Failure of Human Rib Cortical Bone during Low Rate Compression Tests

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I. INTRODUCTION

Accurate material failure properties are essential for finite element (FE) models to correctly predict injury. For cortical bone, failure strain is particularly important as the fracture of cortical bone is strain-controlled [1]. Despite this, compressive failure properties for cortical bone are rarely reported in the literature. This omission may be a result of cortical bone's ability to sustain load at deformations (strain) considerably beyond the ultimate point, particularly at low loading rates [2-4]. In these cases, cortical bone specimens may be sustaining load post-fracture [2], post-fragmentation (catastrophic failure) [3], or even without experiencing final failure [4]. Given the ability of cortical bone to withstand compressive loading beyond the ultimate point or failure, it can be difficult to identify an exact failure strain. Even the definition of failure could be subjective, with the appearance of fracture lines, macroscopic cracking, or fragmentation into separate pieces all constituting some form of failure of the material. Furthermore, previous studies evaluating compressive loading on human cortical bone have been limited to the long bones, and it is unclear how failure behaviour in the rib may differ. Therefore, the purpose of this study was to evaluate the macroscopic damage and load-bearing capabilities of human rib cortical bone samples loaded beyond the ultimate point in compression.

II. METHODS

Five rib cortical bone samples were obtained from the pleural rib cortex from one male subject (age=45 yrs). The cylindrical samples, aligned with the long axis of the rib, were fabricated from whole ribs using a low-speed diamond saw and a Computer Numerical Control mill. The target sample height and diameter were 2 mm and 1 mm, respectively, to maintain a 2:1 ratio [5]. Uniaxial compression tests were performed on an electric-dynamic material testing machine (800LE4, Test Resources Inc.) using a custom-designed, small-sample compression press with rigid loading platens (Fig. 1), a deflectometer (Model 3540-001M-ST, Epsilon Technology Corp), and a uniaxial load cell (1210ACK-300-B, Interface). All samples were tested at a target strain rate of 0.005 strain/s. Each sample was compressed to a different strain after reaching the ultimate stress, with the exception of the final sample, which was compressed as much as possible without risking damage to the experimental devices. The observed maximum strains were 3%, 6%, 16%, 21%, and 50%. After testing, all samples were assessed for evidence of macroscopic damage. All data were collected at 500 Hz, down-sampled to 100 Hz, and then filtered using a 1-49 Hz notch filter. The test loads were divided by the initial cross-sectional area of each respective sample to calculate stress. Strain was calculated by dividing the deflection by the initial height of each sample.

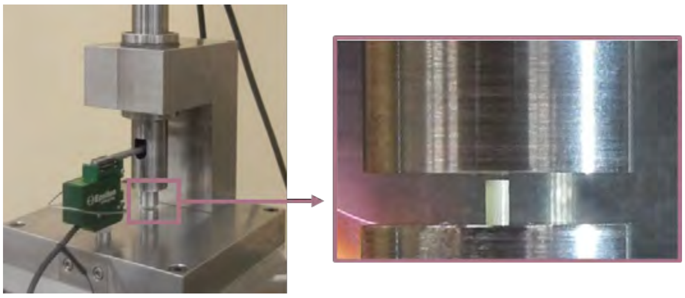

Fig. 1. Custom compression press (left) and a sample on the lower loading platen (right).

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III. INITIAL FINDINGS

The stress-strain curves for all samples exhibited a small drop in stress after the ultimate point, with continued ability to bear substantial load, relative to the peak load, until unloading (Fig. 2). Despite the differences in strains, the 3%, 6%, and 16% strain samples showed qualitatively similar levels of damage (Fig. 3). The 21% sample exhibited slightly more damage and had a small drop in stress at ~15% strain. Oblique fracture lines could be observed in all of these samples, but none developed large macroscopic cracks that led to fragmentation or catastrophic failure. Even the sample loaded to 50% strain was mostly intact, with visible macrocracks, but had not yet completely fragmented or experienced catastrophic failure. This sample sustained a relatively constant load until a distinct drop in load around 25% strain. Afterward, the sample still sustained over 50% of the peak load until the test ended.

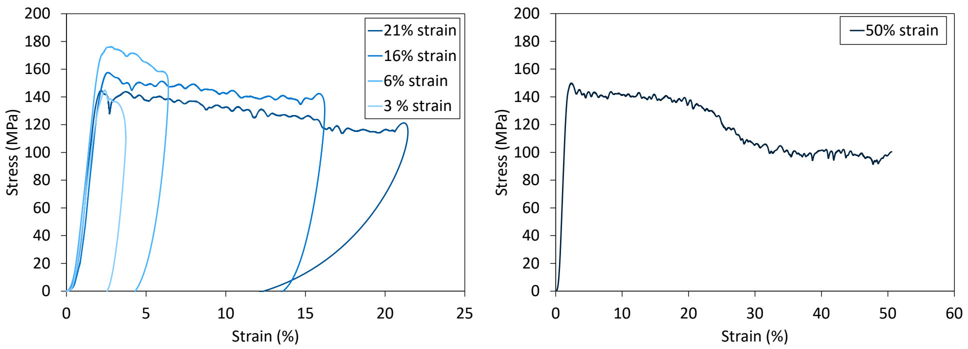

Fig. 2. Stress-strain curves for samples loaded to 3%, 6%, 16%, and 21% strain (left) and one sample loaded to 50% strain (right). The 50% sample experienced a dwell period before unloading so the curve was truncated.

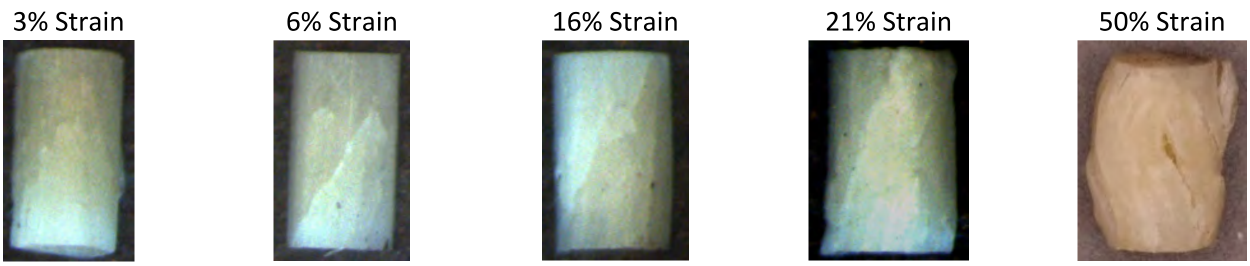

Fig. 3. Pictures showing the damage to each sample post-loading.

IV. DISCUSSION

The post-ultimate stress-strain behaviour observed in this study was comparable to other studies conducted on cortical bone at similar loading rates; however, these studies did not include data beyond 7% strain [5-6]. Similarly, the oblique fracture lines and cracks observed in this study were consistent with the oblique and conical fractures reported in previous studies [4][6]. The samples loaded from 3% to 21% strain all showed fracture lines without much additional macrodamage accumulation over this range, indicating that these fracture lines were initially formed at or before 3% strain, which is near the ultimate point. Macrocrack formation is known to occur after the ultimate point; however, tissue disruption was observed only in the 50% strain sample. Due to the large gap between 21% and 50% strain, it is unclear when these cracks formed, but it was likely coincident with the drop in stress at 25% strain. The uncertainty in damage timing and lack of complete sample failure observed in this study demonstrates the need for further work to explore compressive failure in rib cortical bone. Future work should increase the density of strain levels tested to better evaluate when certain types of macrodamage occur. Additionally, higher strain rates should be evaluated since previous studies have demonstrated that loading rate affects stress-strain curve shape and failure progression [5].

V. REFERENCES

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