Damage propagation in osteon-inspired structures: the role of the cement line

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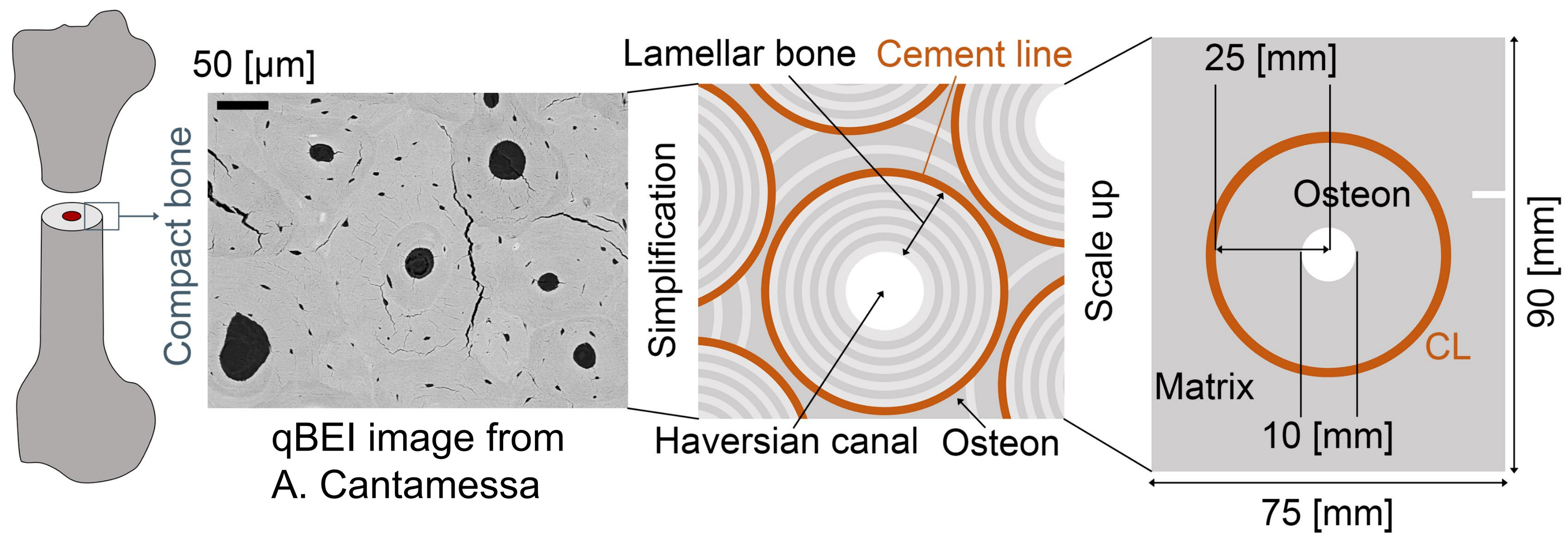
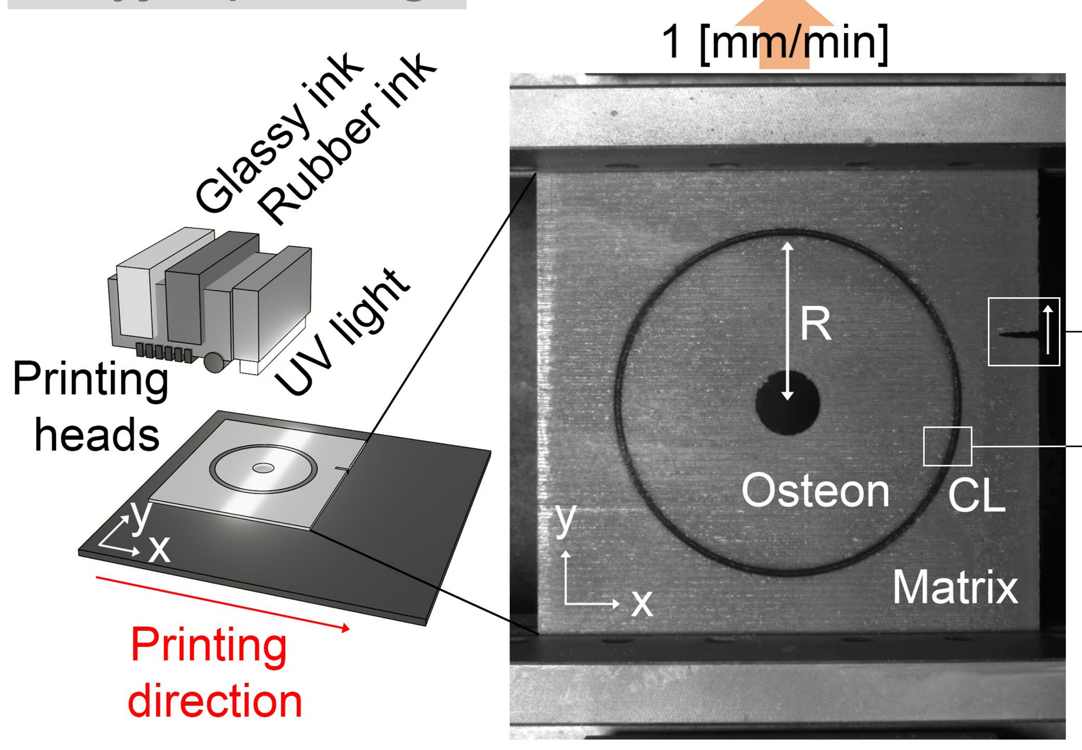
Introduction

Bone is well known for its ability to tolerate and repair damage. Damage propagation is hampered by several toughening mechanisms at different length scales, providing high strength and toughness. Osteons are important for bone toughness as incoming cracks can be deflected by the cement line or twisted by the lamellae to protect the bone vascular system. The main goal of our project is to integrate 3D multimaterial printing, mechanical testing and computer simulations into a research platform to explore the damage behavior of osteon-inspired materials.



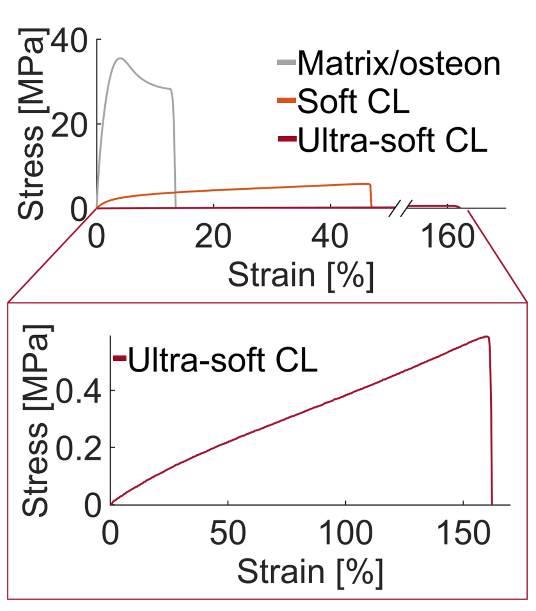
Experimental part: method

Polyjet printing:



2 parameters:

- Notch position: 0.3R/0.4R/0.5R
- CL properties:



Computational part: method

Damage model:

Initiation

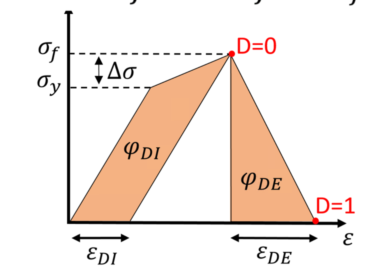
If $\omega_D = \int \frac{d\varepsilon^{pl}}{\bar{\varepsilon}_D^{pl}} = 1$

→ damage initiation starts

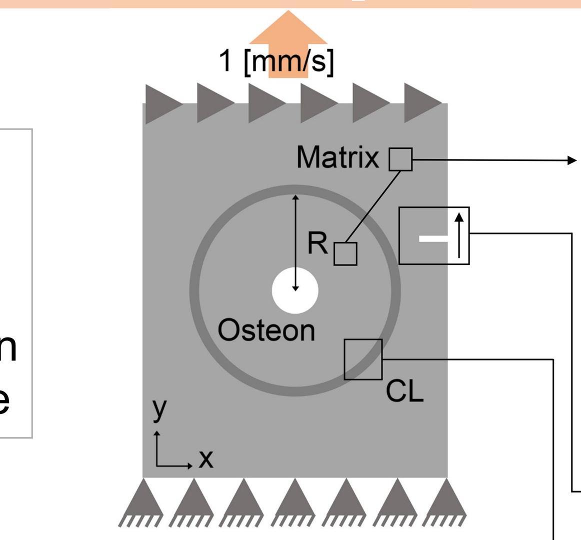
$\bar{\varepsilon}_D^{pl}$ equivalent plastic strain at the onset of damage

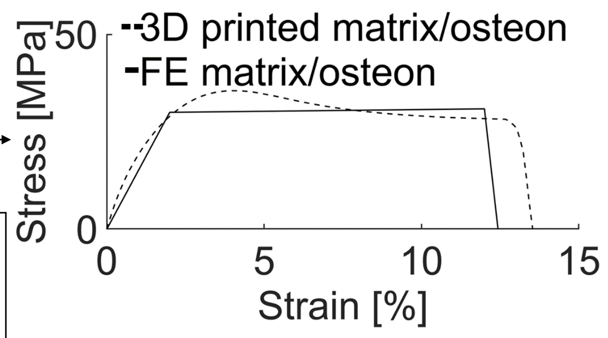
Evolution

$D = \frac{L\dot{\varepsilon}^{pl}}{\bar{u}_f^{pl}} = \frac{\dot{u}^{pl}}{\bar{u}_f^{pl}}$ with $\bar{u}_f^{pl} = \frac{2\,G_f}{\sigma_f}$



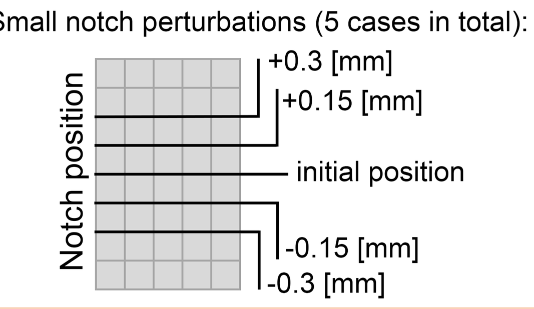
Adapted from Hajar R. et al. *Bone* **130**, 115102 (2020)





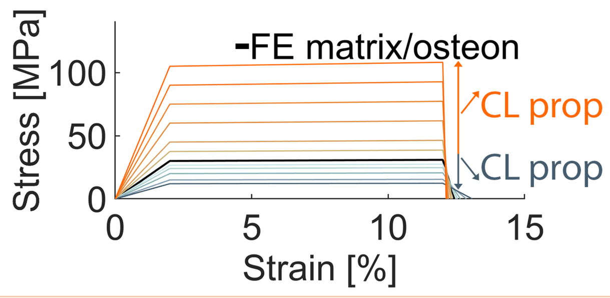
For each notch position + CL prop combination:

Small notch perturbations (5 cases in total):



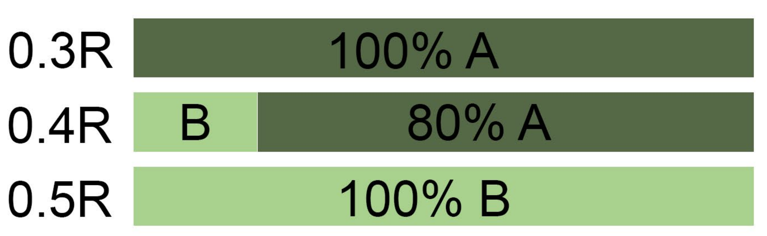
2 parameters:

- Notch position: 0.25R/0.5R/0.75R
- CL properties:



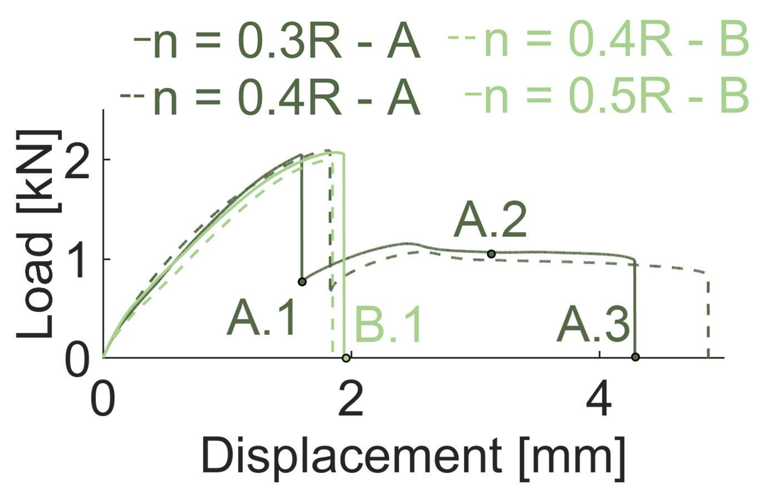
Experimental part: results

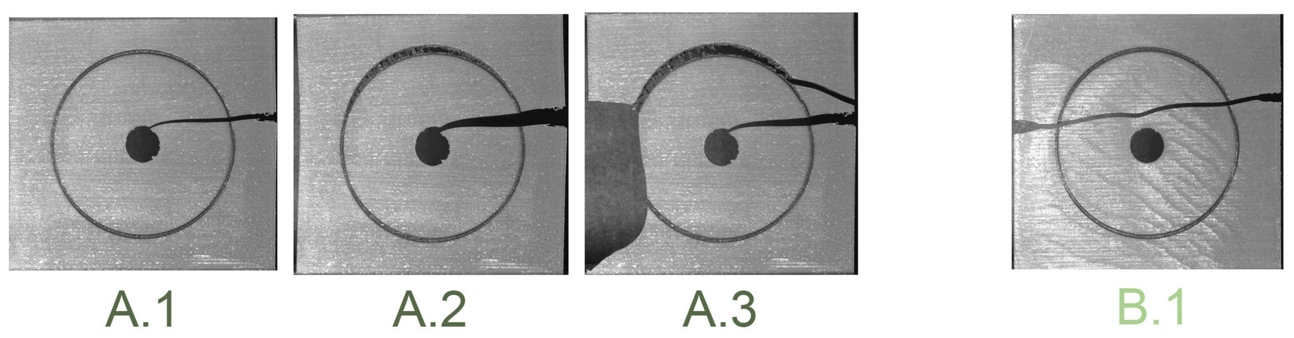
I. Soft cement line



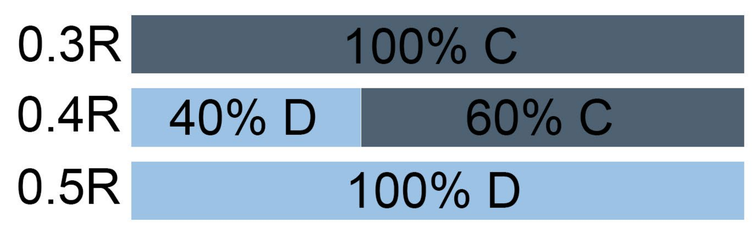
A. crack reaching the Haversian canal

B. crack crossing the osteon



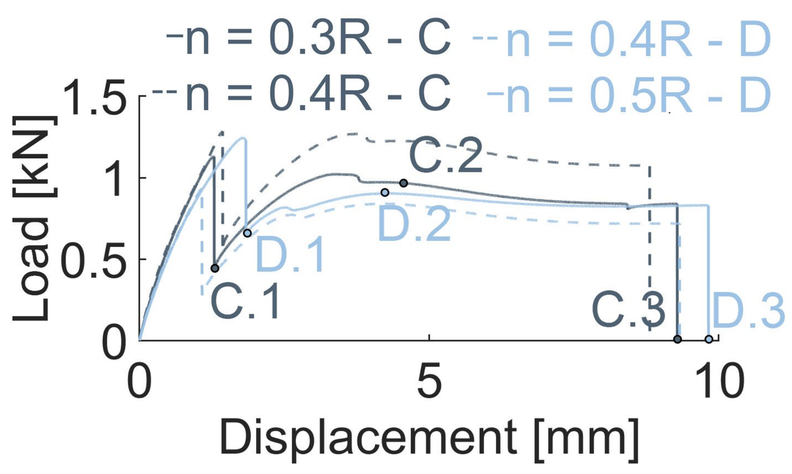


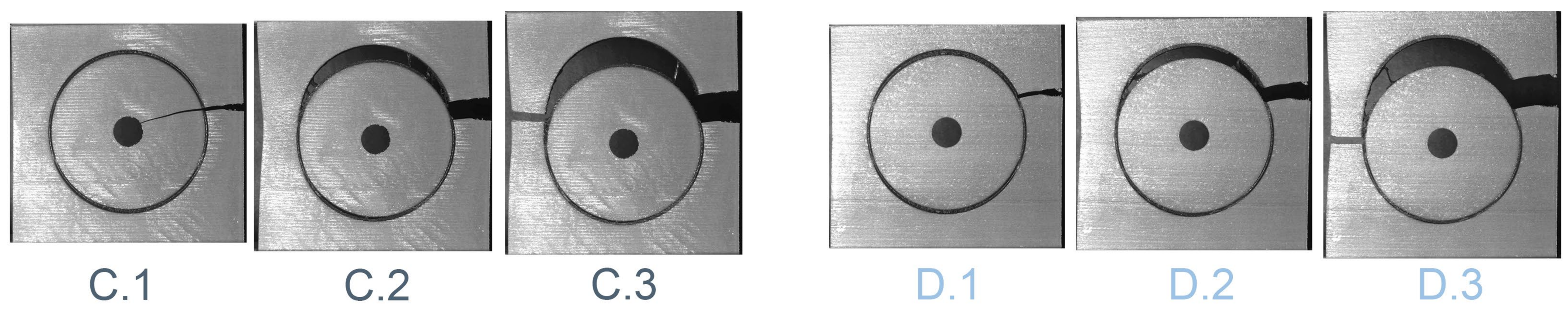
II. Ultra-soft cement line



C. crack reaching the Haversian canal

D. crack trapped in the CL

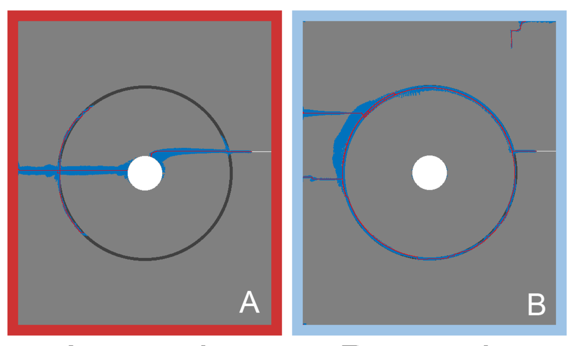




Computational part: results

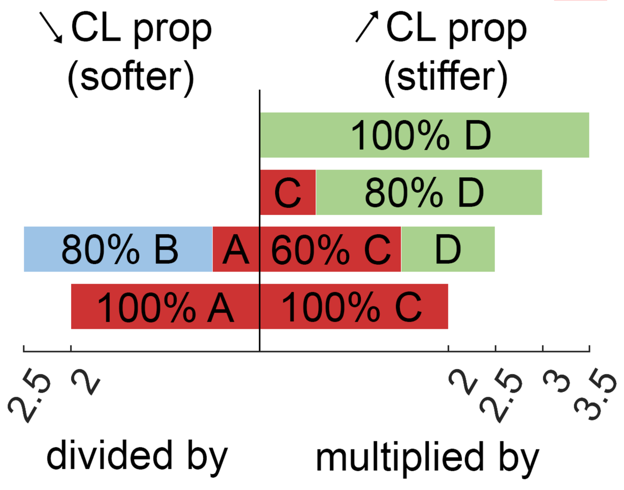
- Undamaged elements
- Damage initiated elements
- Fully damaged elements

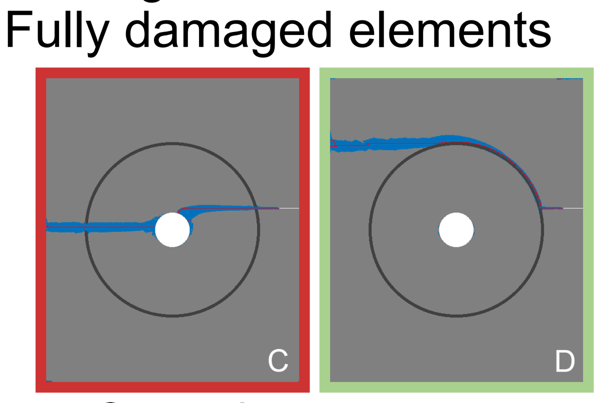
I. Lower position: 0.25R



A. crack reaching the HC

B. crack trapped in the CL

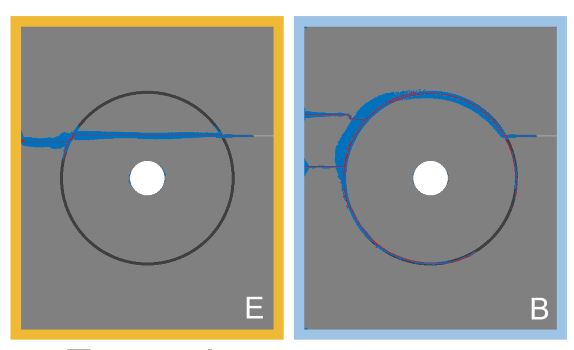




C. crack reaching the HC

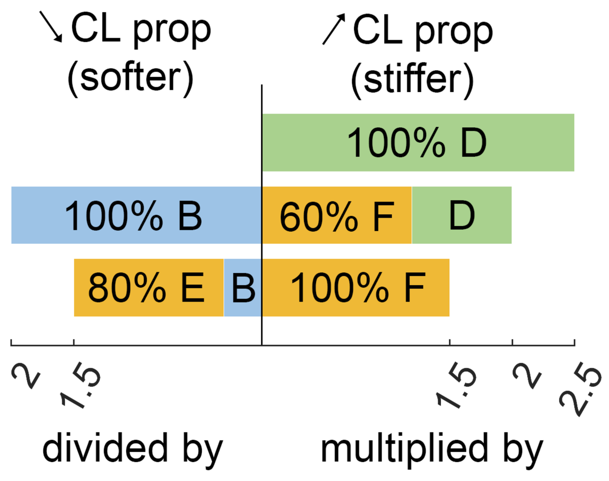
D. crack deflected along the CL

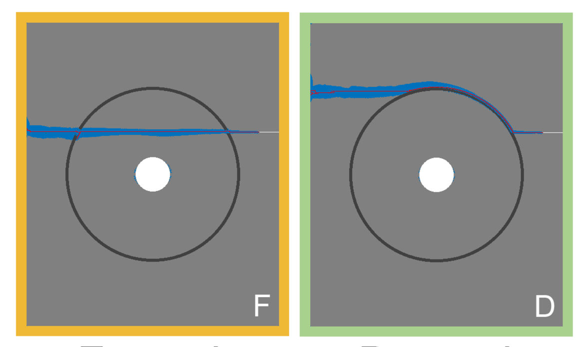
II. Intermediate position: 0.5R



E. crack crossing the osteon

B. crack trapped in the CL

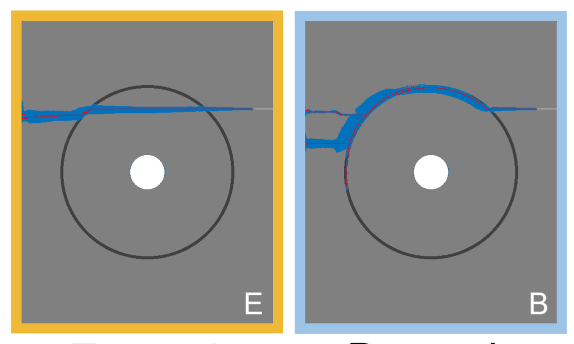




F. crack crossing the osteon

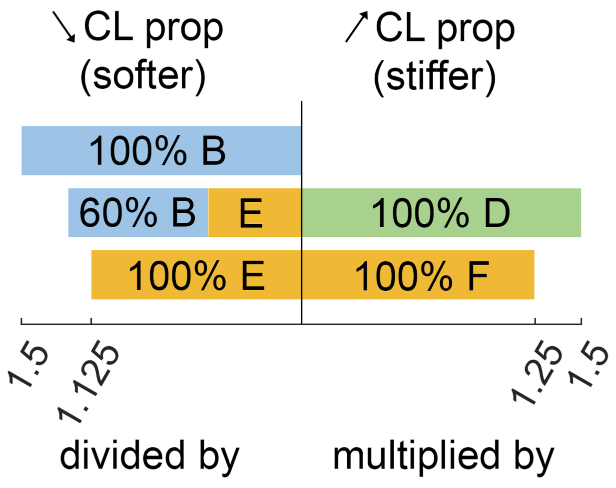
D. crack deflected along the CL

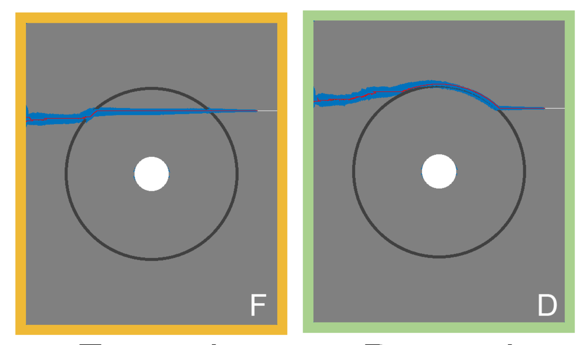
III. Higher position: 0.75R



E. crack crossing the osteon

B. crack trapped in the CL





F. crack crossing the osteon

D. crack deflected along the CL

Conclusion

We show that even a thin interlayer has a large influence on the interaction between a crack and the Haversian canal. Our prototypes show a programmable failure behavior dependent on the interlayer properties. A critical parameter that governs these behaviors is the yield stress. For the same crack propagation pattern, less yield stress contrast is required as the notch is moved up vertically. This work also illustrates that 3D-printed synthetic materials can benefit from strategies used by nature to increase damage tolerance.