EVIDENCE OF SEPARATE DAMAGE AND PLASTIC BEHAVIORS IN HUMAN VERTEBRAL TRABECULAR BONE

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INTRODUCTION

The understanding of nonlinear behavior (*i.e.* time-dependence, modulus degradation, and permanent stresses/strains) and the underlying mechanisms in trabecular bone remains limited. We follow the usual assumption that compliance increases are related to the development of damage and plasticity refers to the accumulation of non-recoverable strains or residual stresses. In experimental studies (Keaveny, *et al.*, 1997; Keaveny, *et al.*, 1999) or theoretical models (Zysset and Curnier, 1996) of trabecular bone, damage and plasticity are often linked explicitly. We investigated the separation of damage and plastic behaviors using experimental and analytical investigations by 1.) examining apparent specimen behavior and 2.) applying a constitutive model assuming independent plastic and damage variables along with finite element methods to specimen response.

METHODS

Using established testing methods (Morgan, *et al.*, 2001), cylindrical specimens of vertebral trabecular bone with anterior-posterior (AP), medial-lateral (ML), or superior-inferior (SI) primary orientation were subjected to 4 trapezoidal strain-controlled loading pulses. The first and third pulses had a peak strain of 0.1% and were “diagnostic” and intended to produce negligible damage. The second and fourth pulses had peak strain levels of 0.8% and 1.2% strain to produce successive levels of damage accumulation. Hold periods were 60 sec. and subsequent zero-strain recovery periods were 180 sec. for each pulse. Axial stress-strain data between 0.004% and 0.09% strain for each trapezoidal pulse was fit using a quadratic least-square regression and tangent moduli were defined as the slope of the regressions at zero strain (Bredbenner and Davy, 2003a).

A multiaxial constitutive model for vertebral trabecular bone was developed on the basis of an additive decomposition of strain with viscous, damage, and plastic strain components describing material time-dependence, stiffness degradation, and permanent deformation, in addition to linear elastic strain components. This unified model and an iterative solution scheme were implemented within finite element analyses (FEA) and applied to the experimental response for a typical SI specimen for the full first damaging trapezoid and reloading period of the second damaging pulse (Bredbenner and Davy, 2003b).

RESULTS

A total of 6 AP, 1 ML, and 9 SI specimens were successfully tested. Paired comparison between tangent moduli for all specimens showed a small but significant reduction following the first diagnostic pulse (0.75% mean modulus reduction, p-value = 0.008). Following unloading for the first diagnostic pulse, residual stresses relaxed to negligible levels when allowed to recover at zero strain (Fig. 1).

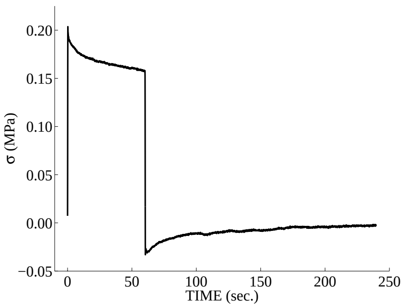

Fig. 1: Experimental response (SI specimen)

The finite element model predicted the experimental response to the first loading ramp quite well and captured the basic features of the reloading ramp, including the stress plateau (Fig. 2.). However, the FEA model did not fully represent the residual strain or hysteresis of the response.

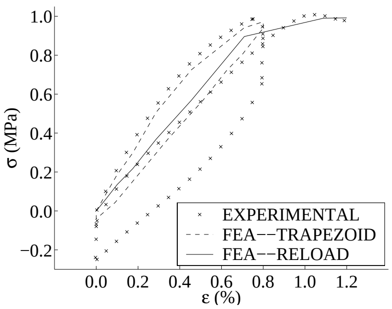

Fig. 2: Experimental vs. FEA response

DISCUSSION

Small, but significant, modulus reduction is demonstrated following the first diagnostic pulse with a peak strain magnitude of 0.1%, well below the yield strain. This evidence, along with studies of damage accumulation under fatigue loading in trabecular bone (Bowman, *et al.*, 1998; Haddock, *et al.*, 2000), calls into question the assumption of explicit coupling of damage and plastic response, at least prior to material yield.

The ability to predict damage measures, such as evolving and accumulated modulus degradation, was achieved despite less satisfactory prediction of permanent deformation, providing further evidence that apparent plastic and damage effects may not be intrinsically related, as often assumed. The actual relationship, particularly the possibility of both coupled and uncoupled damage accumulation, needs further study.

Distinction has been reported between brittle and ductile damage characteristics for trabecular and cortical bone (Keaveny, *et al.*, 1999; Norman, *et al.*, 1998). In continuum damage mechanics theory, unilateral constraints can be imposed on damage evolution (*i.e.* crack closure effects), so that modulus degradation varies with loading conditions, as well as damage accumulation. Although no such distinction is made in the present study, this type of restriction may also lead to improvement in modeling the residual (plastic) response and further work is necessary to determine whether such restriction on the damage description is warranted. It remains that the combined history and path dependence of the mechanical behavior provides a challenging set of problems, even with the controlled geometry and loading of experimental investigations.

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