

NON-LINEAR FINITE ELEMENT MODELING OF HUMAN VERTEBRAL BODIES

Kay Sun ^a; Michael A.K. Liebschner, Ph.D.^a; Tony M. Keaveny, Ph.D.^b

^aDepartment of Bioengineering, Rice University, TX, USA. MS-142, 6100 Main Street, Houston, TX 77005, (713)348-5797, Fax: (713)348-5877, liebschner@rice.edu

^bDepartments of Mechanical Engineering and Bioengineering, University of California, Berkeley, CA, USA

Introduction Bone fractures associated with osteoporosis are an increasing public health problem affecting the growing elderly population¹. As a result, there is a clear need to prevent osteoporotic bone fractures through early detection of fracture risk, requiring an accurate and precise method of predicting the mechanical behavior of bones. The goal of this study was to develop and validate a non-linear finite element modeling technique that simulates the compressive behavior of a vertebral body. We hypothesized that the incorporation of the multi-linear, asymmetric yield criterion, based on the failure properties of cylindrical samples of vertebral trabecular tissue, into the finite element model can successfully describe the apparent yield behavior of the vertebral body. Our specific aims were to: 1) calibrate the compressive yield and ultimate strains of the trabecular tissue by performing a parametric non-linear finite element analysis on each of the vertebral body; and 2) test the validity of the average calibrated compressive yield and ultimate strains by comparing the predictions of the apparent yield properties to that obtained from mechanical testing.

Methods Twelve finite element models of human vertebral bodies were generalized after scanning and mechanically testing of the specimens. The yield criterion was obtained from the average failure properties of 8 mm diameter cylindrical samples of vertebral trabecular tissue² by specifying linear regions along the contour of the normalized stress-strain curve, starting from the yield point (Fig. 1). Predictions using these yield properties consistently underestimated yield and ultimate strains as well as fracture loads. This observation implied that the mechanical properties of the 8 mm cylindrical trabecular samples may not be appropriate, and illustrated the need to modify the yield criterion. Prior attempt to establish a relationship between yield strain and structural stiffness had failed to obtain a strong correlation ($r^2 = 0.1371$), but the yield strains were observed to have only a small deviation of 18%, indicating the independency of yield strain. We therefore performed a calibration study on the the yield criterion, where trabecular tissue yield strain (ϵ_{yield}) and ultimate strain ($\epsilon_{ultimate}$), along with ϵ_{ab} , ϵ_{bc} , ϵ_{cd} and ϵ_{de} were increased by the same magnitude until the predicted fracture load matched the strength determined from experimental testing. The averages of the calibrated ϵ_{yield} and $\epsilon_{ultimate}$ of the vertebral bodies were then incorporated into the finite element model to reiterate and to validate the new yield criterion.

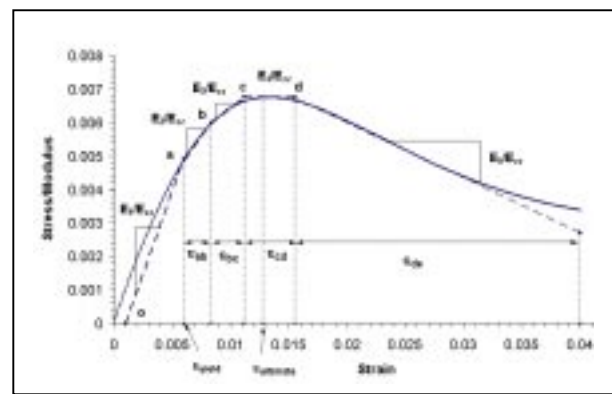


Fig 1. Sectioned normalized stress-strain curve of 8 mm diameter cylindrical samples of vertebral trabecular bone loaded beyond the ultimate point.

Results & Discussion The modified yield criterion for the trabecular tissue, with ϵ_{yield} and $\epsilon_{ultimate}$ of $1.212\% \pm 0.216$ and $2.568\% \pm 0.457$, respectively, successfully predicted the non-linear compressive behavior of human vertebral bodies, with predicted fracture load strongly correlated to measured values ($r^2 = 0.9561$, $p < 0.0001$). Although poor correlations were obtained for the predicted versus measured apparent yield and ultimate strains, this result can be explained by the narrow ranges of each strain observed with the standard deviations of the experimental and predicted yield and ultimate strains of less than 18% and 15%, respectively. In addition, the average predicted apparent yield and ultimate strains differed from the average experimental values by less than 6%, which further validates our modeling technique.

The tissue level yield and ultimate strains determined from the average failure properties of the 8 mm diameter cylindrical trabecular tissue samples, 0.6020% and 1.275% respectively, were significantly lower than the average calibrated strain values of the trabecular tissue. This result along with similar results from a previous study³ may indicate that the bone samples obtained from whole bone behave mechanically different within their continuum compared to the excised sample. Further analysis is required to obtain more information on this discovered behavior.

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