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G. P. Parsamian

V. L. Kish

Timothy L. Norman
Cedarville University, tnorman@cedarville.edu

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DAMAGE EVOLUTION AND FRACTURE BEHAVIOR OF HUMAN COMPACT BONE SPECIMENS IN 3-POINT BENDING

*Parsamian, G; *Kish, V; +*Norman, T (A-NIH)
+*Musculoskeletal Research Center, Morgantown, WV. West Virginia University, Morgantown, WV 26506-9196, 304-293-1072, Fax: 304-293-7070,
tnorman@wvu.edu

Introduction

Post-yield behavior of materials contains key information about their characteristics including rheological characterization, time (history) dependence and damage initiation and accumulation processes. The incomplete understanding of damage processes is greatly responsible for the absence of unique constitutive relations for bone, the importance of which is unarguable for the applications of engineering methods including designing prostheses, describing adaptive changes and studying fracture causes and behavior. In recent years, investigations on the damage behavior of both cortical and cancellous bone have attained considerable attention [1-7]. The goal of this study was to investigate damage evolution in human cortical bone specimens by 1) introduction of various damage measuring parameters and 2) determinination of their evolution laws under three-point bending.

Methods

Forty-two beam specimens (2.3mmx4mmx48mm) were wet machined in pairs from anteromedial, anterolateral and posterior regions of tibial sections obtained from a 58-year-old male cadaver and immediately frozen (at -20°C) in airtight containers until testing. Fourteen specimens from the anterolateral (4 pairs) and posterior (3 pairs) cortices were separated into two groups (G1, G2) by randomly selecting one from each pair to be used for the preliminary experiments. Afterwards they were placed in a 3-point bending fixture with a 40 mm span and tested on a servohydraulic testing machine. The loading protocol consisted of load-unload cycles under displacement control with gradually increasing maximum deformation. A constant displacement rate of 166.67 μm/sec was applied for both loading and unloading phases resulting in strain rate of $0.00375s^{-1}$. Specimens from G1 were tested with an aspect ratio (span to height ratio) of 17.4:1 and G2 with 10:1. In order to measure strains at the outermost fibers of beams (tensile side), two retroflective markers were attached 4mm apart and centered at the midspan axis of the surface perpendicular to the loading direction. Their relative displacements at the outermost location was recorded using a laser extensometer (Electronic Instruments Research).

Load and deformation data was recorded and the stresses in the elastic range of loading in the outermost fibers were calculated using equations derived from Bernoulli's Beam Theory. Yield, total and residual strains, yield and peak stresses together with Young's moduli for each loading and unloading cycle were determined. Damage evolution was characterized by means of two parameters $\boldsymbol{\alpha=1-E_N/E_0}$ (stiffness loss) and $\boldsymbol{\beta=1-\varepsilon_{rN}/\varepsilon_{TOT}}$ (where ε_{rN} = residual nonlinear strain after Nth cycle, ε_{TOT} = total strain at Nth cycle). All tests were performed at room temperature and the specimens were constantly kept wet.

To assess damage, fractured specimens were fixed in 100% alcohol and stained in ascending solutions of basic fuchsin dye. Two 250μm slices were cut and polished; one from the midspan region close to the fracture surface and another from the overhanging side of the specimen. These were observed using Laser Scanning Confocal Microscope (Zeiss LSM 510).

Results

Damage evolution parameter $\boldsymbol{\alpha}$ demonstrated a declining behavior varying from linear to nonlinear (curvilinear) in the nature of its relationship with number of cycles. Parameter $\boldsymbol{\beta}$ demonstrated a consistent linearly decreasing behavior for both groups. Typical relationships between $\boldsymbol{\beta}$ and the number of cycles are shown (Figure 1). Mean proportionality constants were 0.04087±0.0086 and 0.03013±0.0031 for G1 and G2, respectively.

Fracture patterns demonstrated mixed mode failure behavior for G1 specimens and shear failure for G2. Histological observations revealed characteristic microcracking patterns in compressive and tensile sections [7] and extensive delamination patterns along the cement lines and interlamellar spaces in the shear zone. It was also interesting to observe delamination failure patterns in the sections obtained from the overhanging parts of the specimens.

Discussion

Damage development in materials is a multistage process initializing at the material's microstructure. Characterization of thermomechanical responses of the damaging material consists of determination of effective moduli and damage evolution laws. Compact bone, being quasi-brittle in nature, is ideally suited for adapting various components of the generated strains as parameters for damage evolution studies. The analysis of temporal variations of yield strain, peak stresses or post-yield strain was not successful in predicting observed stiffness variations. However, the ratio of residual and total strains did demonstrate an interesting trend. The amount of the decrease in the ratio was the same after successive cycles. This is an important observation considering that it can be very useful in successful decomposition of total strain into elastic, nonlinear and damage parts. It was also interesting to observe that this was true for the case when shear stresses have significant influence; this suggested a loading mode independent phenomenon.

Analysis of failure patterns revealed that mixed mode failure was the dominant mode of failure [8] for high span to height ratio beams resulting in failure along the tensile fibers followed by propagation along high shear stress planes (close to neutral axis). The presence of delamination cracks in the neutral axis region of the sections obtained from the overhanging regions of beams could give interesting new insights into the characterization of interfacial properties within bone tissue.

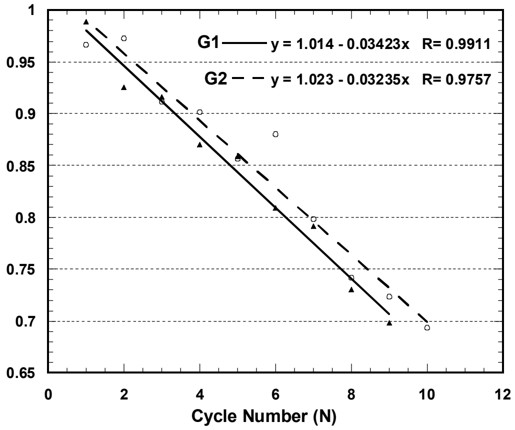

Figure 1. Typical relationships of β and the number of cycles for a specimen from G1 and a specimen from G2.

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