Chapter 8

Summary and Future Work

8.1 Summary

In this thesis, we aim to develop robust multi-level micromechanical constitutive models for human bone tissues. In Chapter 3, the hierarchical microstructure of human bones is considered, and a multi-scale micromechanical homogenization scheme is proposed. At a scale of several hundred nanometers, collagen molecules which are organized into staggered schemes form a contiguous matrix where hydroxyapatite crystals grow and embed themselves, building up the mineralized collagen fibrils. The proposed framework predicts that the pattern of mineralization and the shape of the mineral crystals serve to improve the mechanical function of collagen fibrils along the longitudinal axis. The numerical results in comparison to the experimental data from nanoindentation tests reflect a predictive precision and demonstrate the capability of the current micromechanical model to simulate the key behavior at this scale.

At a scale of 3-10 μm, the extracellular bone material is represented as mineralized collagen fibril inclusions embedded in a foam of extrafibrillar mineral crystals. In addition, the proposed model takes the orientations of mineralized collagen fibrils into account [2]. The homogenization scheme for the extrafibrillar mineral foam is validated by the experimental data of enamel's mechanical properties and an equation from the study of Lees [3]. Enamel has very limited amount of collagen tissue; as a result,

the underestimation of elastic properties of the extrafibrillar mineral foam due to the presence of collagen is minimized. At a scale above the ultrastructure, where osteocyte lacunae are embedded in extracellular bone material matrix, the extravascular bone material is observed. The proposed constitutive model is in agreement with the experimental data.

In Chapter 4, the effect of collagen fibril orientations on the elastic properties of bone lamellae or lamellar units are investigated. The effective anisotropic linear elastic properties of bone lamellae of lamellar units are obtained based on the multiscale homogenized model proposed in Chapter 3 combined with a micromechanical framework of layered composite and fibril orientation patterns observed in experiments. Several fibrillar orientation patterns within the lamellae are considered. In particular, comparison and validation between our micromechanical model based on the single layer fiber orientation and nanoindentation experimental results in two orthogonal directions is presented.

Chapter 5 is devoted to investigate the effects of accumulation of diffuse damage in human bone upon the material properties of lamellae. A three-parameter formulation is adopted to characterize the evolution of density of microcracks. An effective elastic micromechanical damage formulation for bone with evolutionary matrix cracking is then proposed based on Ju and Tseng's micromechanical damage formulation [4, 5]. It is demonstrated that microdamage exists in bone in vivo, accumulates with age and contributes to the degradation of bone's material properties. The predicted mechanical

behaviors of the lamellae are consistent with the experimental observations in the literature.

In Chapter 6, on the basis of constant-shear model, the fracture behaviors of human cortical bone at the lamella level are studied with the framework of linear-elastic fracture mechanics combined with multi-scale effective elastic micromechanical model for lamella. By taking advantage of cumulative probability function or Weibull distribution, the effect of collagen fiber breakage is simulated. The distribution and evolution of fiber bridging stress, crack mouth opening, and stress intensity factor then are analyzed by considering the probable fiber breakage. Crack bridging by collagen fibrils in toughening cortical bone was first time investigated systematically.

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 in Chapter 7. The ensemble-volume and orientation averaging procedures are employed to derive the equations. The effects of age-related changes in vertebral cancellous bone on effective stiffness and collapse stress in both horizontal and vertical directions are first time studied simultaneously. The predicted mechanical behaviors of human vertebral cancellous bone are generally consistent with experimental observations in literature. This model could serve as a theoretical framework for cancellous bone and provide assistance in understanding the connection between structural changes and biomechanical competence.

8.2 Future Work

The complex hierarchical structure of bone has prevented us from having a complete, quantitative understanding of how it deforms and fractures. In addition, the plasticity and toughening mechanisms of bone are active at the various length scales. However, the advances in experimental techniques and better computational tools are allowing us to have more rigorous analysis of bone behaviors. By understanding of how micro- and macro-scale features control bone's physiology, we may find new treatment for bone-related diseases.

Among the critical issues unresolved, most importantly, we still lack rigorous models that link structures at the various length scales with properties – in particular, the role of nano- and micro- structural arrangements of bone in its macroscopic behavior. Finding this link is an opportunity to bridge the gaps not only in our understanding of bone, but also in the variety of other biological and natural materials that contain similar hierarchical structures.

Other major challenges include carrying out measurements at multiple length and time scales and developing models that capture the dynamical properties of bone [6]. Even greater challenge is to describe bone as a living material that remodels, adapts, and responds to a variety of biochemical and mechanical factors. Consequently, an interdisciplinary approach may be necessary to forge a path to better quantitative models of the bone material.

The proposed tasks for the next phase of this research are summarized as follows:

1. Investigate mode-dependent crack-evolution micromechanical damage models:

Microcrack growth in bone appears to be self-limiting in tension, but less restricted in compression, indicating strain mode-dependent crack extension [7, 8]. Microcracks formed from cyclic tension have decreasing growth rate with increasing length, and typically arrest in less than 10000 cycles [7]. By contrast, microcracks produced under compression tend to be long linear cracks, indicative of more uninhibited growth (**Figure 8-1**). Our micromechanical damage models should be refined based on these experimental observations.

2. Explore combined multi-level micromechanical modeling and numerical simulation via FEM

It will be worthwhile to combine the proposed micromechanical damage models, featuring precise anisotropic stiffness characterization for extravascular bone materials, with the finite element methodology. In the current and past literatures over the last several decades, human bone materials are usually approximated as isotropic materials; this isotropic approximation generates severe limitations upon the simulation results of FEM.

3. Investigate uncracked-ligament bridging at the microstructural level

At the microstructural level, crack bridging by collagen fibrils and uncracked-ligament bridging has been identified as potent toughening mechanisms. We have already studied crack bridging by collagen fibrils systematically in Chapter 6, however, how the

uncracked ligaments form is as yet unclear. Advanced and detailed experimental observations are required to clarify this physical mechanism.

4. Expand our combined unit-cell model by incorporating SMI index

Our model proposed in Chapter 7 does not contain any plate-like structures common in cancellous bone in other sites of the body. However, the model could be expanded to predict the mechanical properties of cancellous bone with a more plate-like structure. The Structural Model Index (SMI) introduced by Hildebrand, T. and P. Ruegsigger [9] can be easily incorporated into our model. The SMI can be used to quantify the characteristic form of a three-dimensional structure in terms of the volume fraction of plates and rods composing the structure.

5. Propose multi-level micromechanical damage models for the progressive fracture and healing of human bone tissues.

Various fracture criteria have been proposed for human bone tissues, and many experiments have been performed to validate those criteria. However, there is a lack of agreement among different studies. Some authors [10] suggest that strain-based failure theories are better than stress-based ones, while other researchers indicate the opposite [11]. On the other hand, the multi-level progressive fracture and healing of human bones are important topics of research in biomechanics. Since there is experimental evidence that tissue differentiation is mechanically dependent [12], the micromechanical

approaches may be suitable for capturing the healing mechanism of human bones under various mechanical loading and bone microstructures.

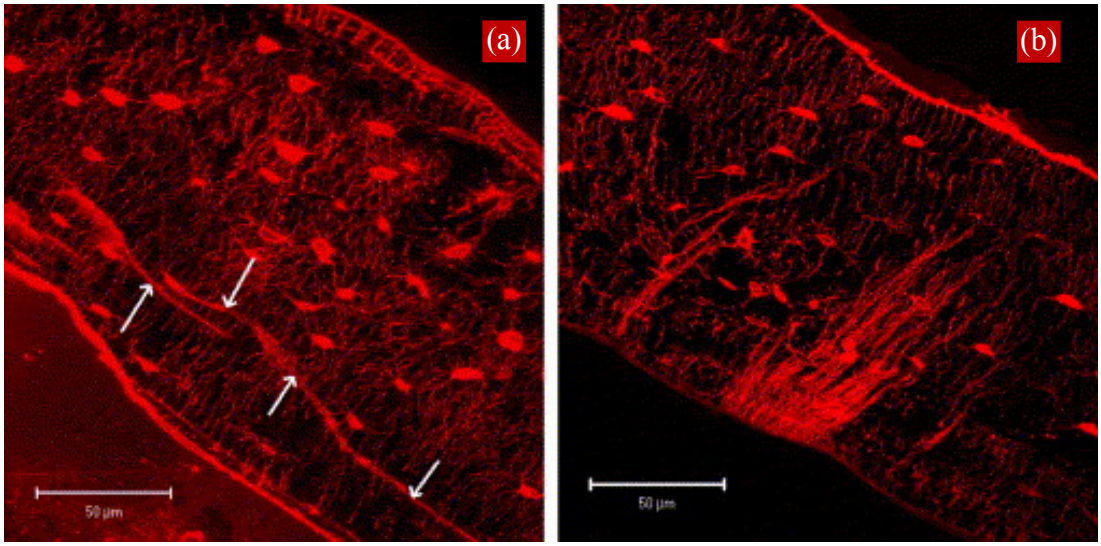

Figure 8-1. The laser scanning confocal microscope images of murine cortical bone subjected to fatigue under four-point bending. In the compressive region (a), long linear microcracks are present. In the tensile region (b), there is a cloudy network of tiny cracks. [1]

8.3 References

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