MONOTONIC AND CYCLIC BEHAVIOUR OF TRABECULAR BONE UNDER UNIAXIAL AND MULTIAXIAL LOADING

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To my beloved parents, wife, and daughter

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In the name of Allah, the most merciful, most benevolent;
I thank You.

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"Anyone who has never made a mistake never tried anything new."
- Albert Einstein

ABSTRACT

Biomechanics of bone has drawn major concern in research due to social and economic demand. In real life, trabecular bone is subjected to multiaxial stresses during routine physiological loading. Fatigue failure of the bone accounts for various clinical implications, thus studies and research to better understand the fatigue failure of the bone are needed. The overall aim of this study is to investigate the effect of torsional loading towards trabecular behaviour under compression in both monotonic and fatigue loading. Samples from femoral bovine trabecular bone were subjected to a series of monotonic and cyclic tests. Hill's criterion was selected to determine the five combined stress ratio of compressive to shear stress for fatigue test. For finite element simulation, effect of morphology and orientation were investigated to predict fatigue life and plastic strain. The ultimate stress of the trabecular bone in monotonic compression and torsion were 14.22 and 8.95 MPa, respectively. In monotonic multiaxial loading, the ultimate stress was reduced to 2.5 MPa in compression and 3.8 MPa in torsion. Under fatigue compression, an endurance limit was found approximately at 25 % of ultimate compressive stress. Under multiaxial fatigue, the ability of the sample to retain shear stiffness with increased number of cycles is strongly correlated to the stress ratio. Fatigue life reduction was significant when the maximum shear stress is at least 24 % of the maximum compression stress. From the computational analysis, it was demonstrated that lower bone volume fraction (BV/TV), trabecular thickness (Tb.Th), and connectivity density (Conn.D) resulted in lower number of cycles to failure, regardless to the loading conditions. However, the number of cycles to failure was found to be negatively correlated to the value of structural model index (SMI). Off-axis orientation effect on the fatigue life of the trabecular bone was demonstrated the worst in horizontal trabecular bone model. In conclusion, the effect of torsional loading onto the mechanical behaviour of bovine trabecular bone was demonstrated throughout this study. It is apparent that torsional forces are the major factor that needs to be considered since these can lead to fatigue fractures. This research is expected to improve the knowledge base for the development of trabecular bone analogous materials.

ABSTRAK

Penyelidikan biomekanik tulang telah mendapat perhatian luas disebabkan oleh tuntutan sosial dan ekonomi. Secara keseluruhannya, pengajian ini bertujuan untuk menyiasat kesan beban kilasan terhadap kelakuan tulang trabekular di bawah mampatan beban monotonik dan kelesuan. Sampel daripada tulang trabekular dari paha sapi telah dikenakan satu siri ujikaji monotonik dan kitaran. Kriteria Hill telah dipilih untuk menentukan lima nisbah kombinasi tekanan untuk ujian kelesuan. Untuk simulasi unsur terhingga, kesan morfologi dan orientasi telah disiasat untuk meramalkan hayat lesu dan keterikan plastik. Tekanan maksimum tulang trabekular dalam mampatan dan kilasan monotonik adalah masing-masing 14.22 dan 8.95 MPa. Dalam tekanan monotonik pelbagai paksi, tekanan maksimum telah berkurang kepada 2.5 MPa untuk mampatan dan 3.8 MPa untuk kilasan. Di bawah mampatan lesu, had kelesuan adalah lebih kurang 25 peratus dari tekanan mampatan maksimum. Di bawah kelesuan pelbagai paksi, kebolehupayaan sampel untuk menanggung kericihan dengan peningkatan bilangan kitaran adalah sangat dipengaruhi oleh nisbah tekanan. Penurunan hayat lesu adalah jelas apabila daya ricih maksimum pada sekurang-kurangnya 24 peratus dari tekanan mampatan maksimum. Dari analisis komputer telah menunjukkan bahawa nilai pecahan isipadu tulang (BV/TV), tebal trabekular (Tb.Th), dan ketumpatan sambungan (Conn.D) yang rendah mengakibatkan bilangan kitaran kegagalan yang rendah. Walau bagaimanapun, bilangan kitaran kegagalan adalah berkadar negative dengan nilai index struktur model (SMI). Kesan orientasi di luar paksi terhadap hayat lesu tulang trabekular telah ditunjukkan paling teruk dalam model tulang trabekular arah melintang. Kesimpulannya, kesan bebanan kilasan terhadap kelakuan mekanikal tulang trabekular sapi telah ditunjukkan dalam pengajian ini. Ianya jelas bahawa daya kilasan merupakan faktor utama yang harus diberi perhatian kerana menyumbang kepada fraktur kelesuan.

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ASTM International	-	American Society for Testing and Materials
Micro-CT	-	Micro-computed tomography
BV/TV	-	Bone volume fraction
Tb.Th	-	Trabecular thickness
Tb.Sp	-	Trabecular space
Tb.N	-	Trabecular number
FE	-	Finite element
HA	-	Hydroxyapatite
BMD	-	Bone mineral density
3D	-	Three-dimensional
ZIB	-	Zuse Institute Berlin
US	-	United States
NA	-	Not applicable
S-N	-	Stress-life
FEM	-	Finite element method
LCF	-	Low-cycle fatigue
HCF	-	High-cycle fatigue
2D	-	Two-dimensional
SMI	-	Structural model index
Conn.D	-	Connectivity density
DA	-	Degree of anisotropy
P	-	Plate-like trabeculae
R	-	Rod-like trabeculae
ROI	-	Region of interest

FESEM	-	Field emission scanning electron microscopy
SEM	-	Scanning electron microscopy
SD	-	Standard deviation

LIST OF SYMBOLS

$\Delta\sigma$	-	Stress range
N_f	-	Number of cycles to failure
N	-	Number of cycles
σ_f	-	Fatigue strength coefficient
b	-	Basquin's exponent
$\Delta\varepsilon$	-	Strain range
ε_f	-	Fatigue ductility coefficient
c	-	Fatigue ductility exponent
N_t	-	Transition of life
σ	-	Stress
ε	-	Strain
E	-	Modulus
R^2	-	Regression coefficient
n	-	Number of sample
σ_i	-	Principal stress direction
σ_{eq}	-	Equivalent von Mises stress
Y_A	-	Uniaxial yield strength
Ys	-	Shear yield strength
p	-	Significance level of the test
σ_{yc}	-	Compressive yield strength
σ_{ultc}	-	Ultimate or maximum compressive strength
σ_{max}	-	Maximum stress
σ_{min}	-	Minimum stress
ε_{max}	-	Maximum strain
ε_{min}	-	Minimum strain

τ	-	Shear stress
γ	-	Shear strain
k	-	Torsional modulus
G	-	Shear modulus or modulus of rigidity
T	-	Torque / torsion
τ_{max}	-	Maximum shear stress
C	-	Compression/ compressive
E_{kin}	-	Kinematic hardening modulus

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

For over 30 years biomechanics research has been widely explored with special interest is sending forth on the influence of trabecular bone towards weakening and failure of whole bone, and how the stimulating remodelling process helps in retaining the bone strength [1]. Clear understanding of the biomechanics of bone is well related in diagnosis and treatment of medical issues such as osteoporosis, bone fracture, bone remodelling, and implant system. Biomechanics of bone has drawn major concern in research due to social and economic demand [2]. Proper understanding of bone mechanics is required to tackle various medical issues. The mechanical behaviour of bone related to its architecture will improve clinical practise in diagnosing osteoporosis. Further evaluation on damage evolution in bone will provide information on dimmed principles of mechanobiology. From here, development of implants can be enhanced while prostheses design and systems will be able to function usefully. On top of that, treatment necessary for defects or complex fractures which usually involve patients at old ages can be developed. At instant, there are interesting alternatives have been proposed in order to tackle issues with bone defects [3, 4], however without prior profound knowledge on the bone itself, these approaches remain speculative.

Failure in most loaded engineering structures has been characterized as fatigue-induced [5]. Fatigue can be defined as the weakening of a material resulted from repetitive applied stresses or strains. Stephens et al. (2000) [6] highlighted six key words from ASTM International (American Society for Testing and Materials) definition of fatigue which imply the process of fatigue in a material, i.e. progressive, localized, permanent, fluctuating, cracks, and fractures. In general, this process involves the nucleation and growth of cracks to final fracture. Fatigue failure in bone has been found to be resulted from worsened deposition or mineralisation of bone matrix, or the unrepaired microdamage accumulation from daily repetitive loads which increase bone fragility [7, 8]. Such failure, while most presented in elderly patients, is also associated with stress fractures [9] in younger people with increase load beyond the bone capacity to remodel. Fatigue failure in bone starts with microcracks initiation, in which occur in regions of high strain and accumulate with increased number of cycles or increased strain. These cracks are often repaired during the remodelling process. However, failed microcracks grow and propagate as a result of interlamellar stresses generated at its tip. As the bone stiffness declines, damage is accumulated rapidly and ultimate failure of the structure occurs as fatigue progresses faster than the rate of remodelling. Despite the known capability of remodelling process to limit bone fragility and to prevent failure caused by microdamage, under-capacity of this process – or lagging response towards elevated load puts the associated bone at risk of sudden fracture. Furthermore, remodelling induction capacity is diminished with age [10].

As fatigue failure in bones contribute to significant clinical implications, studies and investigations to better comprehend fatigue failure in bones are required. Factors affecting fatigue strength of bone include the loading mechanism, frequency, strain rate, age, anatomic site, stiffness, density and temperature, as well as the microstructure of the bone [11]. With advancement of technology, direct quantitative morphological analysis on three-dimensional (3D) reconstructions is made possible with micro-computed tomography (micro-CT). The morphological indices included volume fraction (BV/TV), trabecular thickness (Tb.Th), trabecular separation (Tb.Sp), and trabecular number (Tb.N). As material testing on highly inhomogeneous structures like the trabecular bone is quite complicated and no

standard for the experimental conditions are given in terms of sample size, loading rate, loading mode, and surrounding media, results from literature are also diversified. Some of the variations in mechanical data may be ascribed to experimental effects, introduced by ignoring the structural anisotropy, the proper boundary conditions (e.g. end artefact errors) [12, 13] and size effects [14]. But there is also a natural heterogeneity which complicates the analysis of trabecular bone and large variation in between samples properties may scattered the results in mechanical interpretation especially in bone mechanic study such as creep or fatigue [15].

Progressive collapses of the vertebrae [16] and loosening of implants [17] have been associated to the damage and creep strain which attracts interest in understanding the associated failure. The number of cycles to failure of the trabecular is in direct relationship with the volume fraction, fabric, and applied stress [18]. Lifetime of the trabecular has also been recognised to be influenced by loading direction [19]. Current fatigue assessment on trabecular bone is limited to uniaxial compression. While physiological and traumatic loading are multiaxial in nature, uniaxial assessment limits the reliability of the yielded information. To the author's knowledge, none of the reported works in the literature has ever quantified the behaviour of the trabecular under multiaxial fatigue. Therefore, the outcomes of this present work is hope to shed lights on a few aspects involved in the failure of the trabecular under combined fatigue compression-torsion and contribute information for future development.

1.2 Problem Statement

Bone fracture [20, 21], age-related fragility fractures [8], and implants loosening [17] have been found to be originated by fatigue damage. However, fatigue behaviour of trabecular bone has received only few attentions [18, 22-27]. Even so, these studies are conducted under uniaxial compressive loading, in which may badly align with in vivo physiological off-axis loading directions [28, 29]. This

off-axis loading is influenced by trabecular microarchitectural properties, which are also attributed to osteoporosis. Osteoporosis promote bone fragility and increase the bone's susceptibility to fracture, which has been reported to strike at trabecular bone dominant sites such as hip, spine, and wrist. As the lifespan increases, assessment on bone failure risk becomes more significant. Current practice in osteoporosis assessment determines failure risk of bone by measuring the bone mineral density (BMD). This method however leaves out other contributing factors to the strength of bone such as the morphological information. Furthermore, the feverish lifestyle of older people nowadays has also increase the need of implants and prostheses. Implant loosening has been associated as one of the factor of failure in total hip replacement surgery [30-32] which is associated to the reduction of mechanical competency of the immediate adjacent trabecular [33-35]. As the cost of second surgical procedure is reported to be three times as expensive as the preliminary ones [36], factors such as changes in the trabecular quality with age and osseous-integration process must be well assessed to get the replacement done right the first time [30, 37]. Furthermore, implant systems may also alter the local loading conditions (Figure 1.1). However, research efforts in this area require participation of joined expertise, given the complexity of the problems. Thus, understanding the fatigue properties of bone may provide information on osteoporotic bone behaviour toward normal physiological loading and its associated diagnosis and treatment, as well as improve implant systems in terms of material selection, placement, and etc.

Bone is subjected to multiaxial stresses and strains in vivo [9, 38-40] while less to none known multiaxial fatigue evaluation on trabecular bone has ever be done. Uniaxial loading alone is insufficient to provide the necessary information in bone failure prediction as different failure mode is observed to that of under multiaxial loading. Multiaxial loading demonstrates mixed-mode failure where the damage propagated from one mode (tension) to another (shear). In bioengineering, multiaxial criterion provide better understanding on the relationship of the trabecular tissue structure and its physiology in which will improved implant system and development of bone analogue [41]. Therefore, current work may comprise the following research questions;

- Why previously reported mechanical evaluation failed to describe well of the trabecular bone failure?
- What is the influence of torsional loading on the behaviour of trabecular bone under compressive fatigue and monotonic loading?
- How do the morphology, anatomical site, and orientation affect the trabecular behaviour under multiaxial fatigue loading?

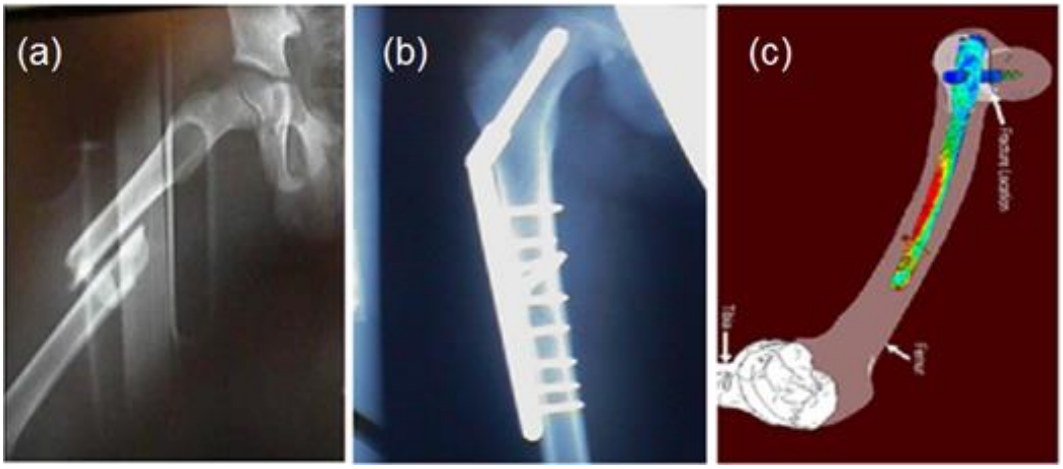

Figure 1.1 Fracture and treatment of an injured femur. (a) Spiral fracture of long femoral bone and separated femoral head, (b) treatment of the femoral fracture after operation, and (c) stress distribution of femoral implant and screws.

1.3 Objectives

Human bone deformed in terms of its microstructural and ultrastructural features with age [8, 42, 43]. In vivo, physiological loading subjected to the bone change microstructural response and thus alter the failure behaviour, stress or strain magnitude as well as loading mode. As the assessments on bone failure under physiological condition with relevant multiaxial loading are scarcely done, damage mechanism of bone, particularly the trabecular structure, remain poorly understood. Furthermore, a strong experimental base is in need to accommodate current advanced numerical models application [44, 45] and theoretical model for deformation

processes. Thus, the overall aim of this study is to investigate the effect of torsional loading towards trabecular behaviour under compression in both monotonic and fatigue loading. The specific objectives of the study are;

1. to investigate the effect of superimposed torsional loading onto the monotonic compressive properties of bovine trabecular bone,
2. to evaluate the torsional loading effects onto the fatigue compressive behaviour of bovine trabecular bone, and
3. to simulate compressive fatigue life and investigate the effect of morphological parameters and sample orientation.

1.4 Scope of Study

Sample of trabecular bone in this study has been gathered and extracted from bovine proximal femur from mediolateral femoral condyles, neck of femur and greater trochanter. This study is divided into two important parts: experiment and computational simulation. The scope of the present study can be summarised as follows;

i. Sample used was extracted from bovine (cow) bone which used in femoral head, neck, and medial-lateral condyles.
ii. Micro-computed tomography (μ-CT) scanned of sample.
iii. Monotonic test: Pure compression, pure torsion, and combined compression-torsion test.
iv. Fatigue test: Pure compression, pure torsion, and combined compression-torsion test with five different stress ratios.
v. Software used for morphology measurement: Image J.
vi. Software used for 3D reconstruction: Mimics 10.01 and AMIRA 4.0.
vii. Software used for finite element analysis: COMSOL Multiphysics 3.4.
viii. Parameter study of the effect of morphology and orientation (vertical, 45 degree, and horizontal)

The study focuses on the effects of multiaxial and torsional loading imposed on trabecular bone structure that probably represent realistic condition adapted during normal physiological loading. Evaluation is associated more into compression fatigue behaviour of trabecular bone. However, details study on the fracture behaviour is not included. Torsional analysis in both monotonic and fatigue part were also excluded.

1.5 Significances and Original Contributions of This Study

Both cortical and trabecular bone have been investigated in terms of their mechanical properties and behaviour upon loading [11, 18, 23-25, 39, 43, 46]. Even though current study investigates trabecular bone exclusively, the mechanics of both types of bones share relevant properties that are complementary to each other. A close relationship in between age-related fragility fractures and stress fracture among youngsters is worth of notice. Microdamage in bone with normal routine can be repaired approximately at the same rate as the accumulation of damage, thus fractures can be avoided. However, with elevated loading as in athletes and army routine, bone microdamage accumulates at higher rate than normal remodelling capacity and often results in failure. As the fracture mechanics of stress fracture are very similar to that of osteoporosis, it is believed that much of the subject presented in current study can contribute to both medical issues and help in improving diagnostic and treatment aspects of the bone related diseases.

Fatigue progressive failure in trabecular bone has been associated with the loosening of implants [47] and other non-traumatic fractures. Complex loading conditions may be presented in vivo, thus multiaxial criteria for trabecular bone is of significant interest. Furthermore, traumatic injuries usually induce off-axis loading. Therefore, present work focused on quantification of the trabecular behaviour under multiaxial fatigue to improve validity and accuracy of the trabecular failure prediction, which was failed to be presented by previous uniaxial assessment. From

here, the effect of torsional loading onto the fatigue compression properties of the trabecular is presented. The study was extended to numerical analyses of microarchitectural parameters and loading orientation by finite element (FE).

1.6 Thesis Structure and Organization

This thesis is composed of seven chapters (Figure 1.2). Chapter 1 is an introduction, which consists of research background, scope of research, objectives of the study, research significance, problems statement, and organisation of the thesis. Chapter 2 is the literature review. The reviews included are from literatures of the recent twenty years, in which critically assessed to support the aforementioned research objectives. Chapter 3 presents the methodology in general from the procedure for sample preparation to data analyses. However, specific methodology for a particular experimental or computational evaluation is presented separately in its associated section. Elaborated assessment for monotonic response of the trabecular samples are delivered in Chapter 4. This chapter is divided into three sections; the monotonic assessment of trabecular samples under compression and torsion, the effects of superimposed torsional loading on monotonic compression evaluation, and the effects of combined monotonic compression-torsion on the samples properties. The main subject of research interest is presented in Chapter 5 which divided into several sections of fatigue assessment. The assessment starts with uniaxial fatigue evaluation, follows by the trabecular response towards superimposed torsion on fatigue compression. This chapter ends with combined compression-torsion fatigue evaluation. In Chapter 6, the computational simulation analyses are presented. The first section demonstrates the trabecular response towards loading mode based on the anatomical sites and morphological indices. Then, the study is extended to clarify the effects of samples orientation and fatigue life assessment which compares the prediction for uniaxial and that of multiaxial loading. At last, Chapter 7 describes general conclusion drew from the whole study, discusses limitations of this study and recommendation for improvement in future works.

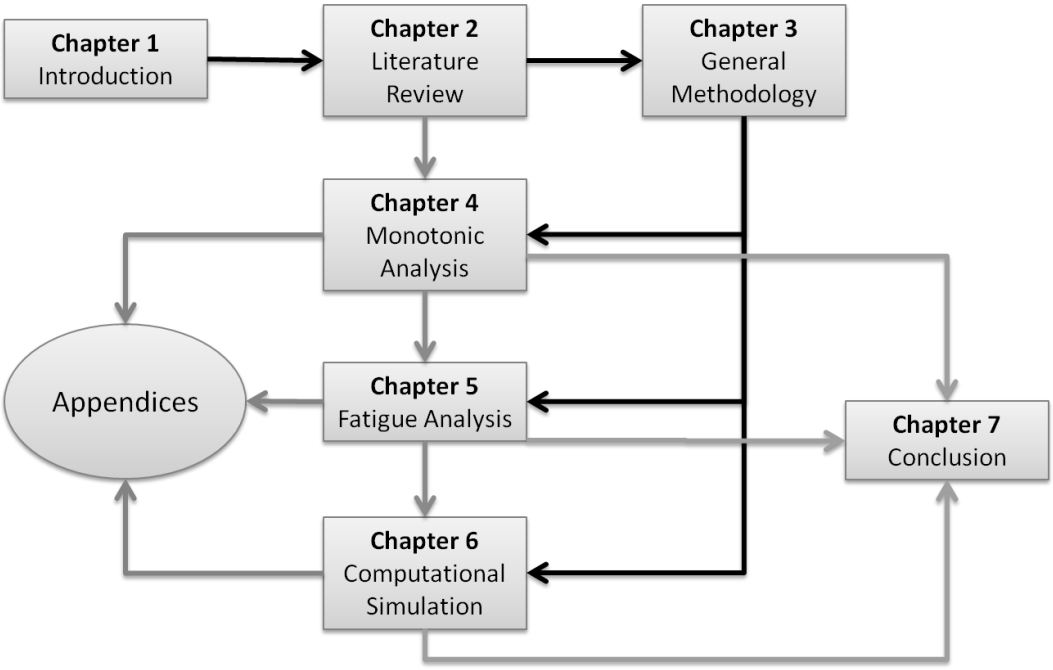

Figure 1.2 Thesis organisation roadmap.

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