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Research Paper

A new constitutive model for simulation of softening, plateau, and densification phenomena for trabecular bone under compression

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ABSTRACT

A new type of constitutive model and its computational implementation procedure for the simulation of a trabecular bone are proposed in the present study. A yield surface-independent Frank–Brockman elasto-viscoplastic model is introduced to express the nonlinear material behavior such as softening beyond yield point, plateau, and densification under compressive loads. In particular, the hardening- and softening-dominant material functions are introduced and adopted in the plastic multiplier to describe each nonlinear material behavior separately. In addition, the elasto-viscoplastic model is transformed into an implicit type discrete model, and is programmed as a user-defined material subroutine in commercial finite element analysis code. In particular, the consistent tangent modulus method is proposed to improve the computational convergence and to save computational time during finite element analysis. Through the developed material library, the nonlinear stress–strain relationship is analyzed qualitatively and quantitatively, and the simulation results are compared with the results of compression test on the trabecular bone to validate the proposed constitutive model, computational method, and material library.

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1. Introduction

The bone tissues such as cervical and lumbar vertebral bodies consist of cortical and trabecular bones. The bone tissues act like sandwich structures, where the outer hard cortical bone has the ability to resist indentation and abrasion, while the cancellous core is tough and has the ability to absorb external energy (Nabhani and Wake, 2002). In particular, since the trabecular bone contains porous media such as voids, it is considered as a cellular material (Gibson, 1985; Gibson et al., 2010).

For this reason, the trabecular bone exhibits a highly complicated nonlinear material behavior. For example, the three stages of material characteristics, such as softening beyond yield point, plateau, and densification phenomena, are observed during compression (Hayes and Carter, 1976; Kefalas and Eftaxiopoulos, 2012). Hence, to predict these phenomena for a complex trabecular bone tissue volume using computational analysis, not only a mechanical model, but also a computational implementation method should be established.

Numerous simulation studies for estimation/prediction of the compressive behavior as well as the equivalent stress distribution for bone tissues have been conducted by many researchers. However, most studies have adopted a simple elasticity-based or a perfect elastoplasticity-based constitutive model with isotropic yield criteria. Accordingly, these models have limitations to analyze the precise material nonlinear characteristics, especially the aforementioned three phases of material nonlinearity, of the trabecular bone.

So far, only little information has been reported in literature regarding the development of a constitutive model and its implicit formulation for a trabecular bone tissue to overcome the limitations in the previous research methodologies (Zysset and Curnier, 1996a; Gupta et al., 2007; Garcia et al., 2009; Charlebois et al., 2010; Hosseini et al., 2012). Zysset and Curnier (1996a) proposed a 3D constitutive model for the trabecular bone, using fabric tensors, that includes anisotropic elasticity and simultaneous accumulation of permanent strain and reduction in elastic properties. The theoretical model was formulated within the framework of continuum damage mechanics, and was based on two fabric tensors characterizing the local trabecular morphology.

Gupta et al. (2007) developed a constitutive model and computational framework for the analysis of a cellular solid-type material, namely, trabecular bone with a yield-envelope expressed in terms of principal strains. The material anisotropy in the stress space was also incorporated in their model by transformation of the anisotropic fourth-order elasticity tensor from the principal material coordinate system to the global mesh coordinate system.

Based on the orthotropic morphology-based Zysset-Curnier model (Zysset and Curnier, 1996a), Garcia et al. (2009) developed a 3D constitutive law to predict the macroscopic mechanical behavior of both cortical and trabecular bones under cyclic overloads. In their research, the damage criterion as well as the plastic yield criterion for the bone tissue was proposed, and a numerical algorithm that includes incremental tangent operators was demonstrated.

Charlebois et al. (2010) proposed a novel constitutive model to analyze the hardening-softening correlation of the trabecular bone under compression. In their study, the damage-plasticity-coupled constitutive model was improved with a nonlocal formulation that ensures a mesh independent solution, and was implemented in a finite element (FE) package.

Hosseini et al. (2012) developed a novel constitutive model and a computational implementation method for the behavior of the trabecular bone under large compressive strains. In this context, the fabric-based anisotropic elasticity law, as well as the local plasticity theory, was introduced, and the isotropic damage evolution model was adopted in the constitutive model. Through the proposed model, nonlinear material behavior and bone failure/fracture were quantitatively simulated.

In the previous studies, anisotropic/orthotropic elasticity as well as yield locus for the trabecular bone was successfully identified based on their own novel models, and the computational implementation technique was introduced as well. However, these models still have limitations in representing the complex phenomena of softening beyond yield point, plateau, and densification of a bone tissue under compressive strains. For this reason, the precise material behavior, especially the nonlinear stress–strain relationship of the bone tissue and structure under large compressive strains could not be simulated using finite element (FE) analysis. In particular, it might be difficult to evaluate the softening-plateau-coupled phenomenon as well as the compressive collapse/failure characteristics induced by excessive external compression.

Further, most of the existing studies could not provide a computational implementation procedure that includes a stress update algorithm of the proposed model such as the algorithmic tangential stiffness method. For this reason, it might be considerably arduous to apply the proposed model to the analysis of a bone tissue and/or structure under arbitrary loadings.

Hence, in the present study, a new type of constitutive model, namely, a yield surface-independent Frank-Brockman elasto-viscoplastic model was introduced to analyze the aforementioned material complexity of a trabecular bone tissue under compression. Furthermore, in order to apply the constitutive model to finite element analysis (FEA), the elasto-viscoplastic model is transformed into an implicit type discrete model, and is programmed as a user-defined material subroutine for a commercial FEA code ABAQUS UMAT (Lee et al., 2015a). During computerization, one of the very robust return mapping algorithms, the consistent tangent modulus (CTM) method, is adopted to increase the rate of the computational convergence and to save computational time.

Through the developed ABAQUS UMAT material library, namely, BONE_MAT (which is named by authors), the three stages of material nonlinear stress–strain relationship of the trabecular bone, namely, softening beyond yield point, plateau, and densification are analyzed numerically. Moreover, the calculated stress–strain relationships of the bone tissue are compared with the results of a series of experiments for uniaxial compression of the trabecular bone tissue, i.e., in the lower and upper femurs, to verify the accuracy of the