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Damage mechanisms and failure modes of cortical bone under components of physiological loading ☆

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Abstract

Fatigue damage development in cortical bone was investigated in vitro under different mechanical components of physiological loading including tension, compression, and torsion. During each test, stress and strain data were collected continuously to monitor and statistically determine the occurrence of the primary, secondary, and tertiary stages associated with fatigue and/or creep failure of bone. The resultant microdamage and failure modes were identified by histological and fractographic analysis, respectively. The tensile group demonstrated Mode I cracking and the three classic stages of fatigue and creep suggesting a low crack initiation threshold, steady crack propagation and final failure by coalescence of microcracks. In contrast, the compressive group displayed Mode II cracking and a two-stage fatigue behavior with limited creep suggesting a high crack initiation threshold followed by a sudden fracture. The torsion group also displayed a two-stage fatigue profile but demonstrated extensive damage from mixed mode (Modes II and III) microcracking and predominant time-dependant damage. Thus, fatigue behavior of bone was found to be uniquely related to the individual mechanical components of physiological loading and the latter determined the specific damage mechanisms associated with fatigue fracture.

Keywords: Fatigue; Damage mechanisms; Mechanical testing; Cortical bone; Physiological loading; Failure modes

Introduction

In vivo strain measurements have shown that during normal daily activities compact bone undergoes tensile, compressive, and torsional loading [6,10,14,23,40]. The magnitudes of in vivo loading are generally below the level required to cause fracture. However, it is well known that cyclic loading in bone results in degradation of mechanical properties including strength and stiffness, leading ultimately to fatigue failures, also termed stress fractures, at load levels well below the fracture loads [3,11,32]. Despite their clinical significance, fatigue failure mechanisms in cortical bone under different mechanical components of physiological loading are still unclear. Such information is necessary to identify the critical loading component and damage mechanism that cause fatigue failures under physiological conditions involving superposition of tensile, compressive and torsional loadings.

Previous studies under Zero-Compression (0C: 0 to $-\sigma$), Zero-Tension (0T: 0 to $+\sigma$), and Zero-Torsion (0R: 0 to $+\tau$) have offered limited insight into the fatigue behavior of bone because they have been restricted to either mechanical or histological characterization of damage accumulation. Consistent with failure in brittle materials, Gray and Korbacher [20] and Pattin et al. [28] show that 0C loading causes modulus loss only in

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the latter half of fatigue life. Conversely, 0T loading resulted in predominant time-dependent damage [8] and demonstrated the three classic stages of fatigue [17] associated with periods of crack initiation, crack growth, and crack coalescence [33,41]. Recent studies [16,21,35] have shown shear damage to be responsible for fatigue failure under torsional loading. It is noteworthy that, despite these individual studies, limited information is available on specific failure modes and damage mechanisms in cortical bone under tensile, compressive and torsional loadings. Furthermore, as daily activity includes simultaneous application of tensile, compressive and torsional loading, it remains unknown which mechanical loading component is the most damaging to the structural integrity of bone.

Hence, distinct from previous studies, the primary goal of this study was to identify the damage mechanisms and failure modes associated with the individual mechanical components of physiological loading using four different characterization techniques (stiffness loss, creep behavior, histology, and fractography). A secondary goal was to identify the loading mode that would accelerate fatigue fractures and significantly deteriorate the structural integrity of bone under physiological loading. It was hypothesized that torsional loading, associated with mixed mode failure in engineering composite materials [22], would be the most aggressive form of loading. Cylindrical dumbbell specimens, machined from bovine cortical bone, were subjected to cyclic tensile, compressive and torsional loadings. The resulting fatigue and creep characteristics of cortical bone were measured in conjunction with histological and fractographic analyses of bone microdamage and fracture.

Experimental procedure

Thirty cortical bone specimens were prepared from the mid-diaphysis of four 18–24 month old bovine tibiae obtained from different animals. Diaphyses were sliced into longitudinally oriented segments and were turned on a CNC lathe (Denford Microturn; Medina, OH, USA) into cylindrical dumbbell specimens with 10 mm gage length and 3 mm diameter (7–8 specimens/tibia). During all phases of preparation, specimens were maintained in wet conditions and were stored frozen at −20 °C until testing.

Specimens were randomly allocated into three groups of ten samples each, and were tested on a MTS MiniBionix system with custom-made grips in an environmental chamber with continuous irrigation of Ca^{++} buffered 0.9% saline at room temperature. The loading regime for the three groups included:

I. Zero to Tension at 50% of the Ultimate Tensile Strength (UTS)
II. Zero to Compression at 50% of Ultimate Compressive Strength (UCS)
III. Zero to Torsion at 30% Ultimate Shear Strength (USS)

The specific loads levels were based on previous studies which demonstrated that the fatigue response at these load levels allows damage to form under all three loading modes and remains similar to lower physiological load levels while reducing testing time [16,28,40]. All fatigue tests were conducted at a frequency of 2 Hz under load control using a haversine wave profile. Failure was defined as either complete separation of the specimen into two parts within the gauge length or a 20% reduction in the torsional fatigue load levels [40]. If fatigue life exceeded 250,000 cycles, loading was discontinued and the specimen was considered to be run out.

During testing, load deformation data were collected continuously for every specimen to monitor mean strain values and to calculate secant tensile, secant compressive or secant shear moduli. Displacements in the axial and angular directions were also monitored for any apparent erratic displacement caused by slippage. Mean strain values were collected corresponding to the mean applied stress and plotted against fatigue life. Reduction in modulus was plotted against fatigue life and compared between the three types of loading. Paired t-tests were used within each group to compare initial moduli with reduced moduli at ten percent increments of fatigue life to determine primary, secondary, and tertiary phases of fatigue in bone [33]. Once a difference ($p < 0.05$) was detected, the new reduced moduli were chosen for further comparison.

After testing, two fracture surfaces from each group were dehydrated in an ascending series of ethanol solutions (70%, 80%, 90% and 100%) and platinum coated for examination under a scanning electron microscope (JEOL 840). From each group, four specimens (two fractured and two run-outs) were also selected for histological examination. The preparation of these specimens included bulk staining with basic fuchsin [5], followed by polymer embedding and sectioning into 100 μm thin slices along the transverse and the longitudinal directions. The slices were examined under fluorescence microscopy (Nikon Eclipse E600; Excitation 528–553 nm) to identify damage morphologies and osteon density.

Results

Because four run out samples were present in the 0T and 0R groups and five run out samples were present in the 0C group, fatigue life could not be compared between 0C, 0T, and 0R groups (0C = 133,292 ± 133,292, 0T = 120,560 ± 123,065, 0R = 111,472 ± 120,979). However, significant differences ($p < 0.001$) were found in the total modulus loss between the fractured specimens in each loading group. Specimens fractured by torsional loading were found to undergo the highest stiffness loss (73% ± 9.5) followed by compressive (24% ± 9) and tensile loadings (11% ± 0.063).

Modulus degradation profiles between the groups were also determined (Fig. 1). 0T specimens displayed

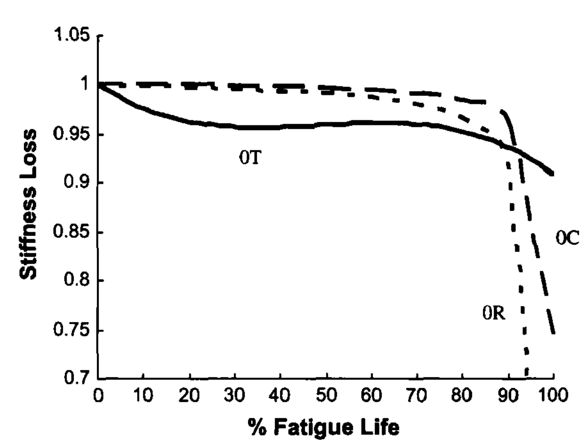

Fig. 1. Average stiffness loss profiles for specimens subjected to Zero-Tension (0T), Zero-Compression (0C), and Zero-Torsion (0R).