ANALYSIS OF TRABECULAR BONE MULTIAXIAL FAILURE USING LARGE SCALE COMPUTATION

Harun H. Bayraktar [1], Ronald Y. Kwon [1] and Tony M. Keaveny [1, 2]

[1] Orthopaedic Biomechanics Laboratory, Department of Mechanical Engineering, University of California, Berkeley, CA

[2] Department of Bioengineering, University of California, Berkeley, CA

INTRODUCTION

Multiaxial failure behavior of trabecular bone is important clinically since multiaxial loads occur *in vivo*, and are associated with hip fractures [1, 2] and implant loosening [3]. Knowledge of the multiaxial failure behavior of trabecular bone also has biological importance since it will enable whole bone finite element models [4] to accurately predict failure loads. To date, no complete multiaxial failure theory for trabecular bone has been developed, mainly due to difficulties involved in experimentally obtaining multiaxial failure data [5]. So far, theories like Tsai-Wu [5] and cellular solids [6] have been used and most recently, by making use of the high-resolution finite element method, a biaxial yield envelope for bovine trabecular bone was obtained [7]. These studies have provided insight into the multiaxial failure of trabecular bone, however, a complete failure criteria still remains unknown. The overall goal of this study was to address this issue computationally by making use of high-resolution finite element models. Specifically, our objectives were to: 1) determine the multiaxial failure envelope for one human trabecular bone specimen in 3-D strain space, and 2) determine the axial-shear behavior of the specimen.

METHODS

A high-resolution finite element model with 66 μm elements obtained from micro-CT images of a human femoral neck specimen was used in this study. Trabecular tissue was modeled as bilinearly elastic with yield strain asymmetry. Post-yield modulus in this model was 5% of the initial modulus. Previously calibrated tissue level modulus and yield strains [8] were used in the materially nonlinear model. In the axial direction, the bone model was less than 3° off-axis, and less than 5° off-axis in the transverse plane from its orthotropic material directions, which were obtained through 6 linear elastic analyses [9]. To determine the multiaxial failure envelope, 114 nonlinear analyses were completed such that they spanned the entire 3-D strain space in 22.5° increments. Similarly, the failure envelope in axial-shear strain space was determined by running 81 nonlinear analyses for 9 different combinations (ε_i-γ_{jk}, $i,k=1,2,3$) in 18° increments. Yield strains along three axes were separately calculated and for the 3-D surface the first chronological yield point was considered.

A custom finite element code employing an implicit incremental method and an element-by-element conjugate gradient solver was used [10]. All analyses were performed on 8 processors of an IBM SP2 parallel supercomputer. Each triaxial and axial-shear analysis required 75 and 60 hrs. CPU time, respectively. In total approximately 13,500 hrs. of CPU time was used for this study.

RESULTS & DISCUSSION

The computed multiaxial failure envelope was similar to a maximum normal strain failure criterion in strain space (Fig. 1, 2), the overall failure envelope being a composite of uncoupled curves along different loading directions (Fig. 1). Hydrostatic pressure reduced the yield strength of trabecular bone by as much as 23% (Fig.2), which is important because commonly used yield criteria such as Von Mises do not predict yielding under hydrostatic pressure. In addition, the results of the axial-shear analysis were consistent with previously reported data for bovine trabecular bone [11] where the failure envelope was asymmetric with respect to the shear axis and maximum shear yield strain occurred in presence of slight compressive loading.

Our results indicate that trabecular bone remains nearly intact in the axial direction although it might be yielded in the transverse direction. Biologically, this may be a way for the bone to protect itself against the effects of damage from non-habitual loading, such as fall. In addition, such behavior may allow healing following damage by protecting the damaged regions after the loading has returned to the physiological state, emphasizing the importance of the microstructure of trabecular in healing and damage repair.

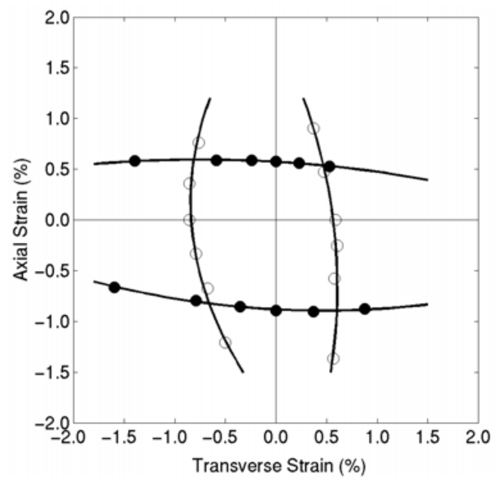

Figure 1. Biaxial plane-strain failure envelope of trabecular bone in axial-transverse strain space. Curves shown are a quadratic fit to the data. Transverse and axial yield behavior are uncoupled.

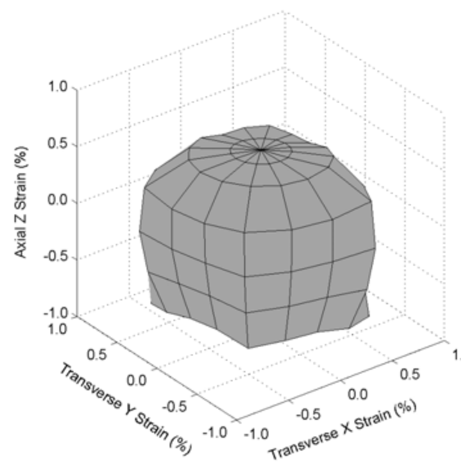

Figure 2. 3-D strain-space failure envelope of one trabecular bone specimen, a result of 114 nonlinear analyses. Rendered surface was obtained by polygons connecting failure points. Unlike common engineering materials, hydrostatic loading reduced the strength of bone.

ACKNOWLEDGEMENTS

NSF (BES-9625030); NIH (AR43784); NPACI (UCB254); NRAC (UCB266); NDRI

REFERENCES

1) Lotz, *et al.*, 1991, J Biomech Eng, 113, 353-360.
2) Lotz, *et al.*, 1991, J Biomech Eng, 113, 361-365.
3) Cheal, *et al.*, 1985, J Orthop Res, 3, 424-434.
4) Keyak and Rossi, 2000, J Biomech, 33, 209-14.
5) Keaveny, *et al.*, 1999, J Biomech Eng, 121, 99-107.
6) Gibson, *et al.*, 1989, Int J Mech Sci, 31, 635-663.
7) Niebur and Keaveny, 2001, Trans. Orthop. Res. Soc., 26, 517.
8) Bayraktar, *et al.*, 2001, Bioeng. Conference, ASME BED-Vol.50, 109-110.
9) Van Rietbergen, *et al.*, 1996, J Biomech, 29, 1653-1657.
10) Niebur, *et al.*, 2000, J Biomech, 33, 1575-1583.
11) Fenech and Keaveny, 1999, J Biomech Eng, 121, 414-422.