RELATIONSHIP BETWEEN CYCLES TO FAILURE AND RATES OF DAMAGE AND CREEP IN FATIGUE TESTS OF HUMAN CORTICAL BONE

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INTRODUCTION

The fatigue failure of bone has been implicated in a number of pathologies. Both implant design and clinical assessment would be enhanced by the ability to simulate fatigue failure. Like most materials, bone exhibits a decreasing fatigue life with increasing stress. During fatigue, bone also creeps and loses stiffness. The adequate characterization of all of these effects is necessary for finite element simulations of fatigue failure.

Using human cortical bone samples, many authors have studied fatigue life as a function of applied stress [e.g. 1,2,3]. Loss of stiffness (typically Young's modulus) due to fatigue has also been studied [2,3], as has creep [4].

Here we present the results of fatigue tests of cortical bone samples taken from four individuals. Samples were tested in tensile fatigue until failure. Unlike earlier works examining the cumulative modulus loss, we find the rate of stiffness loss, which is fairly constant over the majority of the fatigue life. We will present data of applied maximum stress, cycles to failure, rate of modulus loss, and creep rate.

METHODS

Samples of bone were collected from cadavers of four individuals, females aged 55, 69, and 79; and a male aged 55 at death. All samples were taken from the mid-shaft femoral cortex and were oriented with the long axis of the bone.

Samples were tested in tensile (0-T) fatigue until fracture occurred. For each test, we recorded the cycles-to-failure and applied maximum stress, as well as the modulus and creep during the test. Applied stresses were normalized by the tangent modulus, E^*, for each sample. These were determined by low stress tests of the sample before fatigue testing.

As is commonly done in both bone and general damage mechanics, we defined material damage, d, as the fractional loss of modulus,

$$d = 1 - E_i/E_0$$

where E_i is the modulus at the i-th cycle, and E_0 is the undamaged secant modulus.

Both creep and damage were converted to "per-cycle" rates, by dividing the total growth between 10 and 90 percent of the life by the number of cycles during that period. All samples approximated a constant rate of both damage and creep during this portion of the test.

We compared the relationship between normalized stress (σ/E^*) and cycles to failure (N_f), damage rate ($\Delta d/\Delta n$), and creep rate ($\Delta\varepsilon_c/\Delta n$) using power law relationships. Regression analysis was performed via an Excel spreadsheet to determine the constants of regression and goodness of fit, quantified by r^2 values. Finally, the relationship between damage rate, creep rate, and the cycles to failure were studied.

RESULTS

A total of 31 samples were successfully tested, with results presented here. Maximum stresses due to the cyclic load ranged from 0.003 to 0.0067, corresponding to a cycles to failure from 10^6 to 49. Creep rates were on the order of 10^4 to 10^{11} per cycle, while damage grew at average rates of 10^2 to 10^8 per cycle.

A summary of results of the regression analysis are presented in Table 1. We also present graphs of the quantities in Figures 1.

		$y = A\,x^B$		
x	y	A	B	R^2
σ/E^*	N_f	3.8×10^{-29}	-13.5	0.82
σ/E^*	$\Delta d/\Delta n$	4.7×10^{35}	17.1	0.81
σ/E^*	$\Delta\varepsilon_c/\Delta n$	2.3×10^{34}	17.3	0.80
$\Delta d/\Delta n$	N_f	0.72	-0.78	0.98
$\Delta\varepsilon_c/\Delta n$	N_f	0.038	-0.76	0.96
$\Delta d/\Delta n$	$\Delta\varepsilon_c/\Delta n$	0.015	0.99	0.95

Table 1. Results of fitting relationships of normalized stress, cycles to failure, creep rate, and damage rate to power laws. All results were significant (P<0.0001).

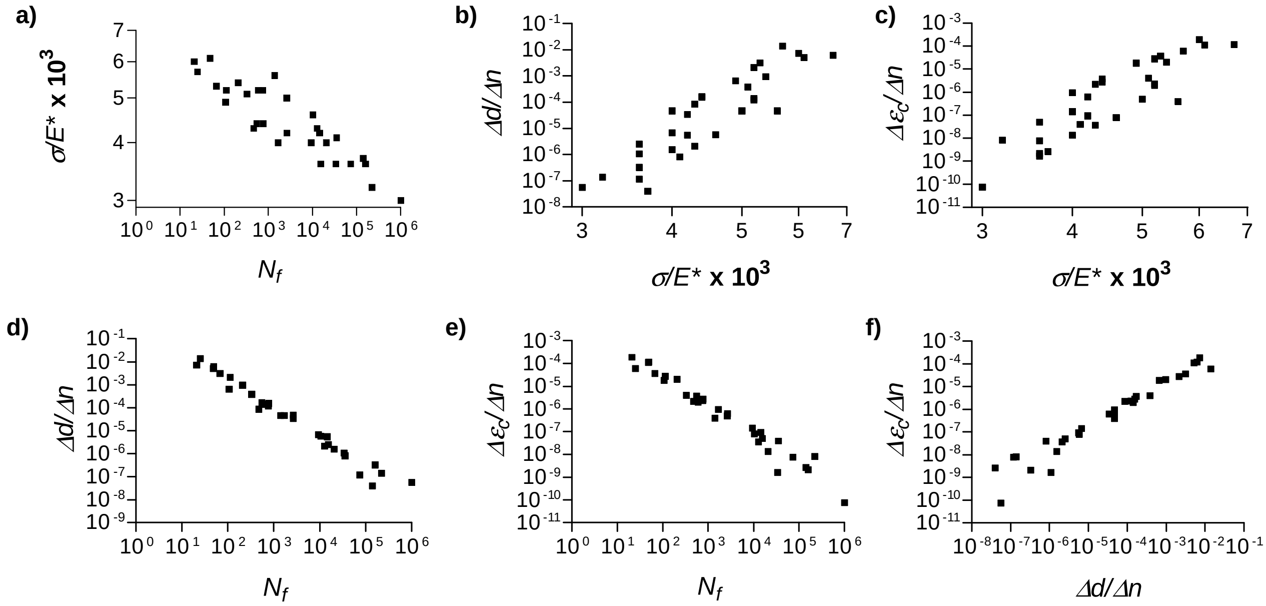

Figure 2. Graphical relationships between results.

DISCUSSION

As reported in other works, cycles to failure [1,3,4], damage [3,4], and creep rates [2] all correlate well with applied stress (Table 1, Figure 1a-c). However, when we compared cycles to failure as a function of damage rate (Figure 1d), we found exceptional agreement as measured by the r^2 value in Table 1. Results were nearly as strong for creep rate (Figure 1e). Finally damage rate and creep rate correlate very strongly (Figure 1f). Such strong correlations are furthermore remarkable when it is considered that, they are from four different individuals.

Where scatter does appear in comparisons of damage rates, creep rates, and cycles to failure, is in low-stress, high-cycle tests. This may be due to a loss of accuracy in experimental measurements, or different mechanisms leading to failure of bone.

It is also worth noting that the initial (0-10%) and final (90-100%) portions of life are not addressed in this study. The damage growth and creep in these areas appears more random.

As we show here, cycles to failure is better predicted as a function of damage rate than stress. This has a theoretical foundation. Modulus loss has been shown to correlate with the presence of microcracks[5]. Failure, likewise, is attributed to accumulation and coalescence of microcracks. Thus, both measures are indicative of the growth of microcracks in the sample during the test.

Although stress clearly influences microcrack growth (and/or other internal damage), internal variations in the structure of the sample, such as mineral density and distribution, cause variations in outcomes. While normalizing stress by the initial modulus is a step towards accounting for sample variation, these results show how more deterministic these predictions could be.

There are two immediate and practical outcomes of this observation. First, this promotes the observation of damage or creep as predictors of failure in bone. Such observation has already been promoted for orthopedic implants [6].

The second implication is on computer simulations. Because the rates of damage growth and creep growth are so consistent with cycles to failure, the number of degrees of freedom when performing parametric studies could be reduced. For example, a single choice of stress dependent constants for cycles to failure would determine the parameters for damage and creep.

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