et al. (2009) started by developing a simple composite model for the cortical bone, using a matrix, simulating the interstitial matrix of the bone, and a fiber simulating the osteon structure. Najafi analyzed the influence of different variable that defined the bone microstructure, using a simple crack and calculating the Stress Intensity Factors (SIF) on both crack tips. Later Najafi et al. (2007) introduced the influence of the Haversian channel on the osteon and of the cement line, between the osteon and the matrix, creating a more complex model for the cortical bone. Finally Najafi et al. (2007) have also simulated the crack propagation on the neighborhood of the osteon and have studied the crack attracting and arresting phenomenon's.

Huang et al. (2006) have also studied and validated their bone like model, using several osteons and different material properties. Budyn et al. (2007) and Abdel et al. (2012) have developed multiscale models, using a large number of osteons, including the effects of different sizes of Haversian channels and different types of cement lines, and have studied the crack propagation and arrest, considering different points of origin.

Finally Zahan et al. (2009) have developed a fully tridimensional model of a bone like structure to analyze the crack propagation of different cracks in space. Using all these experiences and numerical simulations one can now develop new materials and used them in different applications, where the crack propagation resistance is important. Libonati et al. (2013), using the results from crack propagation near a single osteon by Vergani et al. (2014), have developed a new bone like material, using the appropriate fibers and matrix. In order to achieve this goal one must also understand the influence of the base material properties, like the Young's modulus, of the fracture resistance of the final material.

2. Material and Methods

2.1. Osteon Structure

Cortical bone is comprised of two basic structures, the osteon and the interstitial lamellae which represents the remnants of previous osteons in a constant process of bone remodeling. Fig. 1 a) shows both these structures which can be compared to several fibers and a matrix, in a composite like material. Fig. 1 b) shows the structure of an osteon, with its Haversian Canals, a circular opening in their center, where the vascularization of the tissue occurs, and the Haversian Lamellae, concentric layers of mineralized matrix that forms most of the osteon. Fig. 1 c) shows the Lacunae, where the osteocytes cells can be found, and the several Canaliculi that connects Lacunae to one another, enabling the oxygen and nutrients to be shared. Finally Fig. 1 d) show the Interstitial Lamellae which can be compared to the composite matrix.

2.2. XFEM Crack Propagation

The extended finite element method, XFEM, is an evolution of the classical finite element method based on the concept of partition unit, i.e. the sum of shape functions is equal to one. This method was initially developed by Ted Belytschko et al. (1999). The XFEM based on the concept of partition of unity Babuska et al. (1996), adds a priori known information about the solution of a given problem, to the FEM formulation, making possible, for example, to represent discontinuities and singularities, independently of the mesh. This particular feature makes this method very robust and attractive to simulate the propagation of cracks, since it is no longer necessary to have a continual updating of the mesh. The XFEM is then referenced as a Meshless method. In the XFEM, enrichment functions are added to additional nodes, in order to include information about discontinuities and singularities around the crack. These functions are the asymptotic near-tip solutions, which are sensitive to singularities, and the Jump function, which simulates the discontinuity when the crack opens.