

The Influence of Ductility of Trabecular Tissue on the Apparent Strength of Trabecular Bone

⁺Hausselle, J; ¹Keavany, T M
⁺University of California, Berkeley, CA
jerome.hausselle@berkeley.edu

Introduction

Osteoporosis is widely thought to be associated with a decrease in bone “quality”, which places an individual at increased risk of fracture independent of the risk associated with low bone mass. Although bone quality has many manifestations [1], the most clinically relevant phenotype of reduced bone quality remains to be defined. One possible phenotype is tissue-level ductility. Despite the well-established reduction in ductility that occurs in cortical bone tissue with aging [2], little is understood regarding how any age-related reduction in tissue-level ductility for trabecular bone influences overall trabecular strength, particularly in the highly porous bone that is typical of osteoporosis.

From a mechanics perspective, the relation between tissue-level ductility and apparent-level strength represents a classic multiscale problem. In composites, for example, reductions in ductility at one scale can decrease strength at a higher scale, but the magnitude of this effect depends very much on the hierarchical material and geometric composition of the multiscale composite system [3]. Thus, our goal in this study was to study the effects of tissue-level ultimate strain on the overall apparent strength of trabecular bone. To better understand these effects, we also studied how the tissue-level damage progression is altered by changes in the tissue-level ductility.

Materials and Methods

We parametrically analyzed one highly porous human cadaver vertebral trabecular bone specimen. This specimen ($BV/TV = 7.2\%$) was scanned using micro-computed tomography and converted into a 5-mm cube voxel-based finite element model, using 141,495 40-micron-sized elements. We assumed a tissue-level elastic modulus of 18.0 GPa, a Poisson’s ratio of 0.3, and a von Mises yield stress of 103 MPa. This corresponded to a tissue-level yield strain of $\epsilon_y = 0.57\%$. In our parameter study, we then varied the assumed maximum allowable tissue-level ultimate plastic strain from zero (fully brittle) to infinite (fully ductile), using four intermediate values: $\epsilon_{ult}^p = [0.5, 1, 3, 5] * \epsilon_y$. All analyses, which included large-deformation non-linear effects, were subjected to uniaxial compression along the main trabecular orientation. For those analyses with a limit on the maximum allowable tissue-level ultimate plastic strain, an apparent strain increment of 0.02–0.04% was applied at each step. At each step, any element was tagged as “failed” if it exhibited an absolute value of a principal plastic strain that exceeded the assumed maximum allowable tissue-level ultimate plastic strain. The tissue-level elastic modulus (and strength) of these failed elements was then reduced by 100 and the external loading was then continued to the next step. After each step, we calculated the apparent-level stress and the number of failed elements. All analyses were performed using ABAQUS (v6.6-3, ABAQUS Inc., Pawtucket, RI).

Results

The apparent-level ultimate stress varied two-fold between fully ductile (1.15 MPa) and fully brittle (0.65 MPa) behaviors, with an approximately linear trend between apparent-level ultimate stress and the assumed maximum allowable tissue-level ultimate plastic strain, up until at least 3.5% strain ($R^2 = 0.97$) (Figure 1). At this value, the apparent ultimate stress reached about 90% of the value for the perfectly ductile model. This finding indicates any variation in the tissue-level ultimate plastic strain beyond a value of about 3.5% strain will have little influence on the overall ultimate stress. The proportion of failed tissue at the apparent ultimate point did not show a clear trend ($R^2 = 0.1$) (Figure 2).

Discussion and Conclusion

To the best of our knowledge, this is the first study of its kind that assessed the effects of variations in the degree of tissue-level ductility on the overall apparent strength of trabecular bone. We realize that only one specimen was analyzed, and any results here need to be extended for multiple specimens spanning a wide range of porosities. Further, we ignored tissue-level strength asymmetry, although it is unlikely that accounting for that would appreciably alter our overall findings. Despite these limitations, for this very porous specimen, we found that the

overall bone strength was highly sensitive to the tissue-level ultimate strain for tissue-level ultimate strain values up to about 3.5% strain, but were relatively insensitive beyond that.

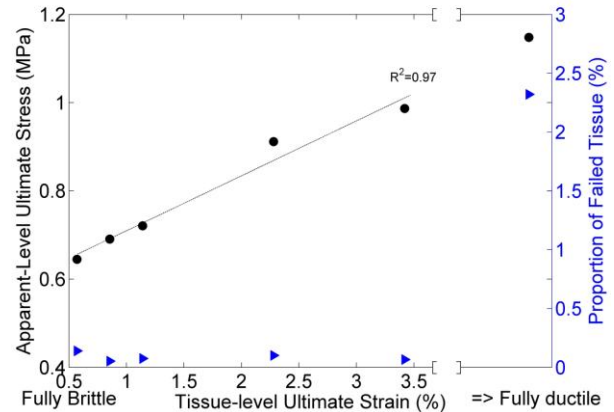


Figure 1: Apparent-level ultimate stress and proportion of failed tissue versus tissue-level ultimate strain.

At this juncture, there is only little information available on the magnitude of the tissue-level ultimate strains in human trabecular bone. In our previous experiments on this issue [4], we found highly variable tissue-level ultimate strain values for individual trabeculae, ranging from 1.8 to 20.2%, with a mean value of 8.8% strain. If tissue-level ultimate strains in trabecular bone are indeed as high as what we found in those experiments, then these current results suggest that variations in tissue-level ductility may not appreciably influence trabecular strength. This would be supported by results from our finite element simulations on whole specimens of trabecular bone, which found excellent agreement between experimental measurements and model predictions of apparent strength; those finite element analyses assumed fully ductile tissue-level behavior [5]. However, such results do not rigorously validate the models because of the dearth of information available on tissue-level ultimate strains for trabecular bone. Thus, there remains a need for more experiments in this area. In the meanwhile, the results of this computational study suggest that tissue-level ductility in trabecular bone can only be an important “bone quality” phenotype if tissue-level ultimate strains in trabecular bone are relatively low.

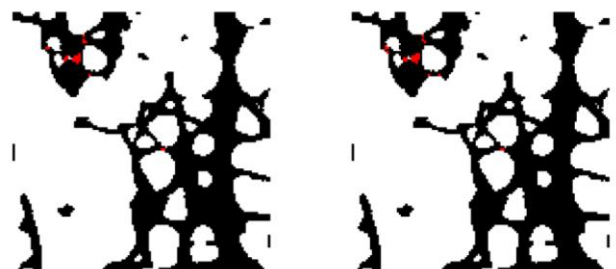


Figure 2: Damaged tissue (in red) at failure for a 1mm-thick section and for tissue ultimate strain of 1.1% (left) and 2.3% (right).

References

1. Bouxsein, M., 2003. *Osteoporosis International* 14 (S5).
2. Mc Calden, R.W., et al., 1993. *The Journal of Bone and Joint Surgery*.
3. Gibson, L.J and Ashby, M.F. 1999. *Cellular solids*.
4. Hernandez, C.J., et al., 2005. *Bone* 37.
5. Bevil, G., et al., 2009. *Journal of Biomechanics* 42.