INTRODUCTION

Bone damage has been implicated as a contributing factor governing bone fragility in diseases such as osteoporosis and in repetitive loading injuries such as stress fractures. There is a genuine need for more adequate models to predict the mechanical failure (fracture, collapse) of skeletal structures using the tools of engineering stress analyses. However, the mechanical properties of bone vary with respect to anatomic site, age, and disease factors. Along with the inherent variability in these properties there is uncertainty in predicting bone properties in living subjects using non-invasive measurements. This makes a probabilistic modeling approach attractive for more realistically modeling bone mechanics. The objective of this project is to develop a computational analysis capability to investigate and model the non-linear mechanical behavior of cortical bone using probabilistic mechanics concepts.

METHODS

The initial probabilistic damage model for bone was chosen as an isotropic elasto-visco-plastic damage continuum mechanics (CDM) model [Zhu, 1992; Zhu and Cescotto, 1995]. Primary model features include the following: i. Inelastic strains are assumed to result from either plastic flow or damage accumulation. The onset of damage accumulation and plastic flow is governed by two independent threshold surfaces in stress space. The yield criterion and the damage threshold are described by closed, convex surfaces in stress space, both of which can change by a linear hardening rule. Plastic hardening incorporates both isotropic and kinematic hardening. ii. Damage is defined by two scalar damage variables, one associated with the shear stresses and the other associated with a volumetric damage that only accumulates under positive (tensile) volumetric stress. The model incorporates 9 material constants including 2 elastic moduli, three plasticity parameters, three damage parameters, and a time constant. A uniaxial version of the model was implemented in MATLAB for simulating axial loading. An extensive series of simulations were carried out to investigate the roles of the material parameters vis-à-vis known general behavior of bone (from experimental uniaxial test data). Parameter fits from these simulations were used to generate random variable descriptions of the CDM material model internal variables. Probabilistic calculations were then performed using the general-purpose probabilistic analysis software NESSUS.

The initial analysis investigated the probabilistic behavior of the model when driven to a specific strain level by computing the probability of bone failure at that strain level. Probability of bone failure was defined as the probability of reaching a specific reduction in modulus (resulting from the damage process). Modulus reduction at failure for each experimental data set was computed and used as a random variable describing strength. The performance function for this analysis was defined as \( g = R - S \)

where \( R \) is the strength random variable (modulus reduction limit at failure) and \( S \) is the model computed response (computed reduction in modulus). The probability of failure is defined as \( p[g \leq 0] \).

RESULTS AND DISCUSSION

The parameter estimation produced a set of material model random variables that best described the behavior of the material under uniaxial loading. The average reduction in modulus compiled from the curve fits to the experimental results was 52% (±18%).

The predicted probability of failure for a set of given strain levels is given in Figure 1 as a function of strain rate. Slower strain rate simulations resulted in lower probabilities of failure for a given strain level. At a strain level of 1.5%, the model predicts a probability of failure of from 62% for the slowest strain rate to 98% for the highest strain rate.

SUMMARY

A probabilistic damage model for bone was developed based on an elasto-visco-plastic damage continuum mechanics (CDM) material model formulation. The uniaxial implementation of the model accurately predicts the experimental behavior of cortical bone uniaxially loaded to failure. Furthermore, using a probabilistic modeling approach, the model can be used to predict the probability of failure given a set of uncertain material model parameters and boundary conditions. This general framework will be implemented into a general purpose finite element code so that fracture predictions of skeletal structures can be made.

REFERENCES


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