How to protect a weak spot inside a load-bearing architecture material: a lesson from bone

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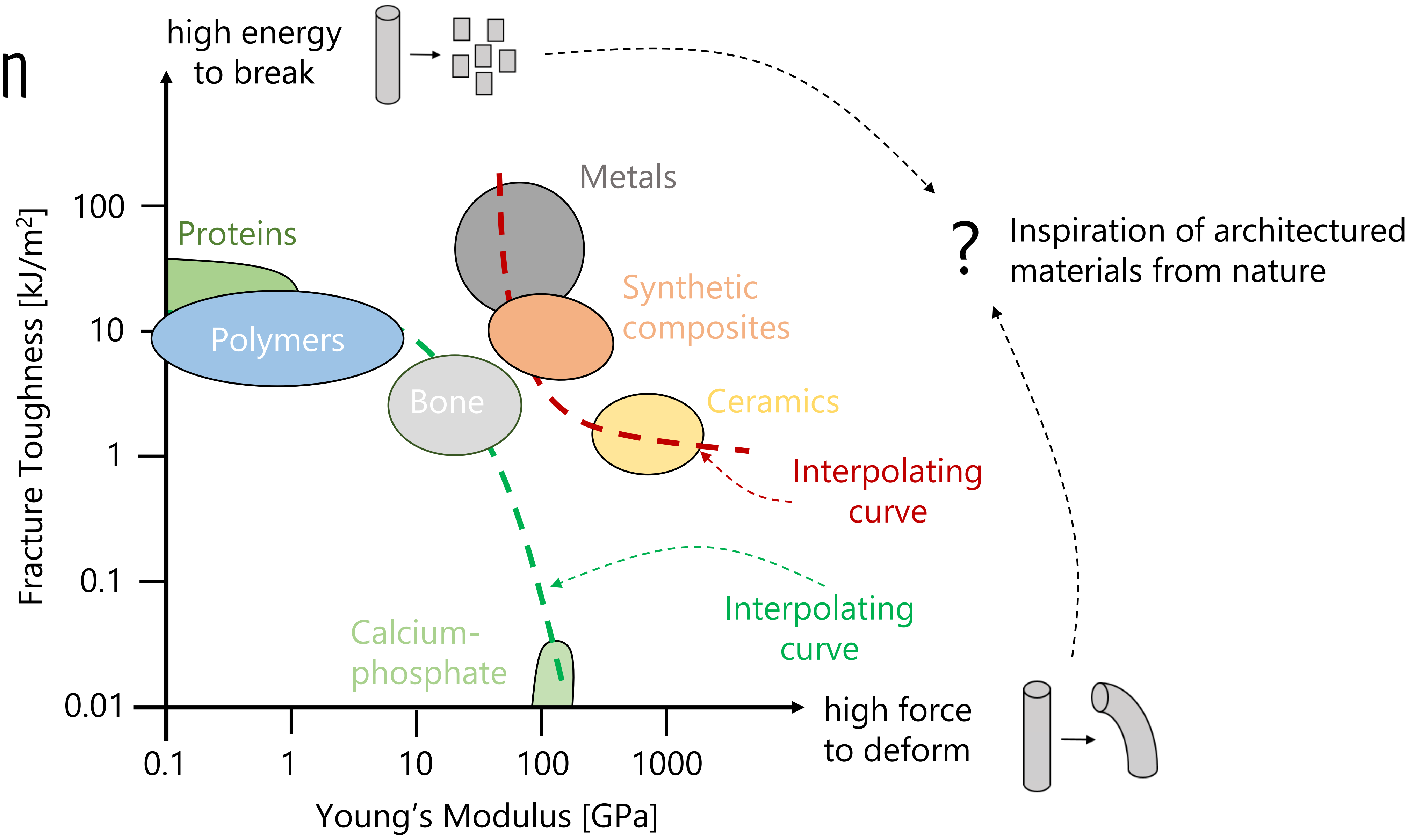
MBBM

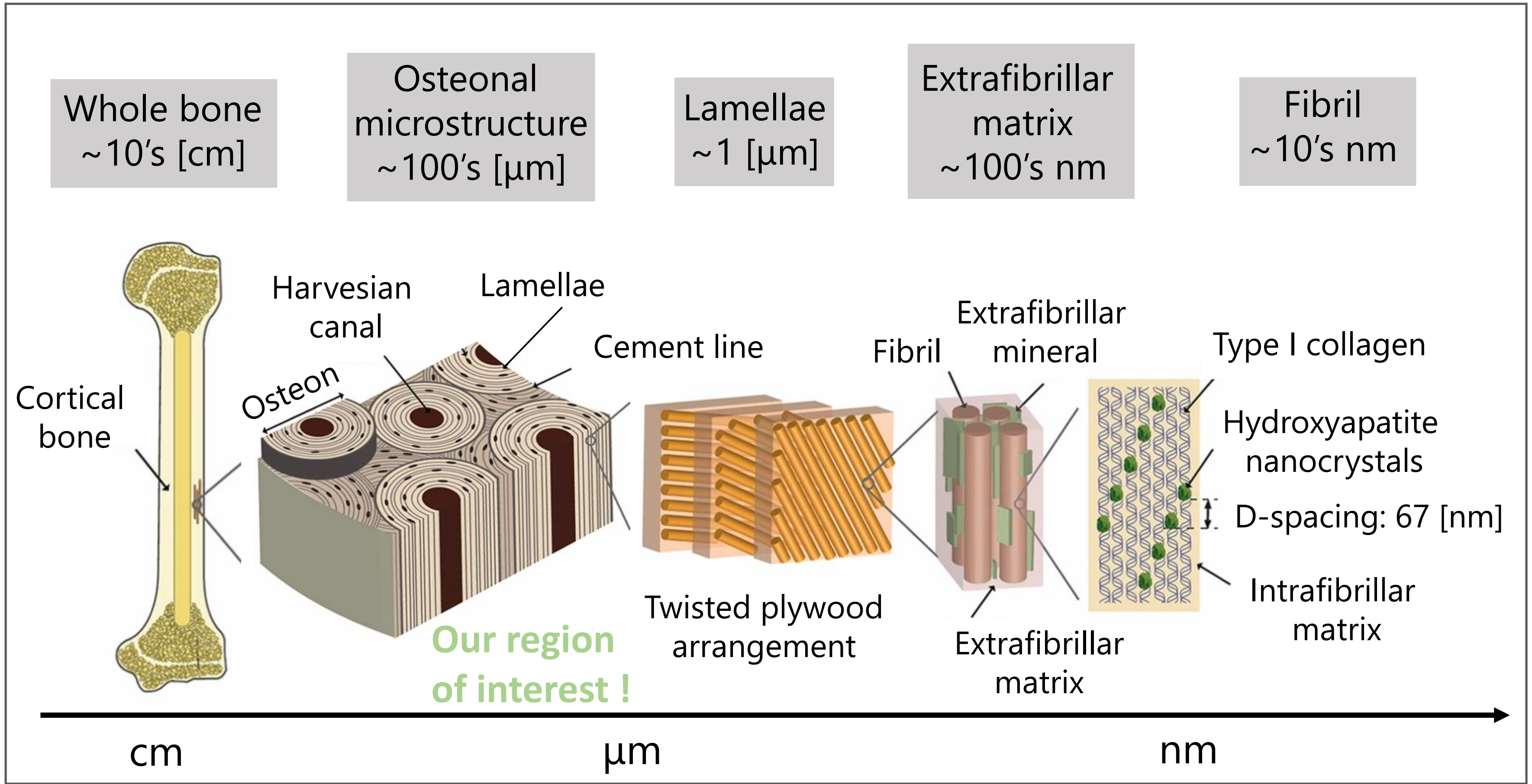
Introduction

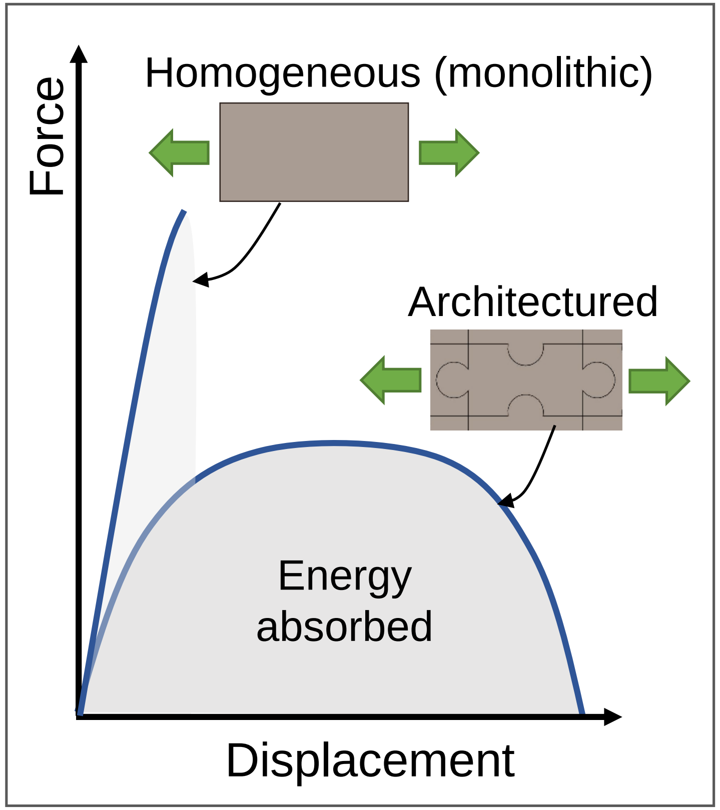


Introduction

What can be defined as architecture?

Intermediate structural arrangement bridging elementary building blocks (**nm**) and component size (**cm**):



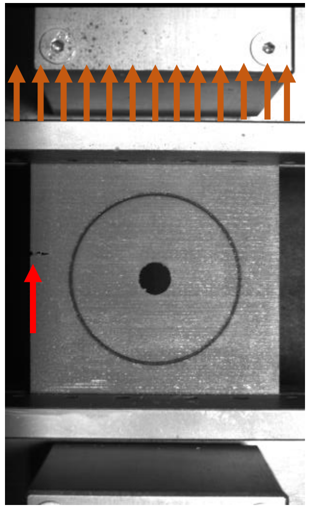


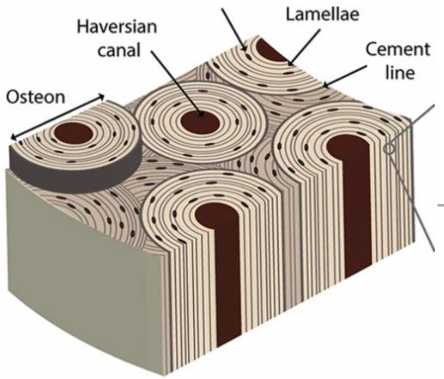
Adapted from Elizabeth A. Zimmermann et al. *Sci Rep* **6,** 21072 (2016)

Aims

Combine 3D printing & computational modeling to explore the fracture behavior of osteon-inspired materials.

3D printed samples
with programmable failure behavior

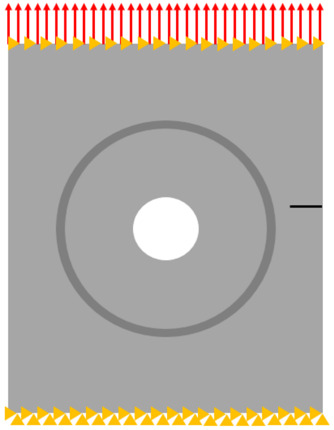




Adapted from Elizabeth A. Zimmermann et al. *Sci Rep* **6,** 21072 (2016)

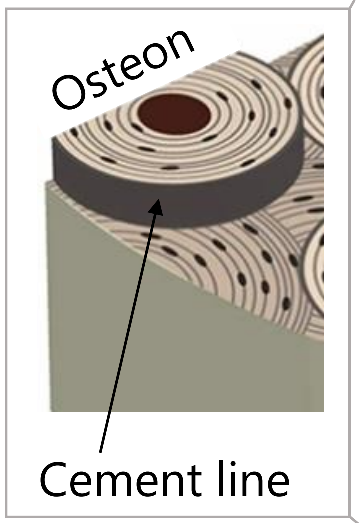
Dynamic FE analysis on 2D models
to simulate programmable failure behavior

SIMULIA ABAQUS



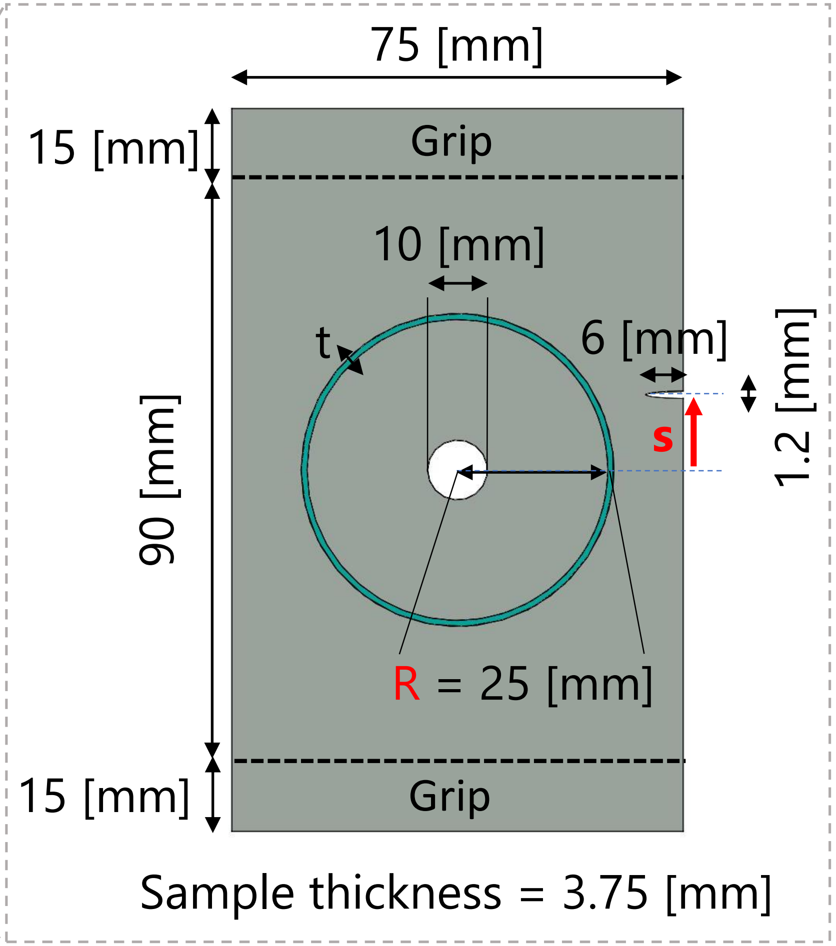
Experimental part: method

Osteonal microstructure ~100’s [µm]



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

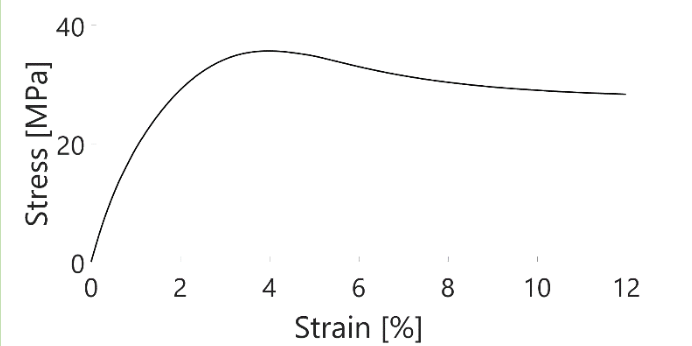
Scale up



Samples tested in tension with:

Fixed parameters:

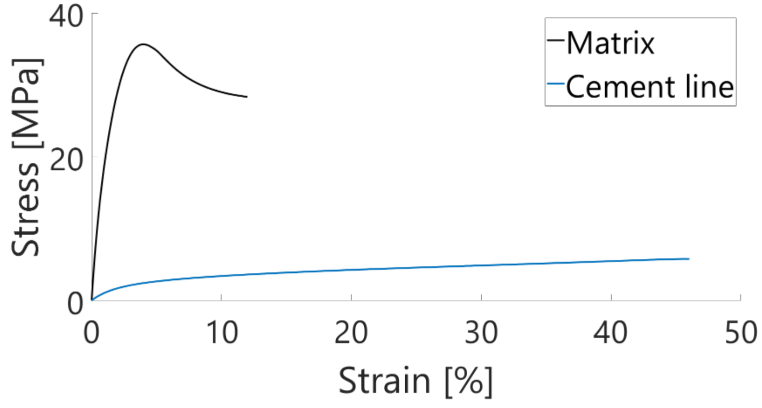
- Samples dimensions
- Haversian canal dimensions
- Osteon dimensions
- Cement line thickness t = 1 [mm]
- Test speed: 1 [mm/min]
- Matrix material properties (Gray60)



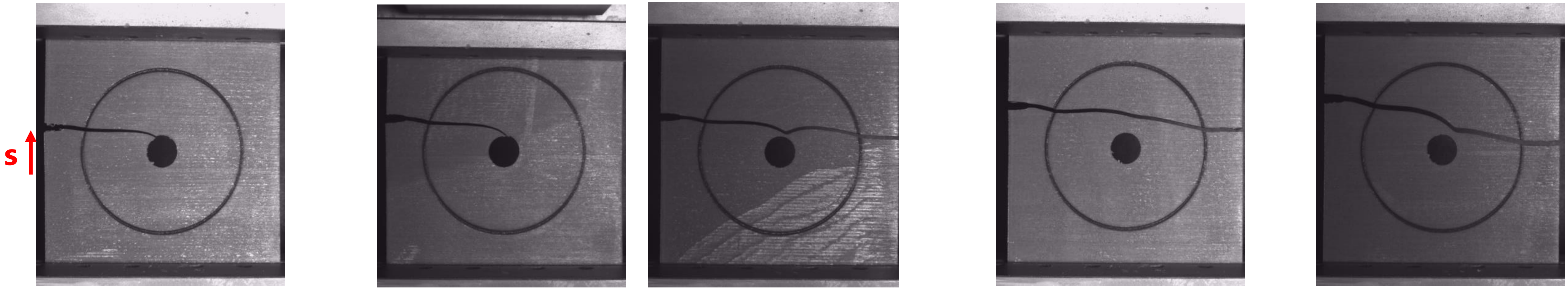
Explored parameters:

- Crack vertical position (s)
- Cement line material properties

Experimental part: results



First configuration: soft cement line (Shore95)



s = 0.3R

s = 0.4R

s = 0.5R

s = 0.6R

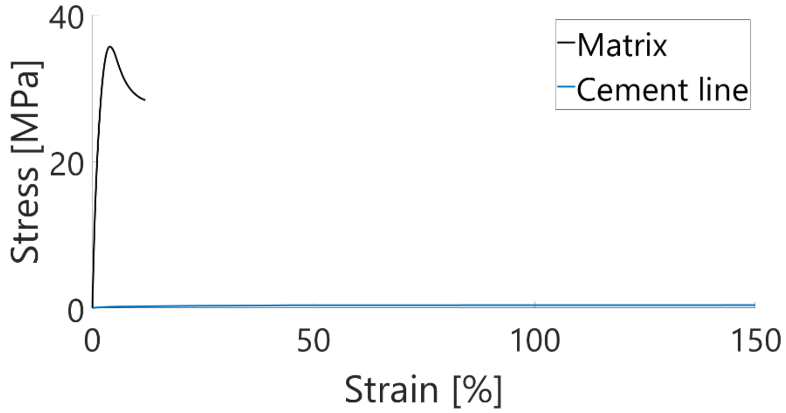
Stable position:
100% cases, crack reaching the hole

Unstable position:
- 80% cases, crack reaching the hole
- 20% cases, crack crossing the osteon without entering the hole

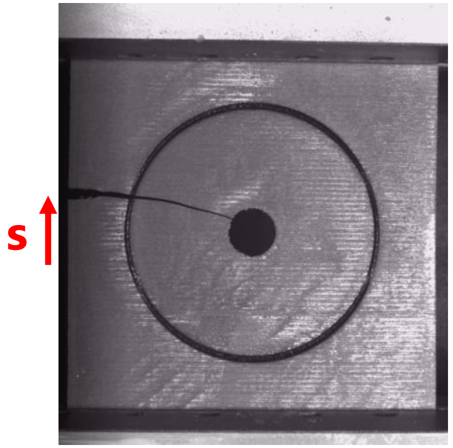
Stable positions:
100% cases, crack crossing the osteon without entering the hole

R = inner radius of CL

Experimental part: results

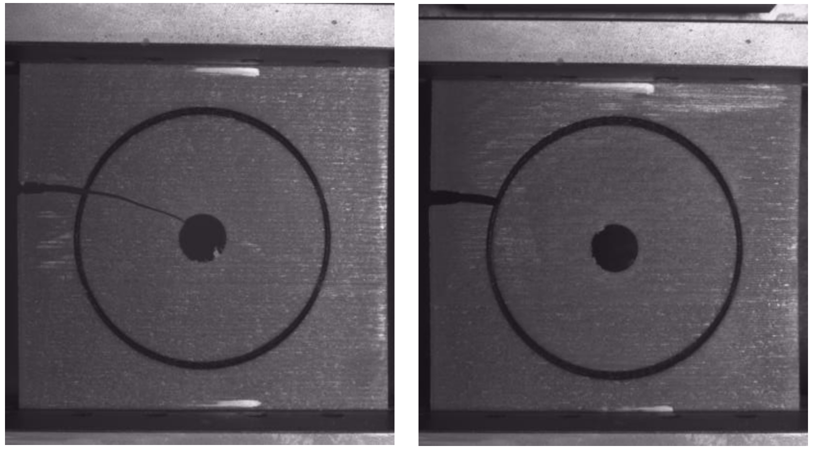


Second configuration: ultra-soft cement line (TangoBlack)



s = 0.3R

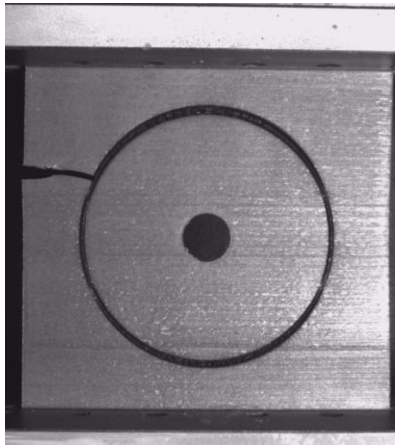
Stable position:
100% cases, crack reaching the hole



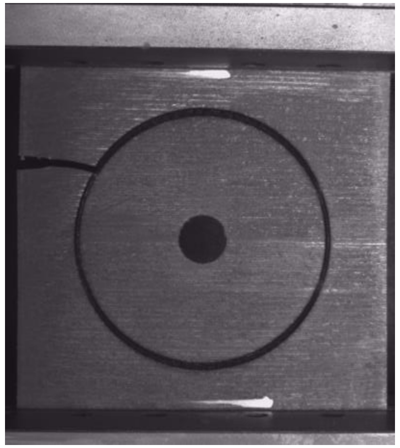
s = 0.4R

Unstable position:

- 37.5% cases, crack reaching the hole
- 62.5% cases, crack trapped inside the cement line



s = 0.5R

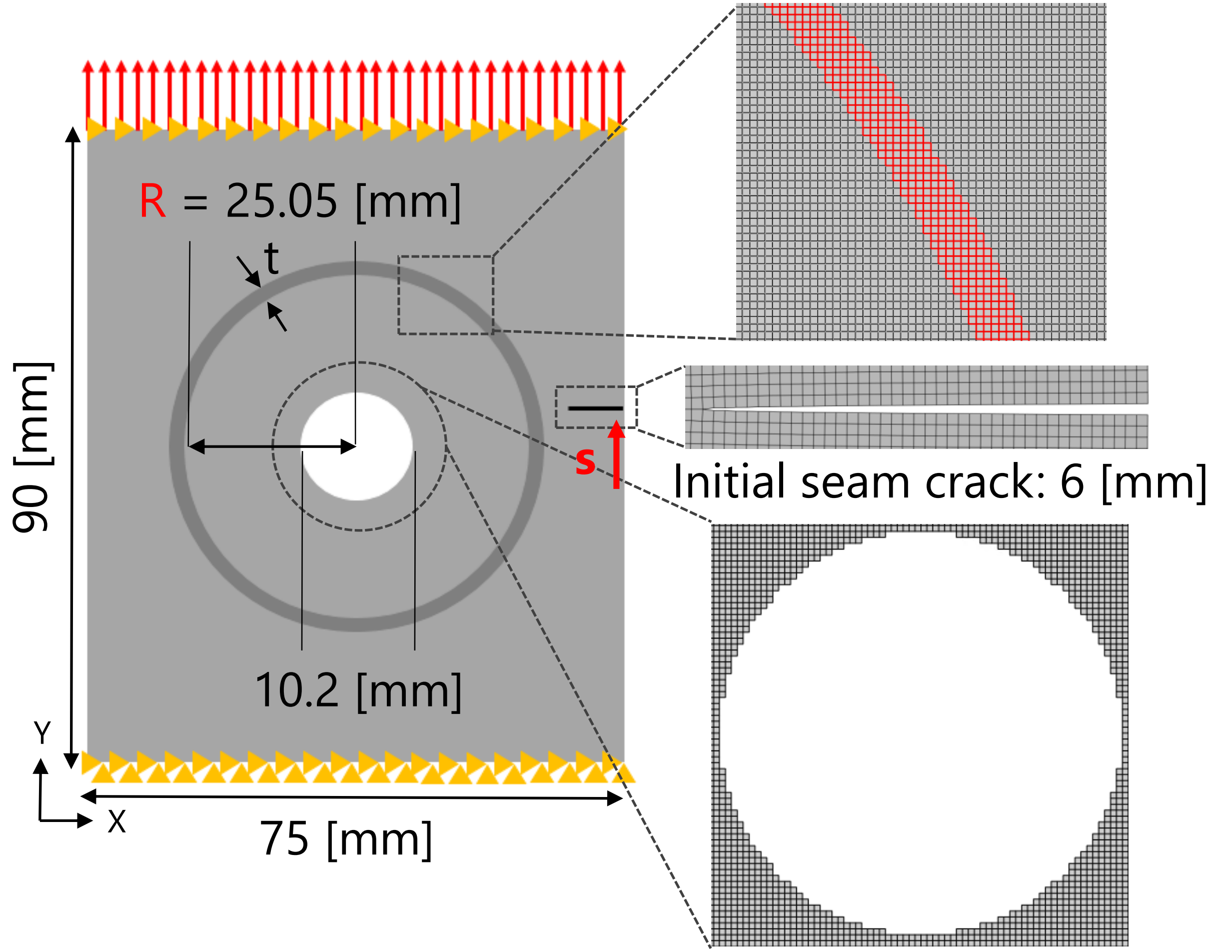


s = 0.6R

Stable positions:
100% cases, crack trapped inside the cement line

R = inner radius of CL

Computational part: method



Model simulated with:

Fixed parameters:

- Model dimensions
- Haversian canal dimensions
- Osteon dimensions
- Cement line thickness: t ~ 0.9 [mm]
- Displacement applied: 1 [mm/s]
- Matrix material properties
- Ductile damage parameters
- Perfectly square elements (0.15 [mm] side length)

Explored parameters:

- Crack vertical position (s)
- Cement line Young's modulus and Yield stress

Top nodes blocked along x
Bottom nodes blocked along x & y

Computational part: method

Damage initiation

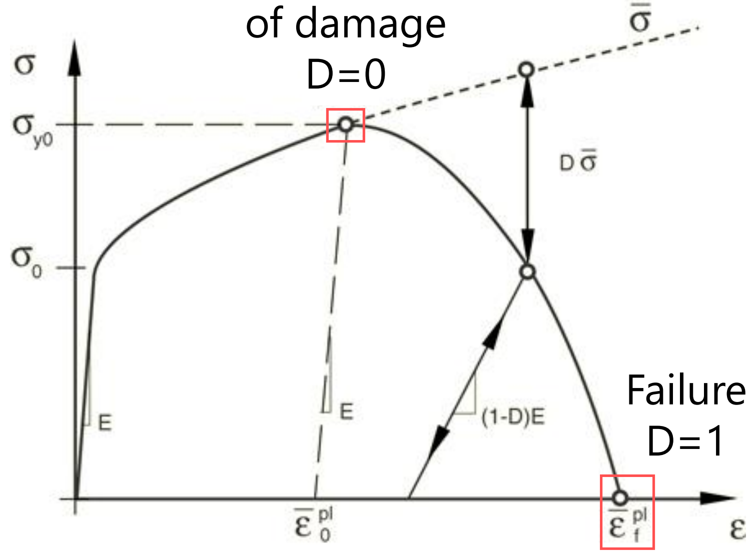
+

Damage evolution and element removal

Damage initiation criterion based on an equivalent plastic strain at the onset of damage:

$$\omega_D = \int \frac{d\varepsilon^{pl}}{\bar{\varepsilon}_D^{pl}} \geq 0$$

- ω_D ↗ monotonically with plastic deformation
- When ω_D = 1, damage initiation start



Stress-strain curve with progressive damage degradation

(adapted from Abaqus 6.14 Documentation)

Damage variable:

$$D = \frac{L\dot{\bar{\varepsilon}}^{pl}}{\bar{u}_f^{pl}} = \frac{\dot{\bar{u}}^{pl}}{\bar{u}_f^{pl}}$$

with $\bar{u}_f^{pl} = \frac{2G_f}{\sigma_{y0}}$

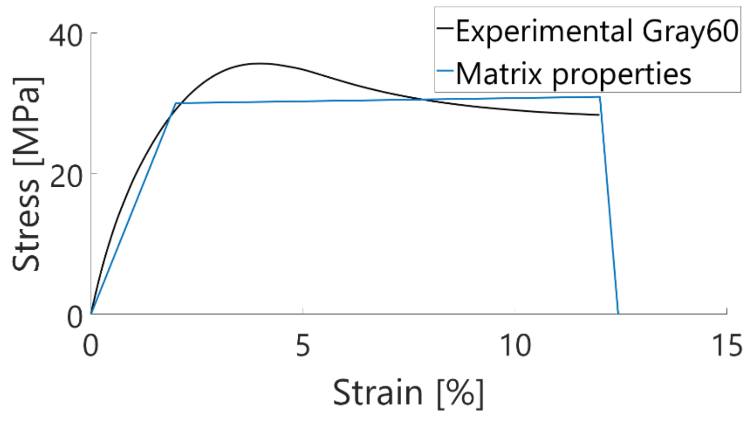
Computational part: method

Matrix material properties: (Based on Gray60 experimental results)

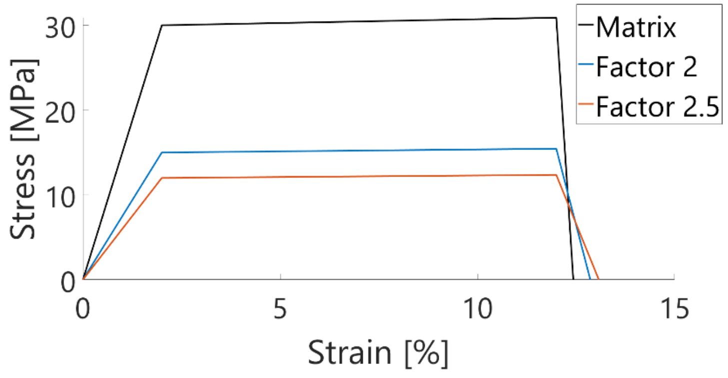
- Young's modulus: E = 1500 [MPa]
- Yield strength: σ_y = 30 [MPa]
- Yield strain: ϵ_y = 2% [-]
- Ultimate strain: ϵ_u = 12% [-]

Properties assumed:

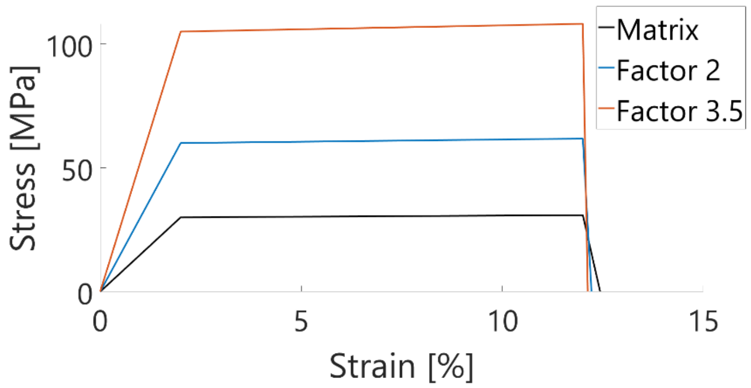
- Strain hardening: $\Delta\sigma$ = 0.9 [MPa] (3% σ_y)
- Fracture energy per unit area: G_f = 0.01 [mJ/mm^2]



Cement line material properties defined based on matrix:



Decrease E and yield stress



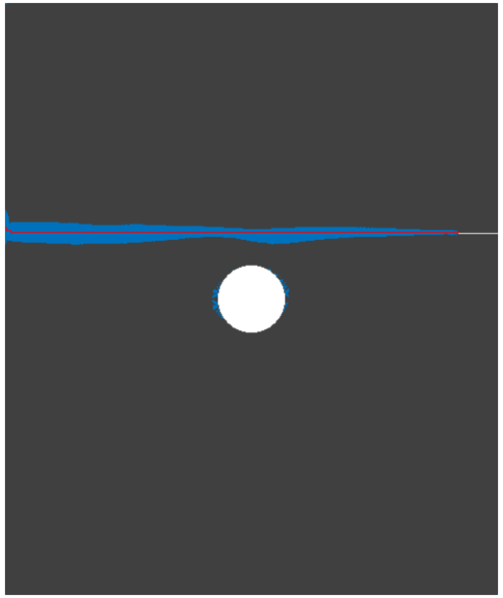
Increase E and yield stress

Computational part: results

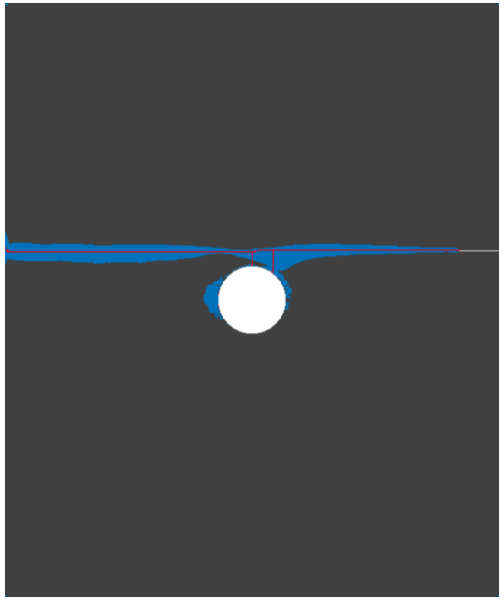
Initial crack position ?

On the model without cement line, what corresponds to a switch of crack propagation behavior ?

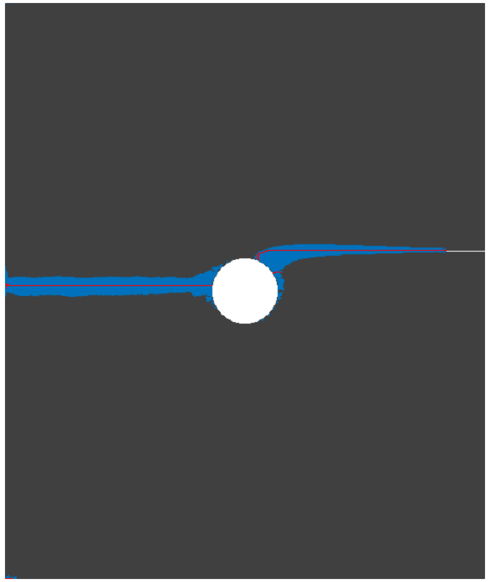
- Undamaged elements
- Damage initiated elements (under plastic deformation)
- Fully damaged elements



s = 0.4R



s = 0.3R



s = 0.25R

Notch is progressively moved downwards

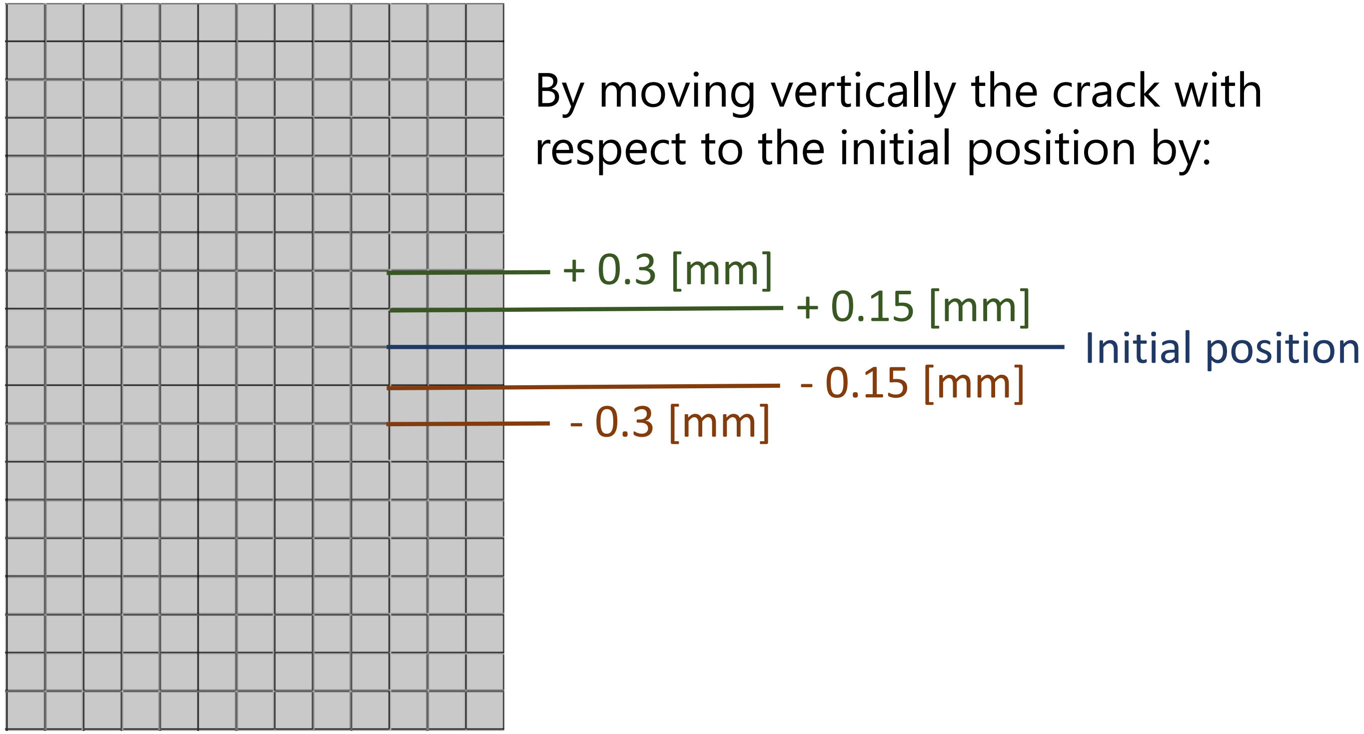
Position selected for the next steps as **initial position**

R = inner radius of CL

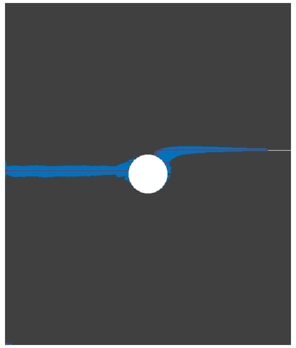
Computational part: results

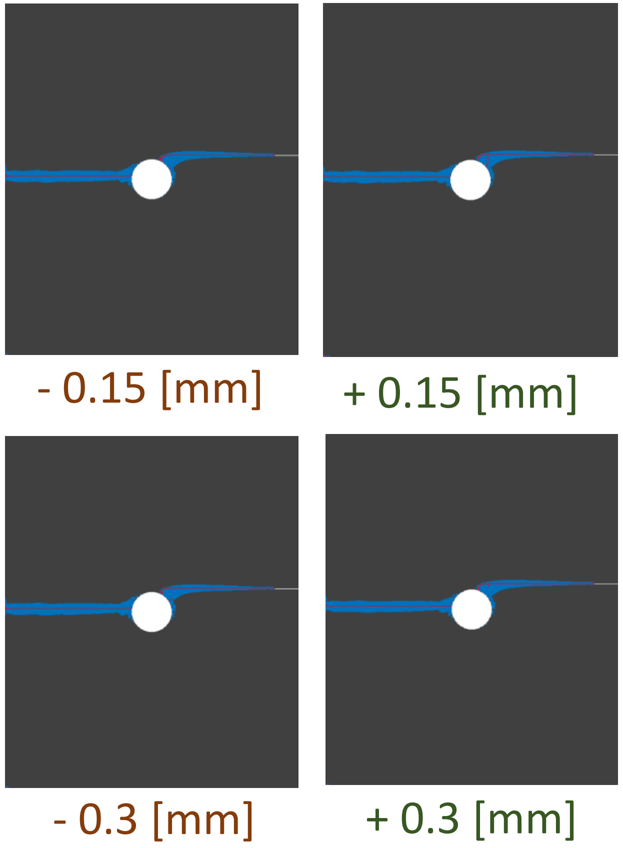
Four cases of small perturbations for the crack position:

By moving vertically the crack with respect to the initial position by:

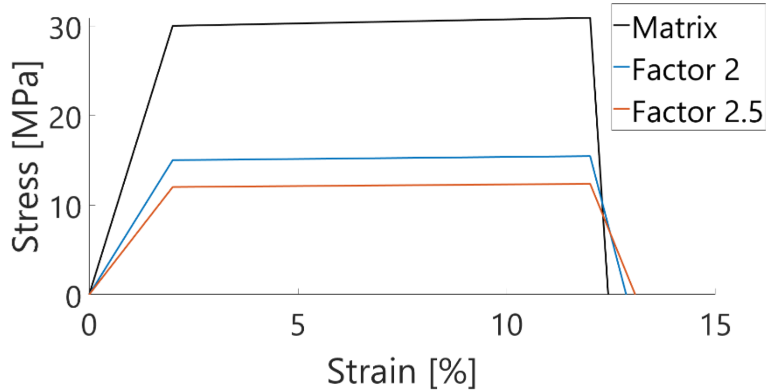


Example of study on the model without cement line

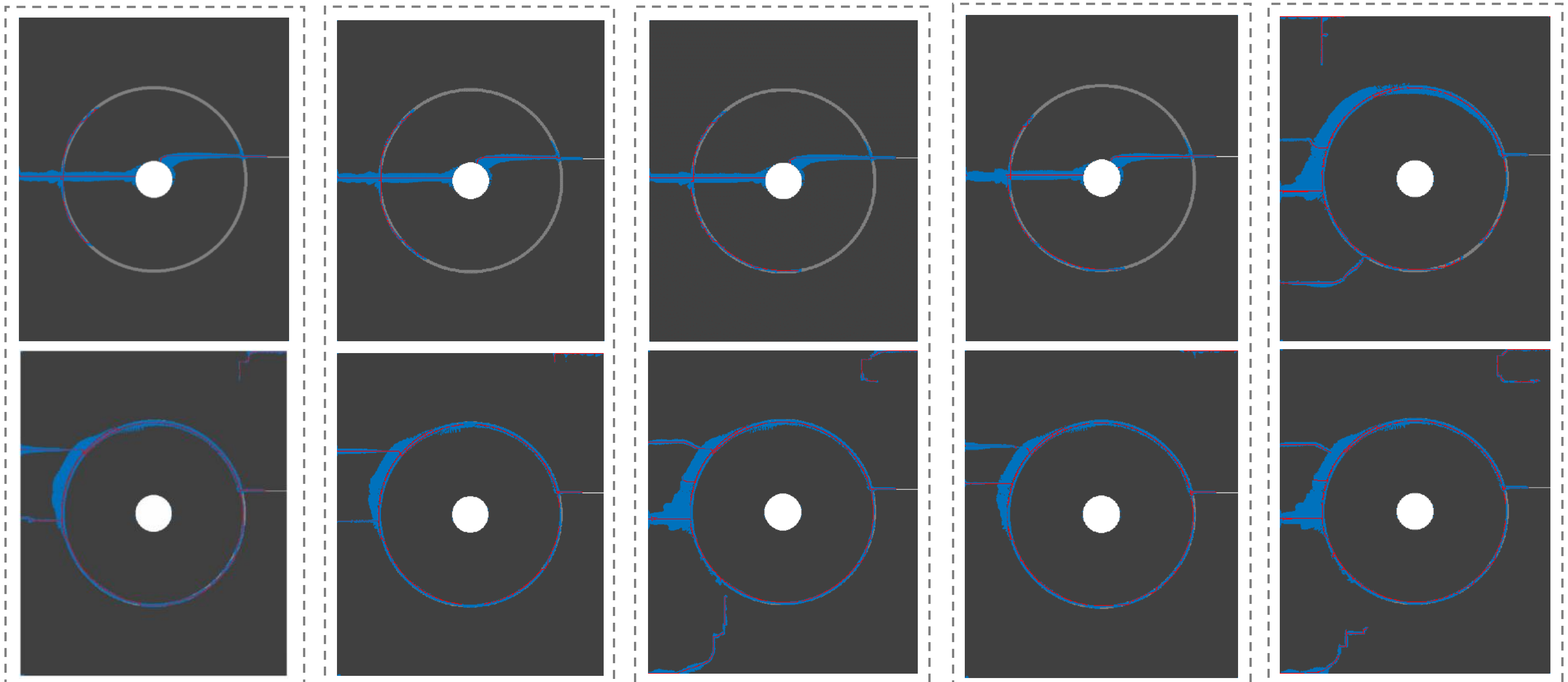

Initial position



Computational part: results



CL’s Young’s modulus and yield stress **decreased** compared to matrix.



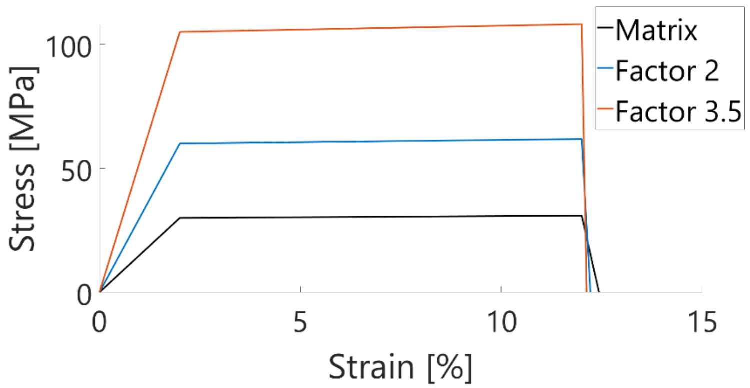
Initial position | - 0.15 [mm] | + 0.15 [mm] | - 0.3 [mm] | + 0.3 [mm]

Factor **2**:
- 80% cases reaching the hole
- 20% cases trapped in the CL

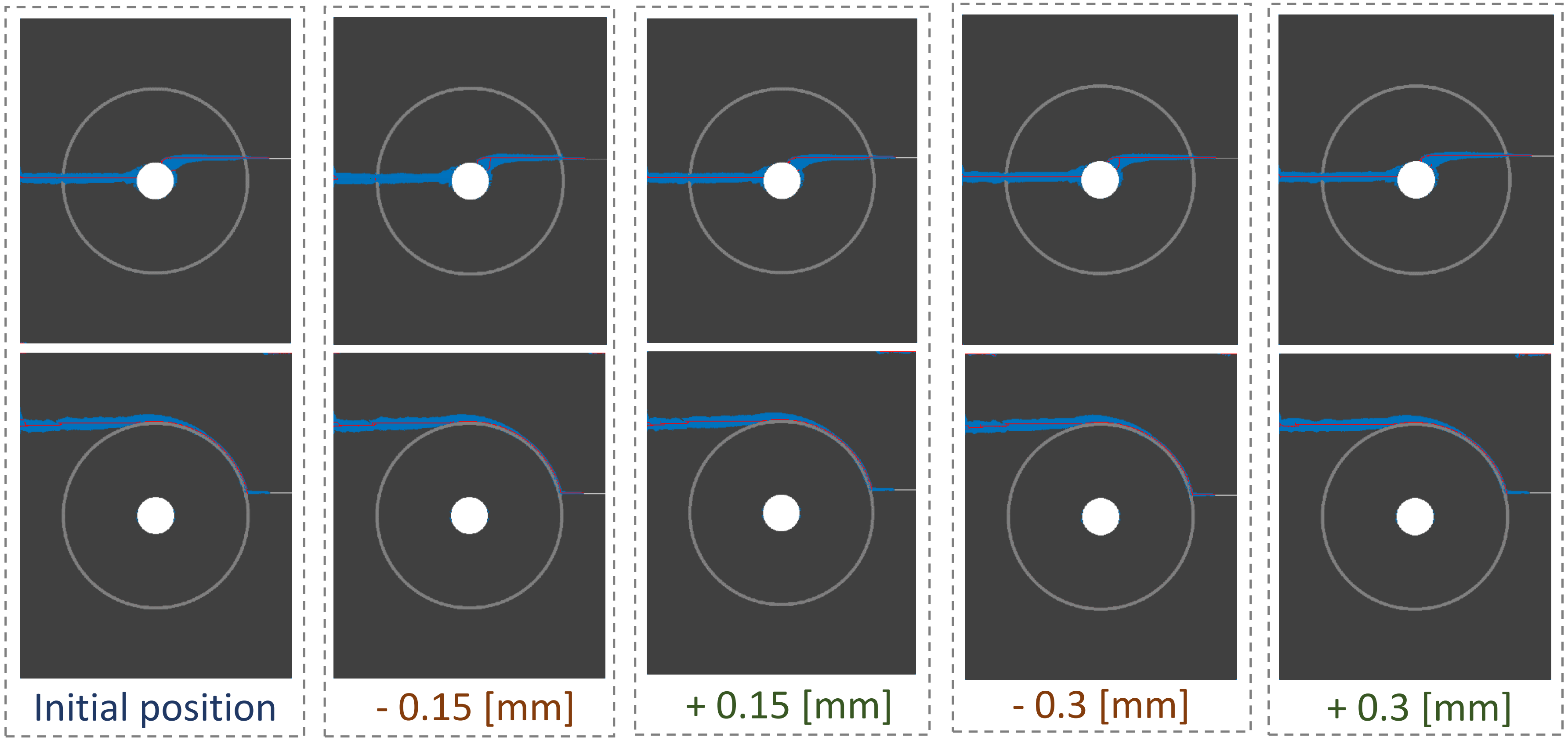
Factor **2.5**: 100% cases trapped in the CL

Undamaged elements | Damage initiated elements (under plastic deformation) | Fully damaged elements

Computational part: results



CL's Young's modulus and yield stress **increased** compared to matrix.



Factor **2:** 100% cases reaching the hole

Factors **in between**: unstable situation

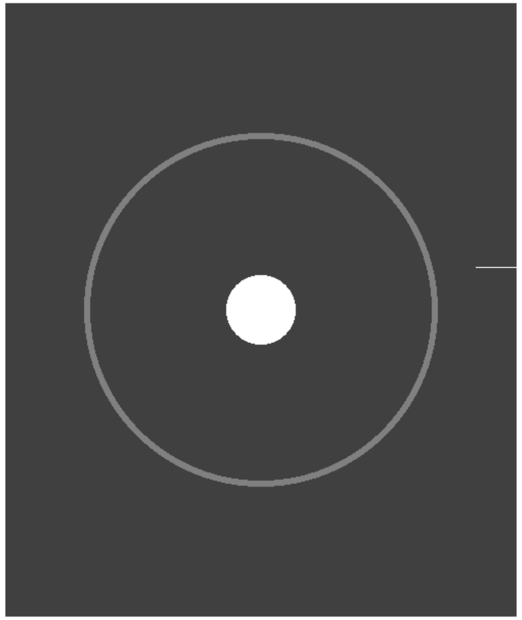
- Factor **2.5**: 40% reaching the hole 60% deflection
- Factor **3**: 20% reaching the hole 80% deflection

Factor **3.5:** 100% cases deflection along the CL

Undamaged elements | Damage initiated elements (under plastic deformation) | Fully damaged elements

Computational part: results

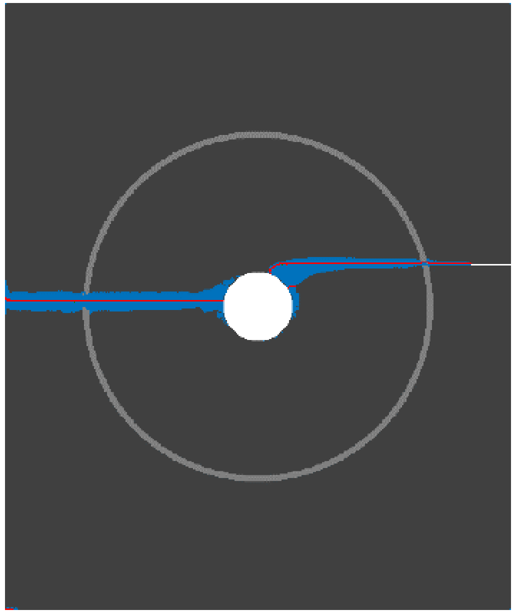
Animations of the main crack behaviors



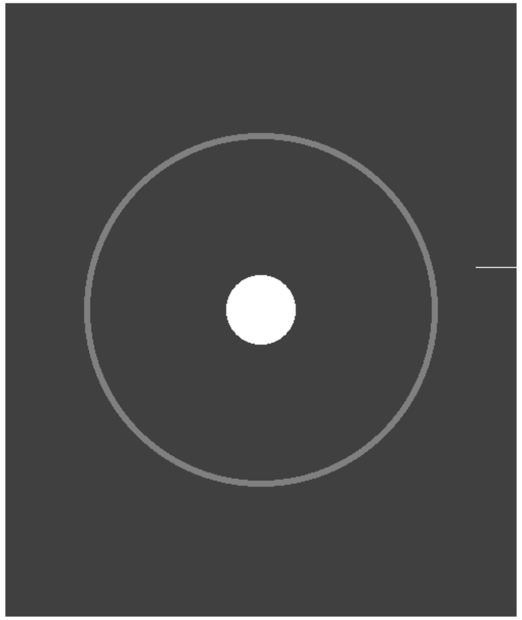
Reaching the hole

Computational part: results

Animations of the main crack behaviors



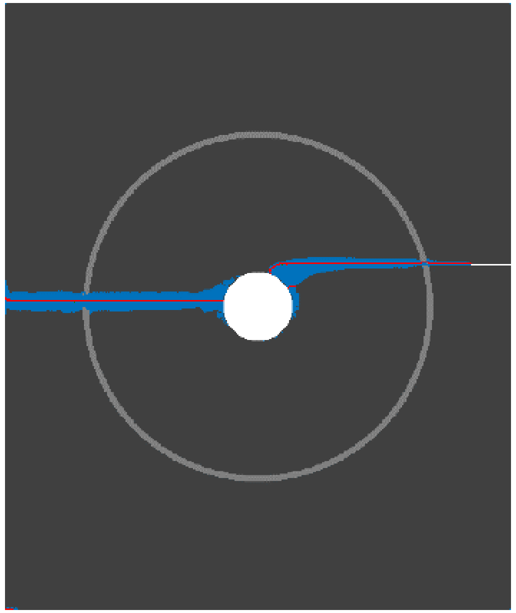
Reaching the hole



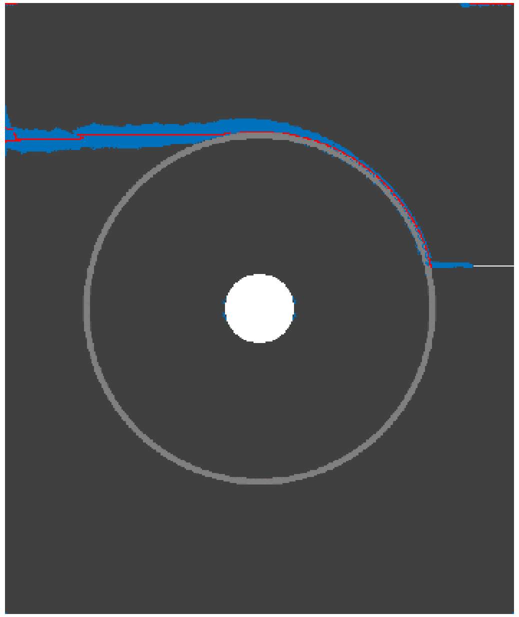
Deflection along the CL

Computational part: results

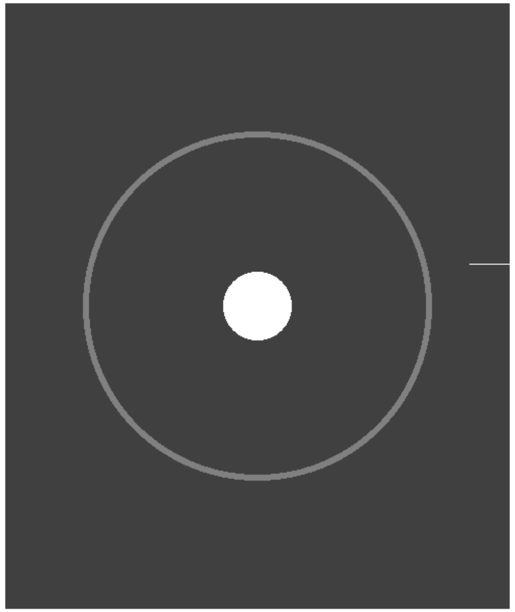
Animations of the main crack behaviors



Reaching the hole



Deflection along the CL



Trapped in the CL

Conclusion

Asymmetry in crack propagation behavior observed for both parts:

Three behaviors observed for the experimental part:

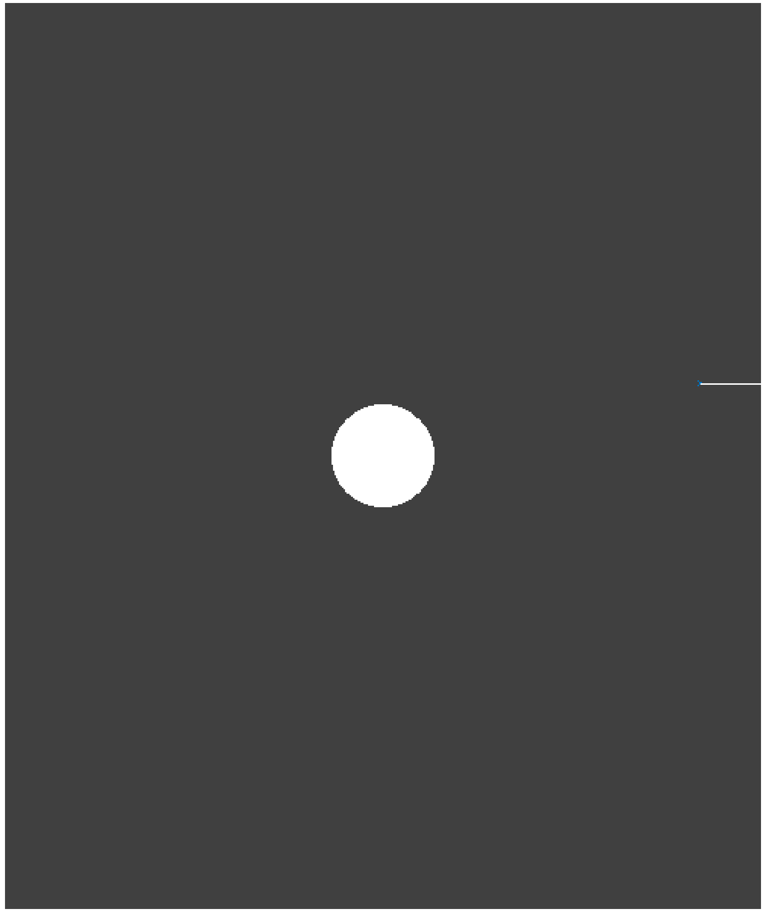
- Crack reaching the hole if $s \leq 0.3R$ for both material
- Crack trapped in the CL if $s \geq 0.5R$ for the ultra-soft CL material
- Crack crossing the osteon without entering the hole if $s \geq 0.5R$ for the soft CL material

Three behaviors observed for the computational part :

- Crack reaching the hole if ↗ or ↘ E and yield stress stay under factor 2
- Crack trapped in the CL if ↘ E and yield stress is greater or equal to factor 2.5
- Crack deflected along the CL if ↗ E and yield stress is greater or equal to factor 3.5

The soft material (experiment part) was not able to trap the crack compared to similar case in the computational part.
→ Printing the material in an architecture gave higher stiffness than expected from tested alone ?

Outlook



Introduction of several interlayers ?

Thanks to all co-authors!

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ETH zürich

Thank you for your attention!

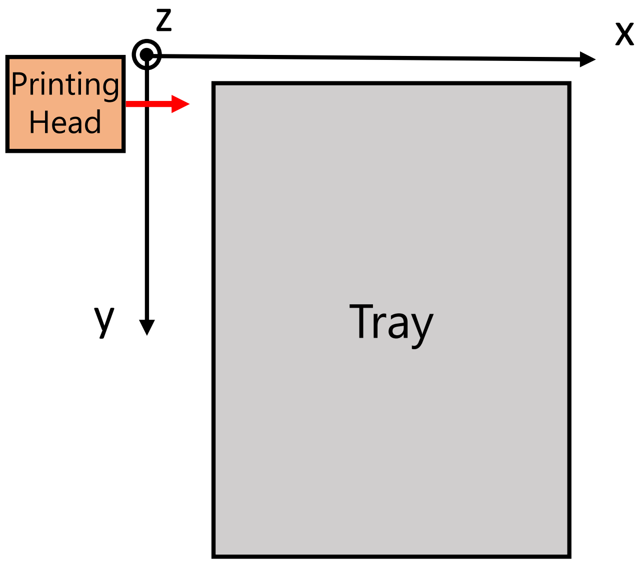
Tim Volders

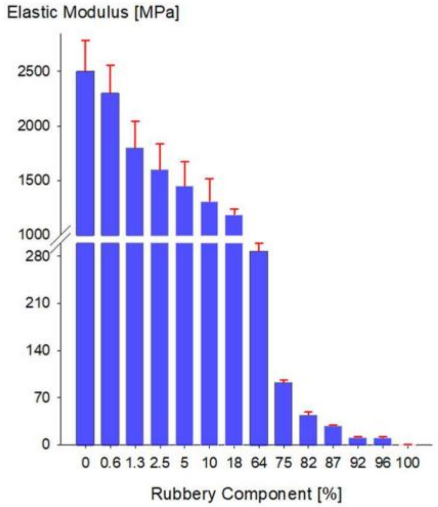
Printer specifications

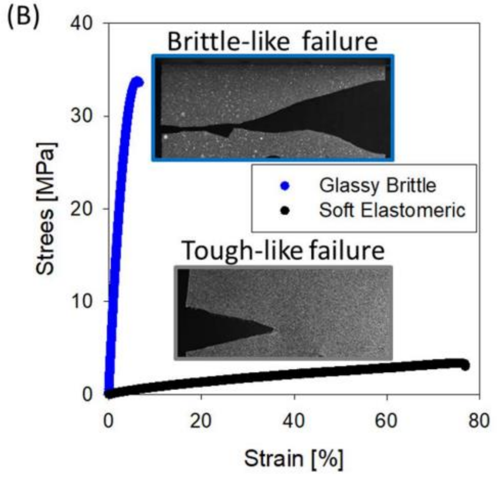
Stratasys
Objet260 Connex2 3D printer

Resolutions:

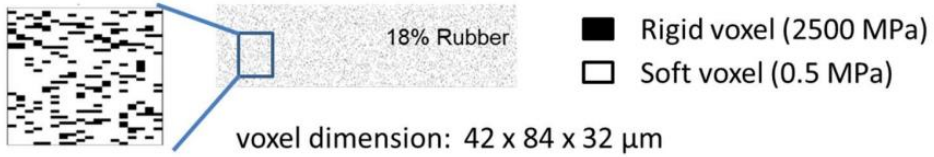
- Along x = 42 [μm]
- Along y = 84 [μm]
- Along z = 32 [μm]







Voxel-based materials



Simulation specifications

- Number of intervals of output extraction (evenly spaced in time): 1000 extractions/s
- Simulation over 2 seconds.
- Incrementation set on automatic / stable increment estimator set on global
- Linear bulk viscosity: 0.06 (by default)
- Elements used: CPS4R (Four-node plane stress element)
- 297636 nodes and 296360 elements
- CPU times around 1-2 days
- The force and displacement outputs are filtered (during the simulations) using a second order Butterworth filter with a cut-off frequency of 150 [Hz]