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FATIGUE LIFE PREDICTION IN A CANCELLOUS BONE STRUCTURE

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ABSTRACT

Repetitive cyclic loading of bone during daily course activities is one of the primary causes of bone fracture in humans. Stress and fragility fractures in elderly generation that have been associated with cancellous bone result in reduction of bone strength due to osteoporosis. The aim of this study is to predict the failure of cancellous bone as a function of density and porosity. In this study, two of medial-condlye bovine cancellous bone specimens were loaded in cyclic compression. Monotonic static compressions were tested to determine the boundary conditions of fatigue testing. The loading transferred to the cancellous bone are chosen between 16%-55% of the ultimate stress. The result showed different hysteresis loop with large variation in strain between both medial-condyle of cancellous bone. The two specimens adapt different physiological apparent load until failure. From the results, it can concluded that the same anatomic site with different value of bone density and porosity imply a large effect of the fatigue behavior in relation to modulus degradation and strain changes.

Keywords : *Fatigue, Cancellous Bone, Porosity, Density*

1.0 INTRODUCTION

Repetitive cyclic loading of bone during the daily course of activities is one of the primary causes of bone fractures in humans [1]. A typical loading for bone is cyclic loading that is variable in time; behaviors under such loading can termed ‘fatigue behaviors’ [2]. The study of bone fatigue can occur at strain magnitudes comparable to those measured on living bones in the physiological loading environment during vigorous activity in animals and humans [3]. Significance amounts of fatigue damage occur throughout the loading history; damage which must be repaired in order not to lead to fatigue failure of skeletal elements.

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Excessive fatigue loading of bones in vivo can lead to micro crack accumulation and coalescence, reducing stiffness and strength and increasing the risk of fracture [4]. Aged-related osteoporosis is a systemic disease characterized by reduced bone mass and deteriorated bone micro-architecture which associated in decrease in strength and in Young's modulus as a result of significant disturbance in bone structure [2]. This includes a decrease in the number of cancellous and their thickness. The advantage of using the compressive fatigue tests is the ability to conduct variable test with the use of small numbers of samples. Even if these failure types are of known, data for cancellous bone exposed to cyclic loading are still insufficient.

Studies have shown that the volume fraction of cancellous bone strongly influences the mechanical properties specifically the compressive strength, stiffness and elastic modulus. Hence, understanding the damage properties of cancellous bone is important to understand bone fractures. The proximal femoral head exhibited of hip contact forces has been studied for average patient [5]. The contact force has developed the maximum peak forces during human activities and it has contributed such a loading method to be applied on fatigue analysis in cancellous bone. The relationship between morphology of cancellous bone to the mechanical properties and failure mechanism can be accessed through experimental and computational means [6]. Computer simulation (microCT) has become more accessible in the past years, but these data are still connected to many problems such as the high costs of the microCT scans and the rare availability of the high end scanning facilities.

The underlying deformation and damage mechanism within cancellous bone with respect to the physiological activities are not yet sufficiently investigated. Thus, it is necessary to evaluate bone quality parameters such as the morphological index of the cancellous bone structure. It is suggested that more than 75% of the load adjacent to endplates is carried by cancellous bone [7]. In this study, loading were applied resulted from the human gait analysis on femur transferred to the cancellous bone and were analyzed to mimic the normal walking condition. In order to understand the relation between morphology and the prediction failure of cancellous bone, an understanding in knee's fundamental biomechanics and gait loading is a must [8]. To obtain the boundary conditions, the monotonic test were first tested and performed into the fatigue testing. This paper aims to determine the prediction of the compressive fatigue behavior on cancellous bone specimens as a function of density, porosity and volume fraction.

2.0 MATERIAL AND METHOD

2.1 Specimen Preparation

Using a Bosch circular saw, specimens of cancellous bone were taken from fresh bovine femoral section. The femur bone were divided and cut into section of medial-condoyle with the physiological axis [9]. The cancellous bone were then again extracted using a precision cutting tool (Allied Techcut,USA) into a cubic shape (10mm x 10mm x 34mm in length). The precision cutter consists of diamond-resin bonded wafering blade with a minimum speed of 150-250 rpm under constant water irrigation to prevent heat-related damages [5]. The specimen then submerged in the ultrasonic cleaner (Crest ultrasonic, model P11000SR, USA) with a chemical detergent (Pumicized citrius, Gent-l-kleen,USA) at the temperature below 46°C [1]. The specimens were then air-jetted and vacuum suction to remove the loose particles and remove excessive marrow [6]. The specimens were then aligned in a custom jig for better vertical oriented and sealed in an airtight bag placed in a -20°C freezer and frozen overnight while the adhesive fully cured [9].

2.2 Morphological Data

Archimedes principles were used in order to measure the volume fraction and tissue density for each specimen. By using the water displacement method, investigators have correlated variations in cancellous bone volume with mechanical load carrying capabilities [10]. Each specimen was removed from the vacuum chamber and weighed to obtain the submerged weight (W_s;g). The specimens were placed into a centrifuge tube with blotting paper to remove the residual water from pore spaces and each specimens were weighed in air to obtain hydrated weight (W_h;g). According to Archimedes' principle, the volume of the hydrated cancellous bone tissue (V_b;cm^3);

$$V_b = (W_h - W_s)/\rho \qquad (1)$$

Where ρ=0.9971 is the density (g/cm^3) of d istilled water at 25°C and 1atm. Thus, the volume fraction (V_f:%) of cancellous bone for each specimen is calculated using the equation:

$$V_f = V_b / V_t \qquad (2)$$

Thus, the porosity is given by;

$$\text{Porosity} = 100\% - V_f \qquad (3)$$

The cancellous material density is given by:

$$D_{app} = \rho \text{ x } W_h / (W_h - W_s) \qquad (4)$$

2.3 Compressive Static and Fatigue Testing

Each sample is test in an uniaxial compressive testing (Instron universal testing – Model 8847) with 10kN maximum load cell (Fig 3.1). For testing, specimen was aligned in custom jig for better vertical orientation and was placed in end cap and fixed via hot-melt adhesives (DGHL,model HL-E, China) cover about 5mm depth in end cap [6]. Prior to fatigue testing, the specimen was preconditioned by loading for 10 cycles in stress control using sinusoidal waveform to a small load level (approx 2%-16% of the static failure load, 22.9-179.1 N) to ensure full contact [11]. The frequency of this preconditioned loading was fixed at 1 Hz [9]. Based on previous study, the result obtained in monotonic test was to expect the micro damages parameters. This can be seen by increasing compressive strain with decreasing normalized modulus during compressive fatigue loading.

The fatigue tests were performed on a load control sinusoidal waveform and at a frequency of 2.0 Hz. Throughout the test, 16% of the ultimate stress was chosen for the lower stress and 55% for the upper stress [11]. The ultimate applied stress levels were based on the monotonic strength experiment which was done previously. The load applied was adapted from the human hip contact force in human gait analysis or the estimation of body weight of 85kg on average. External cortical contact force loading transmitted about maximum 75% to the cancellous bone and was manipulated into loading magnitude of the test. All fatigue tests were performed at physiological 2 Hz because it is referred to the normal human walking motion amplitude during gait.

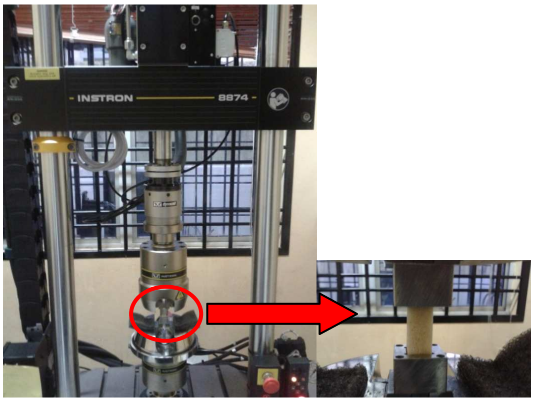

Figure 1: Experimental setup

3.0 RESULTS AND DISCUSSION

3.1 Morphological Data

Table 1 shows the morphological parameters of the tested cancellous samples. The density is depend on the weight in air and in liquid as per Archimedes principle, and varied between specimen 1 and specimen 2 even though the size and anatomic site of both specimens are the same. For specimen 1, the porosity is much lower than specimen 2 which is 40% lower. As for the volume fraction, the specimen 1 shows much higher percentage than specimen 2.

Table 1: Morphology data of cancellous bone

Specimen Number	Weight in air (g)	Weight in liquid (g)	Density (g/cm³)	Porosity (%)	Volume fraction (%)
1	3.333	0.835	1.3343	26.5%	73.5%
2	2.049	0.726	1.54792	60.9%	39.1%

3.2 Fatigue Test

Fatigue tests with simulated physiological loading of human activity in cancellous bone are showed on the hysteresis loop pattern of the S-N curve for certain selected cycle. The two medial-condyle cancellous bones were tested until 250,000 cycles based on the monotonic test that were applied performed earlier. Figure 2 and Figure 3 showed the result of the hysteresis loop for Specimen 1 and Specimen 2 separately based on the different morphological data as per Table 1. The inclination each hysteresis cycle in both specimens was different in maximum strain and no of cycle of failure. These stress-strain cycles of shows an accumulation of residual strain and degradation of modulus.

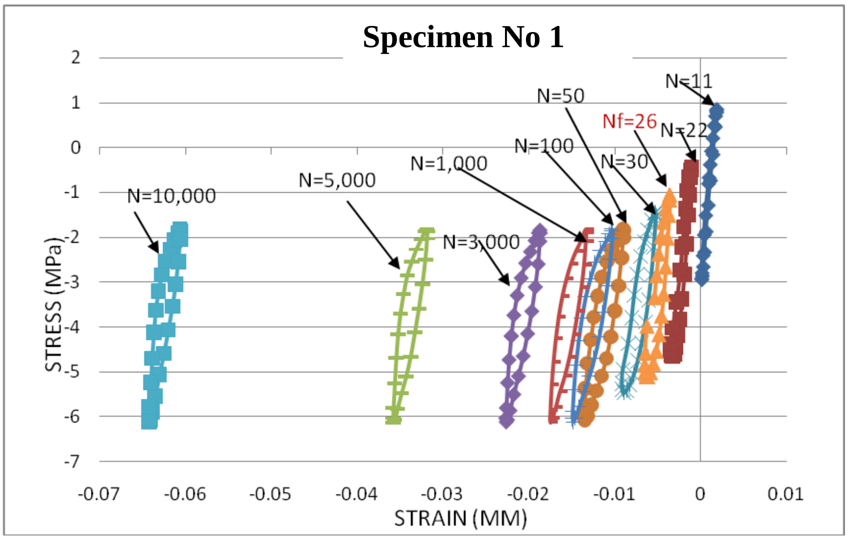

Figure 2: Typical stress-strain curves of a fatigue test for specimen #1. Using the criteria D=0.4, failure was found at Nf=26

From Figure 1, the number of cycle of failure is chosen at cycle of 26 as the secant modulus is reducing to 40% from the initial secant modulus. We chosen the failure criterion to D=0.4 [11] as it corresponded to an average threshold for the rapid increase in strain rate before failure.

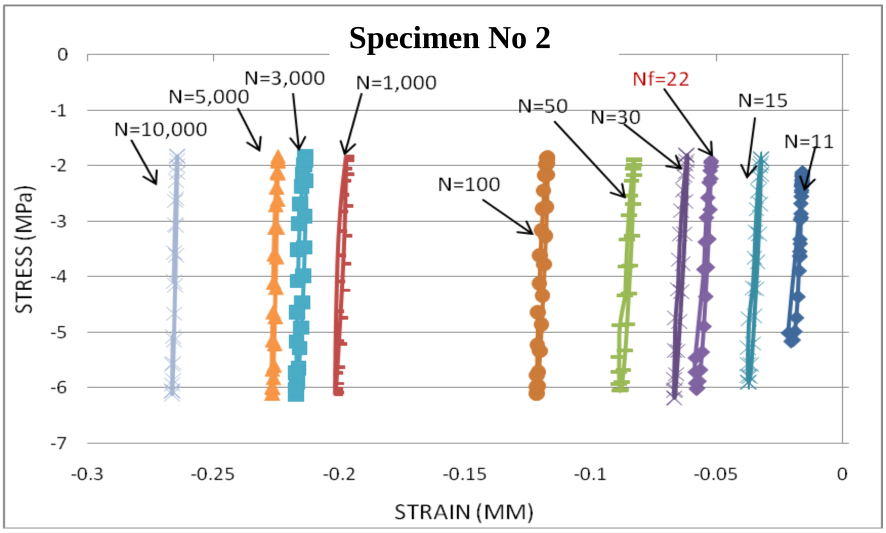

Figure 3: Typical stress-strain curves of a fatigue test for specimen #2. Using the criteria D=0.4, failure was found at Nf= 22.

As for specimen 2 in Figure 3, the number of failure is obtained at cycle 22. Failure defined at this strain range is between 1.2%-1.5%. Although the relative changes of reduction in secant modulus at 40% were defined, it didn't show any significance in size and shape of the hysteresis loop between the first cycle and at the failure cycle (Nf). It can be seen that specimen 2 (Nf=22) is much prone to failure compared to specimen 1 (Nf=26) with the same applied stress. Figure 4 shows the relationship between the maximum strain and cycle to failure between both specimens. Maximum strains are drastically increased in specimen 2 if compared to specimen 1 in after more than 10^2 cycle. It shows that the specimen has failed to localize and gradually decrease the strength of the material.

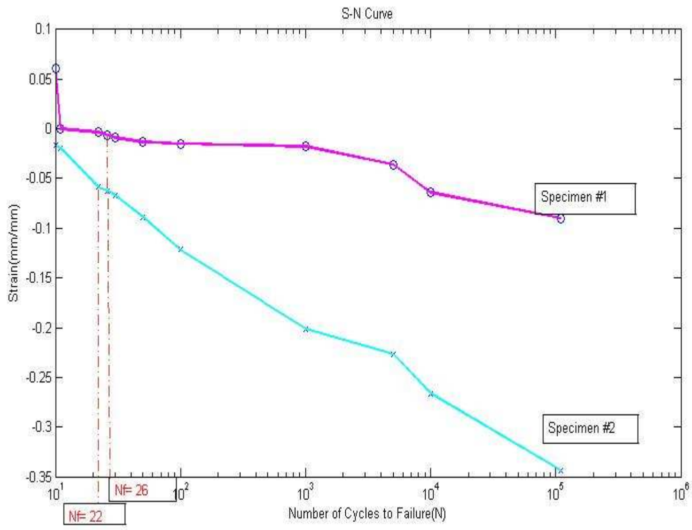

Figure 4. : Relationship between the maximum strain and the number of cycles to failure. The dotted line corresponds to the cycle of failure with D=0.4.

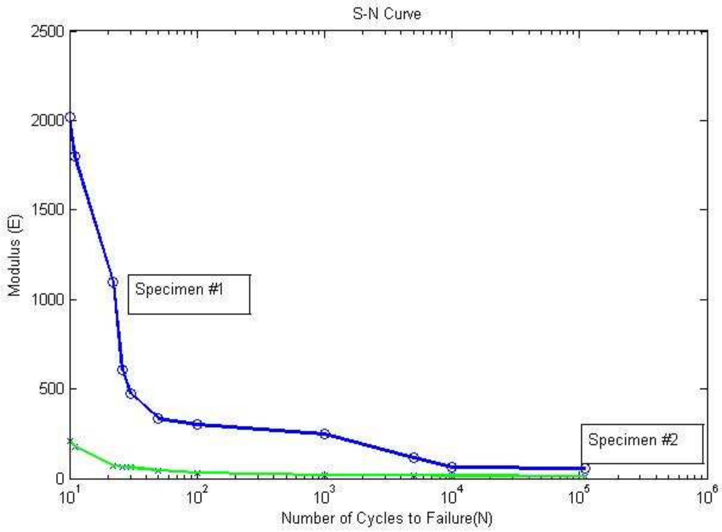

Figure 5: Relationship between the modulus and the number of cycles to failure.

Figure 5 shows an increase of fatigue life with a decrease of the applied stress, normalized by the modulus. Specimen 1 shows that the material is more dense and stiff compared to specimen 2 for the same loading condition. Plots reaching the maximum value from the reduction of secant modulus can also be shown in the decrease in modulus which leads to sample failure.

The low bone density for specimen 1 resulted in highly reduction in strength and modulus, thus this can be conclude that the specimen 2 is more likely responsive to failure than specimen 1. The comparison between the two specimens has shown that the structure of specimen 1 manage to sustain longer than specimen 2 from failure. The reason to the sustainability of specimen 1 is due to the high capability of absorption of loading environment until failure. The different of bone density, volume fraction and porosity at the same apparent stress control will give largely differences in fatigue behavior of cancellous bone.

4.0 CONCLUSION

The relationship for the dependence of the number of cycles to failure with respect to the control stress shows good correlations for both density and porosity to the specimens. The experimental stress-strain curves were analyzed for both medial-condlye bovine cancellous specimens tested under cyclic compression at stresses between 16%-55%. The prediction of failure can be seen in the reduction of secant modulus and normalized modulus with increasing number of cycles with the function of morphological data obtained. Studies in the past have shown that the morphological of cancellous bone effect mechanical properties specifically the compressive strength, stiffness and elastic modulus. Thus, knowledge of this relationship is necessary in predicting whole bone fracture, improving understanding of bone adaptation and assessing the efficiency of drug treatments for clinical problems such as osteoporosis.

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