Toughness Amplification in Natural Composites

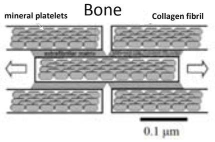
Reza Rabiei and Francois Barthelat
Department of Mechanical Engineering, McGill University

Main findings:
1) High fracture toughness of mineralized biological composites is explained by modeling.
2) The proposed model offers guidelines useful for novel designs of tough artificial composites.

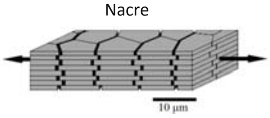
I. Introduction

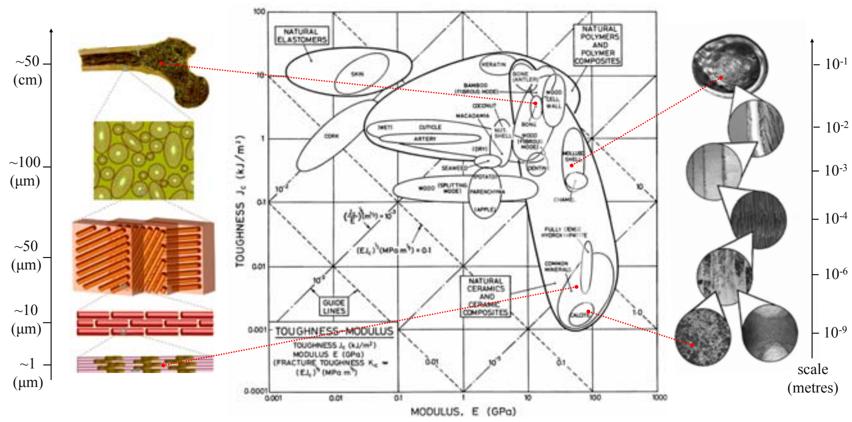
- The "staggered structure" is found in hierarchical structure of several high performance biological composites such as bone and nacre.
- The staggered structure consists of stiff mineral inclusions aligned along one direction with some overlap, and bonded by softer proteins.
- This unique structure leads to interesting combinations of stiffness, hardness and toughness [1] yet it is largely underused in biomedical and bioengineering applications.
- Mechanics of biological composites needs to be elucidated. In particular, which mechanisms are behind their "toughness amplification"?

Bone



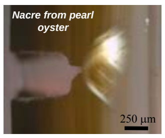
Nacre

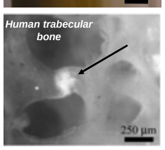




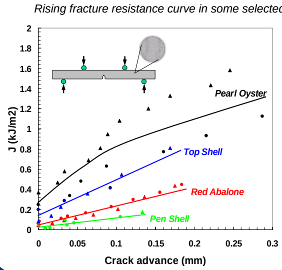
II. Fracture toughness: experiment

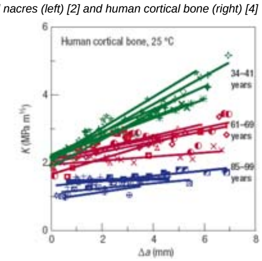
- Fracture toughness: the ability of material to resist crack propagation
- "Stress whitening" occurs in nacre and bone due to light scattering at the voids created by large deformations (images to the right) [2,3].
- Nacre and bone possess high fracture toughness.
- On top of being tough, nacre and bone exhibit a rising crack resistance curve making it harder for the crack to further propagate.
- Rising fracture toughness results in structural stability even though nacre and bone inherit natural flaws.





Rising fracture resistance curve in some selected nacres (left) [2] and human cortical bone (right) [4]





III. Fracture toughness: modeling

- Nacre is chosen as the representative of biological staggered structures for modeling.
- In nacre, <u>tablet bridging</u> and <u>process zone</u> are the two main toughening mechanisms.
- Stress whitening ahead of the crack tip represents the process zone.
- We developed an analytical model to predict fracture resistance curve, $\tilde{J}(\tilde{a})$.
- Fracture resistance is purely expressed in terms of the properties of the structure (i.e. material properties and structural parameters).

Material properties	Structural parameters
Tablet modulus E_m	Tablet thickness t
Interface shear modulus G_i	Tablet aspect ratio $\rho = L/t$
Interface shear strength τ_S	Mineral content $\phi = t/(t+t_i)$
Interface toughness J_i	

Model

Composite properties

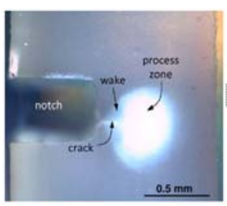
Elastic modulus E — Failure strain ε_{max}

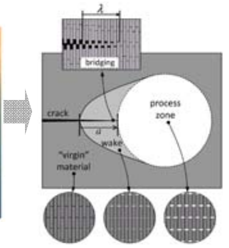
Tensile strength σ_S — **Fracture toughness $\tilde{J}(\tilde{a})$**

$$\begin{cases} \tilde{J} = \dfrac{\frac{2}{\pi}\tilde{a}}{1-\alpha F\left(\dfrac{d\tilde{J}}{d\tilde{a}}\right)} & \text{for } 0 \le \tilde{a} \le \dfrac{\pi}{2} \\ \tilde{J} = \dfrac{1}{1-\alpha F\left(\dfrac{d\tilde{J}}{d\tilde{a}}\right)} & \text{for } \dfrac{\pi}{2} < \tilde{a} \end{cases}$$

$$\alpha = \frac{1}{4}\left(\frac{E\varepsilon_{max}}{\sigma_S} - 1\right)$$

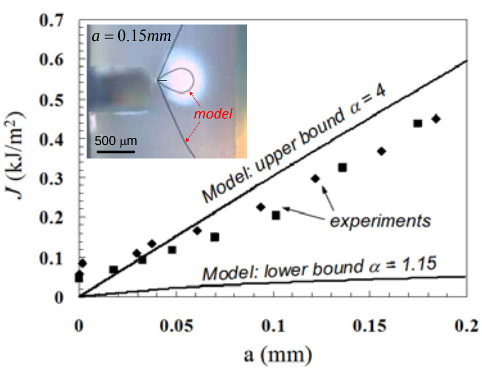
$$F(n) = 2\left(\frac{(1+n)\sqrt{1+2n}}{n} - n.\cot^{-1}\left(\frac{n}{\sqrt{1+2n}}\right) - \frac{(1+2n)^{3/2}}{n^2}\ln\left(\frac{1+2n}{1+n}\right)\right)$$



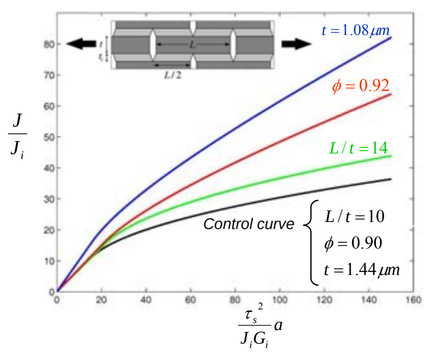


IV. Results

✓ The modeling results are in excellent agreement with experiments conducted on top shell [4].

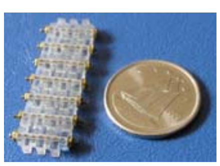


✓ Using small tablets with high aspect ratio and high volume concentration leads to high toughness [5].



V. Conclusions

- The analytical model proposed here can explain high fracture toughness of biological mineralized composites.
- Tablet bridging and process zone toughening largely contribute to the toughness of the staggered composite.
- This study provides implications for novel designs of artificial tough ceramics with biomedical and biomimetic applications.



References

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4. Ritchie, R.O., et al., Fatigue Fract Engng Mater Struct, 2005. 28: p. 345-371.
5. Bekah, S., R. Rabiei, and F. Barthelat, BioNanoScience 1 (1-2), 2011. p. 53-61.