Monotonic and Cyclic Behavior of Trabecular Bone Under Uniaxial and Multiaxial Loading

By

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OUTLINE

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  • Problem Statement
  • Objectives

• Methodology
  • Sample Preparation
  • Experimental Setup
  • Computer Simulation

• Results & Discussion
  • Mechanical Behaviour of Bovine Trabecular Bone
  • Fatigue Behaviour of Bovine Trabecular Bone
  • Computational Analyses

• Conclusion
INTRODUCTION
BACKGROUND

• Bone: The skeletal system
  • Cortical bone
  • **Trabecular bone**

• Bone mechanics
  • Mechanical properties
  • Fatigue properties
  • Multiaxial Behaviour of Trabecular Bone
  • Failure criterion

THE FATIGUE PROCESS

- Cyclic deformation
- Fatigue damage
  - Hardening (softening)
  - Saturation (microstructural changes in the bulk)
  - Crack initiation (surface)
  - Crack propagation (localized trans-, inter-granular processes)
  - Strain localization

BASIC DISLOCATION MECHANISMS

FATIGUE FAILURE MECHANISMS
PROBLEM STATEMENT

• Bone fatigue fracture
• Multiaxial stresses and strains in vivo
• Osteoporosis
• Research questions
  • How do the **orientation** affect the trabecular behaviour under multiaxial fatigue loading?
  • What is the **influence of torsional loading** on the behavior of trabecular bone under compressive fatigue and monotonic loading?
OBJECTIVES

• To simulate compressive fatigue life and investigate the effect of sample orientation.

• To evaluate the torsional loading effects onto the fatigue compressive behavior of bovine trabecular bone
METHODOLOGY
RESEARCH DESIGN

START

Sample preparation (sectioning, cleaning, storage & assembly)

μ-CT scanning & image analysis

Morphological parameters

3D model reconstruction

Computational simulation

Effect of orientation

Experiment

Failure surface

Fatigue

Monotonic

Mechanical behaviour

Fatigue

Fractograph analysis (FESEM)

Data analysis

END
SAMPLE PREPARATION
EXPERIMENTAL SETUP

Instron 8874 universal testing machine

- Hydraulic actuator
- Cross head
- Load cell
- Stainless steel endcap
- Specimen
- Mounting material

Graph showing stress over time:

- $\sigma_{\text{max}}$
- $\tau_{\text{max}}$

Time (sec)
COMPUTER SIMULATION

MIMICS software

AMIRA software

(a)  

(b)  

innovative • entrepreneurial • global
COMPUTER SIMULATION

**Figure**: Models preparation and orientation

**Figure**: Boundary condition
BOUNDARY CONDITIONS

- $F_x = -1E6 (-0.3434t^7 + 1.1756t^6 - 1.5667t^5 + 1.0239t^4 - 0.3369t^3 + 0.0490t^2 - 0.0013t + 0.0002)$
- $F_y = -1E5 (-1.1068t^7 + 3.8818t^6 - 4.8999t^5 + 2.4244t^4 - 0.0797t^3 - 0.2734t^2 + 0.0542t - 0.0010)$
- $F_z = -1E5 (-2.9006t^7 + 7.0557t^6 - 3.5732t^5 - 3.5934t^4 + 4.4087t^3 - 1.6199t^2 + 0.2244t + 0.0048)$
**Table:** Parameters used in fatigue modelling of trabecular bone

<table>
<thead>
<tr>
<th>Property</th>
<th>Parameter</th>
<th>Value</th>
<th>Property group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue strength coefficient</td>
<td>$\sigma_f'$</td>
<td>26.4 MPa</td>
<td>Basquin</td>
</tr>
<tr>
<td>Fatigue strength exponent</td>
<td>B</td>
<td>-0.155</td>
<td>Basquin</td>
</tr>
<tr>
<td>Fatigue ductility coefficient</td>
<td>$\varepsilon_f'$</td>
<td>0.0134</td>
<td>Coffin-Manson</td>
</tr>
<tr>
<td>Fatigue ductility exponent</td>
<td>C</td>
<td>-0.097</td>
<td>Coffin-Manson</td>
</tr>
<tr>
<td>Q</td>
<td>critical plane evaluation</td>
<td>3</td>
<td>NA</td>
</tr>
<tr>
<td>Initial yield stress</td>
<td>$\sigma_{ys0}$</td>
<td>50.4 [MPa]</td>
<td>NA</td>
</tr>
<tr>
<td>Kinematic tangent modulus</td>
<td>$E_{Tkin}$</td>
<td>0.05$E_0$</td>
<td>NA</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSIONS

1) FATIGUE BEHAVIOUR OF BOVINE TRABECULAR BONE
2) COMPUTATIONAL ANALYSES
FATIGUE BEHAVIOUR OF BOVINE TRABECULAR BONE

Table: Summary of the lifetime curve obtain in different stress states.

<table>
<thead>
<tr>
<th>Stress state</th>
<th>Lifetime curve</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>$\sigma_{\text{norm}} = 1.1602 - 0.067 \log(N_f)$</td>
<td>0.86</td>
</tr>
<tr>
<td>CD</td>
<td>$\sigma_{\text{norm}} = 1.1386 - 0.074 \log(N_f)$</td>
<td>0.75</td>
</tr>
<tr>
<td>CT</td>
<td>$\sigma_{\text{norm}} = 1.1033 - 0.086 \log(N_f)$</td>
<td>0.68</td>
</tr>
<tr>
<td>TD</td>
<td>$\sigma_{\text{norm}} = 1.1070 - 0.090 \log(N_f)$</td>
<td>0.72</td>
</tr>
<tr>
<td>T</td>
<td>$\sigma_{\text{norm}} = 1.0579 - 0.072 \log(N_f)$</td>
<td>0.82</td>
</tr>
</tbody>
</table>

$$(\sigma/\sigma_y)^2 + (\tau/\tau_y)^2 = 1$$

where

$\sigma_y$ = apparent compressive yield stress
$\tau_y$ = apparent shear yield stress

$$\left(\frac{\sigma_a}{E_0(N_f)}\right)^2 + \left(\frac{\tau_a}{G_0(N_f)}\right)^2 = 1$$

Where,

$\sigma_a$ = maximum cyclic compressive stress
$\tau_a$ = maximum cyclic shear stress

$E_0$ & $G_0$ are initial modulus and modulus of rigidity respectively.

Figure: Monotonic compressive and combined fatigue compressive-shear strength.
FATIGUE BEHAVIOUR OF BOVINE TRABECULAR BONE

Figure: SEM micrograph of trabecular sample subjected to combined compression-torsion loading. (a) Fracture line of the sample (at 100µm), (b) fracture surface of the sample (at 1mm), (c) icicle-like fracture of a trabeculae with stump structure left (at 10µm), and (d) delaminating effect on sample surface (at 100µm).
Figure: Convergence study for the finite element analysis
COMPUTATIONAL ANALYSES

Figure: Comparison between FE simulation and experimental modulus with periodic boundary condition.
COMPUTATIONAL ANALYSES

Figure: Comparison of (a) uniaxial and (b) multiaxial life prediction of the models at different trabecular orientation.
Figure: Comparison of finite element prediction with experimental data from literature showing the relationship of applied strain on the cycles to failure.
Figure: Predicted normalized modulus with increment of applied stress corresponding to the number of cycles to failure.
### COMPUTATIONAL ANALYSES

<table>
<thead>
<tr>
<th>Load per gait loading (%)</th>
<th>Uniaxial Loading</th>
<th>Multiaxial Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>30</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>50</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>90</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

- **Effective plastic strain**
  - $N_f = 37$ for Uniaxial Loading (10% load)
  - $N_f = 5$ for Multiaxial Loading (10% load)
  - $N_f = 171$ for Uniaxial Loading (30% load)
  - $N_f = 45$ for Multiaxial Loading (30% load)
  - $N_f = 8943$ for Uniaxial Loading (50% load)
  - $N_f = 230$ for Multiaxial Loading (50% load)
  - $N_f = 26464$ for Uniaxial Loading (90% load)
  - $N_f = 6862$ for Multiaxial Loading (90% load)

**Figure:** Contour of effective plastic strain predicted by FE simulations under uniaxial and multiaxial loading (final fatigue loading cycles taken from gait loading).
CONCLUSION
CONCLUSION

• The mechanical properties of bovine trabecular bone were observed to be deteriorated by the superpositioned torsional loading. In monotonic test, multiaxial compressive-torsional loading has been found to induce brittle fracture and reduce the strength of the sample by 27%.

• Fatigue life reduction was significant when the shear stress is about 24% greater than maximum compression stress. In other words, even at compression-torsion stress ratio of 4:1, the shear stress manifest itself to dominantly affect the fatigue life of the trabecular bone.
THANK YOU