Analysis of Fracture Processes in Cortical Bone Tissue

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Contents

- Introduction
- Experimental studies
- Numerical simulations
- Bone cutting
Miniature ultrasonic cutting devices for high precision minimal access orthopaedic surgical procedures
Introduction

Research methodology

- Elasto-plasticity
- Viscosity
- Anisotropy
- Strain-rate dependency
- Damage

FE model

Tool-bone interaction
Parameters optimization
Hierarchical structure of cortical bone

[Weiner et al., 1999]
Experimental Studies

Microscale Tests

- Elastic-plastic behaviour
  - Nanoindentation tests

- Bone topology
  - Optical microscopy

Macroscale Tests

- Elastic-plastic behaviour
  - Uniaxial tension tests
  - Creep tests
  - Izod tests
  - Tensile-impact tests

- Visco-elastic & dynamic behaviours
Objective

- To get better understanding of variability and anisotropy of cortical bone under compressive loading;
- To assess the effect of loading rate on various position and orientation;
- To study the effect of microstructure on the variability and anisotropy;
- To develop a 3D model to simulate tool-bone interaction with the main following features:
  - Anisotropic mechanical behaviour in both tension and compression;
  - Variability of properties;
  - Strain-rate dependence;
  - Adequate failure criterion
Experimental Method

- **Material preparation**
  - Low speed diamond-cutter
  - Water irrigation
  - Series of silicon carbide paper to polish
  - 0.9% saline solution
  - Ø6 mm 6 mm specimen
  - Whole-ring section for microstructural analysis
Experimental Method

- **Compression test**
  - 4 anatomic positions
  - Instron 3345
  - Strain measurement: LVDT
  - Strain rate: $10^{-3}$, $10^{-2}$, $10^{-1}$, 1, $10$ s$^{-1}$

- **Microstructure analysis**
  - 12 images across whole ring
  - Olympus BX60M
  - Software: Image-Pro
Results and Analysis

Representative stress-strain relation (Anterior Longitudinal)

\[
\begin{align*}
&y = 3249.7x + 172.6 \\
&\text{R}^2 = 0.9407
\end{align*}
\]

\[
\begin{align*}
&y = 2748x + 78.721 \\
&\text{R}^2 = 0.989
\end{align*}
\]
Progressive damage region (Anterior Longitudinal)
Results and Analysis

Anisotropy: longitudinal vs. transversal

<table>
<thead>
<tr>
<th></th>
<th>Anisotropic ratio (mean)</th>
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</thead>
<tbody>
<tr>
<td>Tension</td>
<td></td>
</tr>
<tr>
<td>$E$</td>
<td>1.63</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>2.37</td>
</tr>
<tr>
<td>$\varepsilon_y$</td>
<td>2.29</td>
</tr>
<tr>
<td>$\sigma_u$</td>
<td>2.44</td>
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<tr>
<td>$\varepsilon_u$</td>
<td>3.46</td>
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<tr>
<td>Compression</td>
<td></td>
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<tr>
<td>$E$</td>
<td>1.65</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>1.64</td>
</tr>
<tr>
<td>$\varepsilon_y$</td>
<td>1.09</td>
</tr>
<tr>
<td>$\sigma_u$</td>
<td>1.64</td>
</tr>
<tr>
<td>$\varepsilon_u$</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Graph showing stress-strain curves for different conditions.
Variability: effect of cortical position

Results and Analysis
Variability: effect of cortical position

Variability between cortices

Variability: effect of cortical position

Young’s Modulus (GPa)

Anterior

Lateral

Medial

Posterior

Longitudinal Compression

Longitudinal Tension

Transverse Compression

Transverse Tension

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

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Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)

Stress (MPa)

Strain (%)
Three-Point Bending Single-Edge Notched Fracture Test

- Experimental analysis of fracture toughness anisotropy of cortical bone tissue
- Loading Rate: 10 mm/min
- Different directions
  - Bone axis (Done)
  - Tangential axis (On-going)
- Cortex positions
  - Anterior
  - Posterior
  - Medial
  - Lateral

Bone Specimen

Three Point Bending Test Instron 3345 (5 kN)
Displacement Measurements

Linear variable differential transformer (LVDT) to measure displacement

Three Point Bending Test Instron 3345 (5KN)
Specimens

Specimens’ Dimensions according to BS 7448-1:1991

- Width: W
- Thickness: B
- Span: S
  - S = 4.6 W
  - B = ½ W

For S = 25 mm
  - W = 5.43 mm
  - B = 2.72 mm
  - a/w = 0.5

Standard BS 7448-1:1991

Bone Specimen
Fracture toughness is presented as J integral

Associated with elastoplastic fracture mechanics

\[ J = \left[ \frac{FS}{BW^{1.5}} \times f\left(\frac{a_0}{W}\right) \right]^2 \frac{(1 - \nu^2)}{E} + \frac{2Up}{B(W - a_0)} \]

- \( F \) - maximum force
- \( B \) - thickness
- \( a_0 \) - crack length
- \( W \) - width
- \( \nu \) - Poisson’s ratio
- \( E \) - elastic modulus
- \( S \) - span
- \( U_p \) - plastic component of work
Analysis

- **$U_p$** — the plastic component of the work done is the area indicated in the Figure 17 in BS 7448-1:1991

- $f\left(\frac{a_0}{W}\right)$ is given by the following Equation or by Table 2 in BS 7448-1:1991

\[
f\left(\frac{a_0}{W}\right) = 3\left(\frac{a_0}{W}\right)^{0.5} \left[ 1.99 - \left(\frac{a_0}{W}\right) \left( 1 - \frac{a_0}{W} \right) \left( 2.15 - \frac{3.93a_0}{W} + \frac{2.7a_0^2}{W^2} \right) \right]
\]

To facilitate the calculation of $K_Q$, values of $f\left(\frac{a}{W}\right)$ are given in Table 2 for specific values of $\frac{a_0}{W}$. 

Figure 17 — Definition of $U_p$ (for the determination of $J$)

$q_c$, $q_u$ or $q_m$ corresponding to $F_c$, $F_u$ or $F_m$
$J_c$ for Cracks Perpendicular to Bone Axis

Average Values of $J_c$ (N/m)

<table>
<thead>
<tr>
<th></th>
<th>Jc (N/m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial</td>
<td>5500</td>
<td>Lateral</td>
</tr>
<tr>
<td>Lateral</td>
<td>5000</td>
<td>Posterior</td>
</tr>
<tr>
<td>Posterior</td>
<td>6500</td>
<td>Anterior</td>
</tr>
</tbody>
</table>
### J_c for Cracks Perpendicular to Bone Axis

<table>
<thead>
<tr>
<th>Cortex Position</th>
<th>Average Critical J_c values (N/m)</th>
<th>Standard Deviation</th>
<th>Normalized Value</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial</td>
<td>5287.76</td>
<td>400.67</td>
<td>0.882</td>
<td>-11.82</td>
</tr>
<tr>
<td>Lateral</td>
<td>5306.71</td>
<td>391.20</td>
<td>0.885</td>
<td>-11.50</td>
</tr>
<tr>
<td>Posterior</td>
<td>5996.28</td>
<td>607.25</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Anterior</td>
<td>5110.53</td>
<td>833.92</td>
<td>0.852</td>
<td>-14.77</td>
</tr>
</tbody>
</table>

- **Posterior** – highest J_c
- **Anterior** – lowest J_c
Finite Element Modelling

- Three FEM were developed
  - Quasi-static tensile model at micro-scale
  - Dynamic fracture model at macro-scale: 2D & 3D Izod test model
  - Dynamic fracture model at macro-scale: 3D tensile-Impact test model
Micro-scale Tensile Finite-Element Models

Osteons

Cement line

$\varepsilon = 1\%$

Interstitial Matrix

$\varepsilon = 1\%$

Homogeneous Bone

$\varepsilon = 1\%$

Osteons

Cement line

$\varepsilon = 1\%$

Interstitial Matrix

$\varepsilon = 1\%$

Homogeneous Bone

$\varepsilon = 1\%$

Osteonal transverse-radial cortical bone section

$\varepsilon = 1\%$

Three-phase Composite

$\varepsilon = 1\%$

Homogeneous Material

$\varepsilon = 1\%$

Microcrack

Homogeneous Material

Microcrack

Homogeneous Material

Microcrack

Homogeneous Material

Microcrack

Homogeneous Material

Microcrack

Homogeneous Material

Microcrack
Crack propagation in microscopic osteonal cortical bone

Finite Element Modelling: 2D Micro-scale X-FEM

Four-phase composite

Three-phase composite
Izod-Test (2D FEM)

- A 2D model with Abaqus/Implicit
- The impact velocity together with the real specimen and hammer dimensions were used as input
- Three different material formulations were used for the bone specimen:
  - linear-elastic
  - elastic-plastic
  - viscoelastic
Different Material Behaviours

FEM results for anterior cortex position for lower energy level of 0.02 J. Horizontal dashed lines represent bounds for experimentally measured values of maximum load.

Comparison of experimental and FEM results for anterior cortex position for higher energy level of 0.5 J.
XFEM: Crack Evolution

STATUSXFEM
(Avg: 75%)

1.000
0.917
0.833
0.750
0.667
0.583
0.500
0.417
0.333
0.250
0.167
0.083
0.000

t = 0
t = 0.32 ms
t = 0.43 ms

t = 0.63 ms
t = 0.64 ms
Izod-Test (3D FEM)

- A 3D model with Abaqus/Implicit
- The impact velocity together with the real specimen and hammer dimensions were used as input
- Viscoelastic material formulation was used for the bone specimen:

Setup of Izod test

FEM Model

Hammer-specimen interaction

Meshing of hammer and specimen (specimen is increased)
Izod Test Models: Validation

- Izod 2D XFEM (Model A)
- Izod 3D XFEM (Model B)

Comparison of evolution of contact force in impact loading (notch size 300 µm)
Izod Test Models: Validation

Distributions of maximum principal strain:
- a) 2D Izod
- b) 3D Izod
- c) quasi-static model
- d) Final crack path in Izod-test specimen
SPH (Smooth Particle Hydrodynamics)

- Based on continuum equations
- Fully Lagrangian formulation
- Accurate for large deformation without re-meshing or element deletion
- Smooth interpretation

Bagci, 2010; Limido, 2007
3D SPH Modeling of Tool-Bone Interaction

- **Model Specification**
  - Specimen size: 6 mm × 3 mm × 0.1 mm
  - Blade thickness: 0.234 mm
  - Inclination angle and length: 18°; 0.7 mm
  - Tip radius: 4 µm
  - Friction coefficient: 0.3
  - Minimum element size: 2 µm
  - Total number of elements: 3.1 million

- **Model Features**
  - Quasi-static loading
  - Explicit analysis
  - Particle elements + continuum elements
3D SPH Modeling of Tool-Bone Interaction
3D SPH Modeling of Tool-Bone Interaction

Boundary conditions
- Fully constrained DOF at bottom
- Symmetry boundary at front and back surfaces
- Constrained left and right surfaces
- Tied constrain between SPH and C3D8R element

Material behavior
- Transverse orthotropic elasticity
- Hill’s anisotropic yield criterion
- Strain-based damage criterion + maximum degradation

<table>
<thead>
<tr>
<th></th>
<th>E1 (GPa)</th>
<th>E2 (GPa)</th>
<th>E3 (GPa)</th>
<th>Nu12</th>
<th>Nu13</th>
<th>Nu23</th>
<th>G12 (GPa)</th>
<th>G13 (GPa)</th>
<th>G23 (GPa)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>22988</td>
<td>14122</td>
<td>14122</td>
<td>0.29</td>
<td>0.29</td>
<td>0.21</td>
<td>5600</td>
<td>5600</td>
<td>8100</td>
</tr>
</tbody>
</table>
3D SPH Modeling of Tool-Bone Interaction
3D SPH Modeling of Tool-Bone Interaction
3D SPH Scratching Model

- **Model Specification**
  - Specimen size: 3 mm × 1 mm × 0.5 mm
  - Blade thickness: 0.4 mm
  - Tip radius: 10 µm
  - Friction coefficient: 0.3
  - Minimum element size: 5 µm
  - Total elements: 1 million elements
  - Cutting speed: 20 m/ min
3D SPH Scratching Model

S, Mises (Avg: 75%)

- 255.08
- 233.82
- 212.57
- 191.31
- 170.05
- 148.80
- 127.54
- 106.28
- 85.03
- 63.77
- 42.51
- 21.26
- 0.00

Step: Step 1
Total Time:
3D SPH Scratching Model

Shear stress: $S_{12}$ (osteon to transverse)

Damage region: SHRCT
3D SPH Scratching Model