Computational Study of Cortical Bone Screw Pullout Using the eXtended Finite Element Method (XFEM)

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Fracture in Abaqus

Two Methods Investigated:

1. **Element deletion**
   - Voids nucleate and propagate as elements are removed from mesh

2. **eXtended finite element method (XFEM)**
   - no elements deleted from mesh
   - Elements are split as crack propagates
Orthopaedic Screws

- Orthopaedic screws used for fracture repair at sites throughout body
- Pullout failure mode reported clinically

Experimental Testing

- Monotonic Tensile Pullout Test
- ASTM F543.23096-1
- Test Rate: 5mm/min

*Feerick and McGarry, Cortical bone failure mechanisms during screw pullout, Journal of biomechanics (2012) article in press*
Experimental Testing

*Feerick and McGarry*, *Cortical bone failure mechanisms during screw pullout*, Journal of biomechanics (2012) article in press
Cortical Bone Microstructure Model

Material 1: 35% volume
Material 2: 65% volume

Model Details
- Commercial screw geometry
- Screw-bone general contact
- COF 0.3

Cortical Bone Properties:
- Drucker Prager plasticity model
- Damage evolution
- Element deletion

Cortical Bone Plasticity

Drucker Prager Plasticity Model

– Pressure dependent yield
– Isotropic hardening

• Parameters* 
  – $K = \text{flow stress ratio}$
  – $\beta = \text{friction angle}$
  – $\Phi = \text{Dilation angle}$

$F = t - p Tan\beta - d = 0$

$d = (1 - \frac{1}{3} Tan\beta)\sigma_y$

[*] Mercer et al, Acta Biomaterialia, 2006; Mullins et al, JMBBM, 2009
Damage Process
Damage Initiation

Shear Criterion

• Predict damage initiation due to shear band localisation.
• Equivalent plastic strain at onset of damage is a function of shear stress ratio & strain rate

Criteria for Damage:

\[ \omega_s = \int \frac{d\varepsilon_{pl}}{\varepsilon_{s}^{pl}(\theta_s, \dot{\varepsilon}_{pl})} = 1 \]

\[ \theta_s = \frac{(q + k_s p)}{\tau_{max}} \]

\( \theta_s \) = Shear stress ratio
\( q \) = Mises equivalent stress
\( p \) = Pressure stress

\[ \varepsilon_{s}^{pl}(\theta_s, \dot{\varepsilon}_{pl}) \]
Damage Evolution

- Characteristic Length: $L$
- Linear damage evolution
- Damaged elements removed from mesh ($D=1$)

\[ G_f = \int_{\bar{\varepsilon}_0}^{\bar{\varepsilon}_f} L\sigma_y d\bar{\varepsilon}^{pl} = \int_0^{\bar{u}^{pl}} \sigma_y d\bar{u}^{pl} \]

\[ D = \frac{L\bar{\varepsilon}^{pl}}{\bar{u}^{pl}} \]
Experimental Longitudinal Failure Mode

*Feerick and McGarry*, *Cortical bone failure mechanisms during screw pullout*, Journal of biomechanics (2012) article in press
Longitudinal Pullout Simulation

Transverse Failure Mode:

- Initial
- Peak Load
- Crack Initiation
- Crack Progress
- Material Detachment
- Final Surface

*Feerick and McGarry, Cortical bone failure mechanisms during screw pullout, Journal of biomechanics (2012) article in press*
Transverse Pullout Simulation

Limitations

• Mesh Sensitivity
  – Larger elements mean larger voids
Limitations

- Unphysical over-closure between newly exposed surfaces in highly deformed meshes.
Limitations

• Too computationally expensive for 3D microstructure simulations

Transverse 3D Microstructure Model

5.8 million C3D4 Elements
eXtended Finite Element Method (XFEM)

- Mesh Independent
- Enriched elements apply additional displacement functions to selected regions of the mesh
- Contact can be applied between newly exposed surfaces
- Abaqus 6.11 release contained UDM facilitates anisotropic damage criteria
- Can not be used with axisymmetric e
**XFEM UDMGINI: Damage Initiation**

- Anisotropic elasticity with anisotropic damage criteria
  - Hashin damage tensile criteria (Index 1 & 2)
  - Max principal stress criteria (Index 3)

Failure Index 1: \( \bar{\sigma}_f = \sqrt{\left(\frac{\sigma_{11}}{\sigma_{ff}}\right)^2 + \left(\frac{\sigma_{12}}{\sigma_{f\tau f}}\right)^2} = 1 \)

Failure Index 2: \( \bar{\sigma}_m = \sqrt{\left(\frac{\sigma_{22}}{\sigma_{mf}}\right)^2 + \left(\frac{\sigma_{12}}{\sigma_{m\tau f}}\right)^2} = 1 \)

Failure Index 3: \( \bar{\sigma}_p = \frac{\sigma_p}{\sqrt{\sigma_{ff}^2 \cos^2 t + \sigma_{mf}^2 \sin^2 t}} = 1 \)

- \( \bar{\sigma}_f \) is the fiber damage initiation criterion
- \( \sigma_{ff} \) is the UTS of the fiber
- \( \sigma_{f\tau f} \) is the shear failure strength of the fiber
- \( \bar{\sigma}_m \) is the fiber damage initiation criterion
- \( \sigma_{mf} \) is the UTS of the matrix
- \( \sigma_{m\tau f} \) is the shear failure strength of the matrix
**XFEM UDMGINI : Crack Propagation**

- **FNORMAL**: Array of defining the normal direction to the fracture line (2D) for each failure index.

- Crack propagates based on energy dissipation (*Damage Evolution*)

\[
\text{Failure Index 1: } \bar{\sigma}_f = \sqrt{\left(\frac{\sigma_{11}}{\sigma_{ff}}\right)^2 + \left(\frac{\sigma_{12}}{\sigma_{ff}}\right)^2} = 1
\]

\[
\text{Failure Index 2: } \bar{\sigma}_m = \sqrt{\left(\frac{\sigma_{22}}{\sigma_{mf}}\right)^2 + \left(\frac{\sigma_{12}}{\sigma_{mf}}\right)^2} = 1
\]

\[
\text{Failure Index 3: } \bar{\sigma}_p = \frac{\sigma_p}{\sqrt{\sigma_{ff}^2 \cos^2 t + \sigma_{mf}^2 \sin^2 t}} = 1
\]

- \( F_{normal} (n, 1) = \text{ori}(n, 1) \)

- \( F_{normal} (n, 2) = \text{ori}(n, 2) \)

- \( F_{normal} (n, 3) = \text{an}(n_{max}, n) \)
Calibration for Cortical Bone

- Asymmetric 4PB
  - Mode 2 / Mixed Mode
- Symmetric 4PB / 3PB
  - Mode 1

Calibration for Cortical Bone

- Simulations (Index 1&2) validated by experiments
  - Crack Patterns
  - Fracture Energy

Department of Mechanical & Biomedical Engineering

* Zimmerman et al (2009) j.biomaterials
Calibration for Cortical Bone

- Introduce index 3
  - Crack deviates from vertical

Mode 1 Phase 0°

Hashin Failure Index
Index 1 & 2

Maximum Principal Stress
Index 1, 2 & 3

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* Zimmerman et al (2009) j.biomaterials
Application: 2D Screw Pullout

- **Longitudinal 0°**
  - Osteon alignment

- **Transverse 90°**
  - Osteon alignment

- **45°**
  - Osteon alignment
Application: 2D Screw Pullout

- Longitudinal: 0°
- Transverse: 90°
- 45°

Osteon alignment
Application: 2D Screw Pullout

Pullout Force ($F_p$) increases with increasing osteon angle.

Normalised Pullout Force ($F_p/F_{pT}$) versus Osteon Angle ($\theta$)

Feerick et al (2012)

Application: 3D Screw Pullout

- Investigate the effect of the helix
- And other unsymmetric features

Cutting Flute

Helical Geometry
Application: 3D Screw Pullout

Osteon Alignment

0 °
(Longitudinal)

90 °
(Transverse)

45 °

183,552 C3D4 Elements
Application: 3D Screw Pullout

Osteon Alignment

0 °
(Longitudinal)
Application: 3D Screw Pullout

Osteon Alignment
90° (Transverse)
Application: 3D Screw Pullout

Osteon Alignment

45°
Pullout Force ($F_p$) increases with increasing osteon angle.

Normalised Pullout Force ($F_p / F_{pT}$) versus Osteon Angle ($\theta$)
Summary

- XFEM predicts crack patterns compared to microstructure models
- Lower computational expense for 3D simulations