tim.volders@uliege.be

Designing Architectured Materials with Tunable Damage Behavior Inspired by Osteonal Bone

Timothy Volders[1], Laura Zorzetto[2], Hajar Razi[3], Richard Weinkamer[2], Davide Ruffoni[1]

[1] University of Liege, Liege, Belgium, [2] Max Planck Institute of Colloids and Interfaces, Potsdam, Germany, [3] ETH Zurich, Zurich, Switzerland, and WoodTec Group, Cellulose & Wood Materials Laboratory, Empa, Dübendorf, Switzerland.

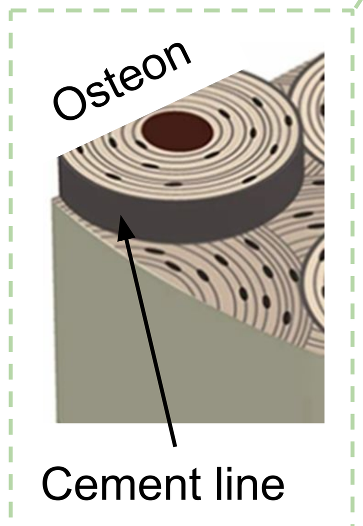
www.biomat.uliege.be

Introduction

The outstanding properties of biological materials make them attractive as models and inspiration for engineering materials. 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. 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.

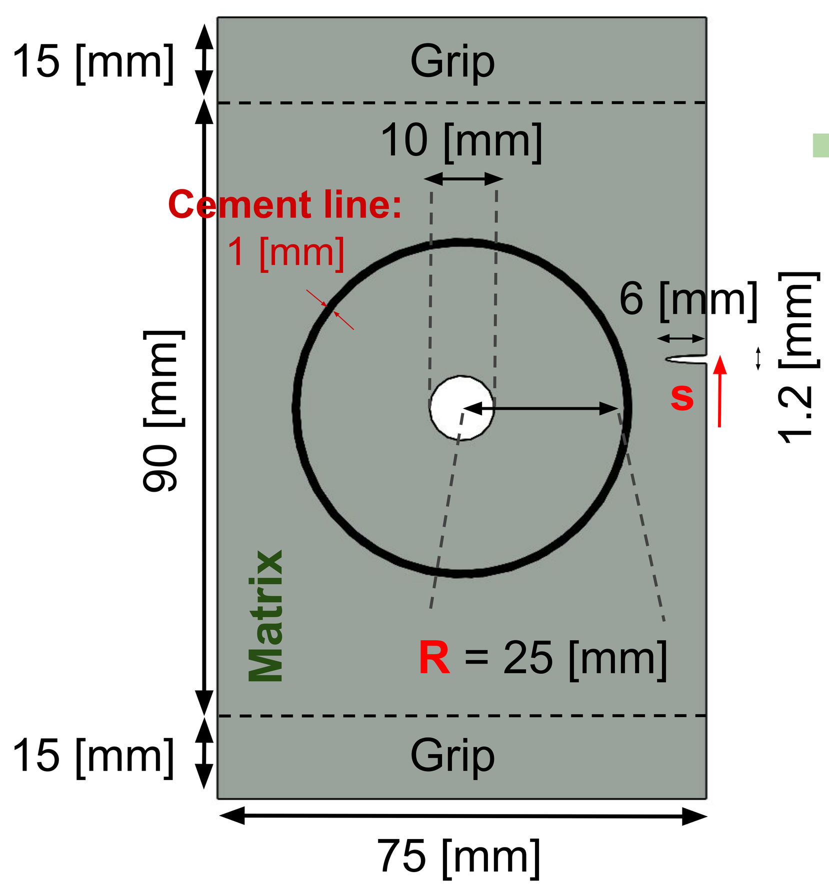
Experimental Part: Methods

Osteonal microstructure ~10[2] [μm]



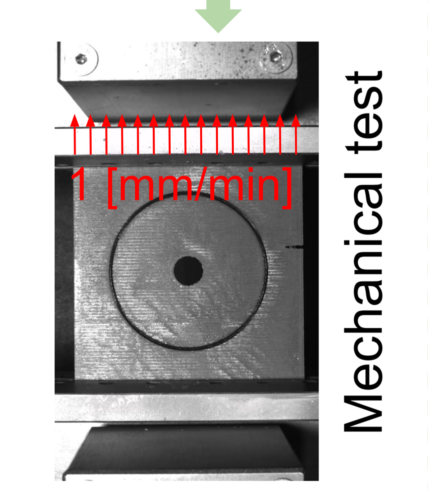
Adapted from Elizabeth A. Zimmermann et al. *Sci Rep* **6,** 21072 (2016)

Scale up



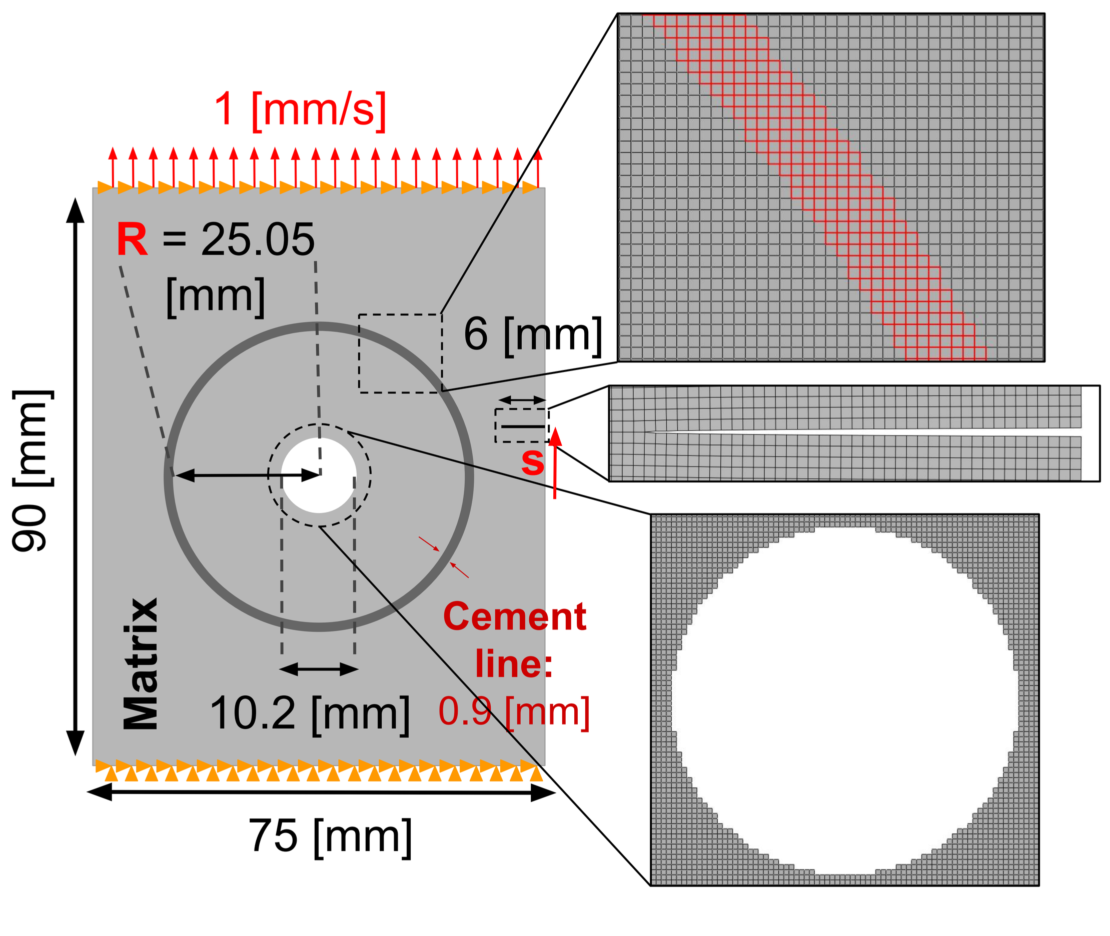
Sample thickness = 3.75 [mm]

3D printed with Objet260 Connex2



Mechanical test

Computational Part: Methods



Damage model

Damage initiation:

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

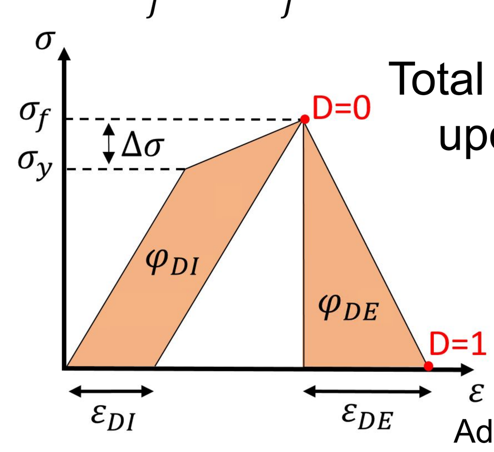
Equivalent plastic strain at the onset of damage

+

Damage evolution:

Fracture energy per unit area

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



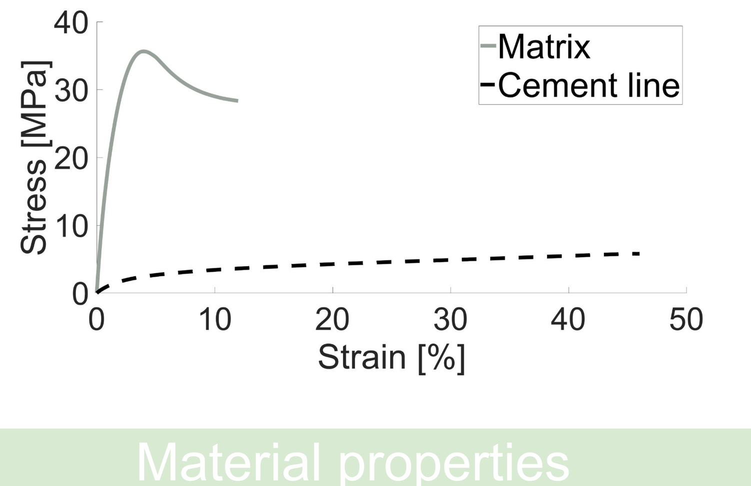
Total energy dissipated upon the damage process = $\varphi_{DI} + \varphi_{DE}$

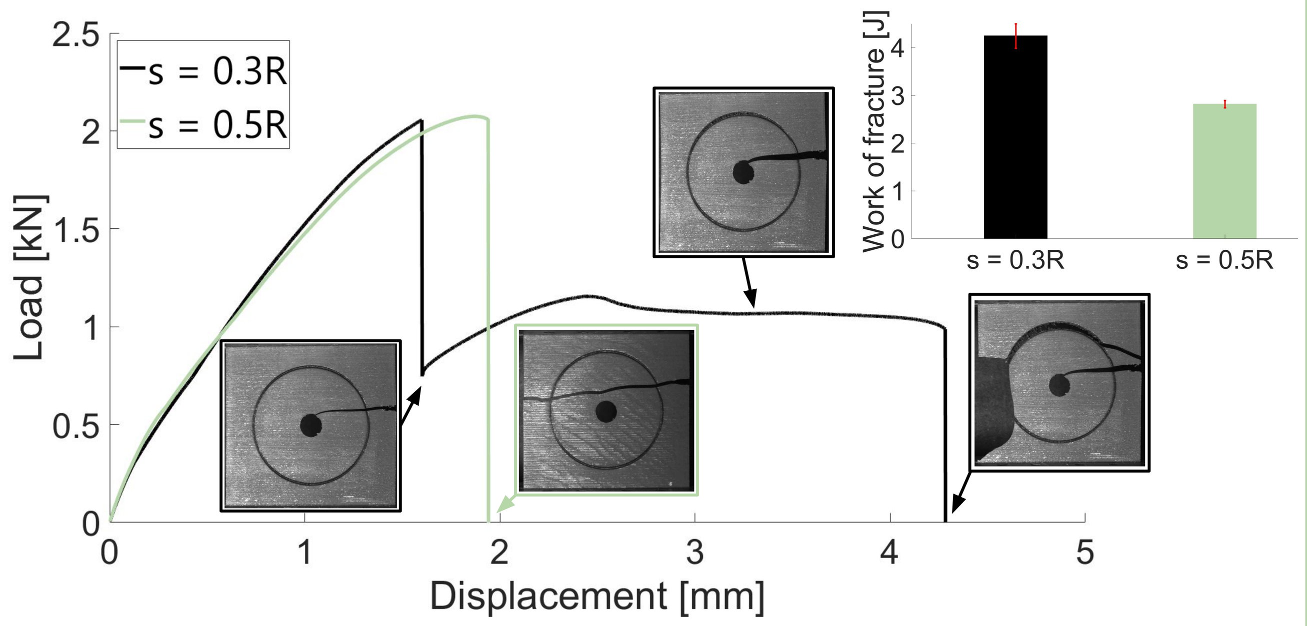
Adapted from Hajar R. et al. *Bone* **130**, 115102 (2020)

Experimental Part: Results

s = vertical position of the notch
R = inner radius of the osteon

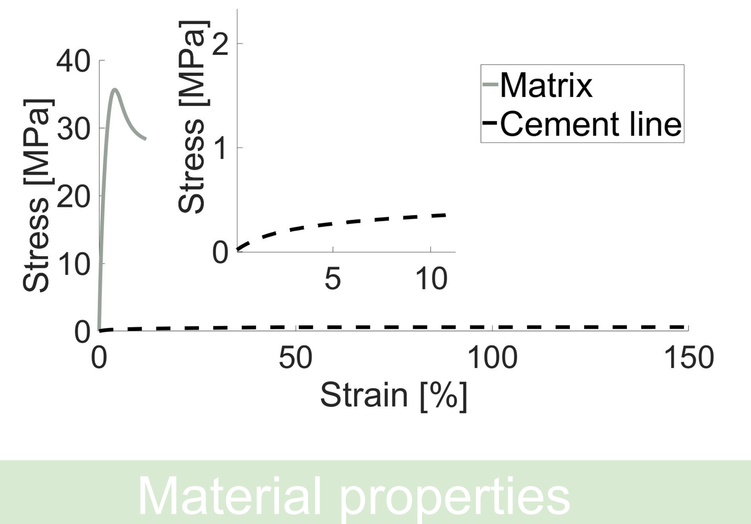
Soft cement line

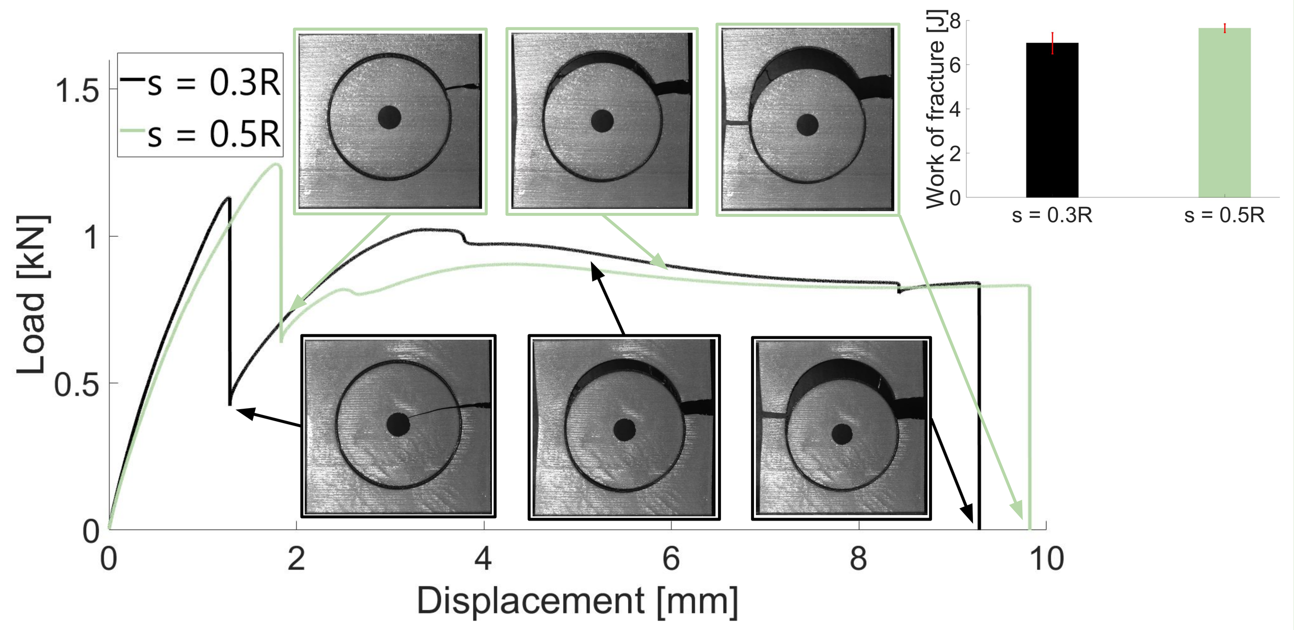




Depending on initial position of notch:
- → crack reaching the hole (s ≤ 0.3R)
- → s = 0.4R: unstable situation (80% cases reaching the hole / 20% cases crossing the osteon)
- → crack crossing the osteon (s ≥ 0.5R)

Ultra-soft cement line



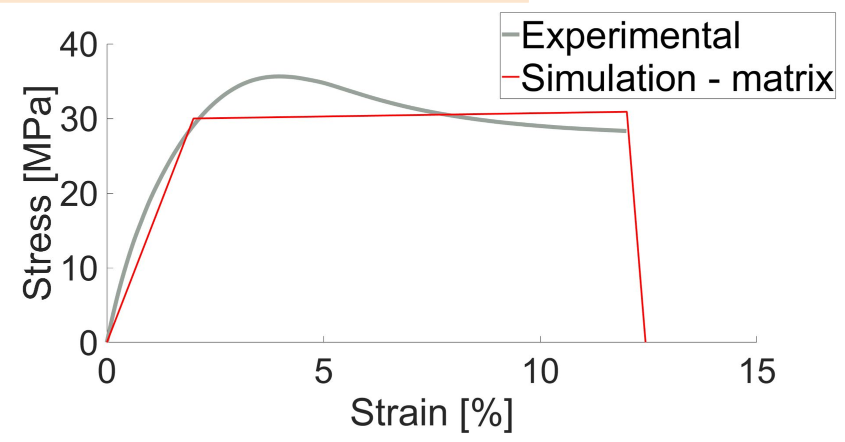


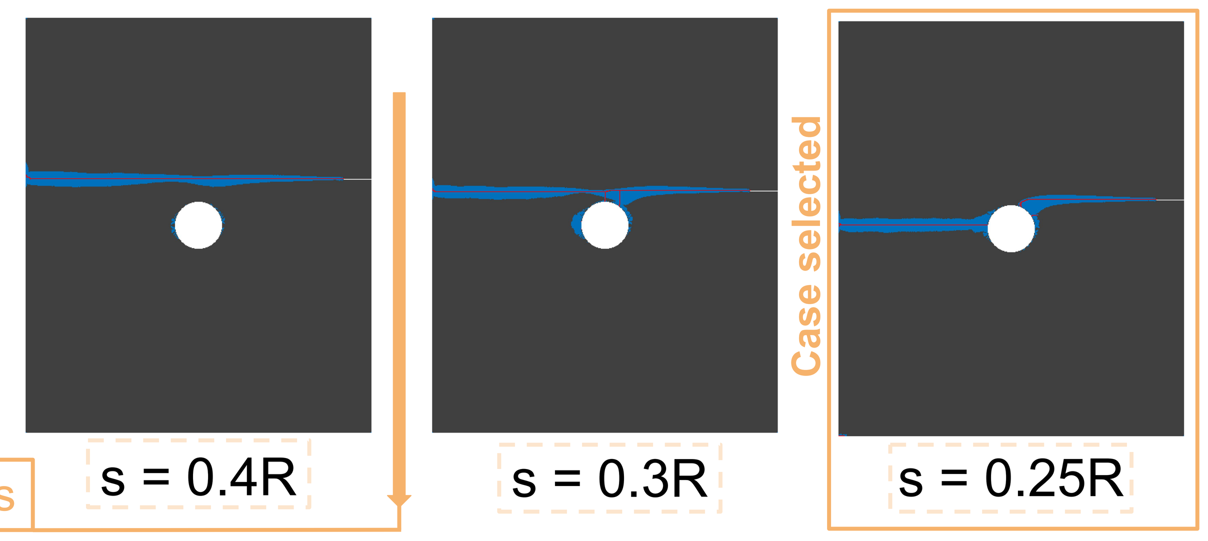
Depending on initial position of notch:
- → crack reaching the hole (s ≤ 0.3R)
- → s = 0.4R: unstable situation (37.5% cases reaching the hole / 62.5% cases trapped in the cement line)
- → crack trapped in the cement line (s ≥ 0.5R)

Computational Part: Results

- Undamaged elements
- Damage initiated elements
- Fully damaged elements

Initial notch position

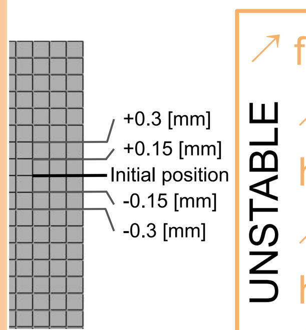




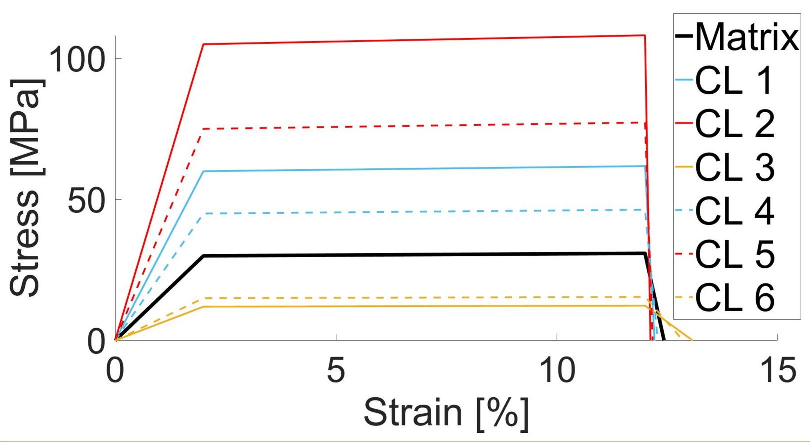
The notch is progressively moved downwards

Introducing the cement line (CL) at s = 0.25R

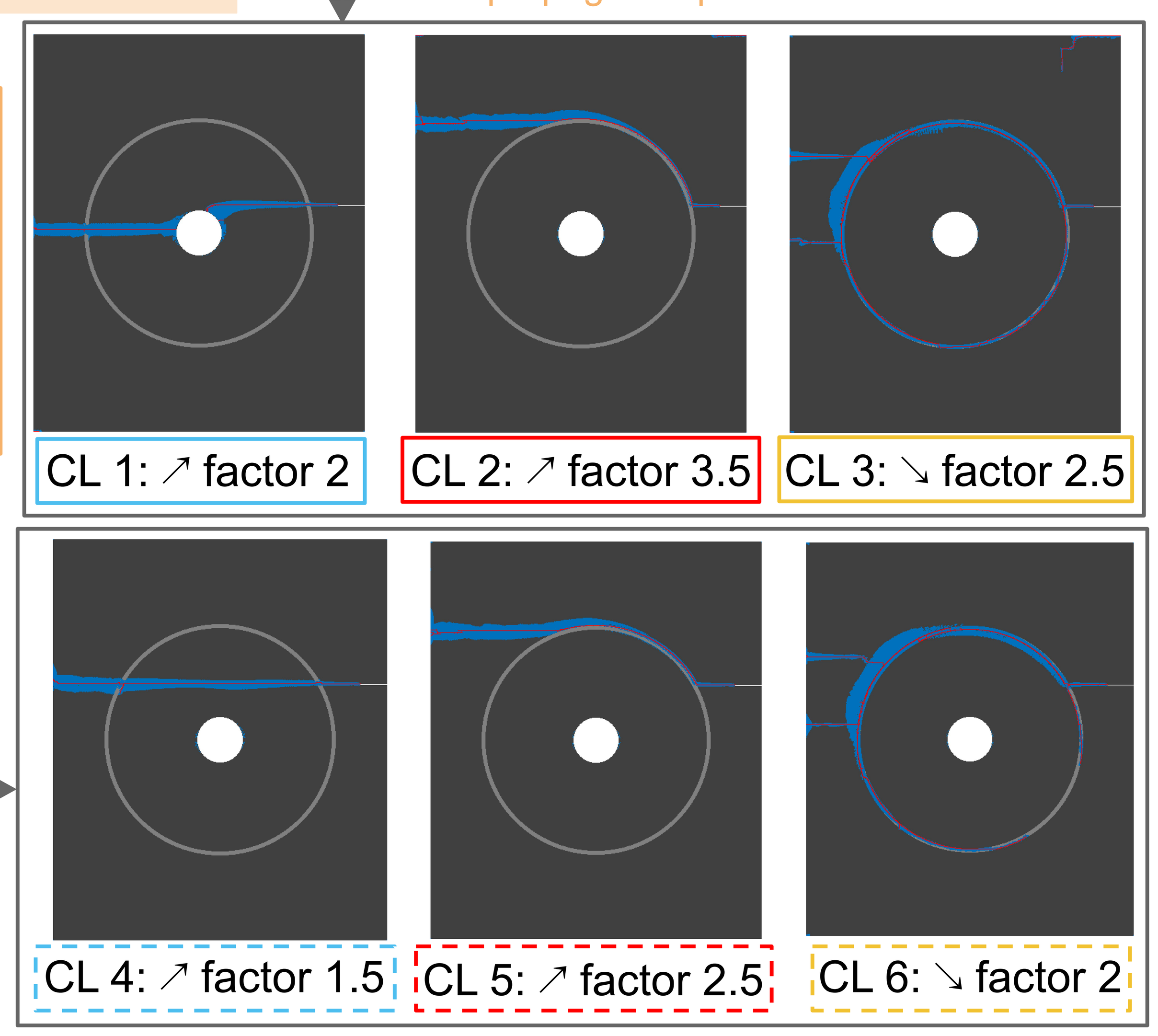
Required factors to get the crack propagation patterns



Small perturbations
- ↗ factor **2:** 100% cases reaching the hole
- ↗ factor **2.5**: 40% cases reaching the hole / 60% cases deflection
- ↗ factor **3**: 20% cases reaching the hole / 80% cases deflection
- ↗ factor **3.5**: 100% cases deflection



CL properties based on matrix by ↘ or ↗ Young's modulus and yield stress



Moving the notch to s = 0.5R

Less ↗ or ↘ factors required for the same crack patterns

Conclusion

Even a minimal interlayer has a large influence on the interaction between the crack and the hole. We highlight that a critical material parameter for damaging behavior is the yield stress of the interlayer. Our prototypes show a programmable failure behavior dependent on interlayer properties. This work shows that 3D-printed synthetic materials can benefit from strategies used by nature to increase damage tolerance.