Simulating the Effects of Manufacturing Defects Based on CT Images

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Johannes Fieres
Volume Graphics GmbH

Volume Graphics

- Developer of leading software for the analysis and visualization of industrial CT data
- For quality control, metrology, damage analysis, and product development
- Used by more than 70% of the "Fortune Global 500" companies in the automotive and electronics industries*
- Founded in 1997
- Located in Heidelberg, Germany

*As of 2016

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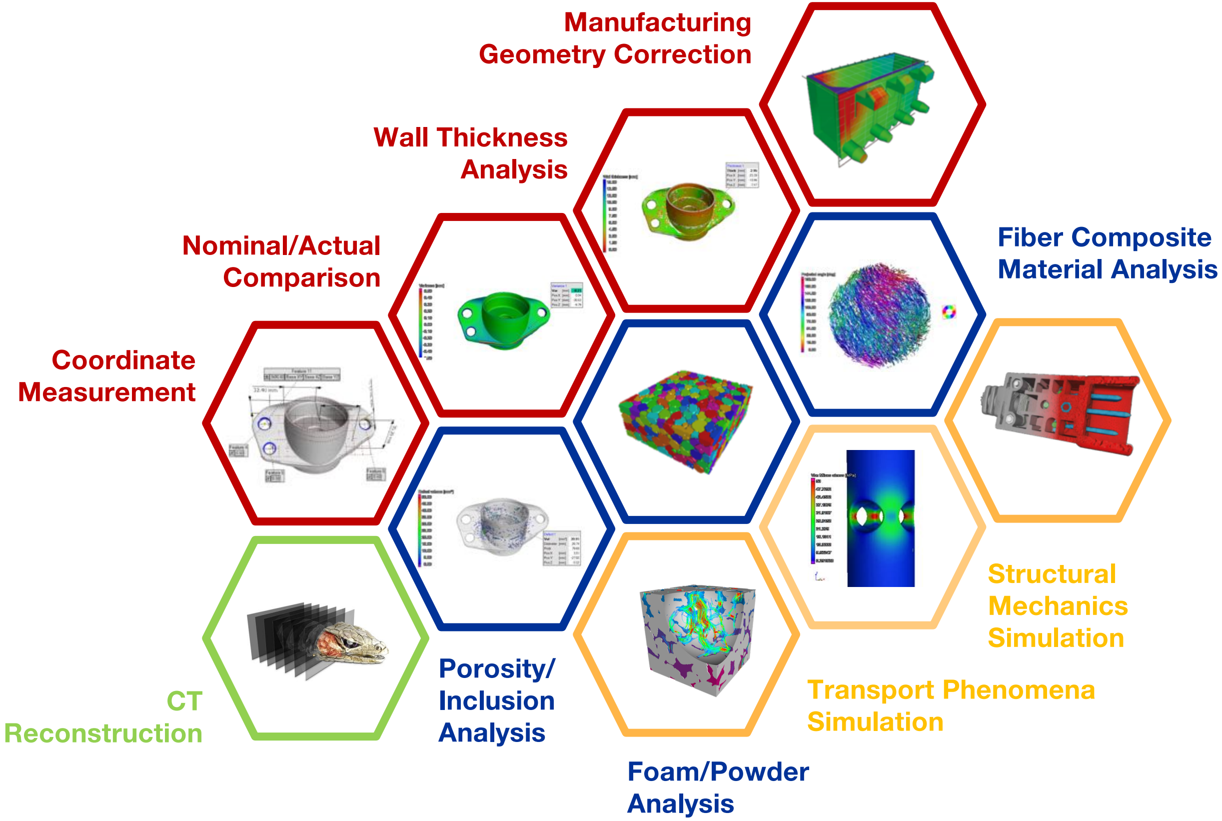
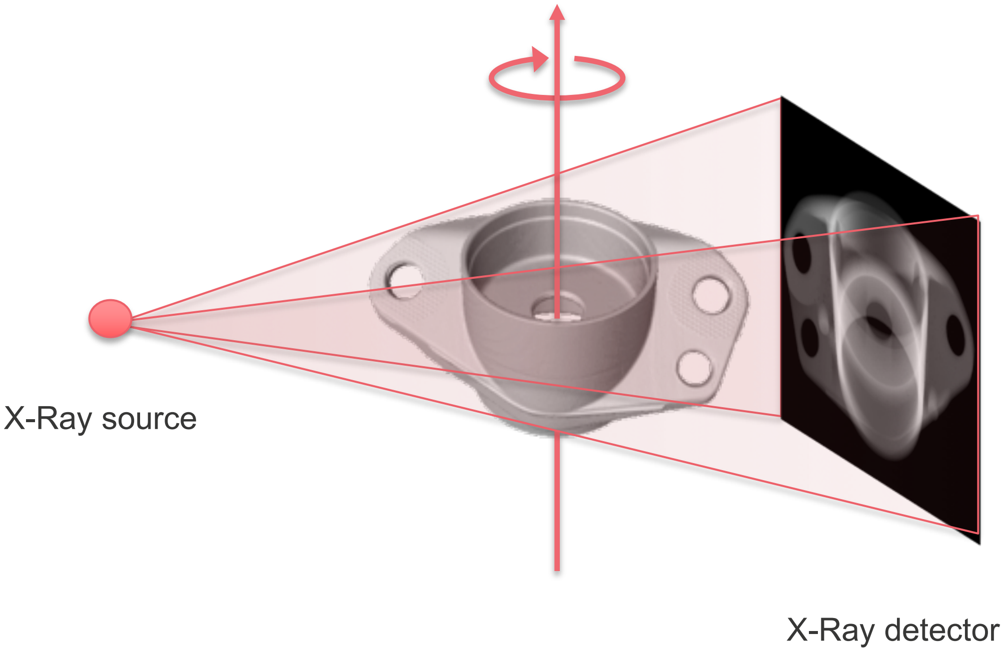


Manufacturing Geometry Correction
Wall Thickness Analysis
Nominal/Actual Comparison
Coordinate Measurement
Fiber Composite Material Analysis
CT Reconstruction
Porosity/ Inclusion Analysis
Foam/Powder Analysis
Structural Mechanics Simulation
Transport Phenomena Simulation

Industrial X-Ray Computed Tomography (CT)



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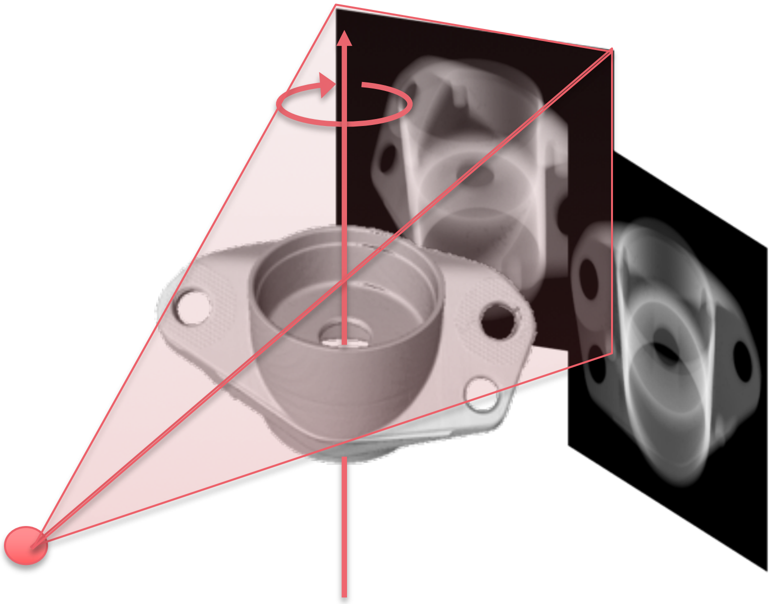

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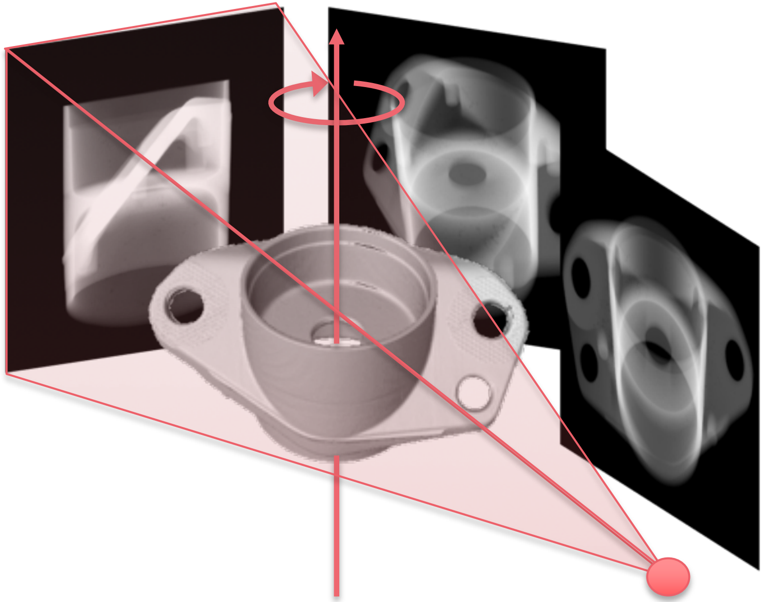

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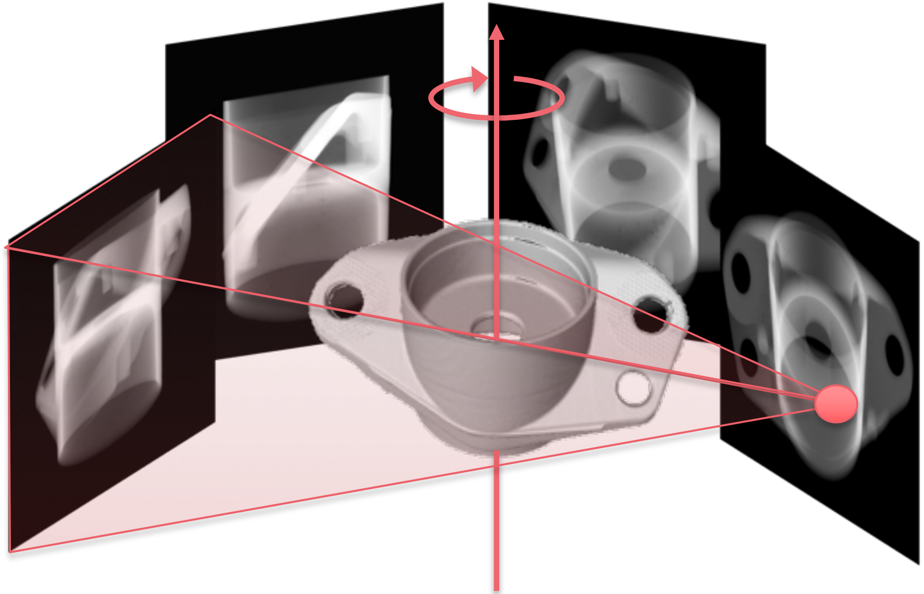

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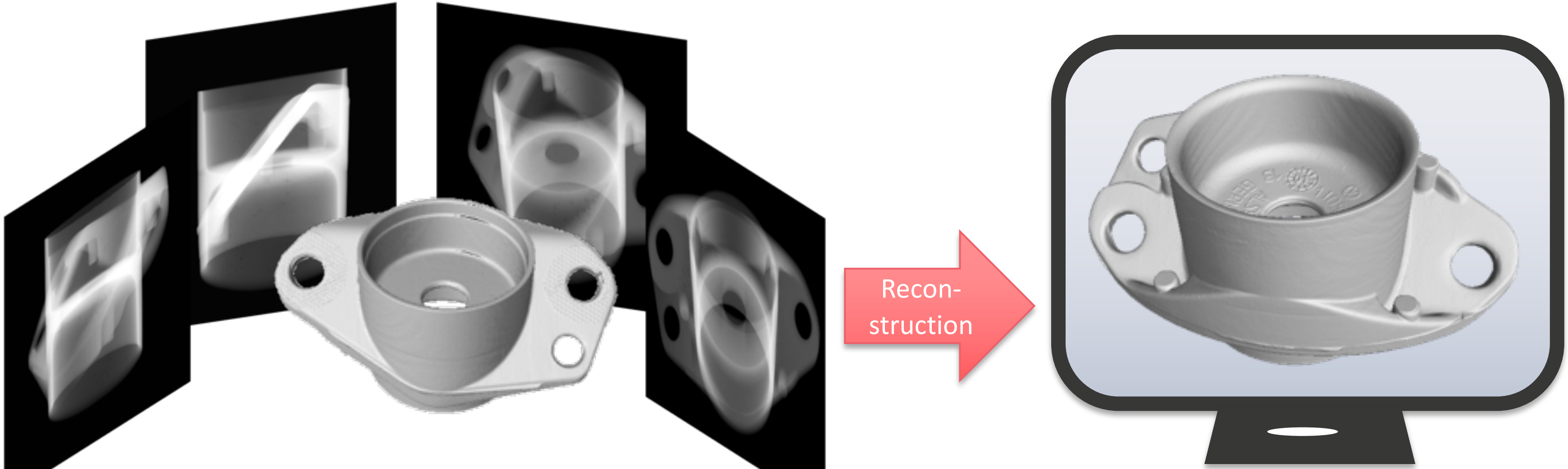
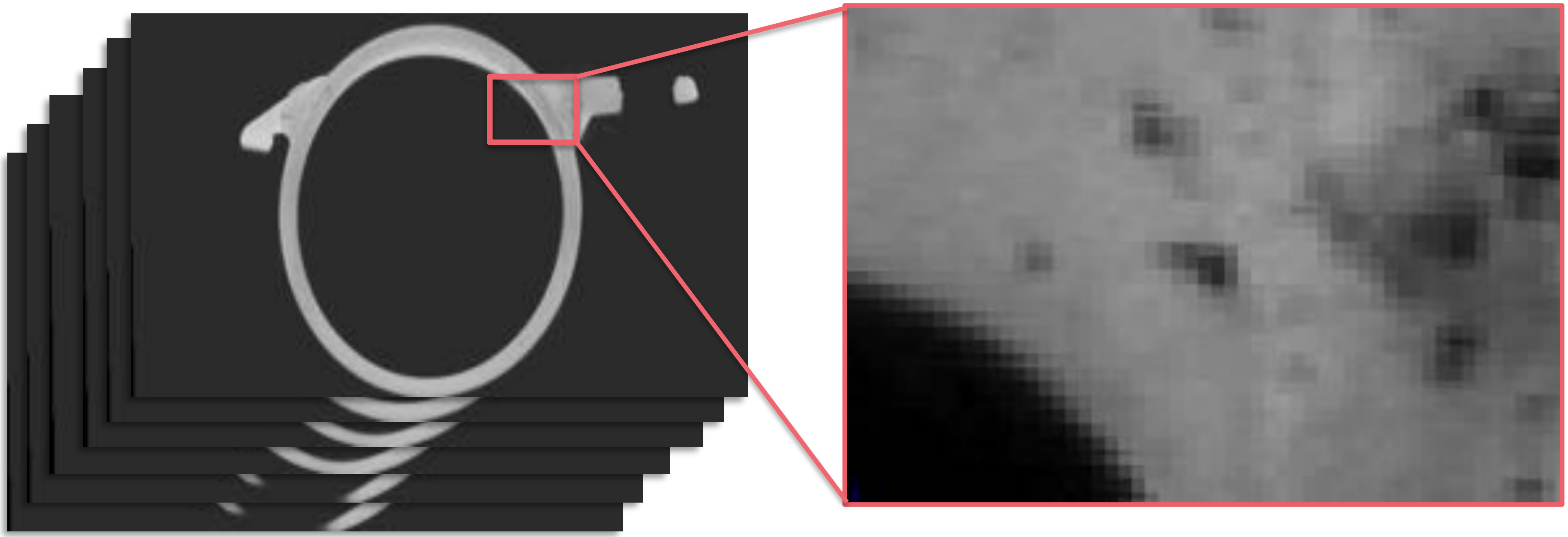


3d volumetric representation of scanned part

CT image data



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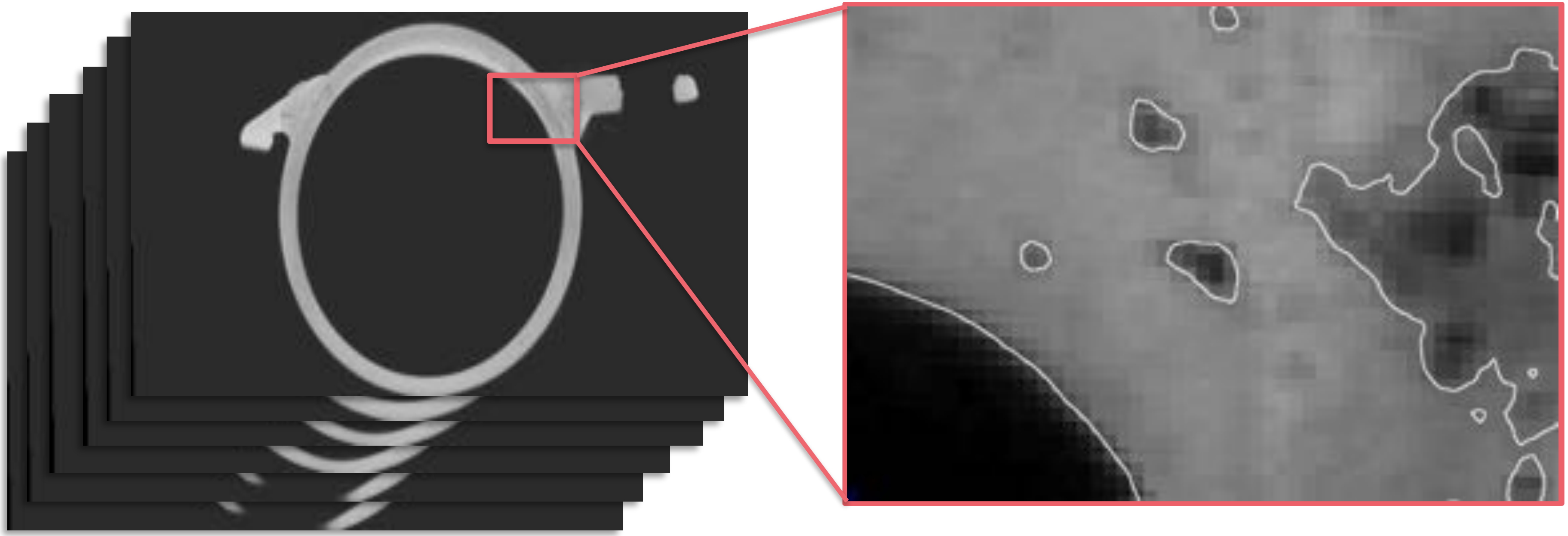
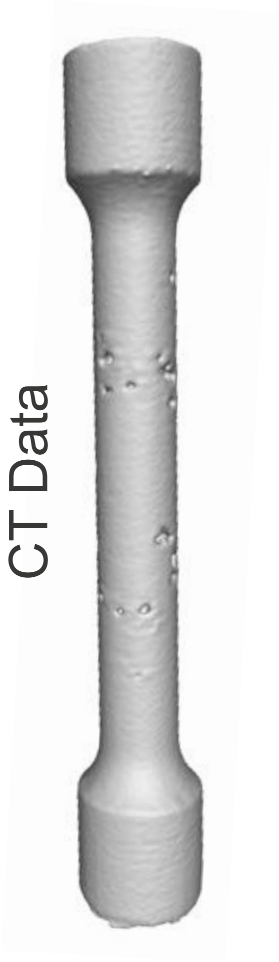


CT image data

Surface determination

CT Data



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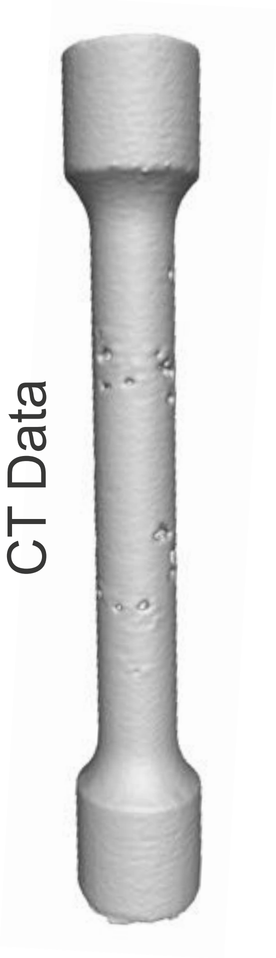
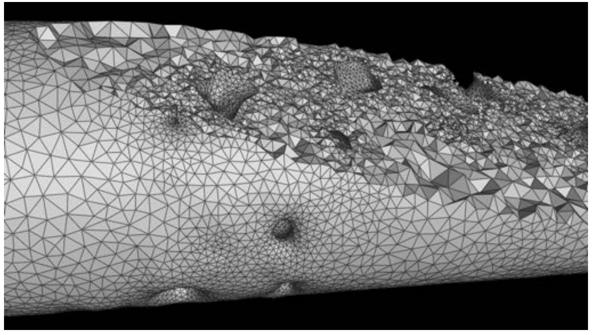
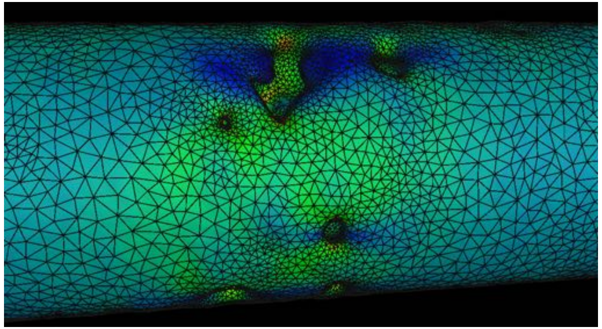
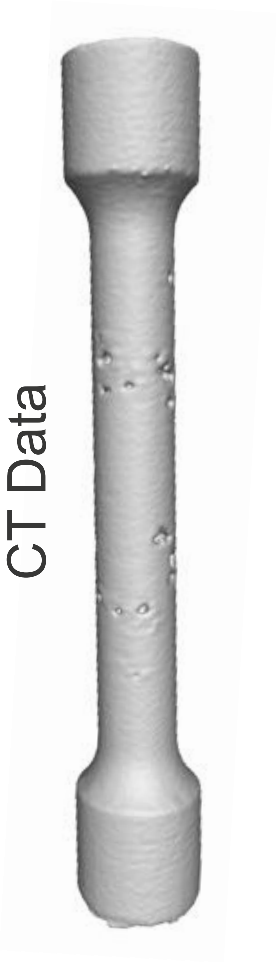


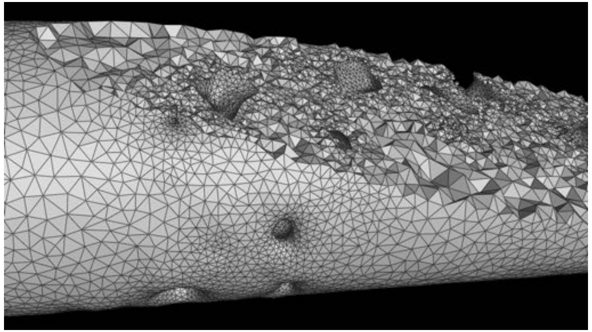


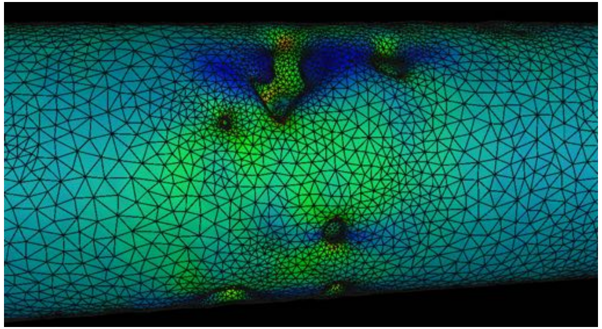


Classical Finite Elements Simulation

CT Data







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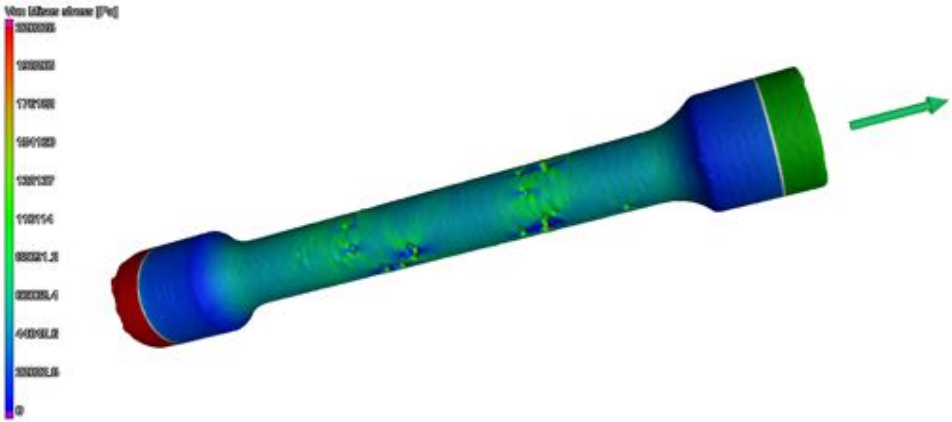
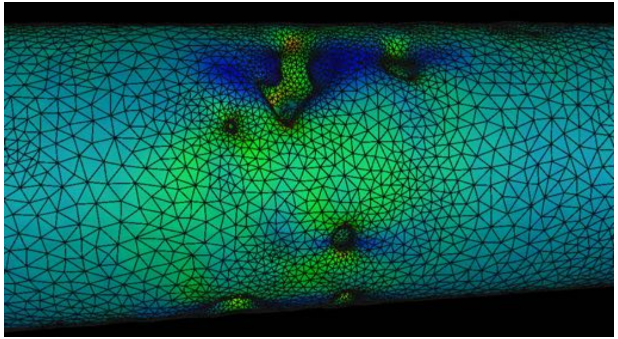
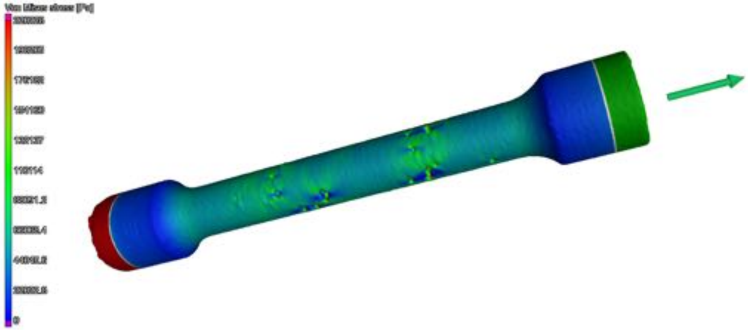


Direct simulation on image data



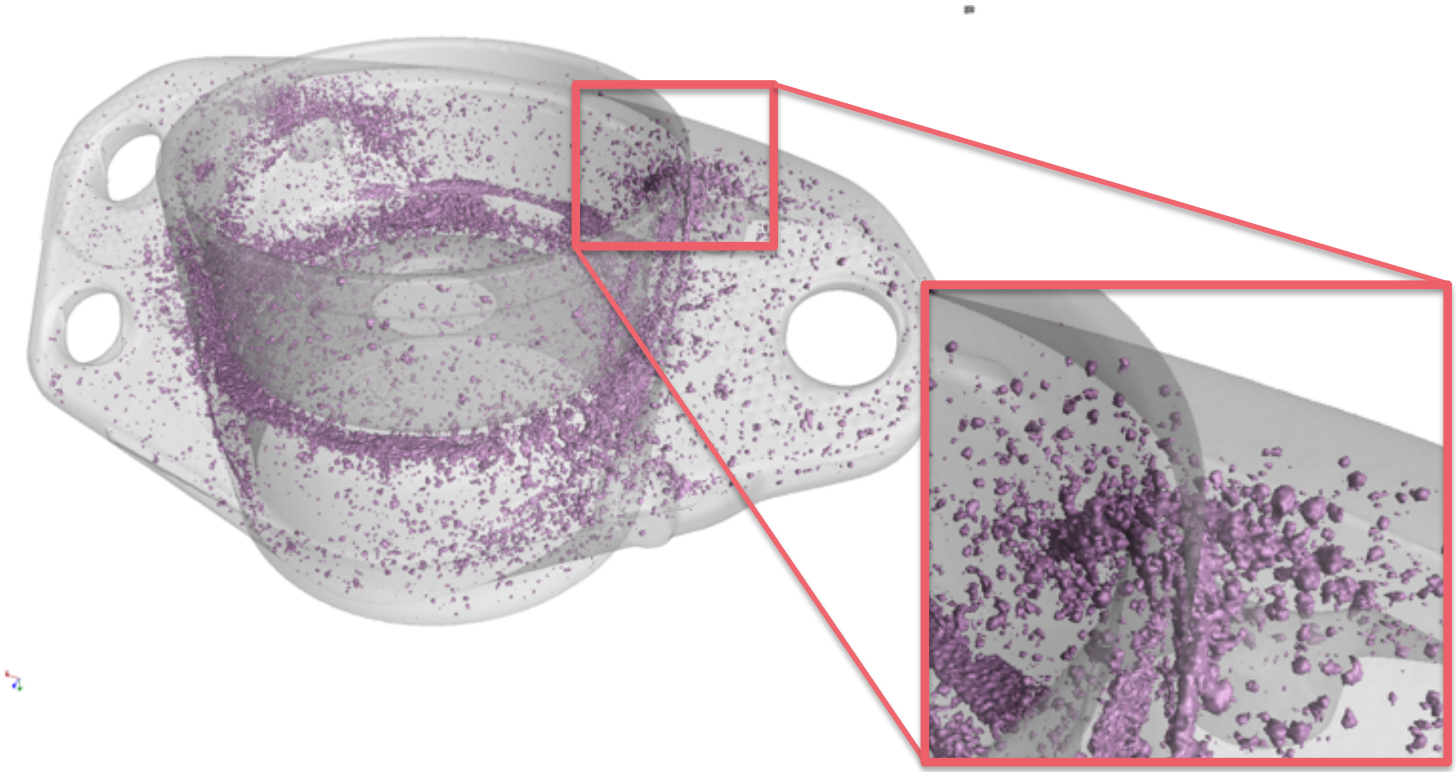
Classical Finite Elements

✓ Can use established simulation workflows
✓ Leverage well known simulation software
✗ Unfeasable for very complex geometries

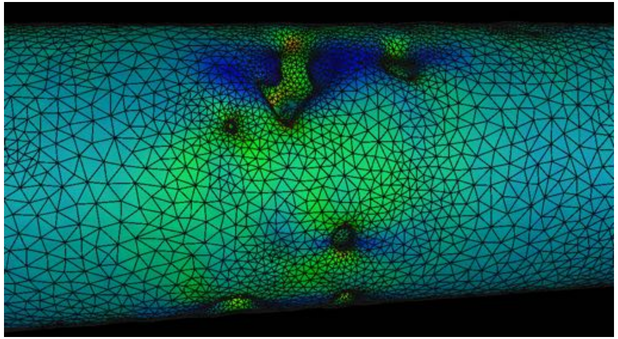


Direct image simulation with Volume Graphics

VOLUME GRAPHICS



How to mesh this ???



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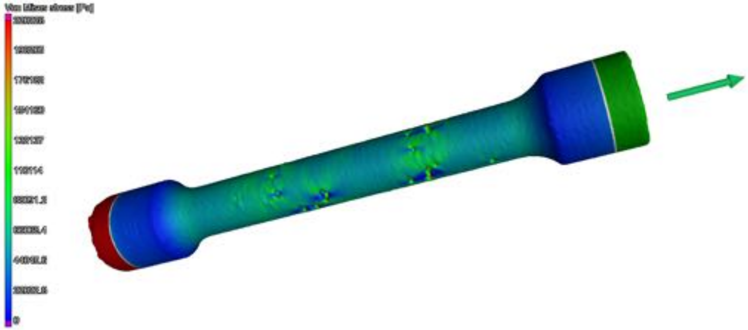
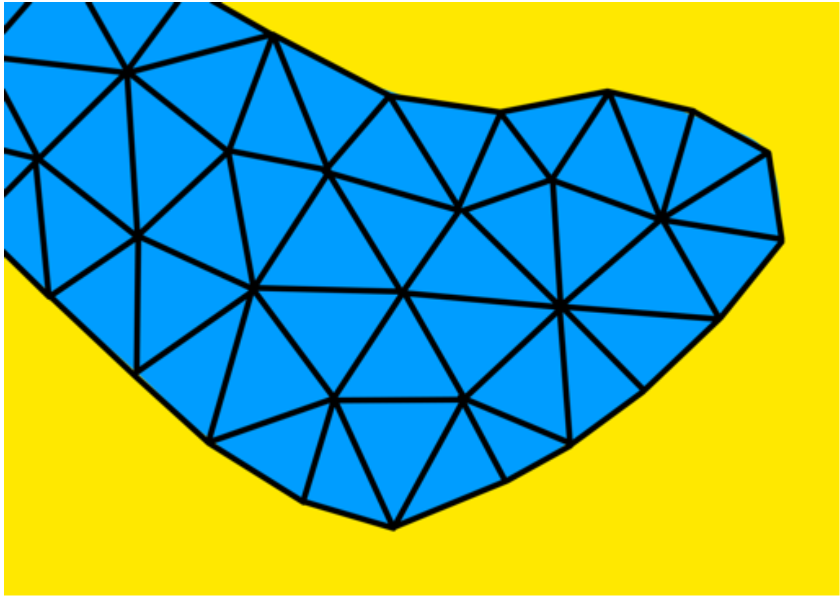


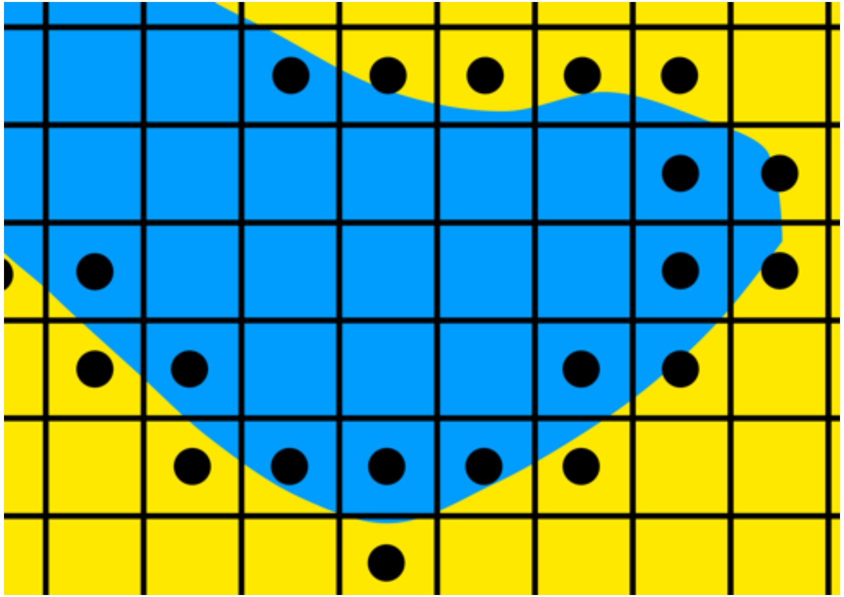
Direct image simulation (with Volume Graphics)

✓ Arbitrary complex geometries
✓ Simple workflow
✓ Fast
✗ Currently limited to linear elasticity

Immersed-Boundary FEM:
The Volume Graphics Approach to Direct Image Simulation

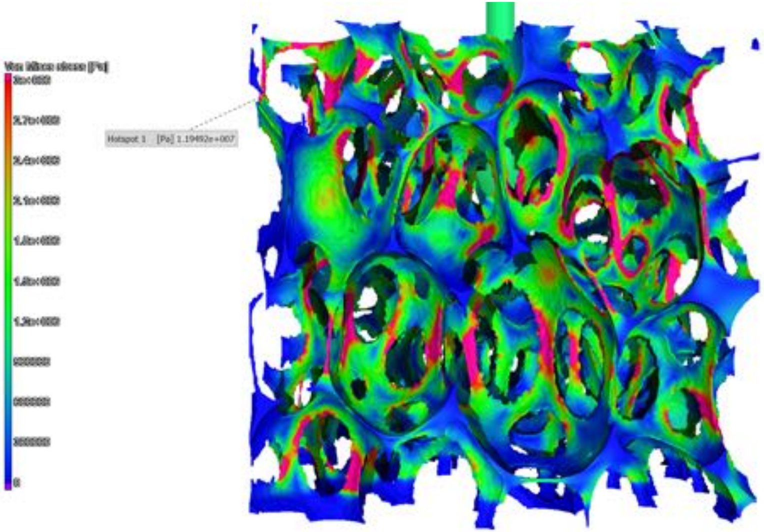


Classical FEM

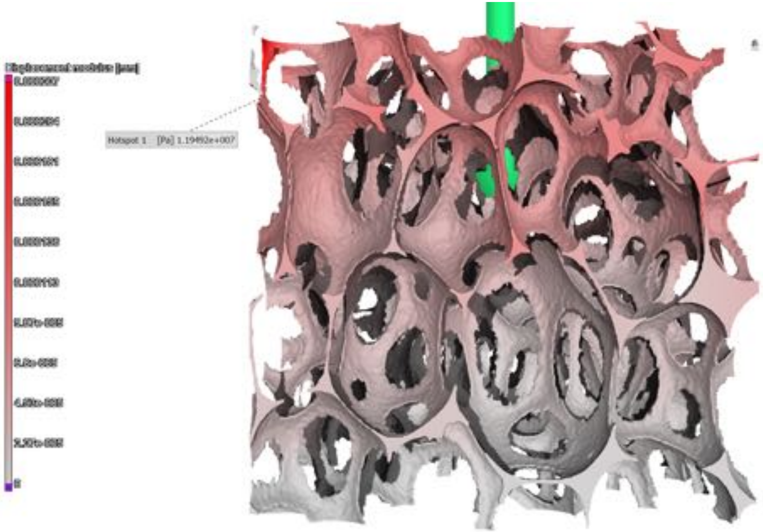


Immersed-Boundary FEM

Example: Aluminum Foam



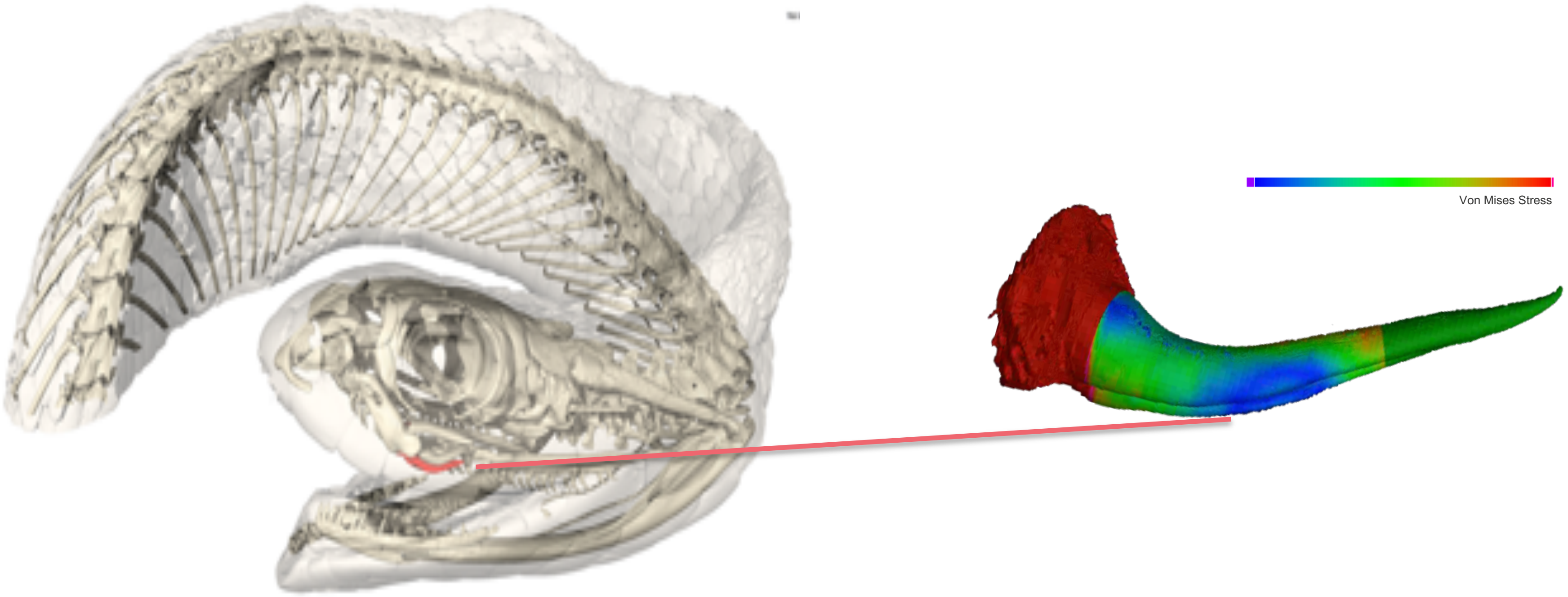
Nominal stress: 0,1 N / 3,0976 mm^2 = 32,3 kPa
Hotspot stress: 11,95 MPa
→ Stress concentration factor: 370



Maximum displacement: 0,227 µm
Strain: 0,227 µm / 1,76 mm = 129 µm/m
→ Effective Young's modulus: 247 MPa
(vs. 69.000 MPa for bulk aluminum)

Example: Biological structure

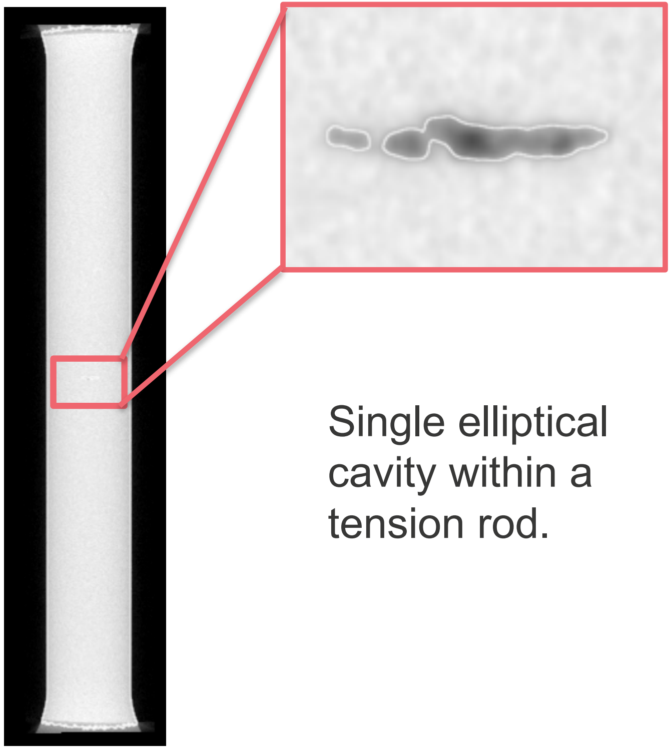
Comparing the mechanics of different snake fangs (poison teeth) [1]



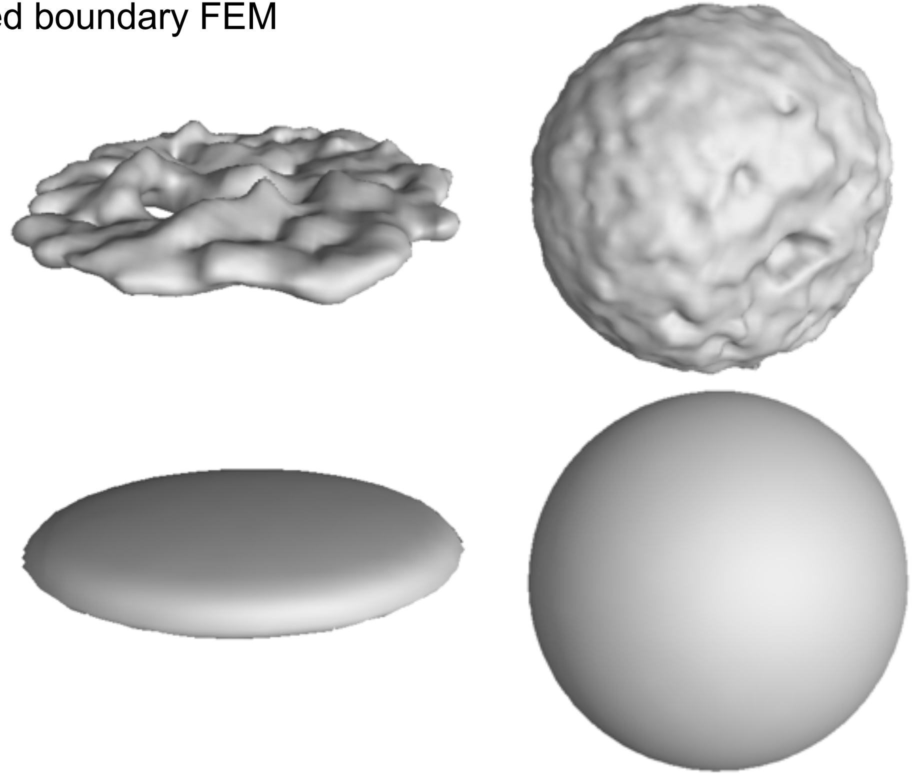
[1] Broeckhoven, Du Plessis: "Has snake fang evolution lost its bite? New insights from a structural mechanics viewpoint." *Biology Letters* 13.8 (2017)

Example: Tension Rod With one Pore

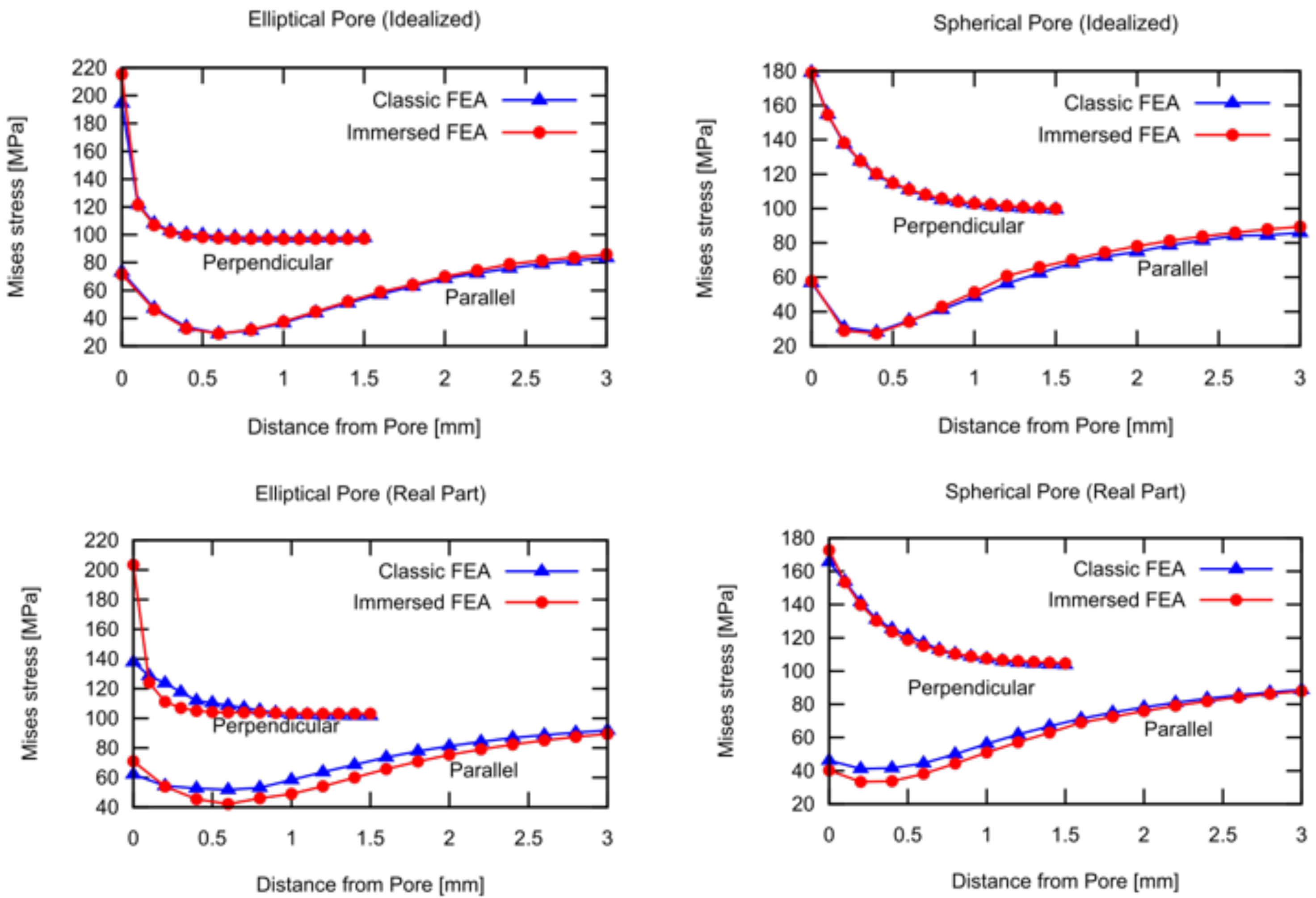
Comparison between classical FEM and immersed boundary FEM



Single elliptical cavity within a tension rod.



J Fieres, F Esposito: Fast and Accurate Simulation of Manufactured Parts with Defects, Tech Briefs 5 (2019)



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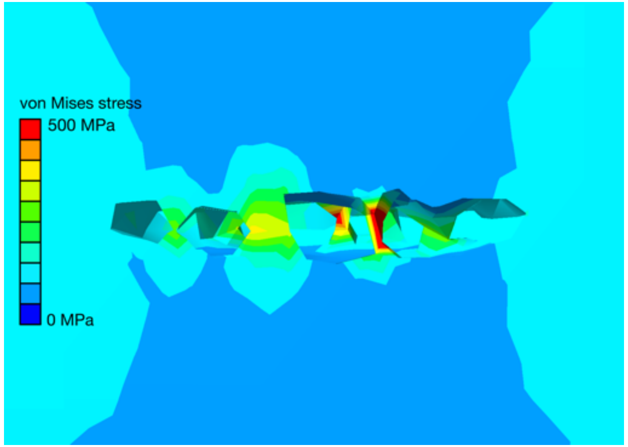
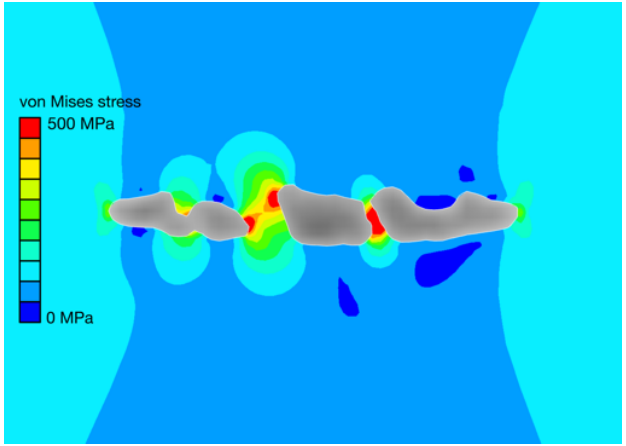


Classical FEM

- Volume meshing (30 min)
- Solving (5 min)



Immersed-boundary FEM

- Direct solving (5 min)

J Fieres, F Esposito: Fast and Accurate Simulation of Manufactured Parts with Defects, Tech Briefs 5 (2019)

Validation study

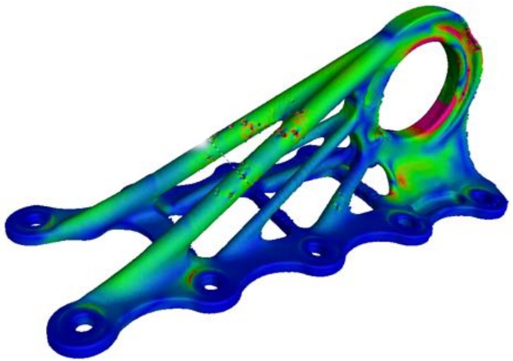
- Aluminum alloy (AlSi10Mg)
- Built additively using laser melting by Concept Laser
- Deliberately built-in porosity
- Six different porosity patterns

18 bionic brackets [1]
(length = 8cm)

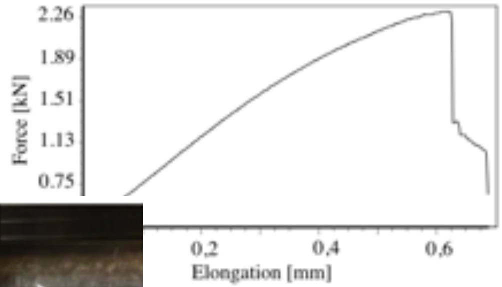
18 tensile rods
(length = 5cm)

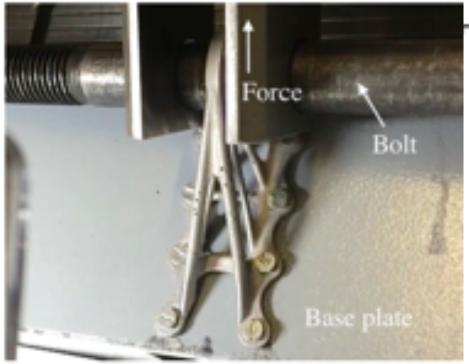
[1] Design by Airbus Emerging Technologies & Concepts, with permission

Validation study



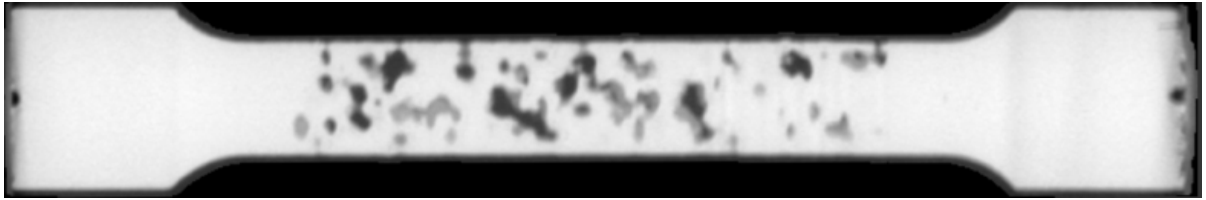
Immersed boundary FE simulation

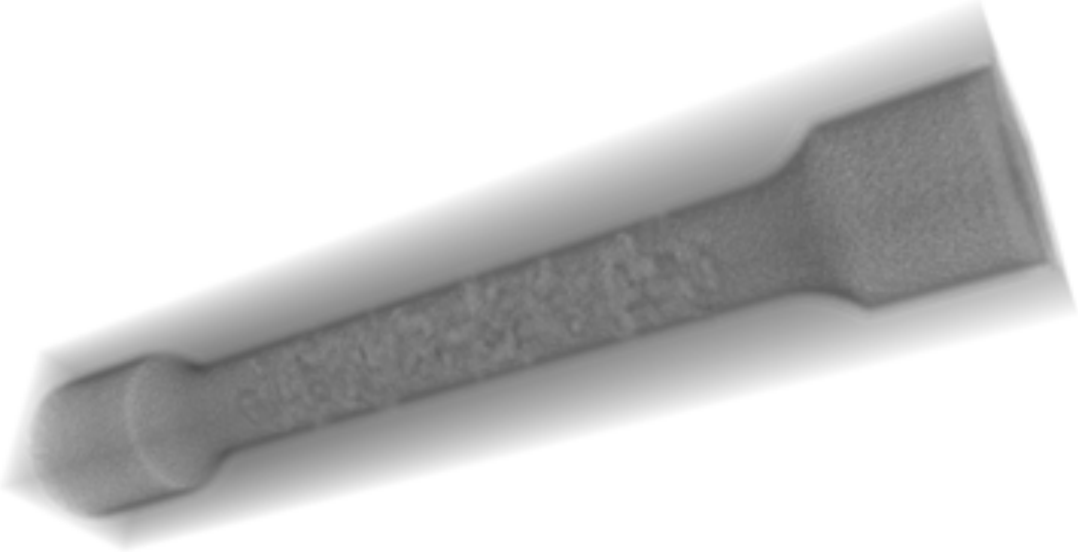




Quasi-static destructive test

Validation Details





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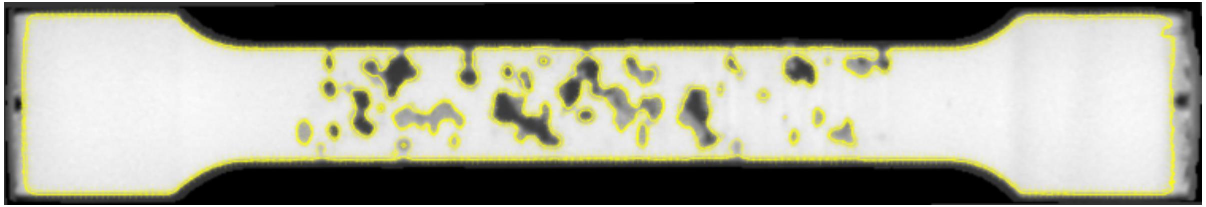

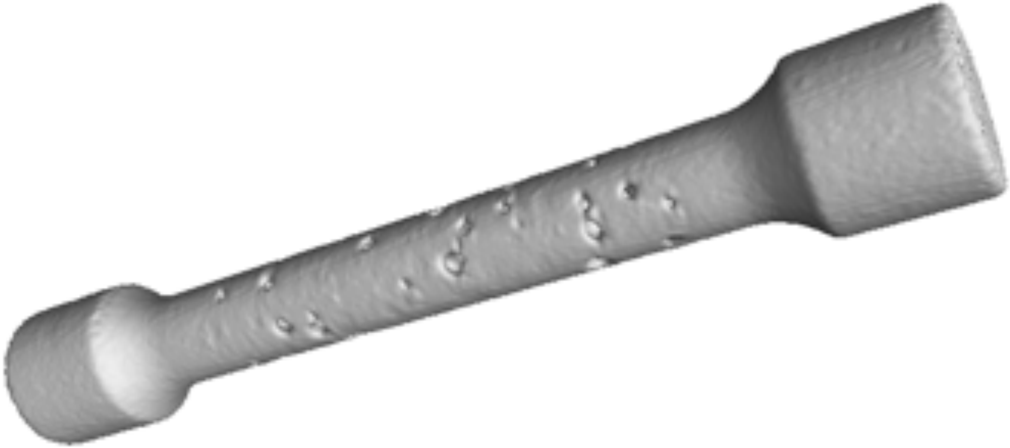

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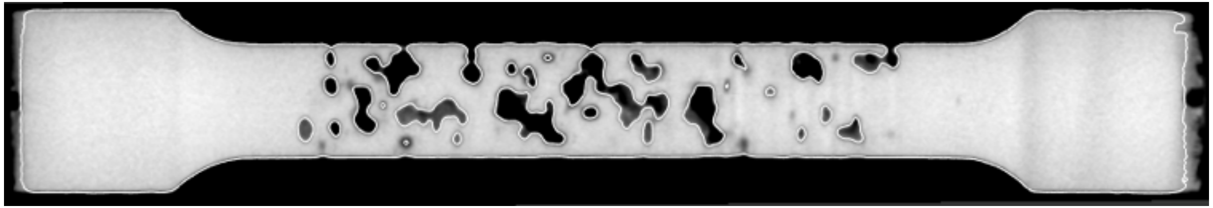

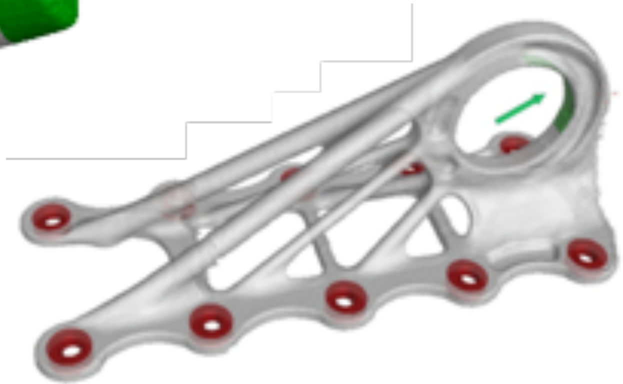

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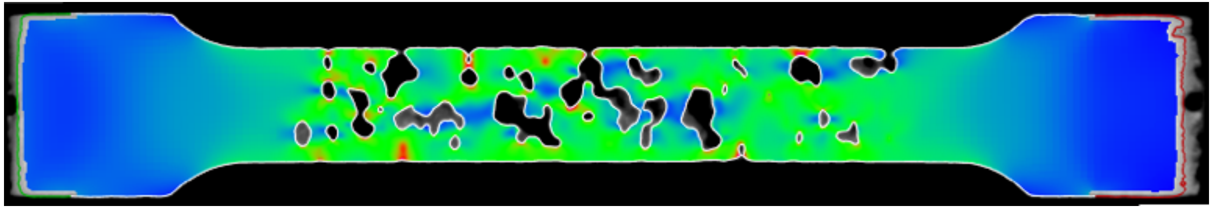
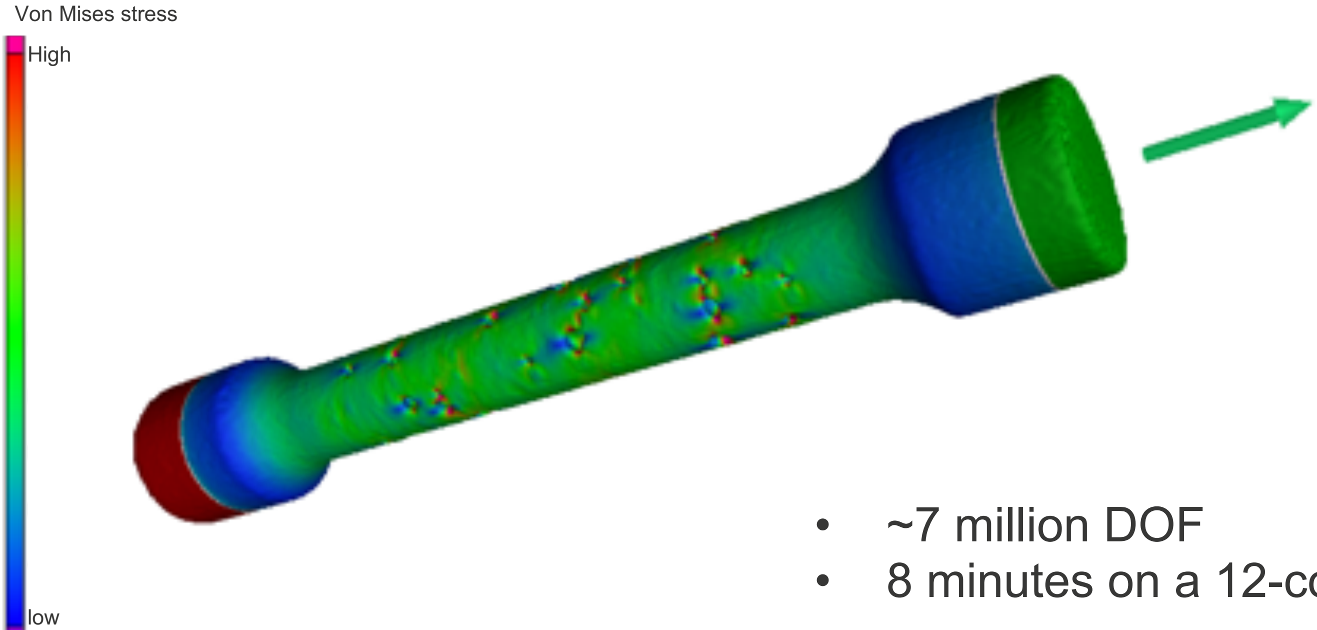
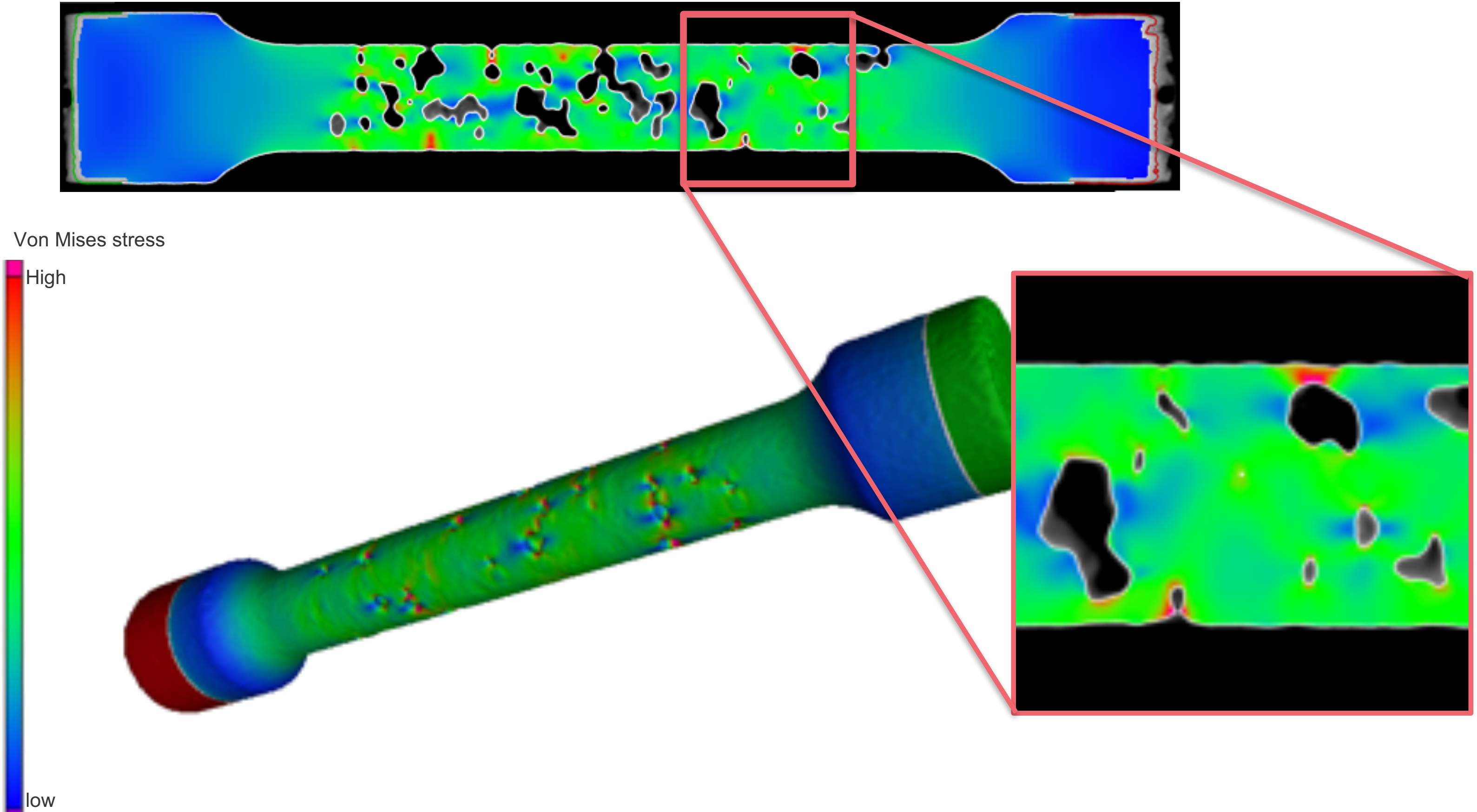




- ~7 million DOF
- 8 minutes on a 12-core workstation

Validation Details



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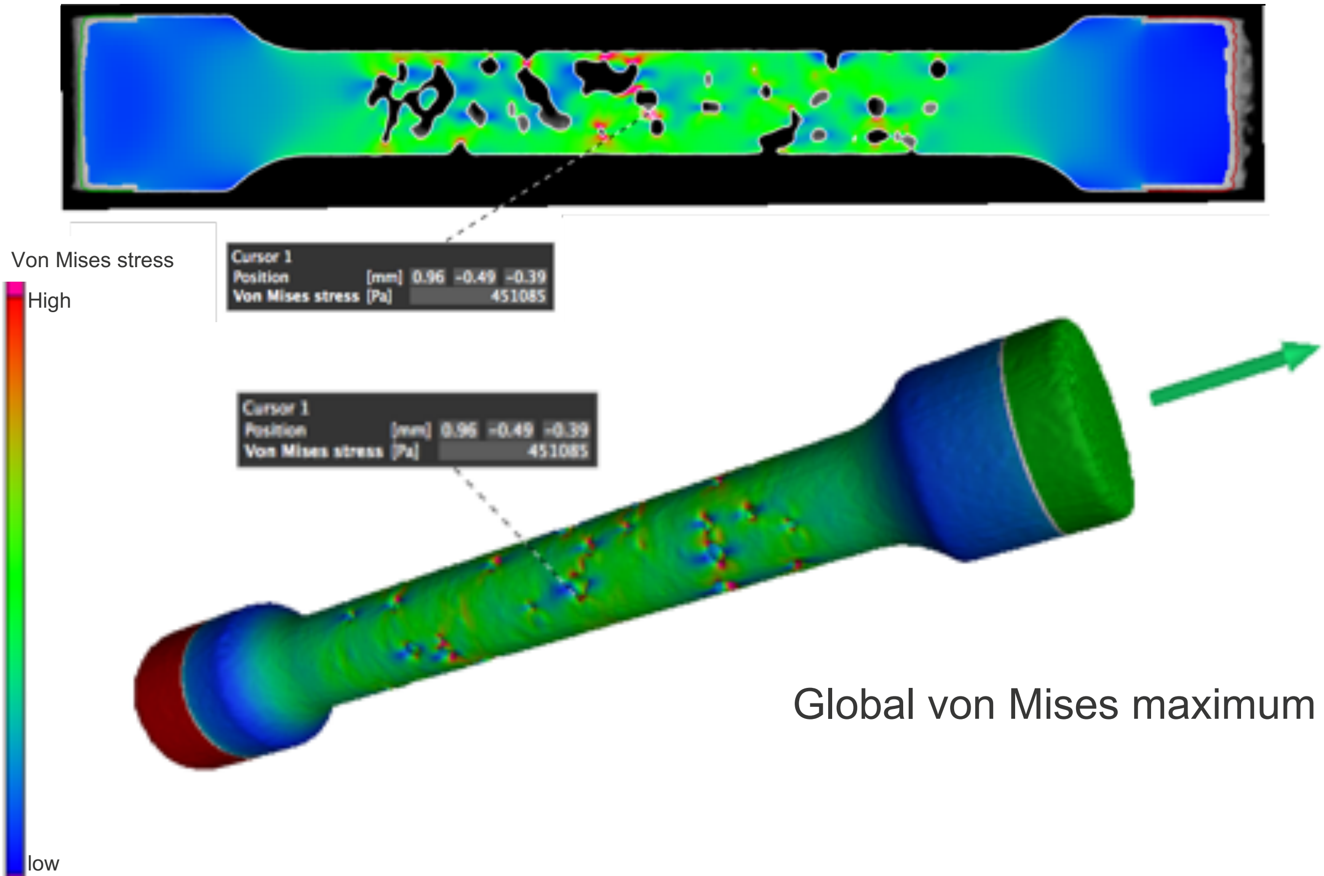
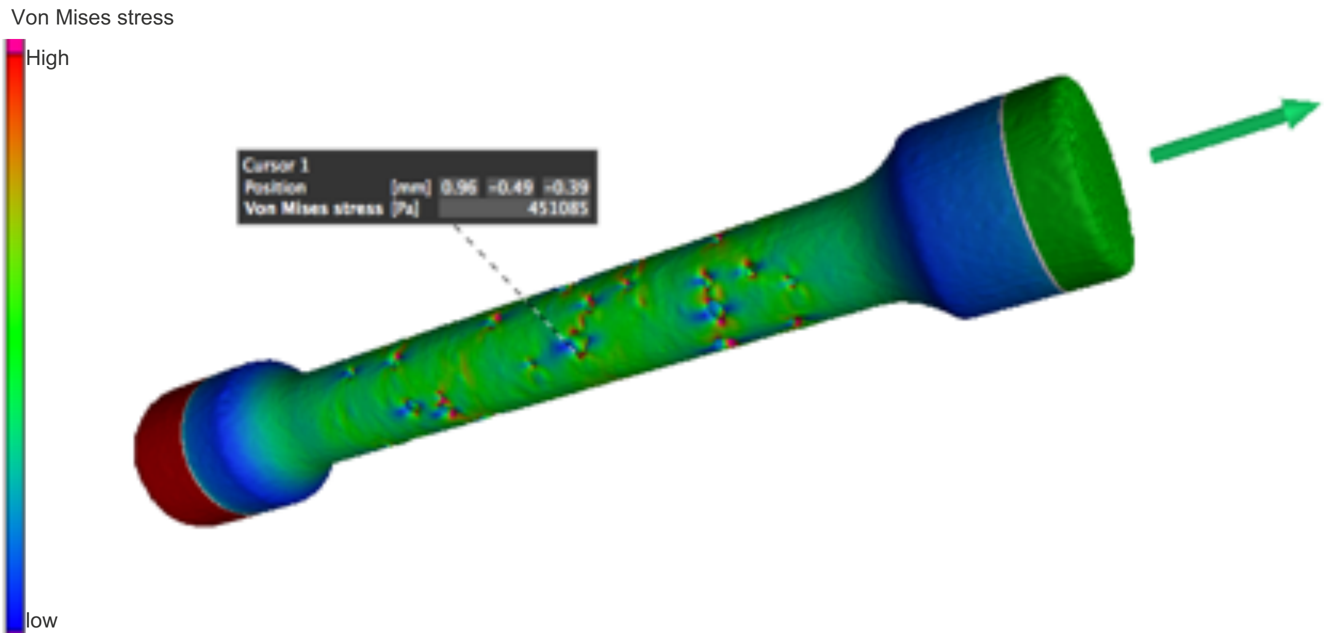


Global von Mises maximum σ_{max}

Validation Details



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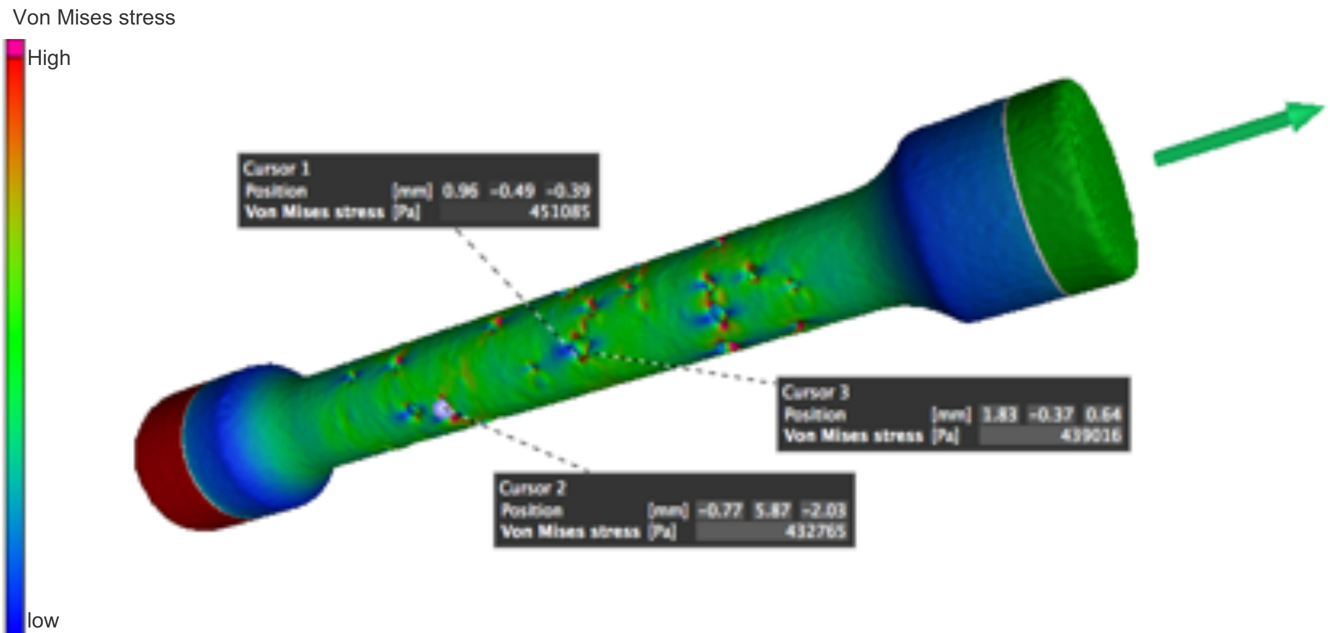


Validation Details

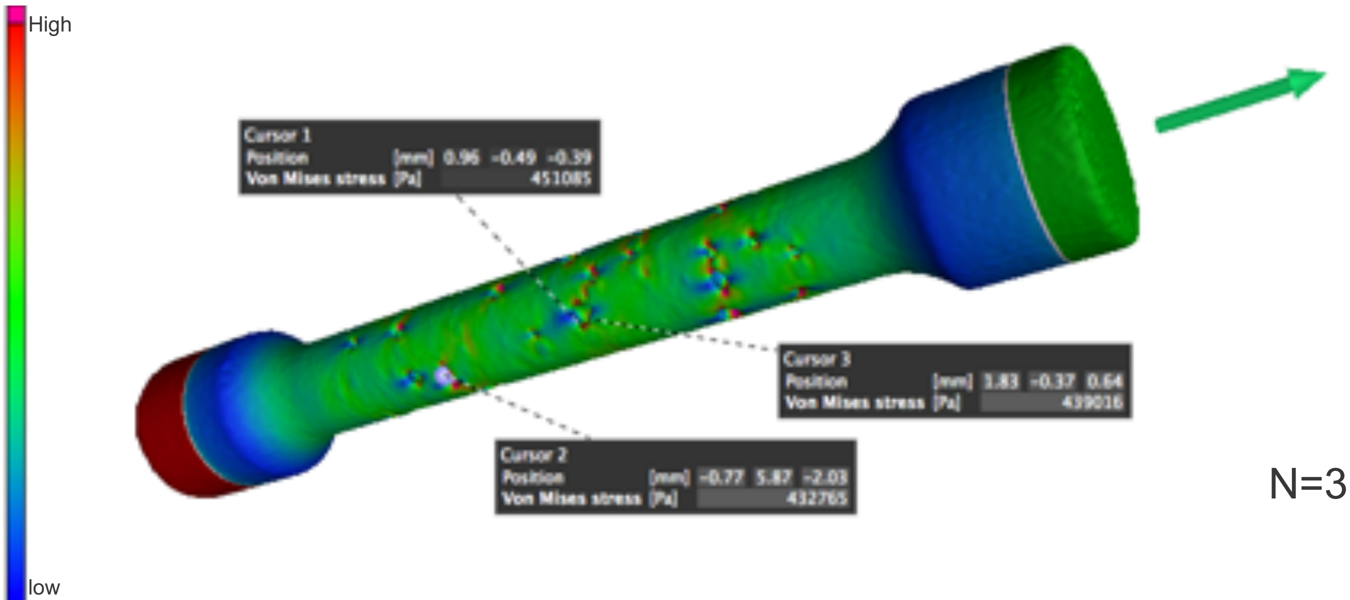
Find largest N local maxima of von Mises stress:

$\sigma_1 (=\sigma_{max}),\ \sigma_2,\ \ldots\ , \sigma_N$

Predictions:

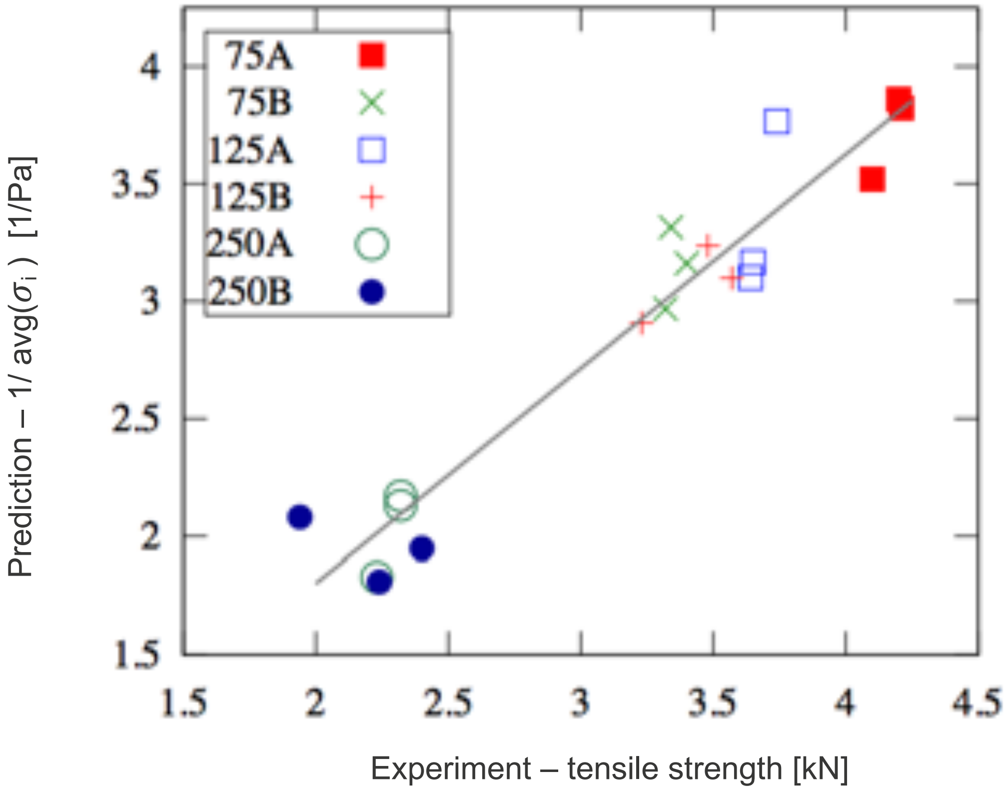
> First crack occurs at either one of these positions

> Ultimate strength $\propto\ 1 / (\Sigma\sigma_i / N)$

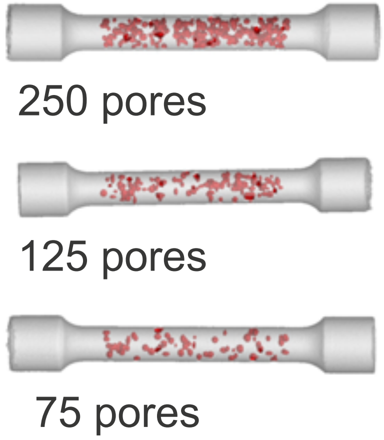


N=3 in this study

Results: Prediction of Tensile Strength



[1]



[1] Fieres, Schumann, Reinhart: Predicting failure in additively manufactured parts using X-ray computed tomography and simulation, 7th intl. conf. fatigue design 2017

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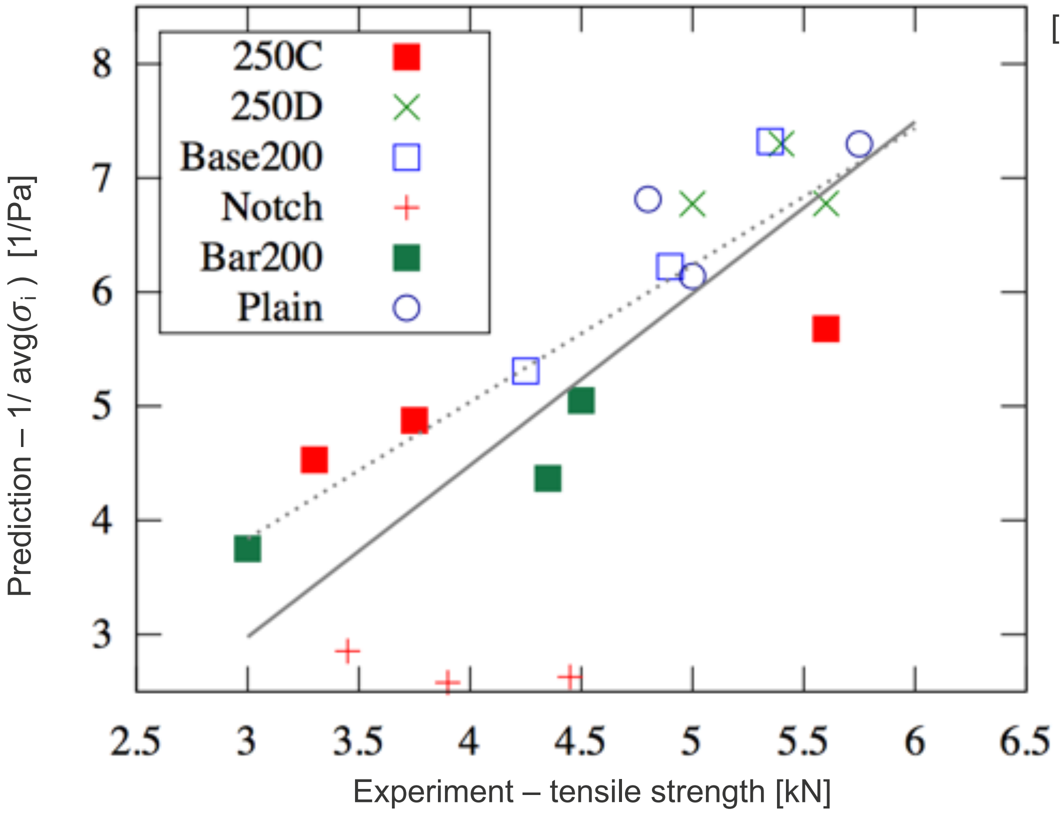

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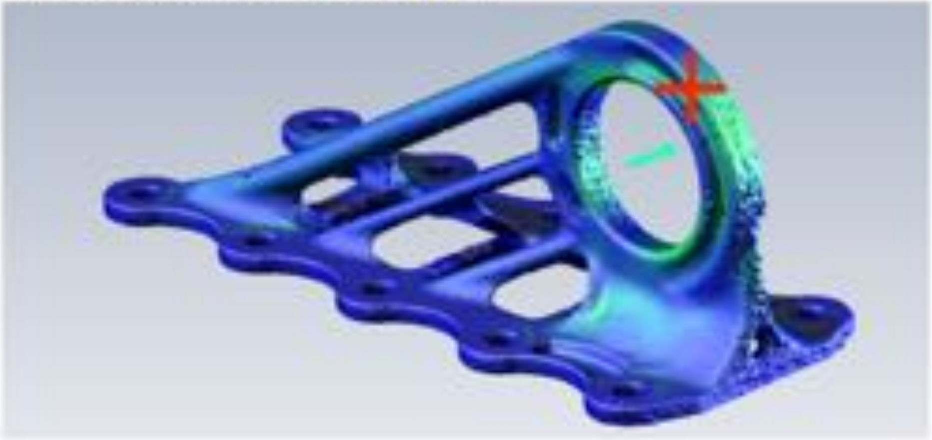
[1] Fieres, Schumann, Reinhart: Predicting failure in additively manufactured parts using X-ray computed tomography and simulation, 7th intl. conf. fatigue design 2017

Simulation vs. Experiment: Crack Locations

250C, specimen 1 of 3, HS_1



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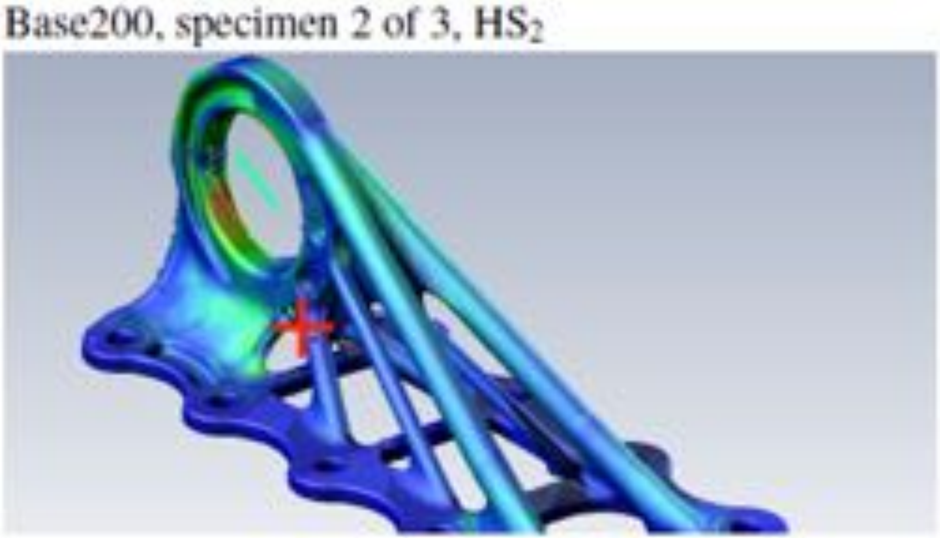
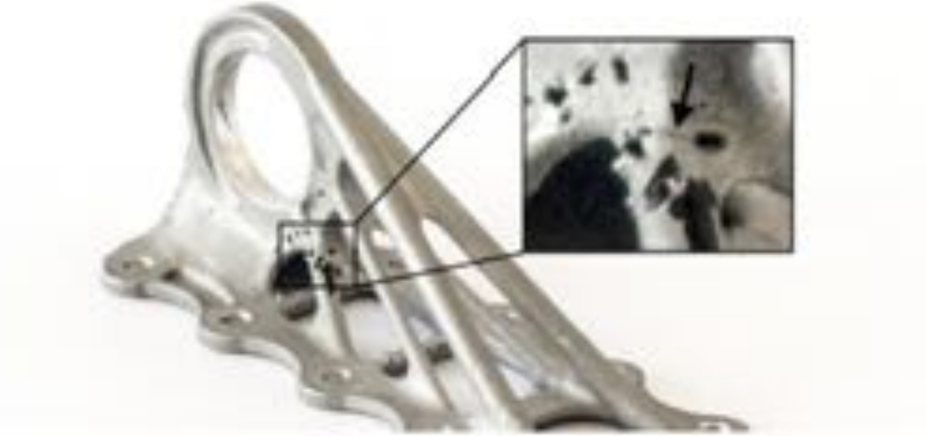
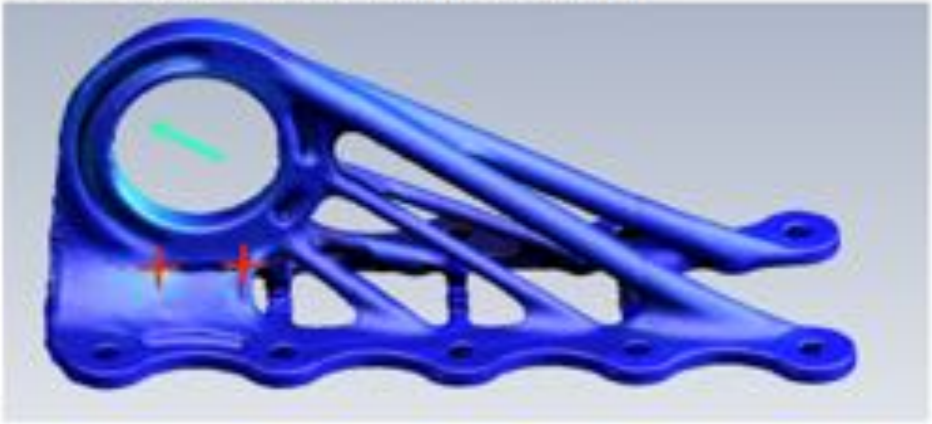




Simulation vs. Experiment: Crack Locations

Notch, specimen 2 of 3, HS_1 and HS_2



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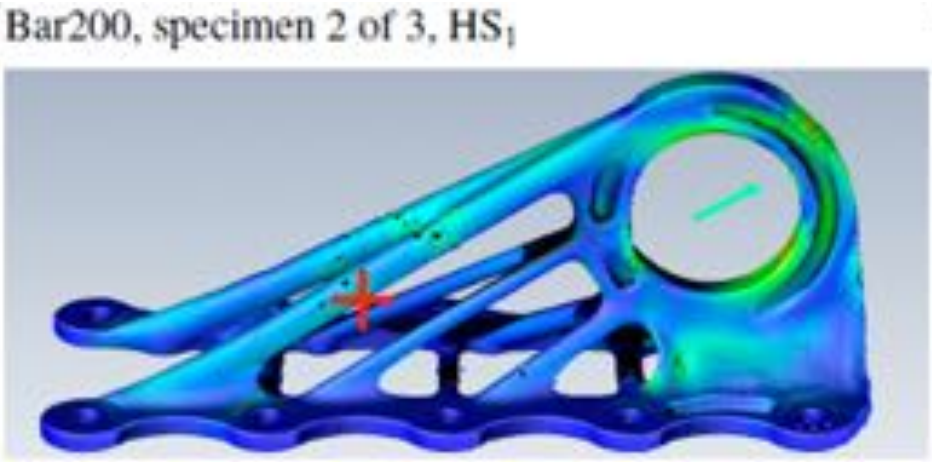

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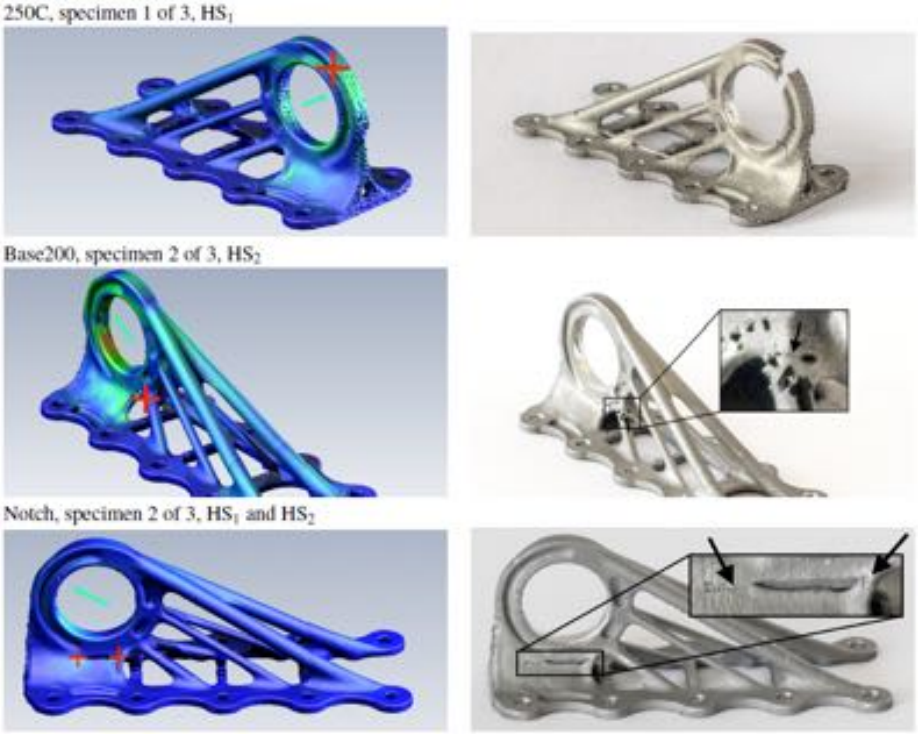
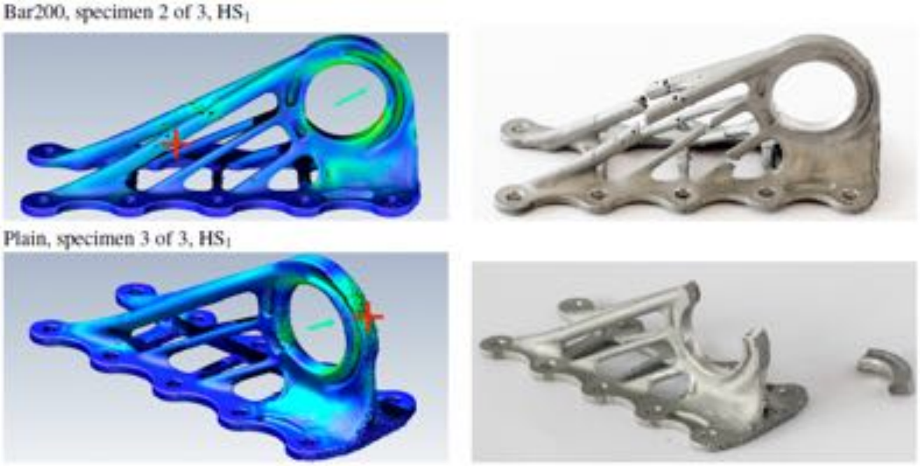
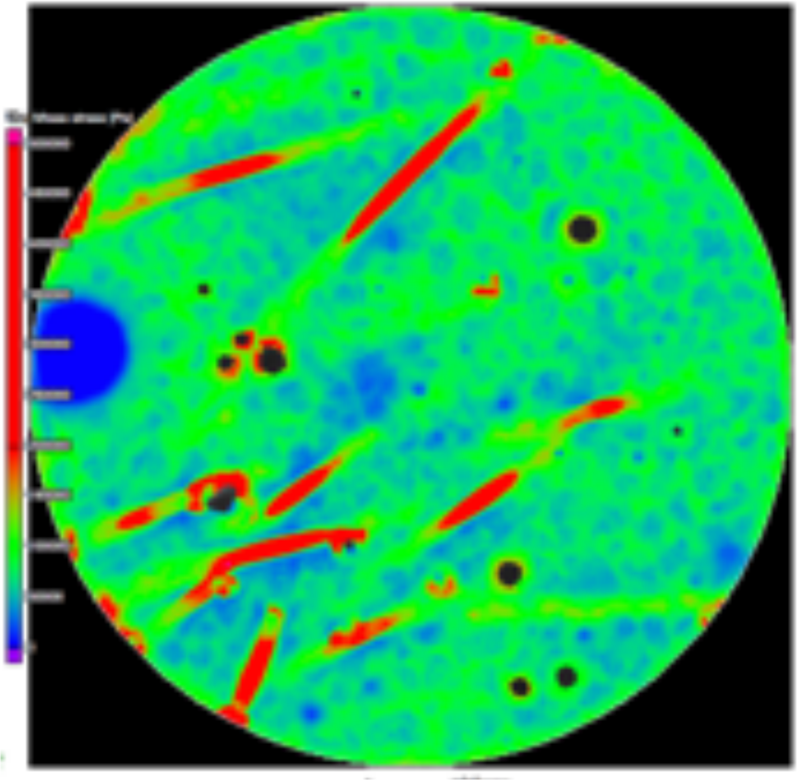
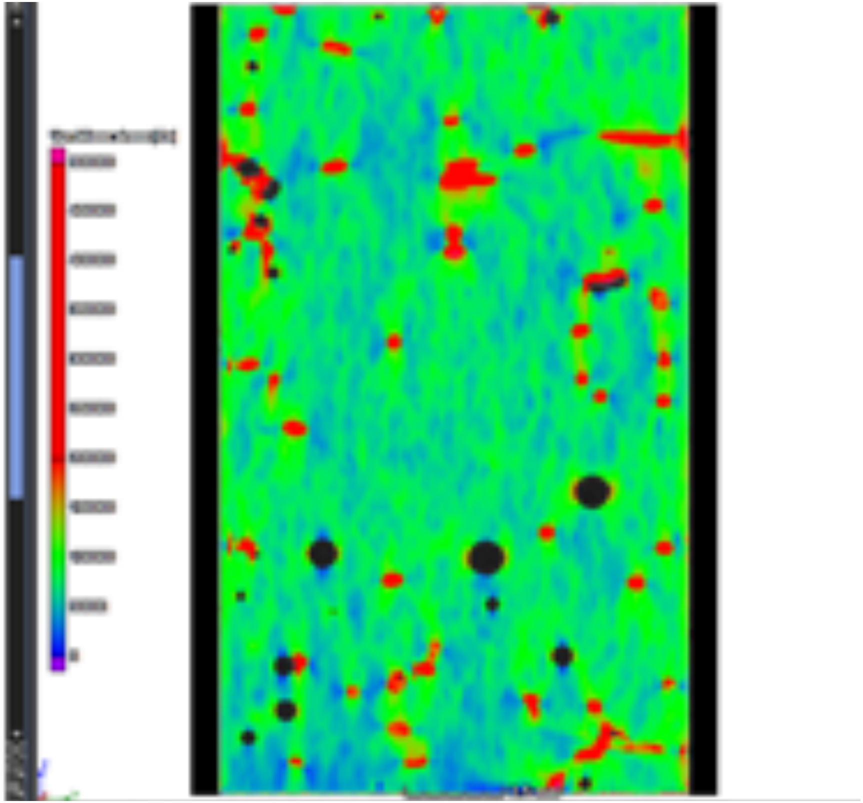




- 12 of 18 specimen cracked at hot spot 1 or 2
- 3 specimen cracked at one of the top 10 hotspots
- 3 specimen cracked elsewhere

Density Dependent Material Parameters





Benefits

Low Effort

- No meshing required
- No simulation expertise required
- Seamless workflow from material segmentation and defect detection to simulation in one software

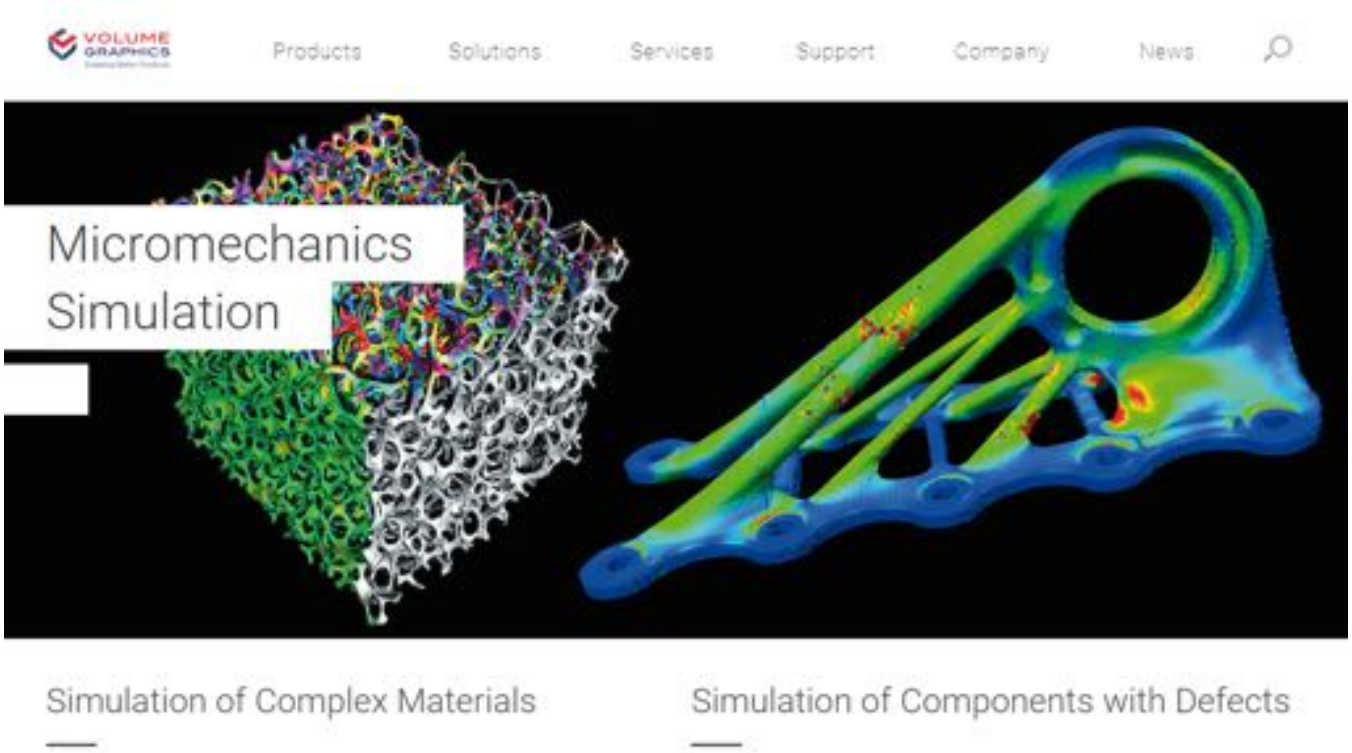
Realistic

- All microstructural details are captured by a subvoxel-precise material segmentation
- Simulated stresses can be directly related to the underlying material microstructure (e.g. size, location and shape of pores or thicknesses of struts in open-cell foams)

Validated

- Predicted fracture locations and tensile strengths validated in experimental tensile tests of 3D printed components with pores
- Effective elastic properties of a cubic lattice validated against a conventional FEM simulation

Micromechanics Simulation on CT Scans



https://www.volumegraphics.com/micromechanicssimulation

Thank You !

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…or approach us in the lunch room!

Example: 3D Printed Component with Pores

Stress concentration caused by a pore