Chapter 1

Introduction

1.1 Motivation

Fractures resulting from minimal trauma result in significant morbidity and mortality in the elderly. These fragility fractures are related to underlying osteoporosis. Osteoporosis is one of the major problems facing women and elder people of both sexes. Each year, an estimated 1.5 million women, about 4 in 10, experience osteoporotic fractures in the USA. Up to 20% of women with a hip fracture die within one year (National Osteoporosis Foundation, 2003). Additionally, up to 25% of hip fracture patients may require long-term nursing home care, and only a third fully regain their pre-fracture level of independence. Hip fractures bring on the greatest osteoporosis-related healthcare expenditure.

According to the world health organization (WHO), osteoporosis should be considered a progressive systemic disease, characterized by microarchitectural deterioration of bone, rather than a natural consequence of aging. Osteoporosis is a disease of bone in which the bone mineral density (BMD) is reduced, bone microarchitecture is disrupted, and the amount and variety of non-collagenous proteins in bone is altered. There are several alternatives of medication to treat osteoporosis. However, the treatments with different agents not only change the extent of

mineralization, but also the morphology of mineral crystals in bone tissue which in turn affect the mechanical properties of it.

In order to have a rigorous computational framework to simulate the behaviors of bone tissue, a physics-based and capable material model of bone is required. Although mechanical models for bone have been studied for many years, bone itself is usually approximated as an isotropic material. Recently, efforts were undertaken to include lower hierarchical levels of bone tissue into mechanical models. At these scales, it is not sufficient to consider only the bone mineral density, but also necessarily take into account the size, orientation, and local distribution of bone constituents. Moreover, there is a hypothesis that toughening mechanisms exist at all characteristic length scales in bone [1]. To understand how bone derives its resistance to fracture, there is a fundamental need for a more realistic modeling of the bone tissue and its fracture behaviors.

1.2 Objectives

One objective of this research is to develop multi-dimensional evolutionary, micromechanically motivated anisotropic material models for accurate modeling of bone tissue. The micromechanics formulation of multi-phase and multi-scale homogenization methodology is employed to derive analytically and estimate the multi-scale effective anisotropic elastic moduli of the microstructure of bone tissue (Chapter 3). In the following chapter (Chapter 4), the effective material properties of multi-level and multi-layer bone lamellae are investigated. Fibrillar orientation patterns within the lamellae are

considered. In particular, comparison and validation between our micromechanical model and experimental data based on the single layer fiber orientation average is presented.

In Chapter 5, an effective elastic micromechanical damage model for bone tissue with evolutionary matrix cracking at the lamellar level is constructed based on Ju and Tseng's [2, 3] micromechanical damage formulation. It is shown clearly that microdamage exists in bone and contributes to the degradation of bone's material properties. In Chapter 6, on the basis of constant-shear model, crack bridging by collagen fibrils in toughening cortical bone is investigated systematically with the framework of linear-elastic fracture mechanics combined with the previous micromechanical model for lamella. In particular, the effect of collagen fiber breakage is considered by taking advantage of cumulative probability function.

A three-dimensional structural model composed of two different unit cells, which have distinct mechanical behavior in the vertical direction, with doubly tapered struts for human vertebral cancellous bone is proposed Chapter 7. This model could serve as a theoretical framework for cancellous bone and provide assistance in understanding the connection between structural changes and biomechanical competence.

1.3 References

1. Ritchie, R.O., M.J. Buehler, and P. Hansma, *Plasticity and toughness in bone.* Physics Today, 2009. **62**(6): p. 41-47.

2. Ju, J.W. and K.H. Tseng, *A Three-Dimensional Statistical Micromechanical Theory for Brittle Solids with Interacting Microcracks.* International Journal Of Damage Mechanics, 1992. **1**(1): p. 102-131.

3. Ju, J.W. and K.H. Tseng, *An Improved Two-Dimensional Micromechanical Theory for Brittle Solids with Randomly Located Interacting Microcracks.* International Journal Of Damage Mechanics, 1995. **4**(1): p. 23-57.