Fracture and Fatigue of Biological Materials: Bone and Teeth

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The Problem!

- 1 in 2 women & 1 in 4 men over 50 will have an osteoporosis-related bone fracture over their remaining lifetime
- Problem treated in terms of loss of bone mass (bone quantity), but this is only a part of the problem – the other issue is bone quality
- 10-fold increase in fracture risk found with aging, independent of bone mineral density

10 million people in the U.S. have osteoporosis

Osteoporotic trabecular bone

Bone damaged by steroids

Failures in bone from impact or fatigue (stress fractures)

(from www.anmds.com)
Bone Quality?

**Outline**

- **Introduction**
  - structural length scales in bone

- **Criteria for fracture**
  - fracture toughness
  - toughening mechanisms

- **Aging, disease and treatment**
  - effect of aging & disease
  - therapeutic treatments

- **Assessment of bone quality**
  - fracture mechanics testing
  - crack path (in bone biopsies)
What Controls Fracture in Materials?

Fracture is a mutual competition between:

- **intrinsic damage mechanisms** ahead of the crack tip, that promote crack propagation, and
- **extrinsic toughening (shielding) mechanisms** behind the crack tip, that inhibit crack propagation

- fracture in cortical bone shares many commonalities with structural ceramics, *i.e.*, the importance of extrinsic toughening mechanisms, principally crack bridging, and resultant resistance-curve (R-curve) behavior

Structural Length Scales in Teeth & Bone

Complex, hierarchical structures

- **building blocks**: collagen & nanocrystalline hydroxyapatite mineral
- **at nanometer scale**: mineralized collagen fibrils
- **at micron scale**: lamellae structure of collagen fibers
- **at micron scale** in dentin: tubules
- **at hundreds of microns** in bone: osteons/ Haversian canals
- **at macro scale**: size and type of the tooth or bone

Dentin:
- 45 vol% apatite
- 36 vol% collagen
- 25 vol% fluid

Bone:
- 45 vol% apatite
- 36 vol% collagen
- 25 vol% fluid
Nature of Inelasticity in Mineralized Tissue

Inelastic deformation results from:

- plastic deformation (in the collagen fibrils)
- microcracking damage (at the peritubular cuffs and in the intertubular matrix)
- poro-elasticity (from fluid in the tubules)?

Experimental Measurements

Fracture toughness, $K_c$

- fracture toughness assessed using crack-resistance curves (R-curves)

Fatigue crack-growth rates

- fatigue-crack growth assessed using $da/dN$ vs. $\Delta K$ plots ($\nu$-$K$ curves)

Fracture Mechanics

$$K_c = Q \sigma_F (\pi a)^{1/2}$$

where

- $\sigma_F$ = fracture stress
- $a$ = crack size
- $Q$ = geometry factor ~1
**Mechanisms of Fracture Initiation**

- two identical notches in a four-point bend bar
- constant bending moment on both notches
- one notch breaks - the other freezes local fracture events just prior to fracture
- crack initiation directly at the notch root implies that initiation of fracture in human cortical bone and dentin is locally strain-controlled

with inelasticity, stresses peak ahead of notch, strains peak at notch

• crack initiation directly at the notch root implies that initiation of fracture in human cortical bone and dentin is locally strain-controlled


**Fracture Toughness of Human Bone**

- bone is tougher in certain directions
- it is much more difficult to break than to split
- it is a factor of two tougher in the transverse orientation

humeral cortical bone

osteons interfaces are sites of preferred cracking

\[ K_c = Q \sigma_F (a) \]

\( K_c \): Fracture Toughness, \( \sigma_F \): Stress Intensity Factor, \( a \): Crack Length

Nalla, Stößenken, Kinney & Ritchie, J. Biomechanics, 2005
in situ loading in SEM

Human cortical bone

R-curve

Koester, Ager, & Ritchie, 2006
STRESS INTENSITY, $K$, (MPa√m)

CRACK EXTENSION, $\Delta a$, (μm)

STRESS INTENSITY, $K$, (MPa√m)

CRACK EXTENSION, $\Delta a$, (μm)
**Origins of Toughening in Bone**

**Crack Deflection**

\[ k_1(\alpha) = c_{11}(\alpha) K_I + c_{12}(\alpha) K_{II} \]
\[ k_2(\alpha) = c_{21}(\alpha) K_I + c_{22}(\alpha) K_{II} \]

\[ K_d = (k_{12} + k_{22})^{1/2} \]

(Bibby et al., 1978; Cottrell & Rice, 1980)

**Constrained Microcracking**

\[ K_{mic} = 0.22 E' f_m \varepsilon_m^{1/2}\frac{\beta f_m K_c}{(1+f_u/(rb))^{1/2}} \]

(Evans & Fu, 1985; Hutchinson, 1987)

\[ K_d = 0.05 \text{ MPa}\sqrt{\text{m}} \]

**Uncracked-Ligament Bridging**

\[ K_{ul} = \frac{-f_u K_c (1+f_u/(rb))^{1/2}}{[1-f_u+f_d(1+f_u/(rb))^{1/2}]} \]

(Shang & Ritchie, 1989)

\[ K_u = 1.5 \text{ MPa}\sqrt{\text{m}} \]

**Collagen-Fibril Bridging**

\[ K_f = 2 \sigma_b f_d (2 \frac{l_f}{\pi})^{1/2} \]

(Evans & McMeeking, 1986)

\[ K_f = 0.1 \text{ MPa}\sqrt{\text{m}} \]

Crack Arrest in the DEJ Region in Teeth

- Cracks in harder enamel do not necessarily break the tooth as they arrest "at" the dentin-enamel junction (DEJ).
- Cracks arrest when they form elastic bridges in the (mantle) dentin due to the formation of uncracked ligaments in the crack wake.

Toughness of the DEJ Region in Teeth

- Toughness of the DEJ assessed from the elastic mismatch between dentin and enamel by whether the crack deflects, arrests or penetrates the interface.

Elastic mismatch: 
\[ \alpha \approx \frac{(E_1 - E_2)}{(E_1 + E_2)} \]

He and Hutchinson (1989)

<table>
<thead>
<tr>
<th>Material</th>
<th>( E_1 )</th>
<th>( E_2 )</th>
<th>( G_{\text{c,DEJ}} )</th>
<th>( G_{\text{c,dentin}} )</th>
<th>( G_{\text{c,enamel}} )</th>
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</thead>
<tbody>
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<td>dentin</td>
<td>64</td>
<td>20</td>
<td>0.53</td>
<td>-25</td>
<td>154</td>
</tr>
<tr>
<td>enamel</td>
<td>1.5</td>
<td>0.5</td>
<td>0.75</td>
<td>0.75</td>
<td>155</td>
</tr>
</tbody>
</table>

- Upper-bound toughness of the DEJ estimated to be \( G_{\text{c,DEJ}} \approx 115 \text{ J/m}^2 \).
- Toughness of the DEJ is intermediate between enamel and dentin.
- It is \( \sim5-10 \) times higher than enamel but still 75% of dentin.

Experimental Proof of Crack Bridging

- Compliance of actual crack is measured before and after machining the wake; results compared to theoretical compliance of traction-free crack (of same length).
- Bridging contribution to toughness of bone measured at $K_{tc} \approx 0.5 - 1$ MPa√m, and occurs over large length scales (hundreds of microns).

Kruzic, Nalla, Kinney & Ritchie, Biomaterials, 2004

Crack Bridging vs. Constrained Microcracking

- Microcracking based explanation for toughening prevalent in the literature.
- Crack bridging will reduce compliance, $C$; microcracking will increase compliance.
- Supports bridging as the main toughening mechanism, rather than microcracking.

Nalla, Kruzic, Kinney & Ritchie, Bone, 2004
### Tomographic Evidence of Crack Bridging

- **Human dentin**
- **Human cortical bone**

X-Ray Computed Tomography, performed at the Stanford Linear Accelerator Center and Advanced Light Source (LBNL)

Kruzic, Nalla, Kinney & Ritchie, Biomaterials, 2003; Nalla, Kruzic, Kinney & Ritchie, Biomaterials, 2005

### Resistance-Curve Toughness Behavior

- Presence of crack-bridging does result in crack-size dependent behavior:
  - Rising R-curves
  - Small-crack effects

- As bridging zones are ~hundreds of microns in size, they can be comparable with the size of the bone (or tooth) - quoted (single-value) $K_{IC}$ fracture toughness values are thus likely size- and geometry dependent

Nalla, Kruzic & Ritchie, Bone, 2004
Kruzic, Nalla, Kinney & Ritchie, Biomaterials, 2003
Qang, Cox, Nalla & Ritchie, Biomaterials, 2006; Bone, 2006
Fatigue of Mineralized Tissue

- Not clear whether this is a cycle- or time-dependent phenomenon.
- "Metal-like" fatigue S/N behavior with frequency-dependent fatigue limit at $10^6$-$10^7$ cycles of ~25 and 45 MPa.
- Comparable at lower frequency to typical masticatory stress levels (~20 MPa).
- Fatigue lives, in terms of cycles to failure, are shorter at lower frequency.

Fatigue Crack Growth in Human Dentin

- Decay in stiffness used to estimate crack lengths from smooth-bar S/N tests.
- Paris power-law relationship, $\frac{da}{dN} = C \Delta K^m$, where exponent $m \approx 8.76$.
- Estimated fatigue threshold, $\Delta K_{TH} \approx 1.06$ MPa\(\sqrt{m}\), ~60% of the fracture toughness.

**Fatigue-Crack Growth Data in Dentin**

- effect of frequency seen in “per cycle” & “per time” data from 1-50 Hz
- as in many materials, growth rates depend upon both $\Delta K$ and $K_{\text{max}}$

Kruzic, Nalla, Kinney & Ritchie, Biomaterials, 2005

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**Cyclic/Static Loading Experiments in Dentin**

- at constant $K_{\text{max}}$, crack barely propagates when unloading cycle is removed
- crack tends to blunts under static loading
- crack “sharpens” under cyclic loading
- clear evidence of cycle-dependent fatigue mechanism
- also evidence of a deterioration in the fraction of bridging ligaments

Kruzic, Nalla, Kinney & Ritchie, Biomaterials, 2005
**Fatigue vs. Slow Crack Growth in Bone**

- high growth rates – time-dependent static mechanisms (creep-dominated)
- low growth rates – cycle-dependent fatigue mechanisms (fatigue-dominated)
- crack growth by alternating blunting & resharpening and cycle-induced damage of bridging ligaments

**Fatigue of Small Surface Cracks**

- small surface cracks (~70-1000 μm) grow faster than large (through-thickness) cracks (> 2 mm) at the same ΔK
- such microcracks grow intermittently and locally arrest at microstructural features, e.g., at the osteon structures

- their faster growth rates can be attributed to their limited wake, which restricts the development of crack bridging
Kitagawa Diagram for Fatigue of Dentin

- Limiting conditions for fatigue failure can be defined by the fatigue threshold $\Delta K_{TH}$ at large crack sizes (> 150 $\mu$m) and by the smooth-bar fatigue limit $\Delta \sigma_{fat}$ at small crack sizes.

Effect of Aging on Dentin - Transparency

- Aging leads to an altered form of dentin – transparent dentin.
- Mineral concentration increases and distribution changes, due to filling up of tubules with mineral.
- Concentration differences due to crystallite size being slightly smaller in transparent dentin.
- Collagen environment is changed in terms of intrafibrillar mineral & overall density of fibrils.

- Reconstructed exit-wave lattice images of intratubular mineral in transparent dentin showing evidence of nanometer-sized single-crystal apatite grains (Mg-rich i-tricalcium phosphate).

atomically reconstructed exit-wave lattice images of intratubular mineral in transparent dentin showing evidence of nanometer-sized single-crystal apatite grains (Mg-rich i-tricalcium phosphate)

atomic force microscopy

X-ray computed tomography

UV Raman spectroscopy
Effect of Aging in Dentin: Property Changes

- Young’s and shear modulus unchanged with transparency.
- Normal dentin “yields”, with extensive post-yield deformation.
- Transparent (old) dentin is brittle - no yielding.
- Fracture toughness is ~20% lower in transparent dentin.
- Fatigue resistance generally lower in transparent dentin.

Kinney, Nalla, Pople, Breunig, & Ritchie, Biomaterials, 2005

Effect of Aging on the Toughness of Dentin

- Aging leads to reduced crack bridging, consistent with reduction in fracture toughness.
- Filled tubules in aged dentin become less effective stress-concentrators.

**Effect of Aging on Human Bone**

- Fracture toughness, and hence risk of fracture, of human bone severely degraded by age.
- Significant deterioration in the collagen.
- Effect may be related to excessive remodeling with age, which increases the osteon density.

**Deterioration in Human Bone from Aging**

- Size and area fraction of crack bridges decrease with age.
- Possibly from excessive remodeling → higher fraction of osteons.
- Significant correlation of decrease in toughness with increase in osteon density.

2-D tomographs show progressively fewer and smaller bridges in older bone.
Deterioration in Bone from Steroids

Glucocorticoids (GC) are steroid hormones widely used for inflammatory diseases, such as arthritis & dermatitis.

Clinical studies show increased risk of bone fracture (GC-induced osteoporosis).

GCs induce slower bone turnover by suppressing bone formation.

Bisphosphonates, e.g., Risedronate (RIS), are effective therapies, inhibiting bone resorption and reducing fracture risk.

GCs lead to "soft spots" - halos of low stiffness hypomineralized bone around larger osteocyte lacunae – toughness (mouse femurs) reduced 20%.

Concurrent RIS treatment suppress such "soft spots" - toughness is increased by 25% (Nancy Lane, UCDavis).

Effect of Raloxifene, Risedronate and Zoledronate on Estrogen-Deficient Bone

Study on rat femurs, ovarectomized (OVX) at 18 mts.

Given Raloxifene (RAL) or bisphosphonates - Risedronate (RIS) or Zoledronate (ZOL) - immediately afterwards, tested after 60 days.

RAL offsets estrogen-deficiency; RIS & ZOL inhibit bone resorption.

Compared to Sham, crack path, which has a radical effect on toughness, markedly different in RIS & ZOL treated bone.

Crack paths are very tortuous in RIS & ZOL-treated cortical bone.

Loss in bone-matrix toughness due to ovarectomy more than compensated by Raloxifene, Risedronate or Zoledronate treatments.
Fracture Risk Assessment from Biopsies

- we can induce stable cracks in cortical bone
- crack path, c.f., microstructure, used to assess toughening or deterioration
- we believe that we can measure a $K_c$ as a quantitative measure of bone quality for living patients

- microcracking, at cement lines, promotes toughness via bridging
- cracks often follow osteocyte lacunae

Koester, Ritchie et al., 2006

Alcohol Strengthens Teeth – at least temporarily!

- compared to water (HBSS), whiskey increases the stiffness, strength & toughness of dentin
- but you do need to keep the alcohol in your mouth, as the effect is reversible!
- effect associated with direct collagen-collagen H-bonding in polar solvents

Nalla, Balooch, Ager, Krusic, Kinney & Ritchie, Acta Biomaterialia, 2005
Bone Quality: Transforming Growth Factors

Role of TGF-β on mouse bone

- TGF-β is a family of proteins (cytokine) that can regulate behavior in bone
- TGF-β can inhibit osteoblast formation - osteoclasts are unaffected
- too much TGF-β (over-expression) leads to (27%) lower bone toughness (and osteoporosis)
- under-expressing TGF-β leads to increased bone deposition, enhanced mineral content, 50% higher bone toughness and more tortuous crack paths

Fracture Toughness

Conclusions

- One measure of bone quality is the fracture toughness. This requires an understanding of fracture mechanisms and how they are affected by microstructure
- Whereas fracture initiation in bone is strain-controlled, (crack-growth) toughness is derived from extrinsic toughening mechanisms, which promote R-curve behavior
- For crack propagation, the salient extrinsic toughening mechanisms are:
  - crack bridging by uncracked "ligaments" (and by individual collagen fibrils)
  - crack deflection along cement lines (transverse orientation)
- Although mechanisms are controlled by the hierarchy of structure, features at coarse length-scales, ~100-200 μm, are most important for fracture toughness
- Aging of dentin and bone identified with a loss in toughness, associated in part with a deterioration in crack bridging (consistent in bone with excessive remodeling)
- Regulation of growth factors (e.g., TGF-β) can have a significant and positive effect on the mechanical properties of bone - at nano to macro length-scales
- Whereas ovariectomies & steroids can prematurely degrade fracture toughness, Raloxifene or bisphosphonate treatments act to restore, or even enhance, fracture resistance - mechanically due to microstructure-induced changes in crack path
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Web page

• www.LBL.gov/Ritchie