Micromechanical Multicyclic Creep Tests of Human Cortical Bone

The Challenge:

Determine the Mechanical Properties of Small Bone Specimens

Background

ElectroForce® 3200 Test Instrument with Standard 4-point Bend Fixture

Bone is a living organ whose structure and function are affected by various factors including mode and frequency of loading, age, and disease[1]. It is a hierarchical composite material that is made up of a collagen matrix and a mineral reinforcement. This dissimilar structure in the transverse and longitudinal orientations results in the anisotropic mechanical behavior of bone[2].

The material properties of bone are being researched on multiple levels (macro, micro, cellular) in order to gain a better understanding of the material changes and their relevance to applications such as fracture assessment and prediction. This research varies from analyzing the forces acting upon whole bone structures, micro-scale machined bone specimens and individual collagen fibers. To add to the complexity for researchers, each level interacts with the next level, and bone has demonstrated a size dependence on its mechanical properties[3].

One specific area of research involves the examination of age-related effects of collagen on the mechanical properties of bone. Creep behavior, commonly used to assess polymeric materials, is appropriate for studying the effects of age-related changes in the collagenous component of bone.

Meeting the Challenge

Research performed at Rensselear Polytechnic Institute by Simon Tang and Deepak Vashishth studies the effects of multicyclic loading on human cortical bone[4]. The Electroforce® 3200 test instrument, in conjunction with a custom 4-point bend fixture, was used to perform the testing in order to assess the viscoelastic and viscoplastic properties of bone on a micro-scale level[5]. This study has a threefold purpose: 1) to study the creep response of bone to multicyclic loading under anatomically-correct loading; 2) to perform these types of tests on a small scale; and, 3) to illustrate and identify age-related trends on the mechanical properties of bone.

Materials and Methods

Eighteen longitudinal specimens of cortical bone, 1 mm thick, were harvested from the medial side of the femur below the lesser trochanter from 6 human cadavers (3 specimens per donor). The specimens (Figure 1) were then cut into parallelpipeds with dimensions of 0.8 mm~1.2 mm x 0.8 mm~1.2 mm x 6.0 mm using a diamond saw blade. Small markings were made on each specimen outside of the mid-span section to note the anatomically correct loading orientation. This was done to ensure that each microbeam was loaded in a manner similar to *in vivo* conditions.

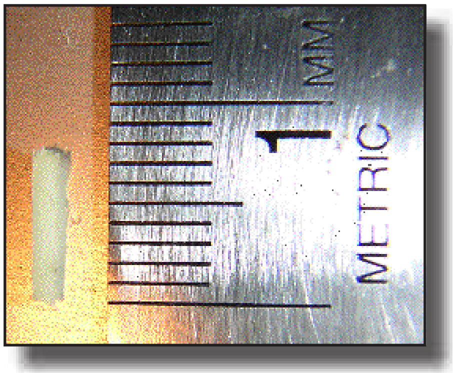


Figure 1 *- Cortical bone specimen sizing.*

Materials and Methods (Continued)

A custom designed 4-point bend fixture (Figures 2 and 3) was attached to the ElectroForce® 3200 instrument. The bend fixture, which has adjustable upper and lower spans, was set so that the upper span was 0.70 mm and the lower span was 2.68 mm. The support points of the top and bottom fixtures are rounded blade edges, thereby minimizing the damage to and contact with the specimen.

Figure 2 *- Bottom span of custom 4-point bend fixture.*

The Electroforce 3200 test system utilizes a proprietary electromagnetic linear actuator design, which provides exceptional force and displacement control. For these tests, the standard system load cell [50 lbf (225 N)] and standard system linear variable displacement transducer (LVDT) [+/- 6.5 mm] were used. This configuration was suitable for the tests due to the robustness of the system and the level of measurability achieved by the LVDT. A customer-provided high resolution digital camera was used to take photographs of the specimens to independently confirm strain measurements.

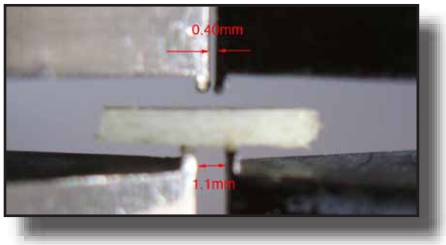


Figure 3 *- Close-up of specimen in custom 4-point bend fixture.*

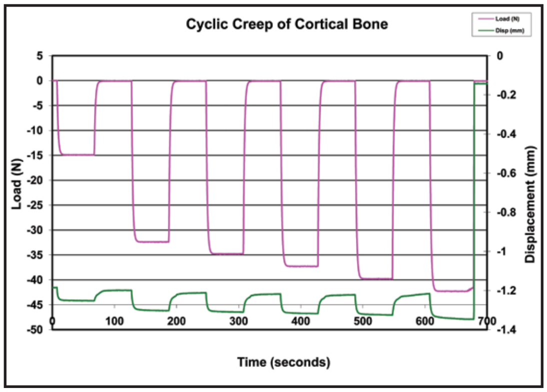


Figure 4 *- Sample data of multicyclic creep test of cortical bone.*

The WinTest® control software's block waveform function was used to implement the test protocol. An initial monotonic displacement-controlled test to 0.5% strain (based upon each specimen's geometry) was applied to each specimen to determine the elastic bending modulus. The multicyclic testing was subsequently performed in load control (Figure 4) and the force, displacement, and geometric parameters of each specimen were used to calculate the stresses and strains desired. The waveform itself consisted of a ramp to a load level, holding that load for 60 seconds, ramping to a nearly unloaded state at -0.1 N, again holding for 60 seconds, and then ramping to a load larger than the previous value. This process was repeated until all loading levels were completed. The stress values were 35, 65, 70, 75, 80, and 85 MPa.

Results and Summary

The bending modulus, which was calculated from the initial bending test, was found to range from 3.7 to 14.7 GPa. Based upon the agreement of these values with those found in existing literature for similar specimen sizes and loading configurations, it was determined that micromechanical testing can now be used to determine the mechanical properties of smaller bone specimens.

In addition, the study also revealed age-related differences in the material properties of bone. Significant differences were observed in the creep rate and creep strain between younger and older donor bone (Figures 5 and 6). It was hypothesized that these results demonstrate a degradation of the collagen network in bone as creep is exhibited by polymers, and the primary polymer in bone is collagen.

Figure 5

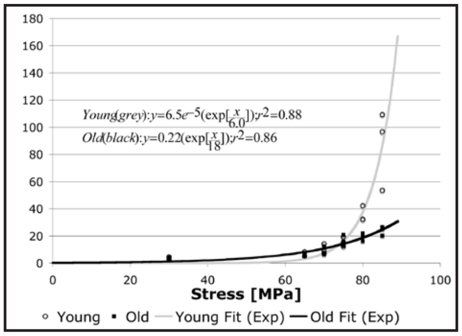
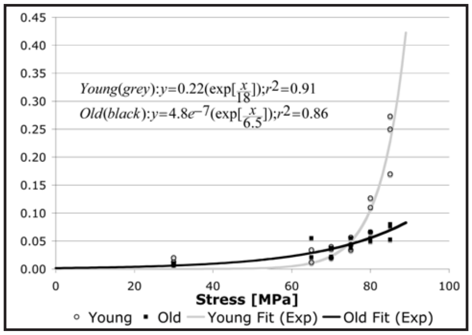


Figure 5 *- Steady state creep rate plotted against load with exponential fits. The creep rate was determined via a linear regression from t=10 to t=50 during the 60 second hold at each load level.*

Figure 6 *- Creep strain plotted against load with exponential fits. The percent strain was determined by comparing the initial unloaded state with the unloaded state immediately after the removal of the load at each level.*

Figure 6



References

1) Moore KL, Dalley AF, Clinically Oriented Anatomy. 4th Ed., Lippincott Williams & Wilkins, Maryland, 1999.
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