



Volume weighted probabilistic methods for nitinol lifetime prediction

Craig Bonsignore

Karthikeyan Senthilnathan

Ali Shamimi

Confluent Medical Technologies | Fremont California

> Introduction

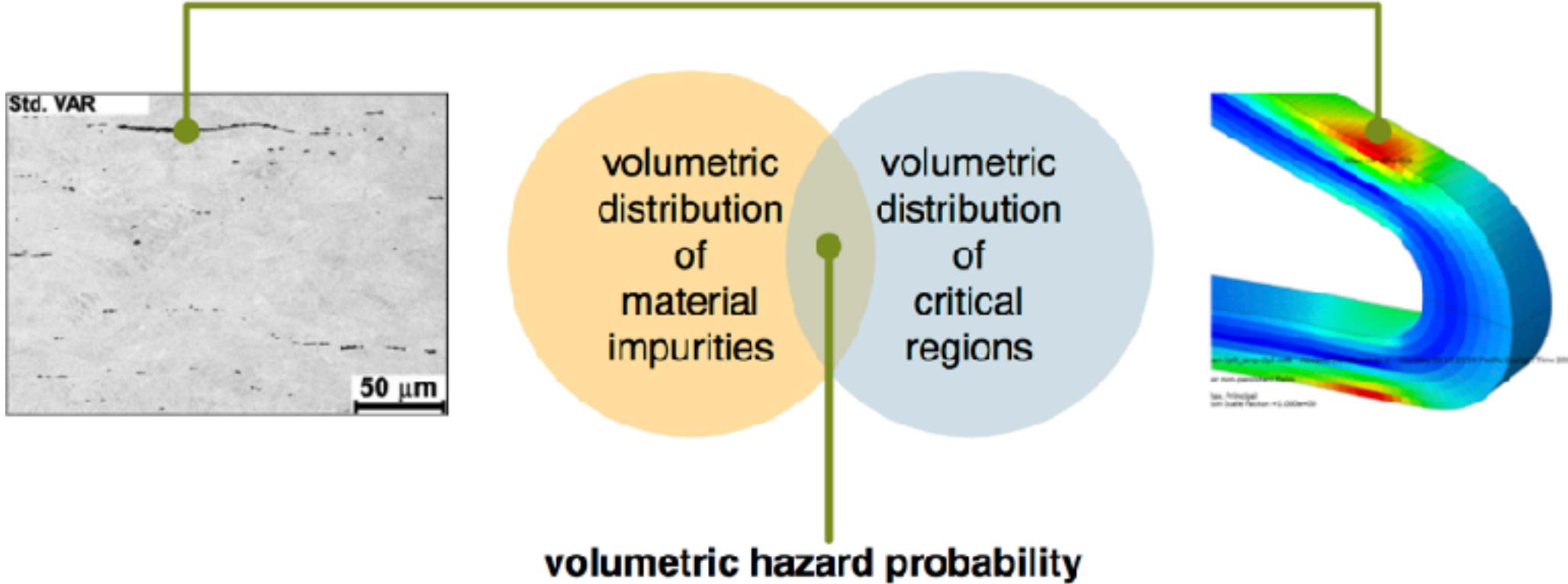
Volumetric FEA methods

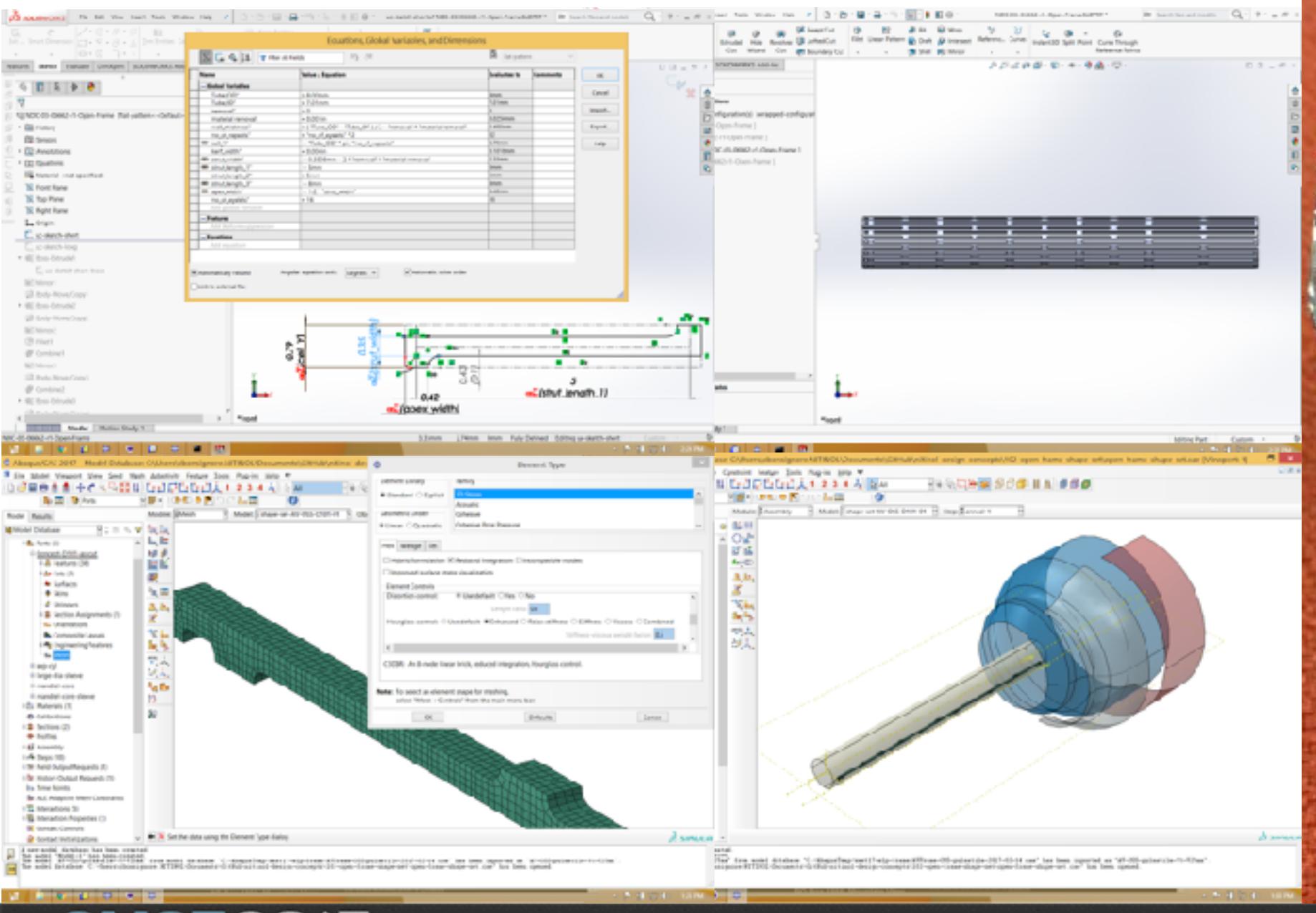
Sub- μm x-ray computed tomography

Monte-Carlo risk assessment

Resources

Motivation



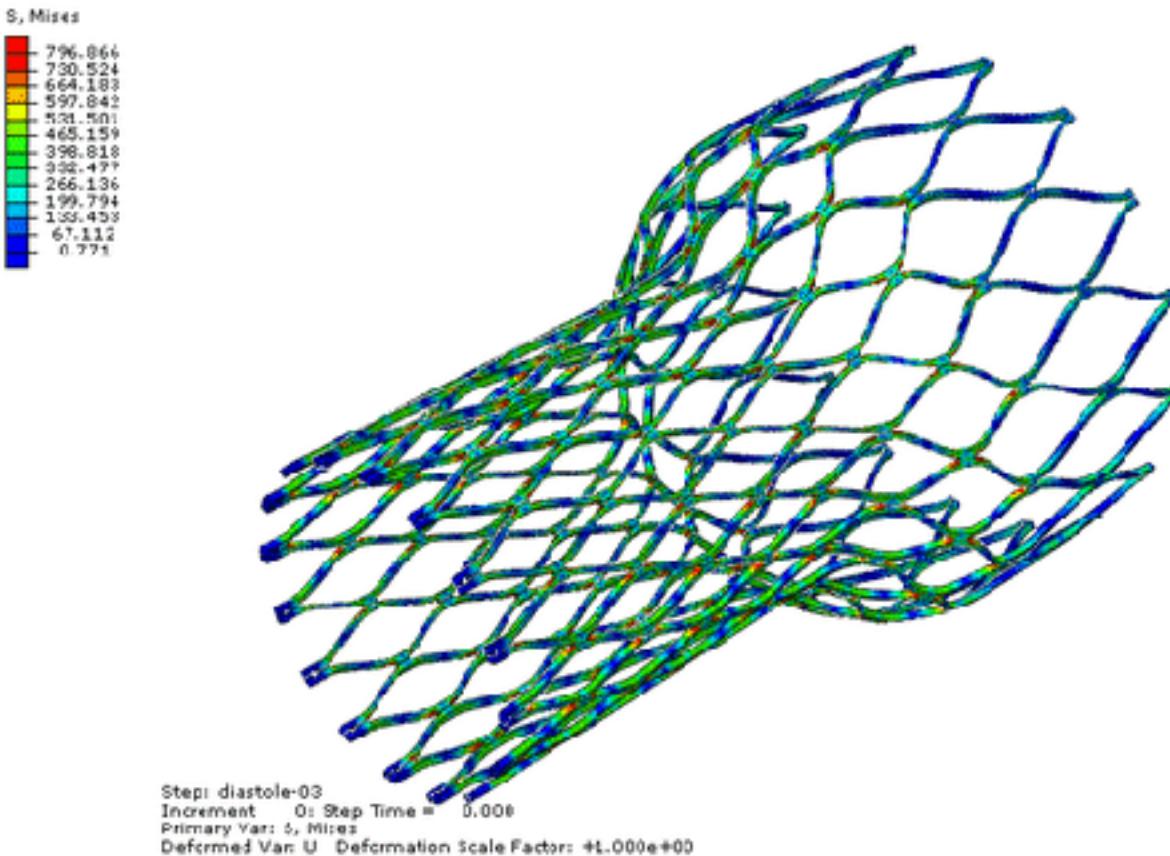


SMST2017

SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES CONFERENCE AND EXPOSITION

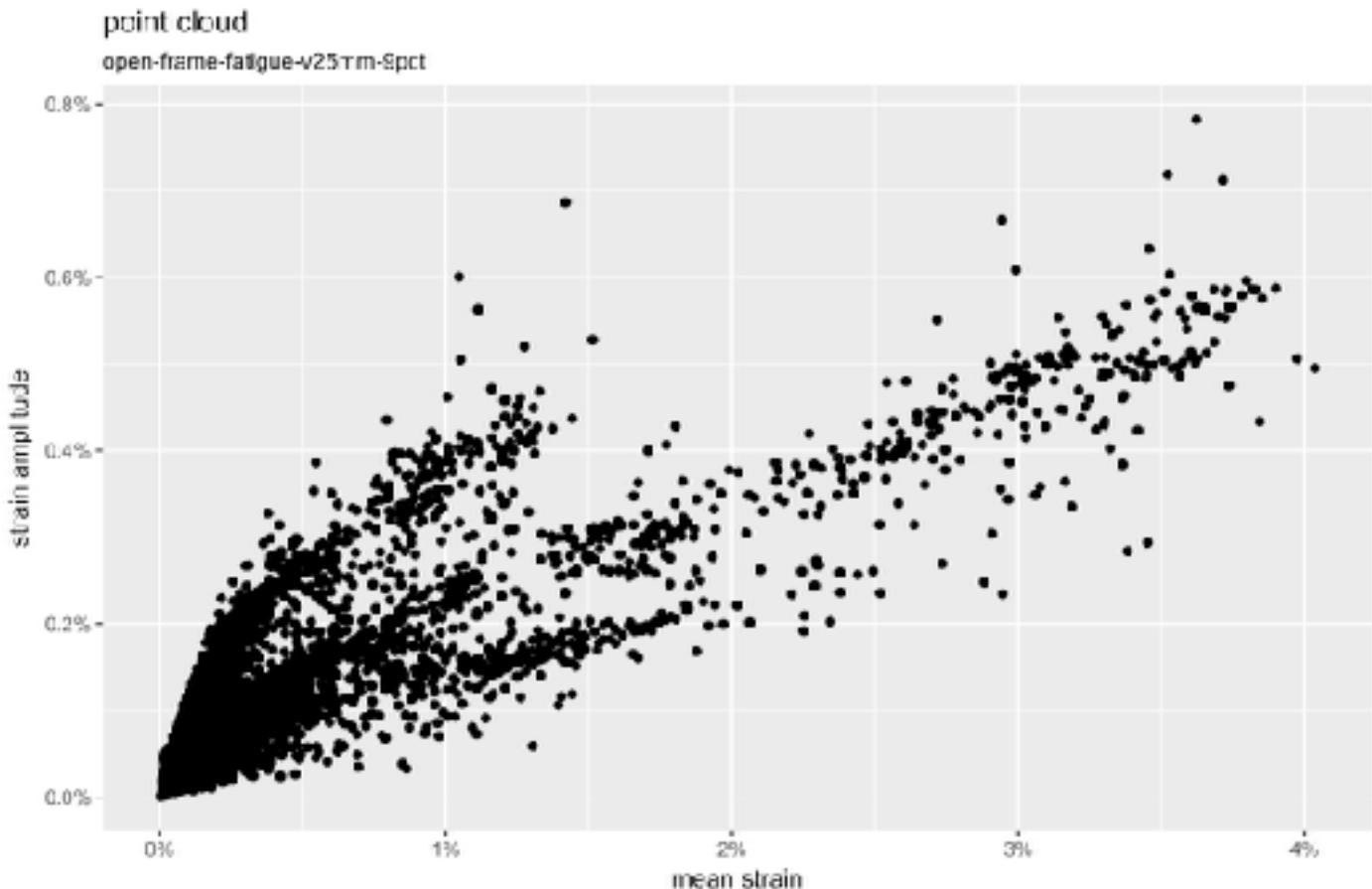
cyclic fatigue condition

9% cyclic change in diameter



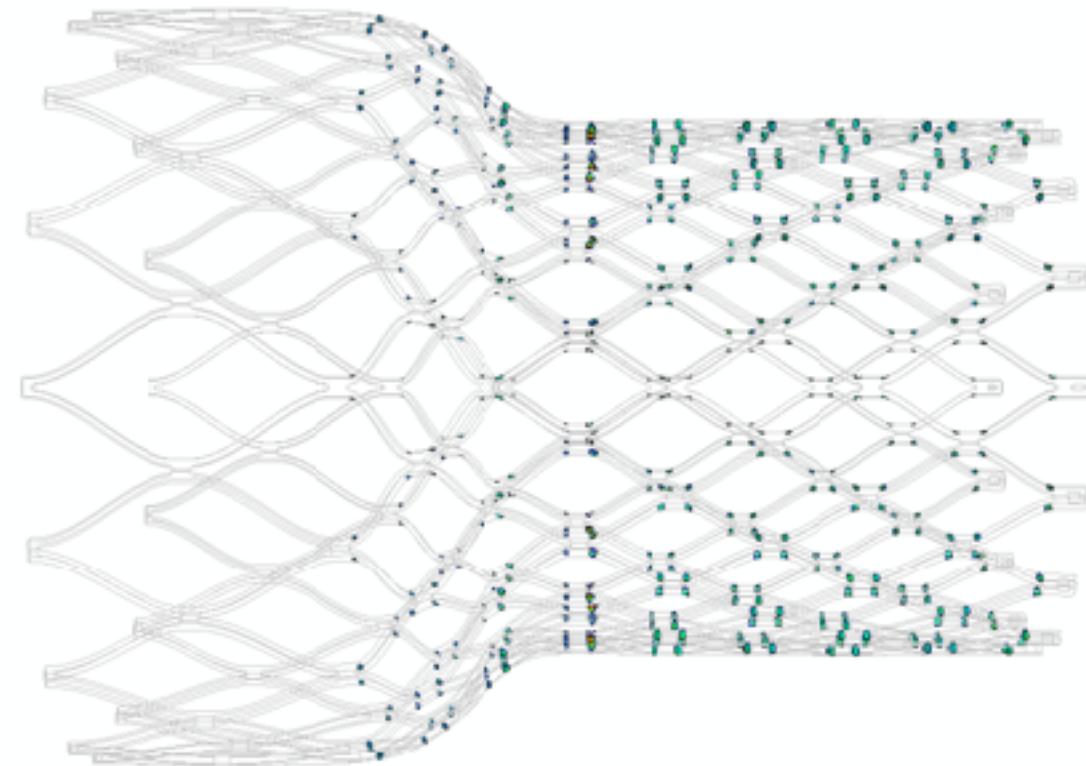
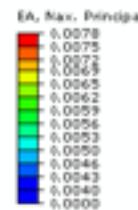
typical point cloud

9% cyclic change in diameter



critical volumes

a small proportion of the volume exceeds a critical limit of strain amplitude.



Introduction

> **Volumetric FEA methods**

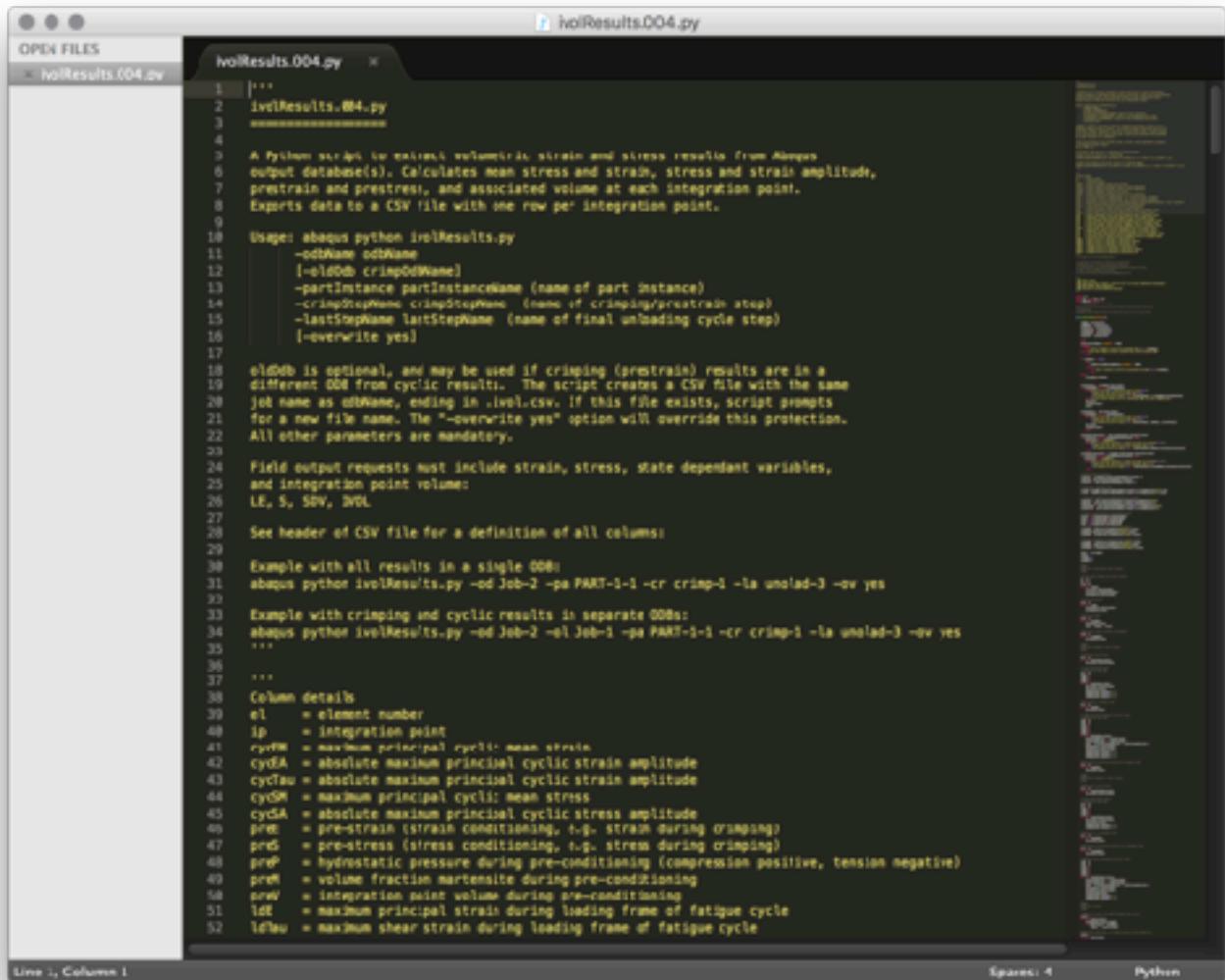
Sub- μm x-ray computed tomography

Monte-Carlo risk assessment

Resources

Tools to extract volume data and more

- integration point volume
- strain, stress at crimping step (pre-strain)
- hydrostatic pressure (tension vs. compression)
- volume fraction of martensite
- mean stress/strain
- stress/strain amplitude
- stress and strain components



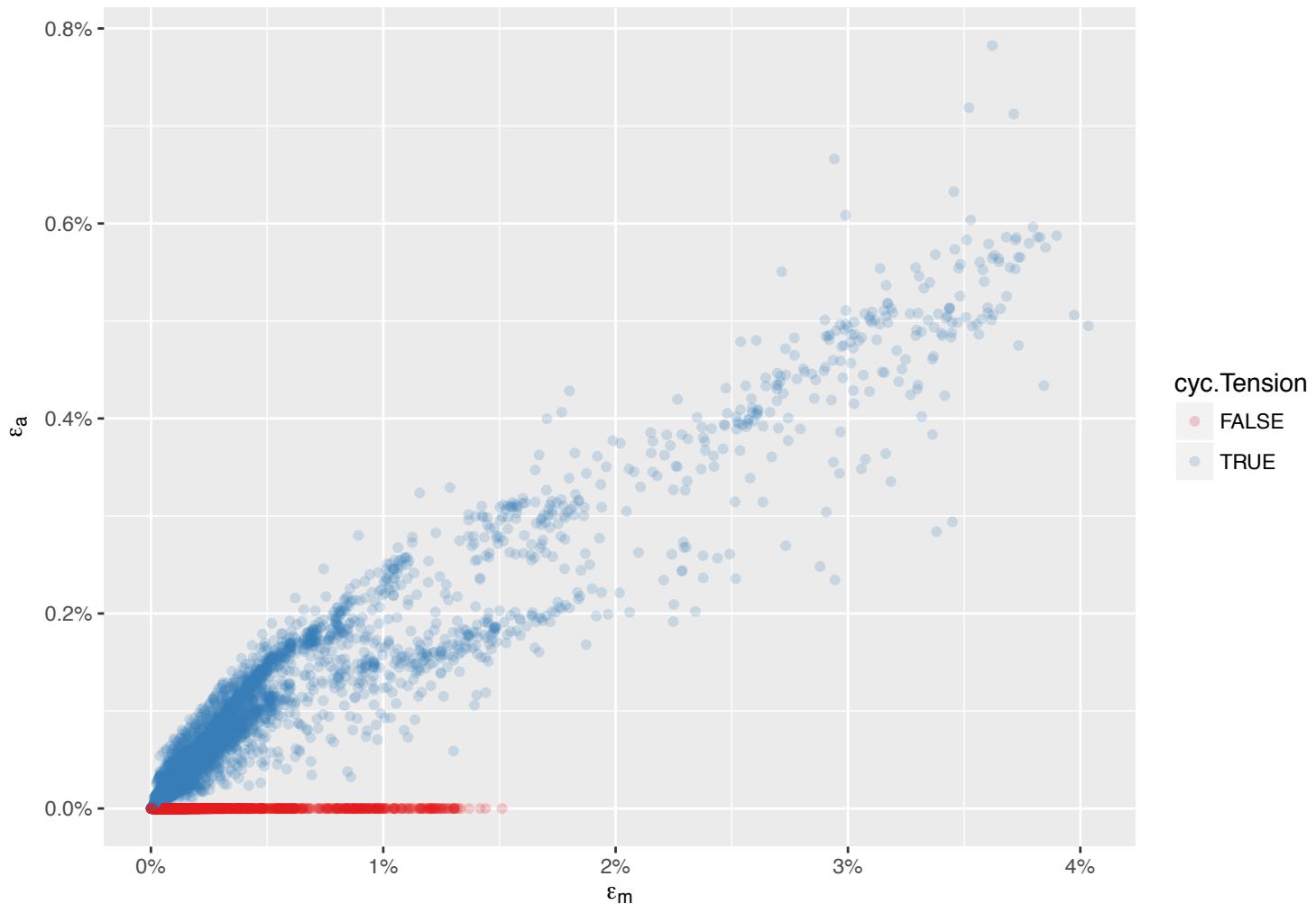
The screenshot shows a Python code editor with the file 'ivolResults.004.py' open. The code is a script designed to extract volumetric strain and stress results from Abaqus output database(s). It calculates mean stress and strain, stress and strain amplitude, prestrain and prestress, and associated volume at each integration point. The script exports data to a CSV file with one row per integration point.

```
#!/usr/bin/python
# ivolResults.004.py
# -----
#
# A Python script to extract volumetric strain and stress results from Abaqus
# output database(s). Calculates mean stress and strain, stress and strain amplitude,
# prestrain and prestress, and associated volume at each integration point.
# Exports data to a CSV file with one row per integration point.
#
# Usage: abaqus python ivolResults.py
#        -odbName odbName
#        [-el0db dbName]
#        -partInstance partInstanceName (name of part instance)
#        -crimpStepName crimpStepName (name of crimping/prestrain step)
#        -lastStepName lastStepName (name of final unloading cycle step)
#        [-overwrite yes]
#
# el0db is optional, and may be used if crimping (prestrain) results are in a
# different ODB from cyclic results. The script creates a CSV file with the same
# job name as odbName, ending in .ivol.csv. If this file exists, script prompts
# for a new file name. The "-overwrite yes" option will override this protection.
# All other parameters are mandatory.
#
# Field output requests must include strain, stress, state dependent variables,
# and integration point volumes:
# LE, S, SEV, SVOL
#
# Set header of CSV file for a definition of all columns
#
# Example with all results in a single ODB:
# abaqus python ivolResults.py -od Job-2 -pa PART-1-1 -cr crimp-1 -la unload-3 -ov yes
#
# Example with crimping and cyclic results in separate ODBs:
# abaqus python ivolResults.py -od Job-2 -el Job-1 -pa PART-1-1 -cr crimp-1 -la unload-3 -ov yes
# ...
#
# Column details
# el = element number
# ip = integration point
# cyrm = maximum principal cyclic mean strain
# cydA = absolute maximum principal cyclic strain amplitude
# cyclA = absolute maximum principal cyclic strain amplitude
# cydR = maximum principal cyclic mean stress
# cydA = absolute maximum principal cyclic stress amplitude
# prE = pre-strain (strain conditioning, e.g. strain during crimping)
# prS = pre-stress (stress conditioning, e.g. stress during crimping)
# prP = hydrostatic pressure during pre-conditioning (compression positive, tension negative)
# prM = volume fraction martensite during pre-conditioning
# prV = integration point volume during pre-conditioning
# idF = maximum principal strain during loading frame of fatigue cycle
# idTau = maximum shear strain during loading frame of fatigue cycle
```

Typical point cloud

strain amplitude vs. mean strain

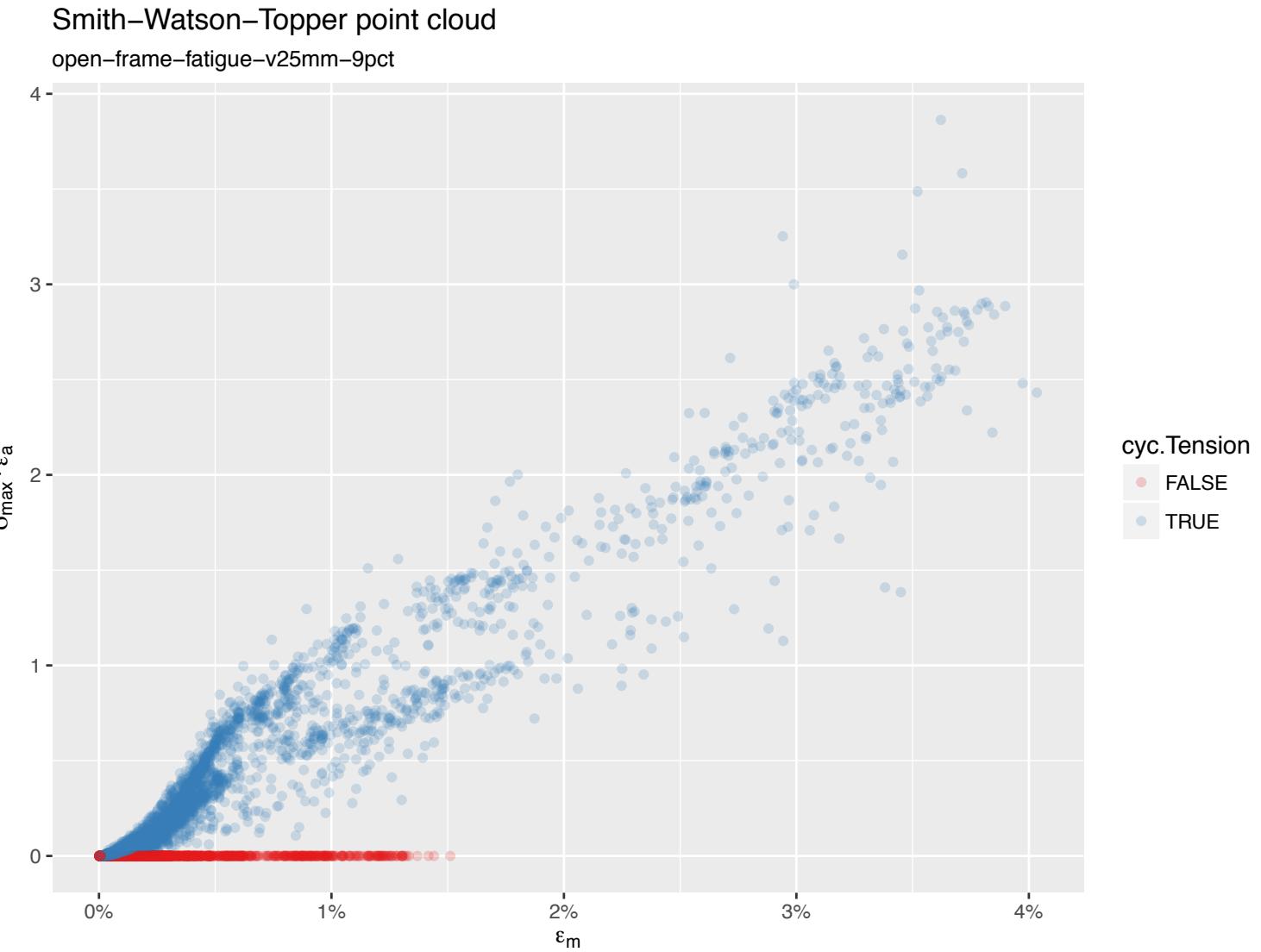
Transform to absolute value, set EA to zero for points in compression
open-frame-fatigue-v25mm-9pct



SWT point cloud

Smith-Watson-Topper

(maximum stress) · (strain amplitude)



Phase map

During the fatigue cycle, elements may:

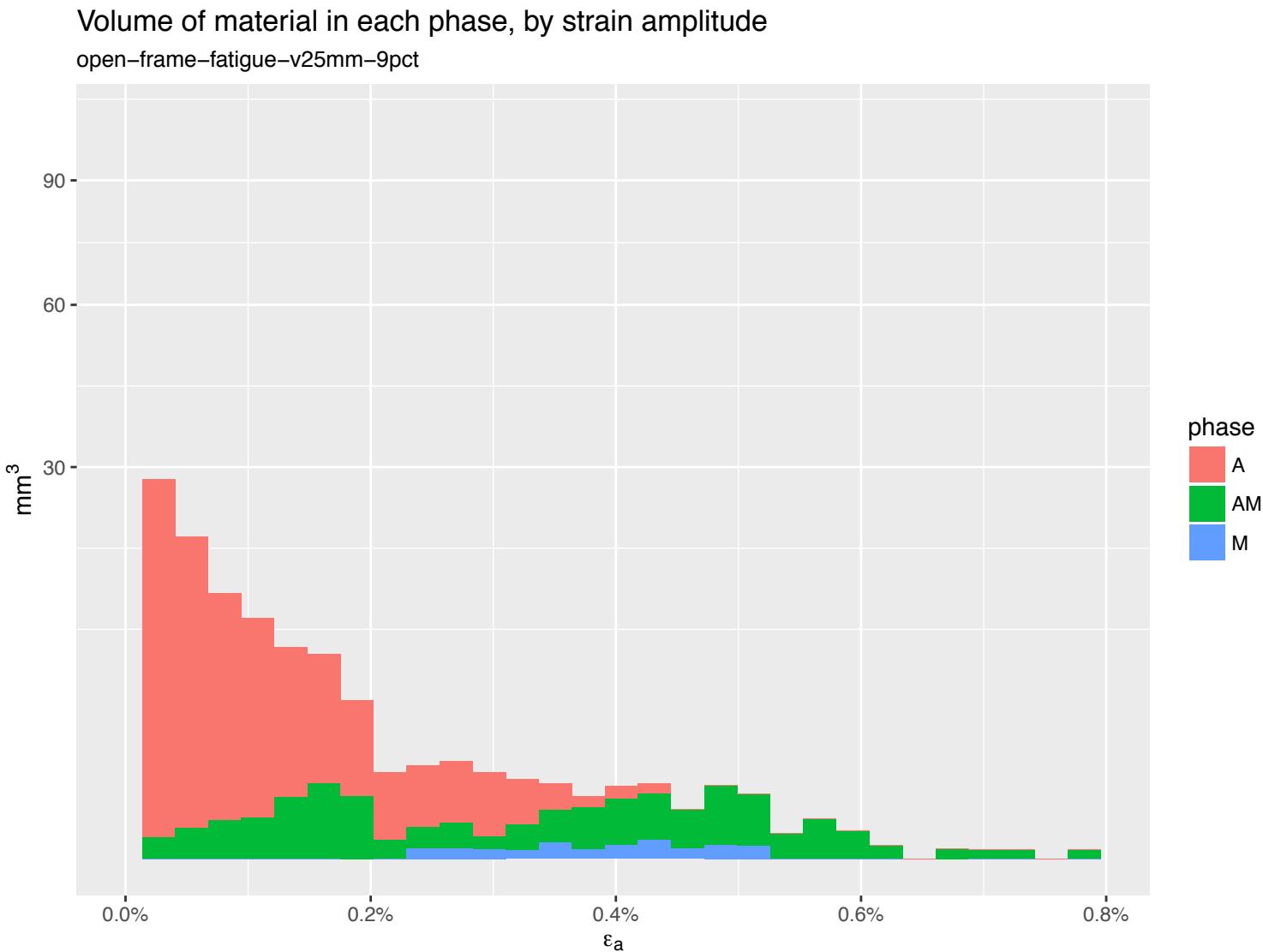
- Remain austenite throughout
- Remain martensite throughout
- Alternate A/M during cycle

Point cloud highlighting phase of each element during cycle
open-frame-fatigue-v25mm-9pct



Volumetric histogram

Measure the total volume of material in each phase, according to strain amplitude (or SWT, or any other criterion)



Introduction

Volumetric FEA methods

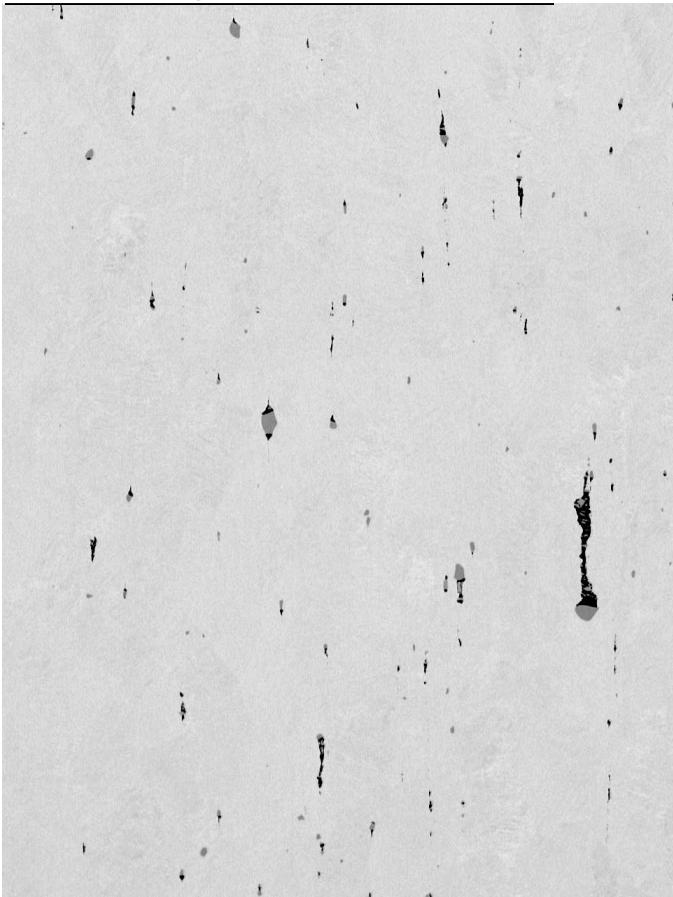
> **Sub- μm x-ray computed tomography**

Monte-Carlo risk assessment

Resources

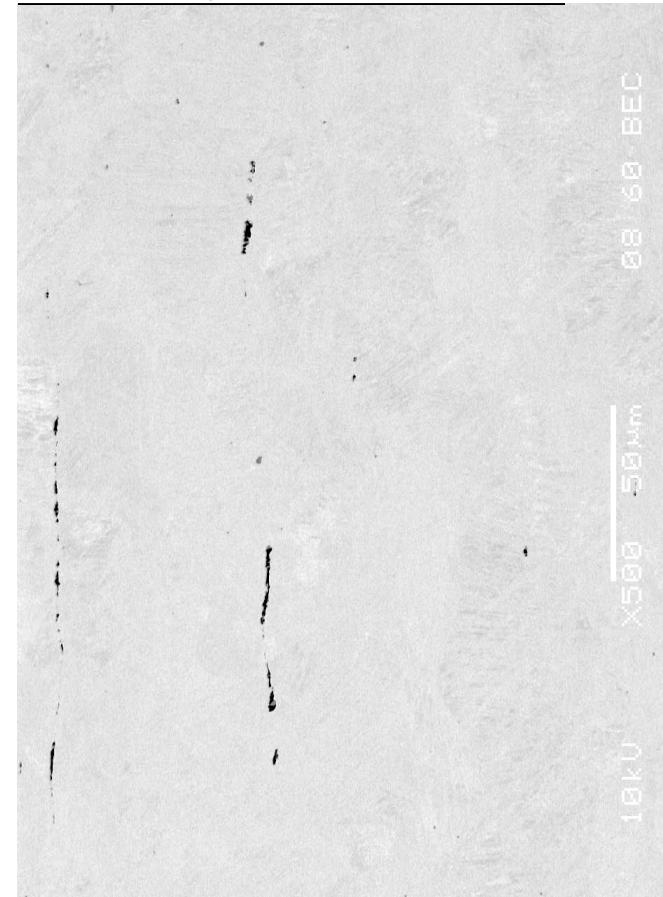
Standard VAR (SE508)

264.46x198.35 µm (1280x960); 8-bit; 1.2MB

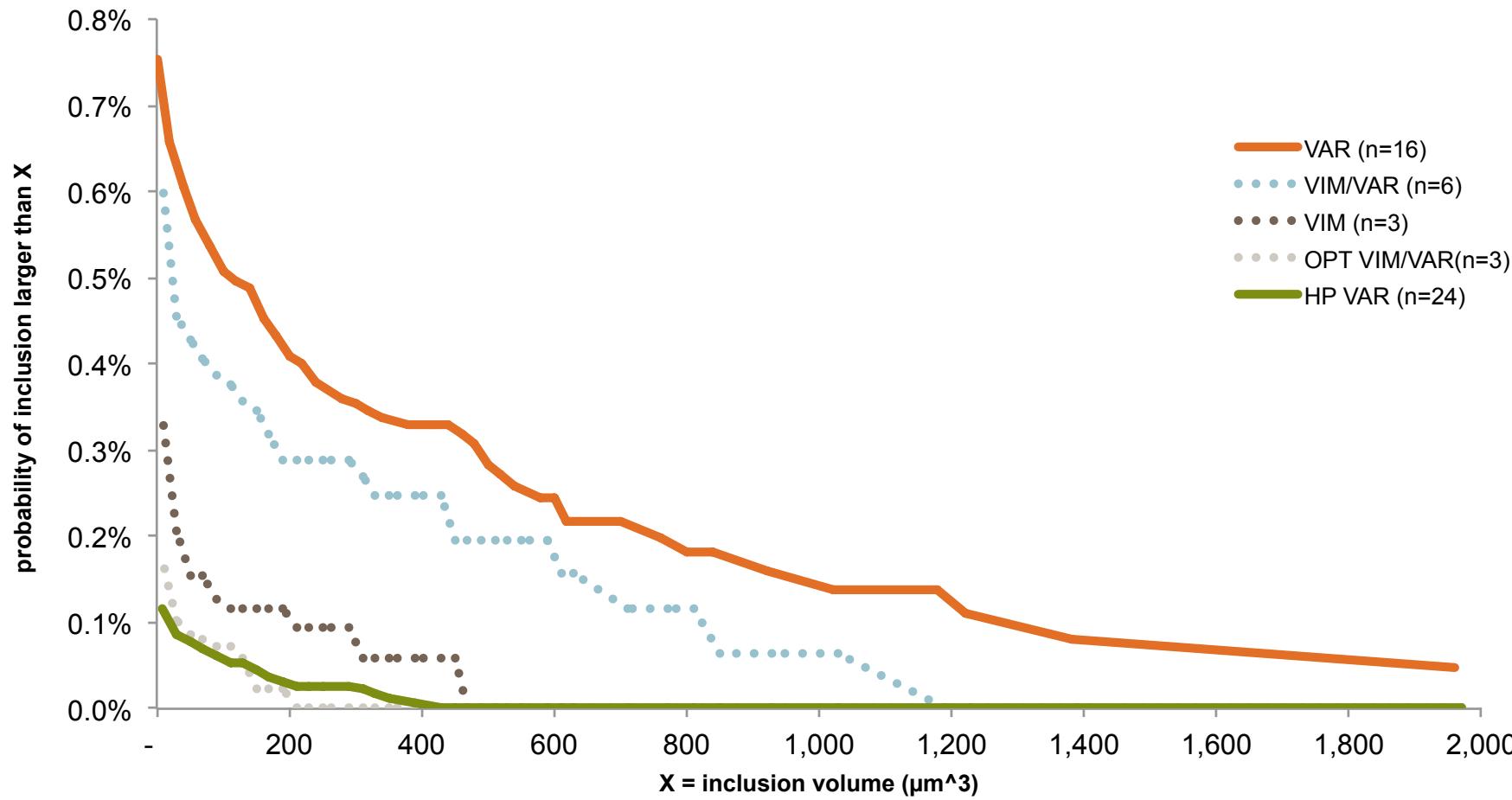


High Purity VAR (SE508-ELI)

264.46x198.35 µm (1280x960); 8-bit; 1.2MB



Approximation of inclusion volumetric probability



Durability performance benefit of high purity material

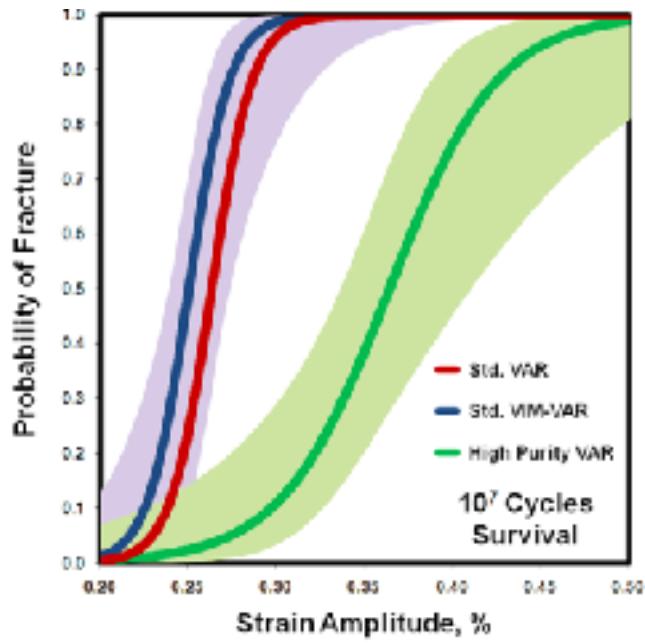


Fig. 8 – Probability of Nitinol wire fracture versus strain amplitude plots with the curve fit line shown bracketed by the 95th percentile upper and lower confidence interval bands.

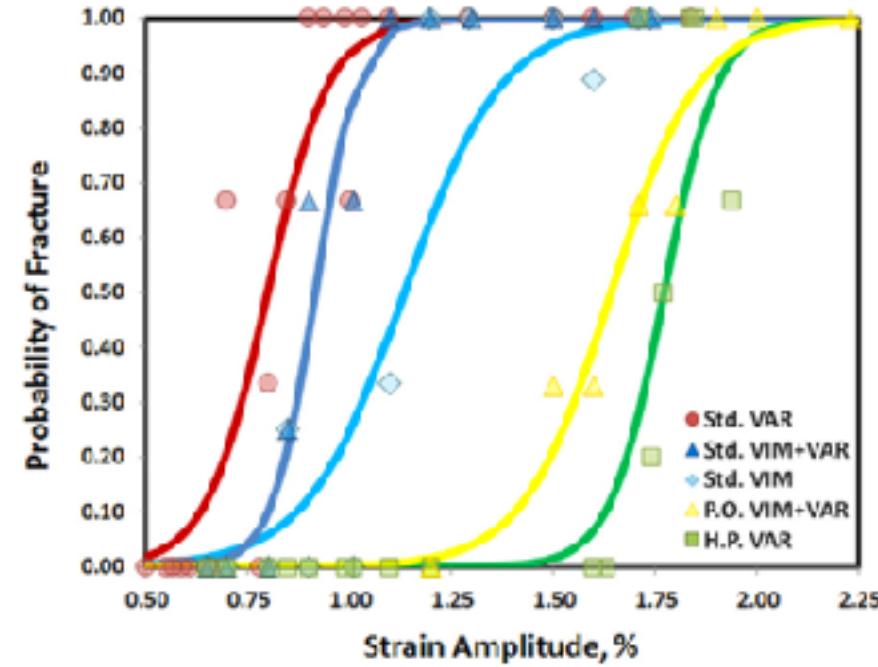


Fig. 9 – Probability of Nitinol diamond fracture at 10⁷ cycles versus strain amplitude plots with a logit sigmoidal curve fit line for each data set.

X-ray computed tomography (XCT) test specimens

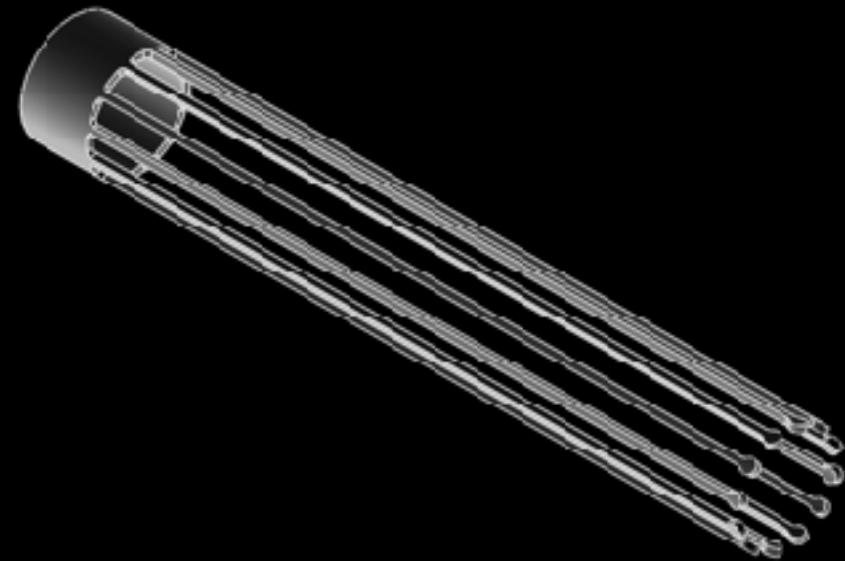
8.00x7.01 superelastic nitinol tubing

0.5mm x 0.5mm x 50mm laser cut “matchstick” samples

scan01: SE508

scan02: SE508ELI

scan03: SE508ELI



XCT scan output: 1,994 16-bit images ($0.50\mu\text{m}^3$ voxel)

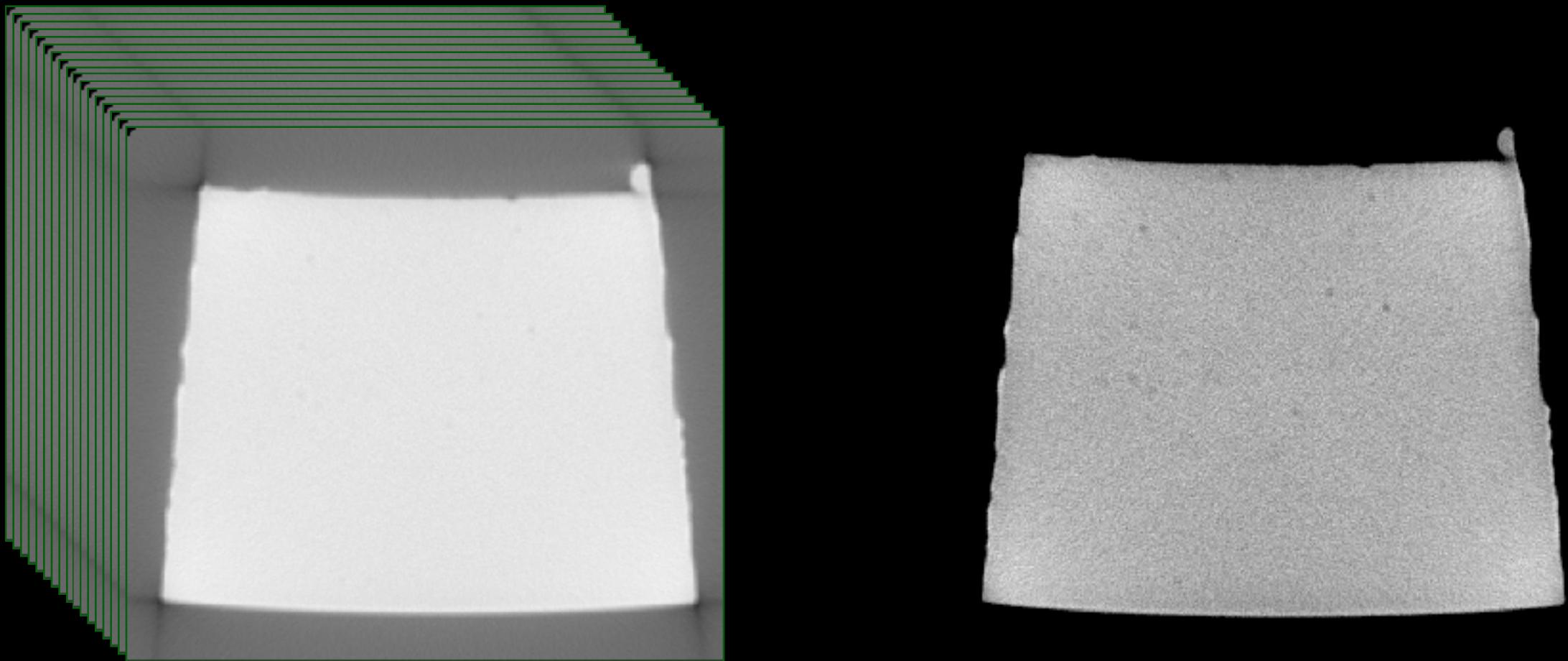
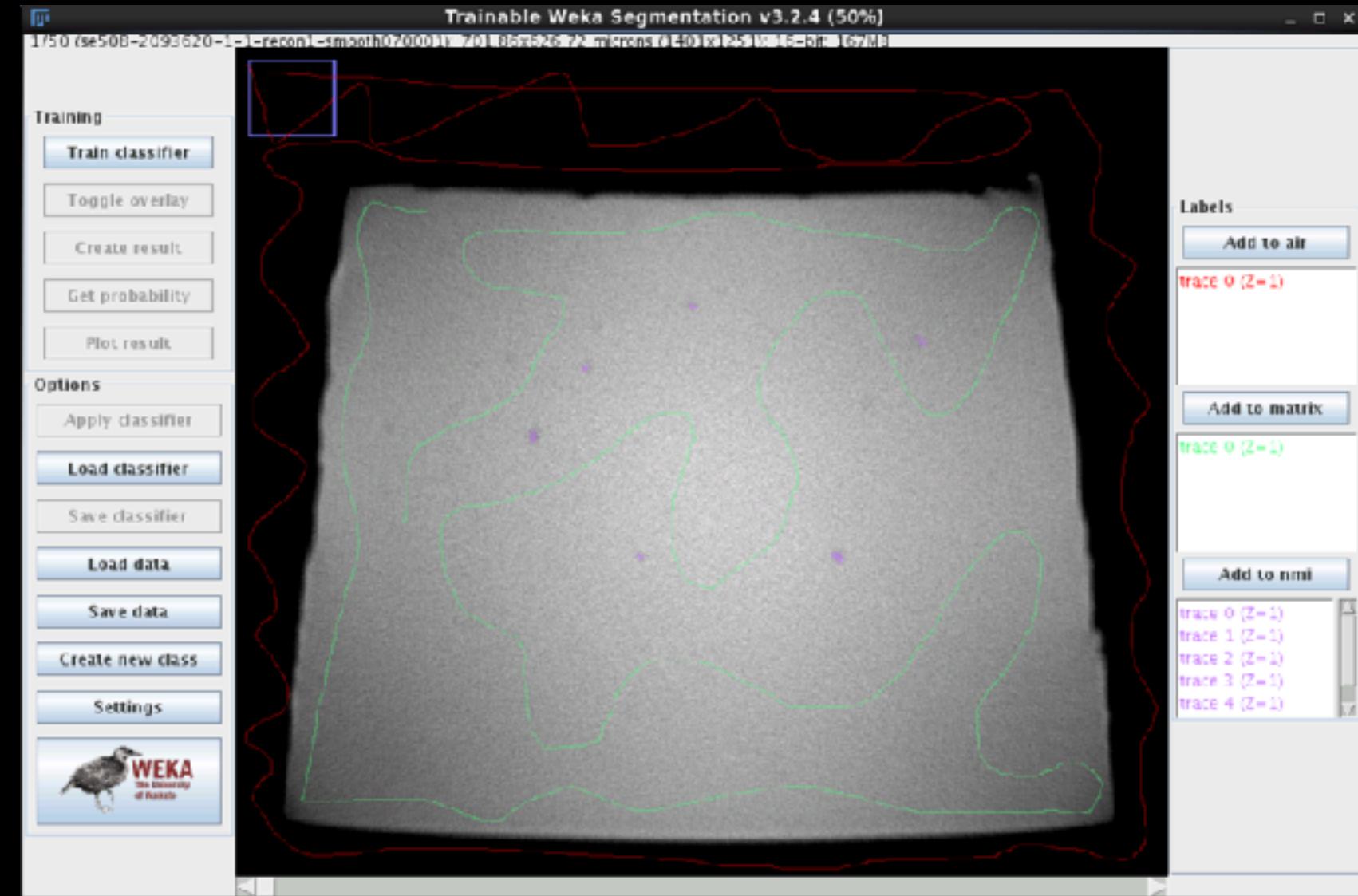


Image segmentation by machine learning

Fiji [1] is just ImageJ [2]

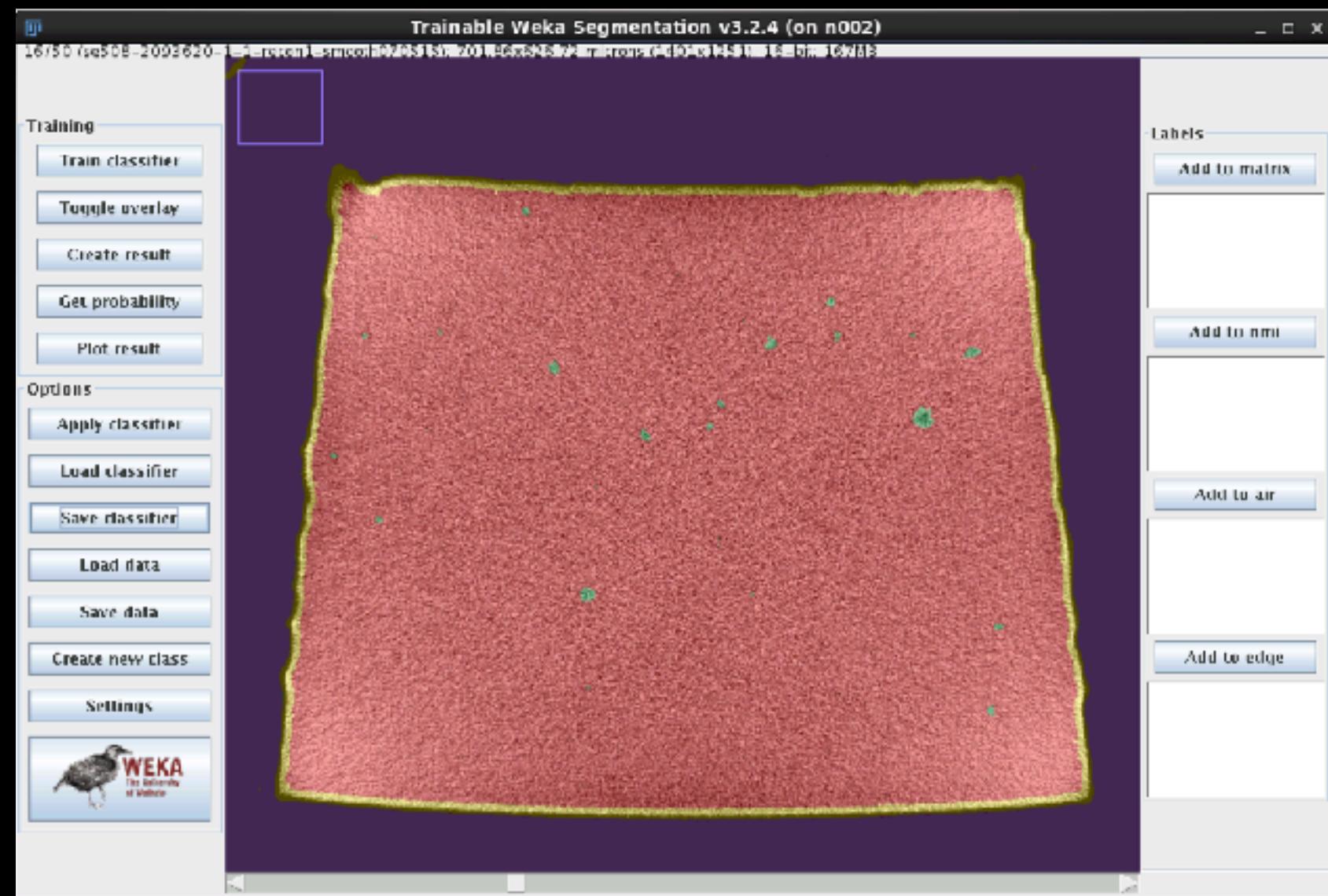
Trainable Weka
Segmentation [3]



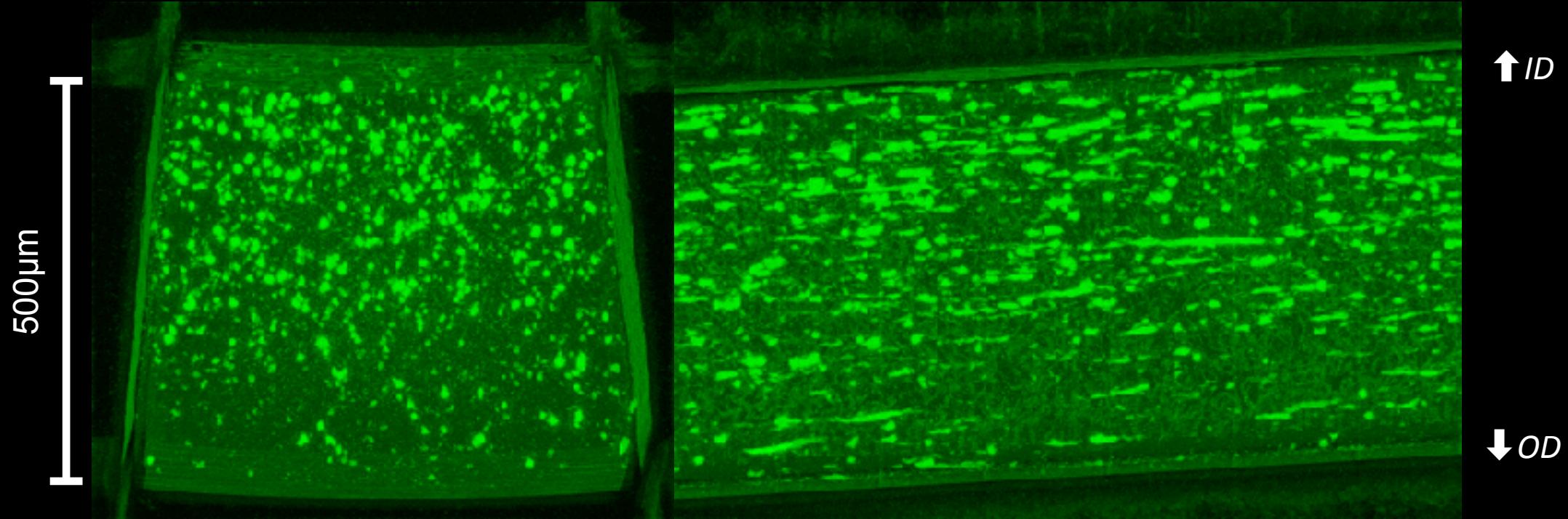
Voxel Classification

Train classifier to identify probability of each voxel as:

- matrix
- nmi (inclusion/void)
- air
- edge

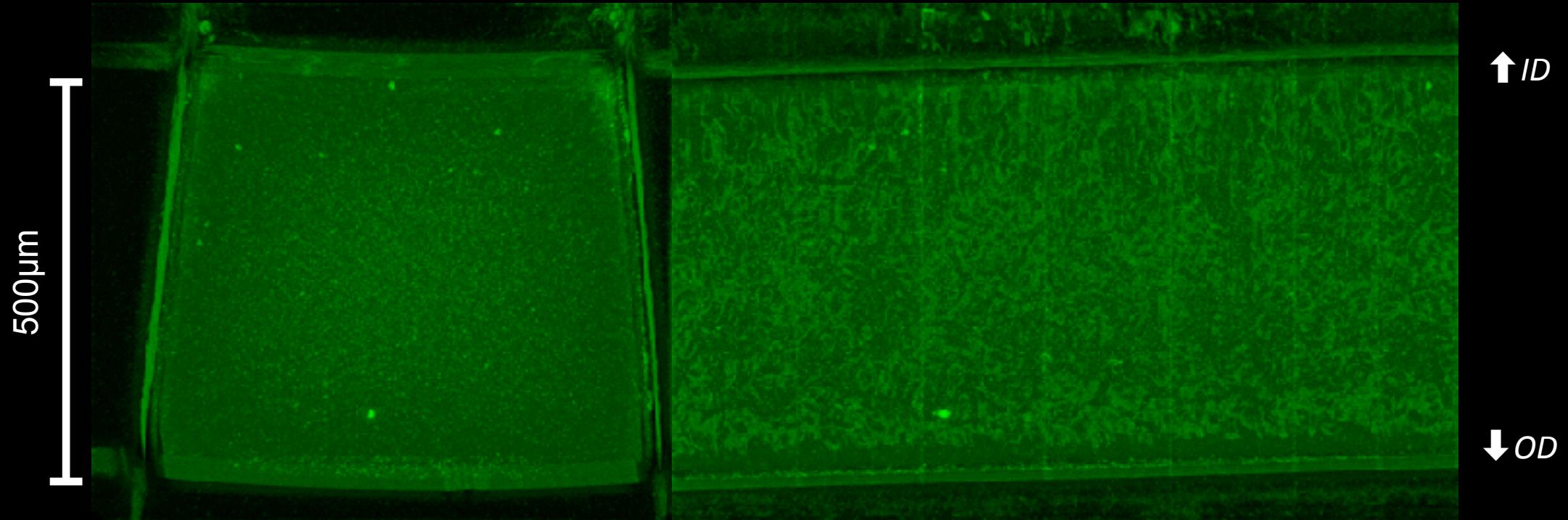


SE508 maximum intensity projection of inclusion probability



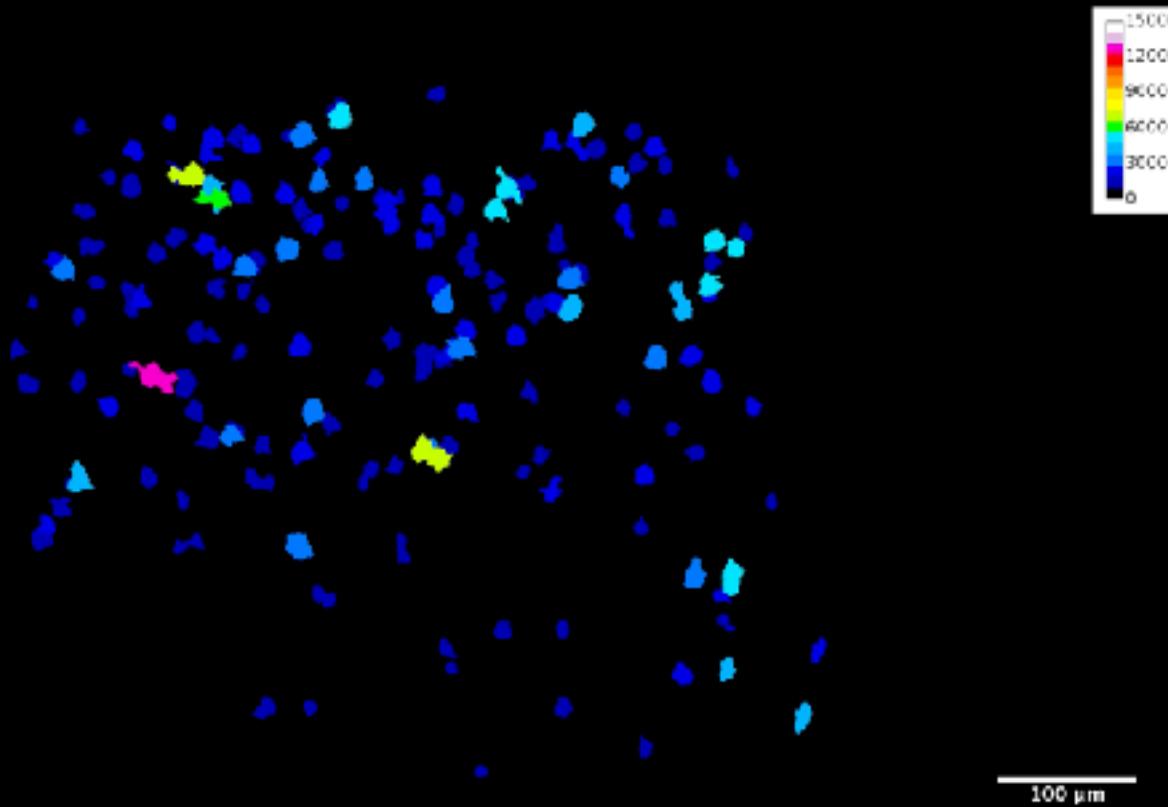
visualization superimposes all inclusions through 500 μm thickness

SE508-ELI maximum intensity projection of inclusion probability



visualization superimposes all inclusions through 500 μm thickness

SE508 inclusion segmentation colored by volume



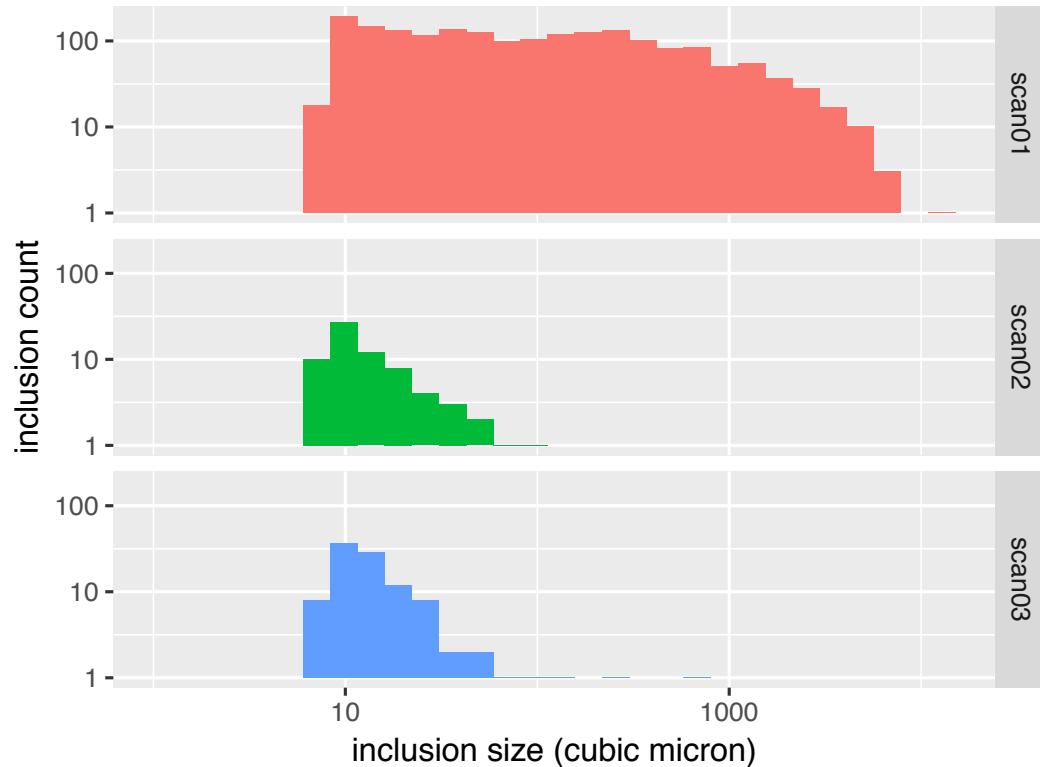
[1] D. Legland, I. Arganda-Carreras, P. Andrey, MorphoLibJ: integrated library and plugins for mathematical morphology with ImageJ, Bioinformatics. (2016) btw413. doi:10.1093/bioinformatics/btw413.

SE508-ELI inclusion segmentation colored by volume

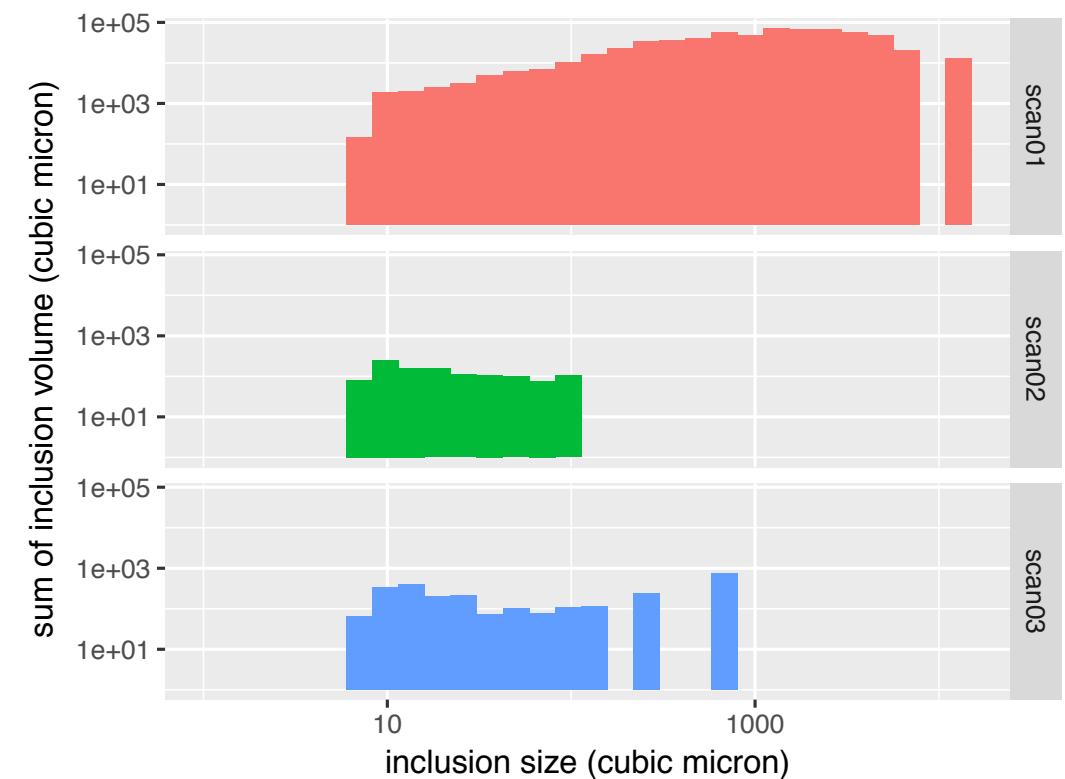


Volumetric distribution of inclusions

inclusion count by size

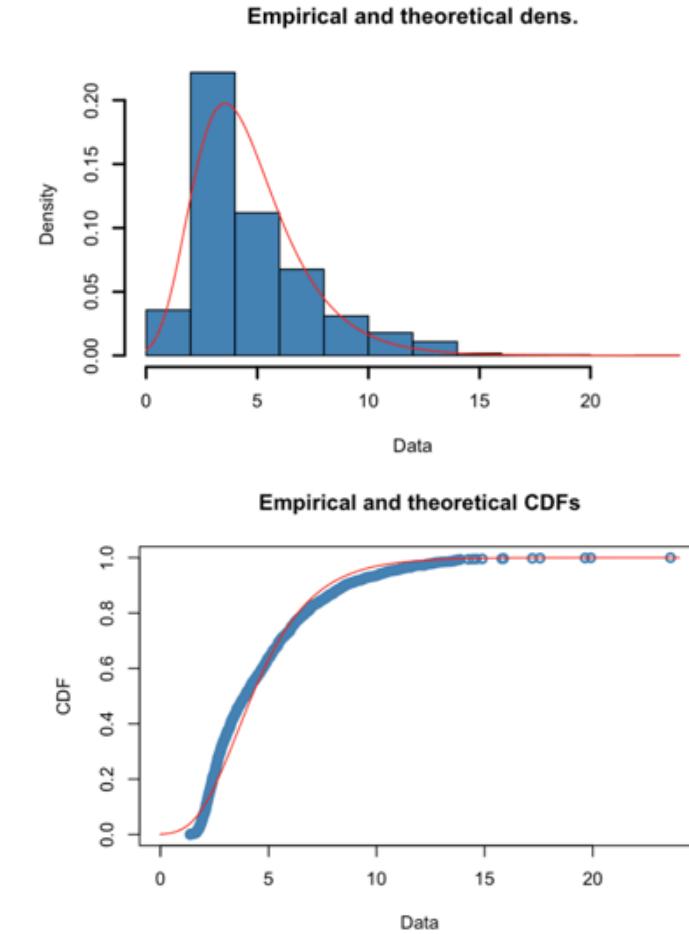
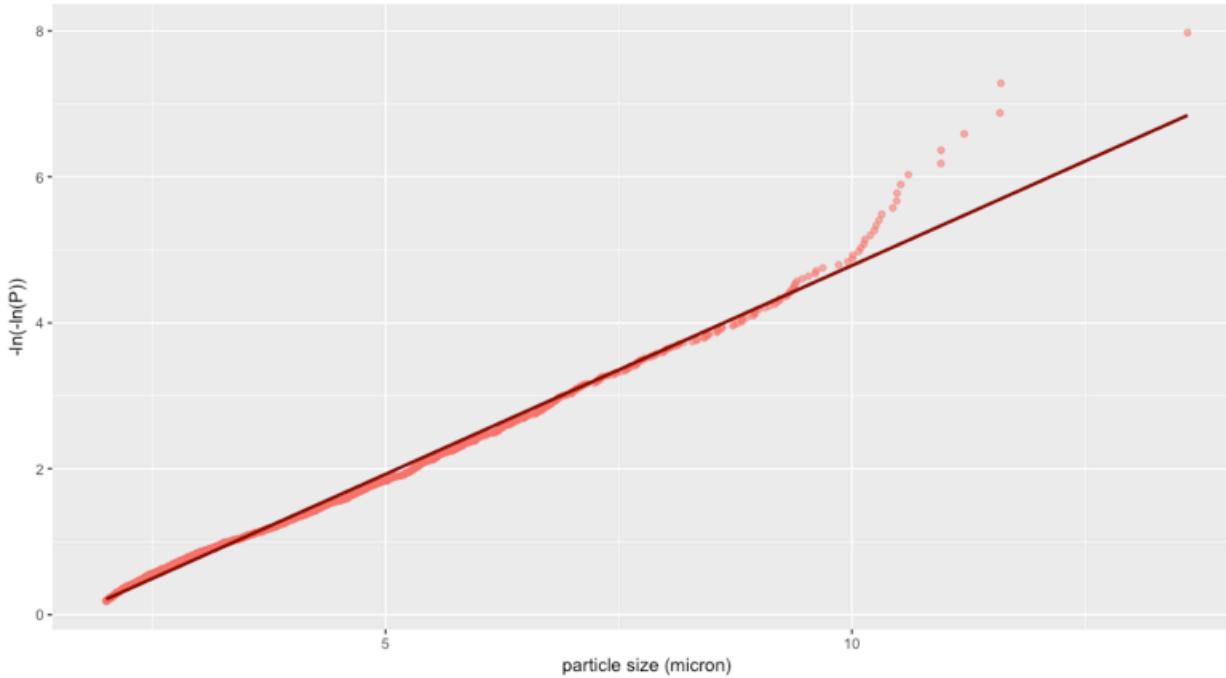


inclusion volume by size



* note log-log scales

$\sqrt{\text{Area}}$ fit to Extreme Value Distribution per Urbano¹



Inclusion density, Gumbel location and scaling parameters

SE508 Inclusion Distribution Parameters

plane	cutoff (μm^3)	inclusion density (1/ mm^3)	Gumbel μ (μm)	Gumbel σ (μm)
xy (transverse)	8	7,475	2.84	1.36
yz (longitudinal)	8	7,475	3.59	1.96
xz (longitudinal)	8	7,475	3.55	1.86



ELI Inclusion Distribution Parameters

plane	cutoff (μm^3)	inclusion density (1/ mm^3)	Gumbel μ (μm)	Gumbel σ (μm)
xy (transverse)	8	340	1.77	0.40
yz (longitudinal)	8	340	2.06	0.40
xz (longitudinal)	8	340	2.27	0.45



Introduction

Volumetric FEA methods

Sub- μm x-ray computed tomography

> **Monte-Carlo risk assessment**

Resources

Quantile function: *calculate random defects with sizes following the Gumbel distribution for each material*

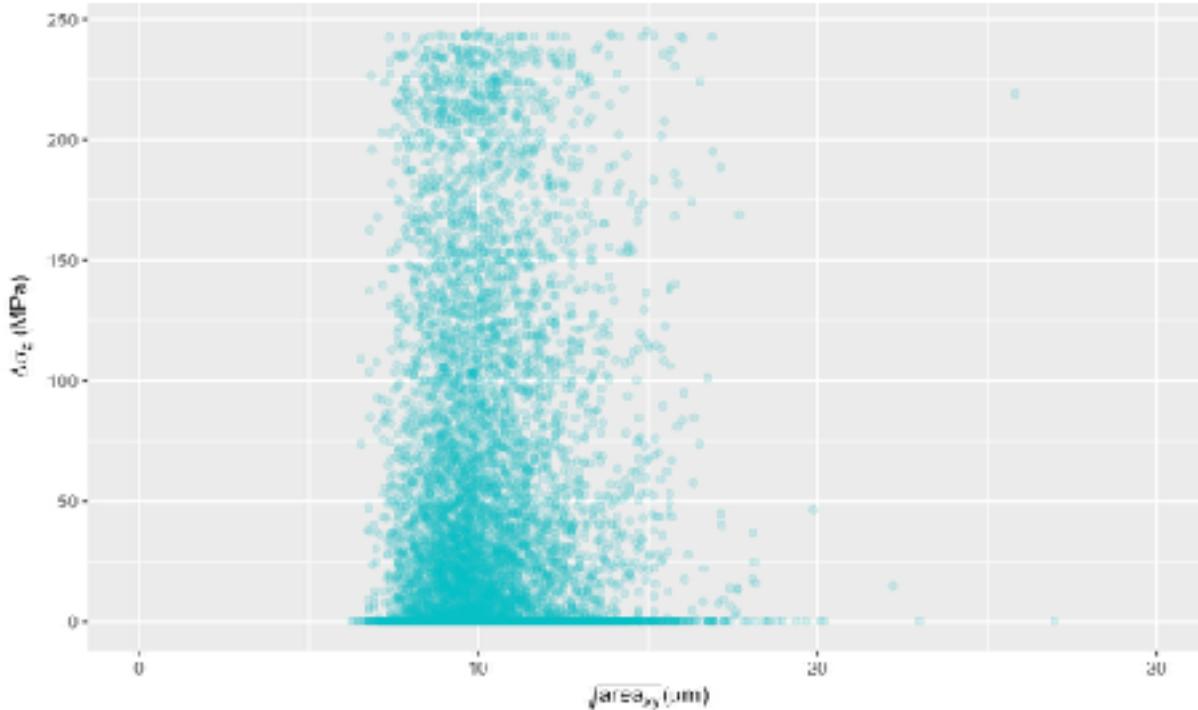
$$Q(p) = \mu - \sigma \ln[-\ln(p)]$$

$Q(U)$ has a Gumbel distribution
for random values of U drawn from
a uniform distribution on the interval $(0,1)$

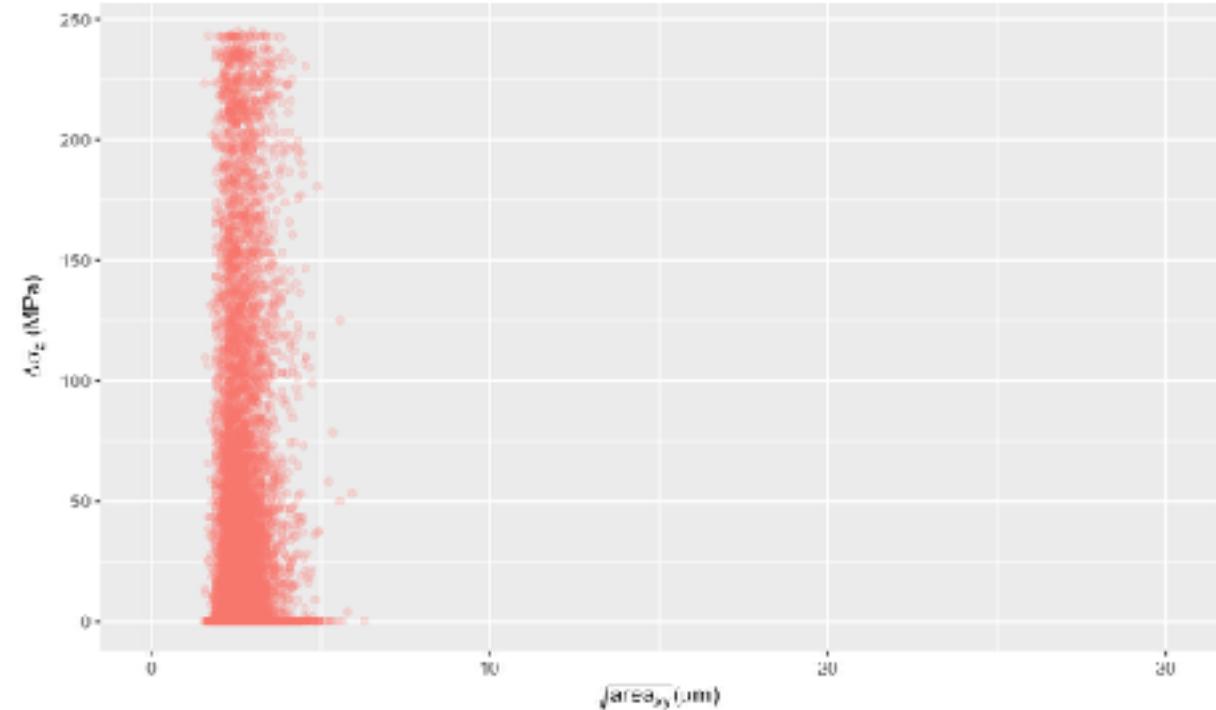


“Fortune cloud”: $\Delta\sigma$ vs. $\sqrt{\text{area}}$ (single run SE508, ELI)

fortune cloud: cyclic stress vs. defect (inclusion) size
single monte-carlo run, se508



fortune cloud: cyclic stress vs. defect (inclusion) size
single monte-carlo run, eli



Estimating stress intensity factor K by Murakami's $\sqrt{\text{area}}$

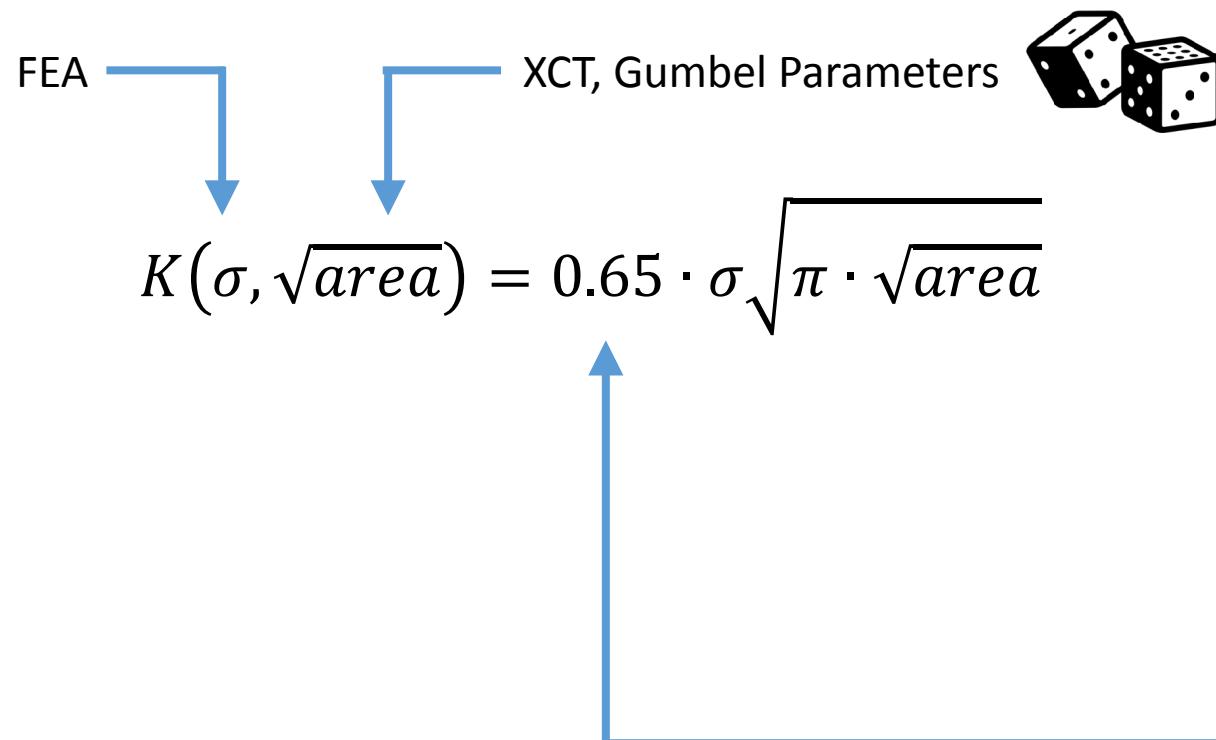
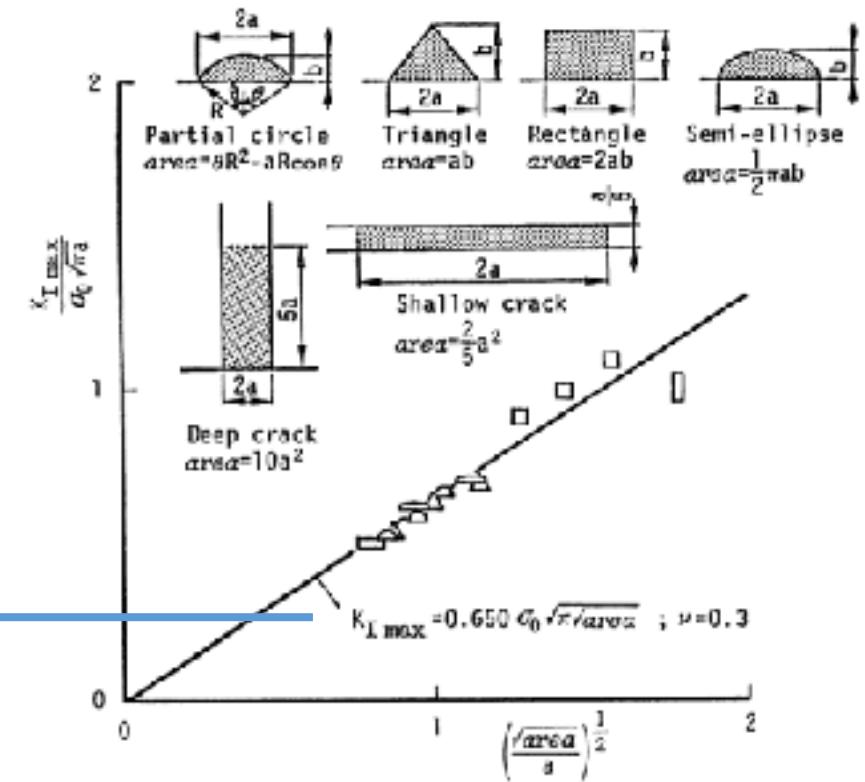


Figure 7 shows the relationship between the maximum stress intensity factor $K_{I\max}$ and $\sqrt{\text{area}}$ for surface cracks (elastic analysis) (24)(25). (See also (20)(66).)



Murakami Y, Endo M (1986) Effect of hardness and crack geometries on ΔK_{th} of small cracks emanating from small defects, In: The Behavior of Short Fatigue Cracks, EGF Pub. 1, pp 275–293

K and ΔK in each plane, at each integration point

$$K_x = 0.65 \cdot \sqrt{\sigma_x \cdot \sqrt{area_{yz}}}$$

$$K_y = 0.65 \cdot \sqrt{\sigma_y \cdot \sqrt{area_{xz}}}$$

$$K_z = 0.65 \cdot \sqrt{\sigma_z \cdot \sqrt{area_{xy}}}$$

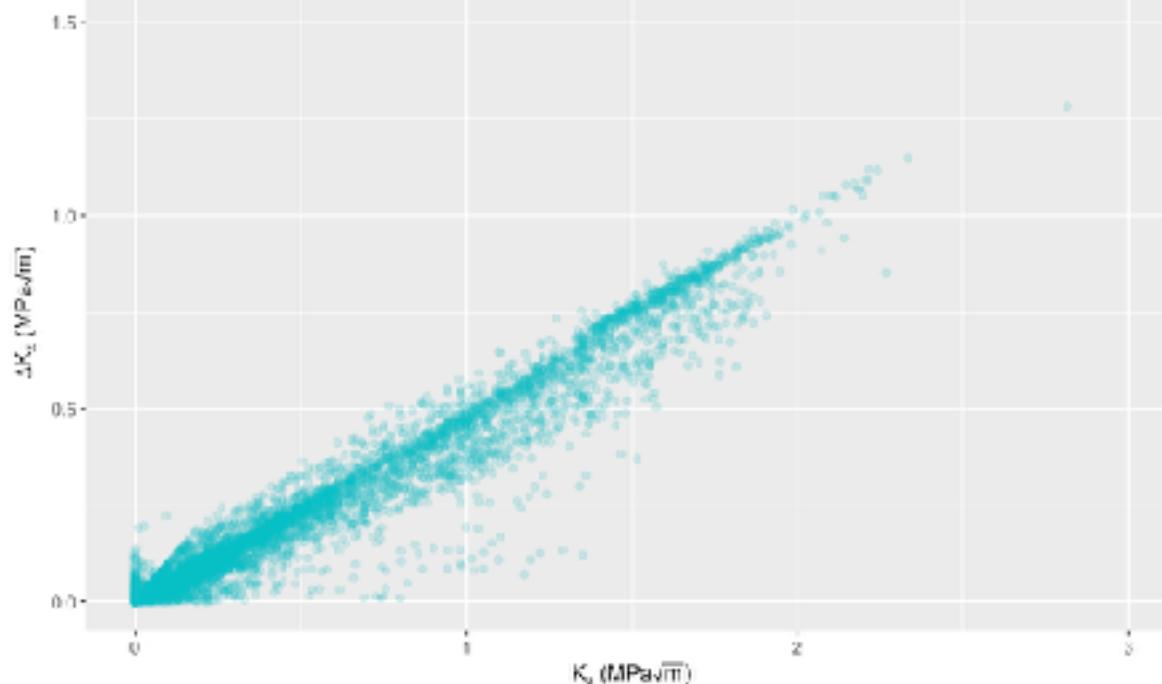
$$\Delta K_x = 0.65 \cdot \sqrt{\Delta\sigma_x \cdot \sqrt{area_{yz}}}$$

$$\Delta K_y = 0.65 \cdot \sqrt{\Delta\sigma_y \cdot \sqrt{area_{xz}}}$$

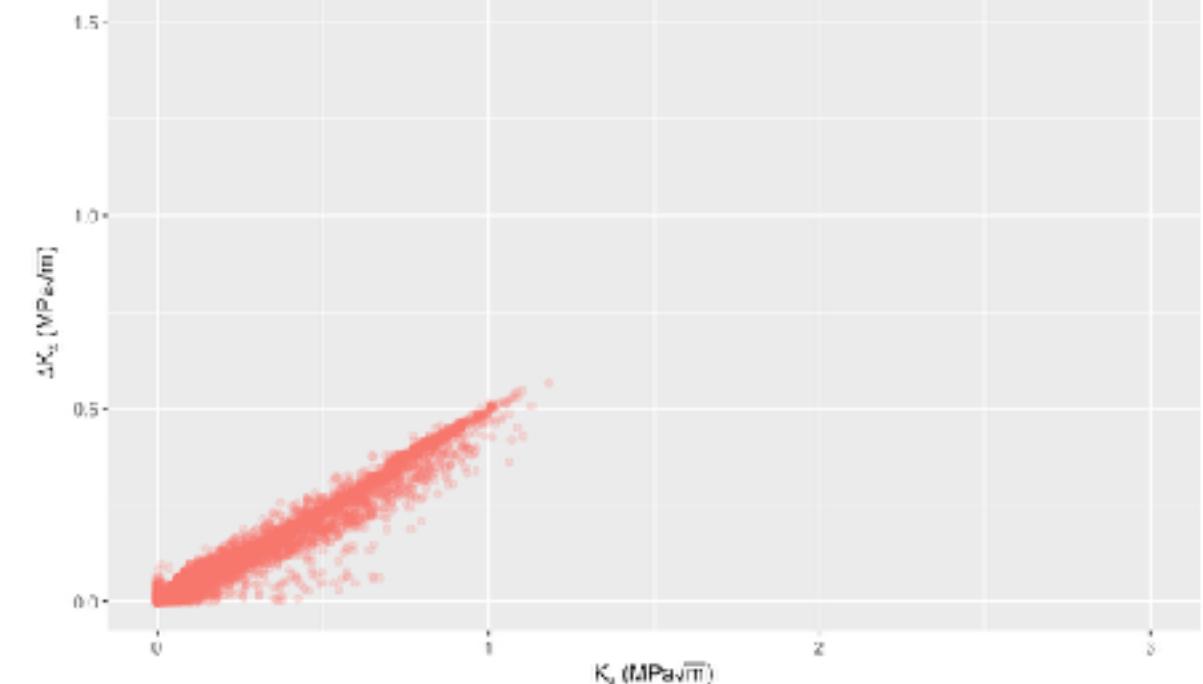
$$\Delta K_z = 0.65 \cdot \sqrt{\Delta\sigma_z \cdot \sqrt{area_{xy}}}$$

“K point cloud” (single run SE508, ELI)

stress intensity factor point cloud
single monte-carlo run, se508

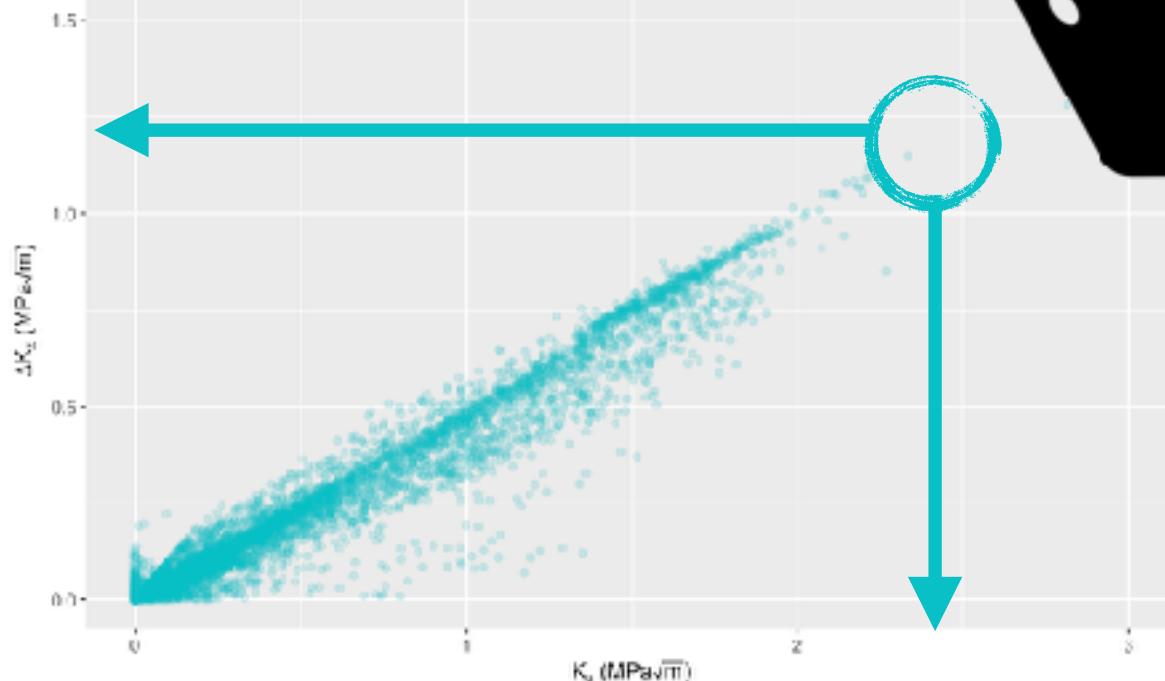


stress intensity factor point cloud
single monte-carlo run, ell

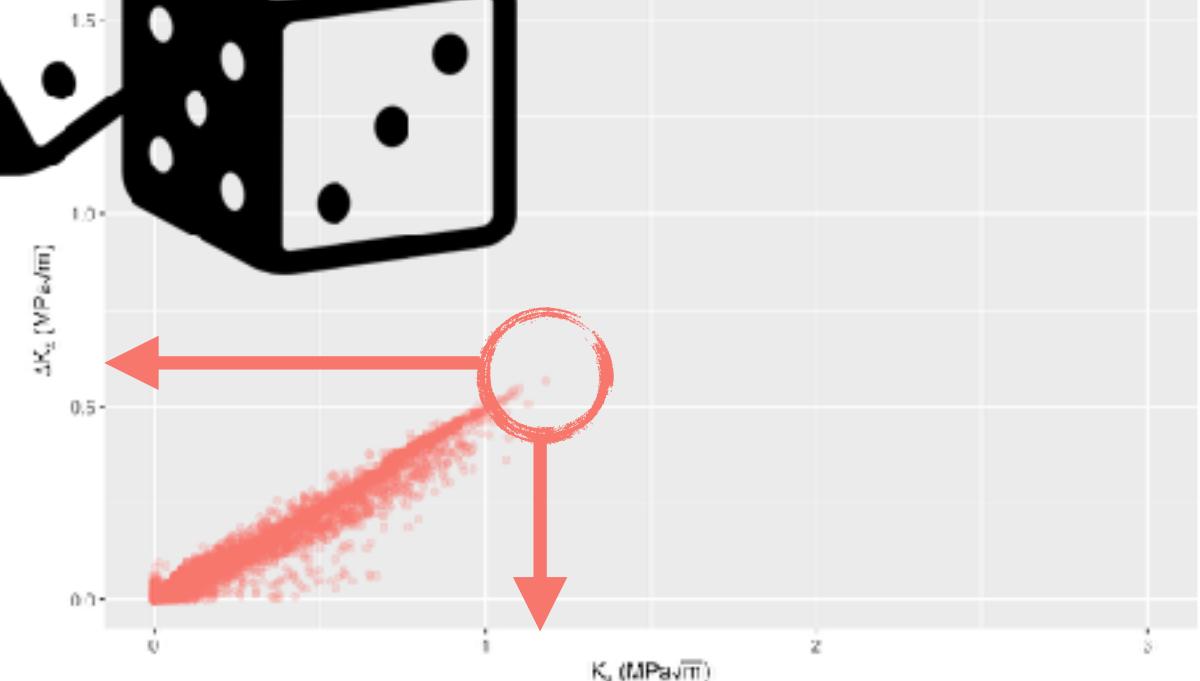


Next: repeat many times, record ΔK_{\max} and K

stress intensity factor point cloud
single monte-carlo run, 2e508



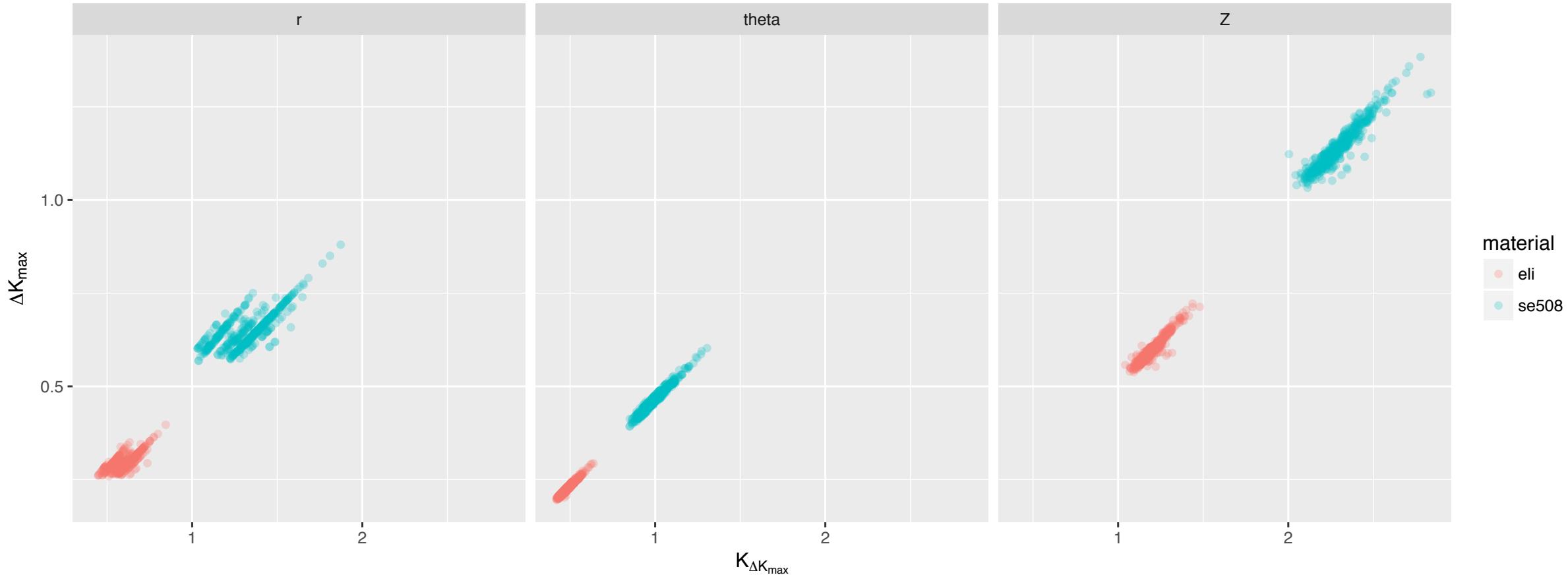
stress intensity factor point cloud
single monte-carlo run, 2e508



Maximum stress intensity factors for 500+500 runs

stress intensity factor: maximum ΔK and corresponding K

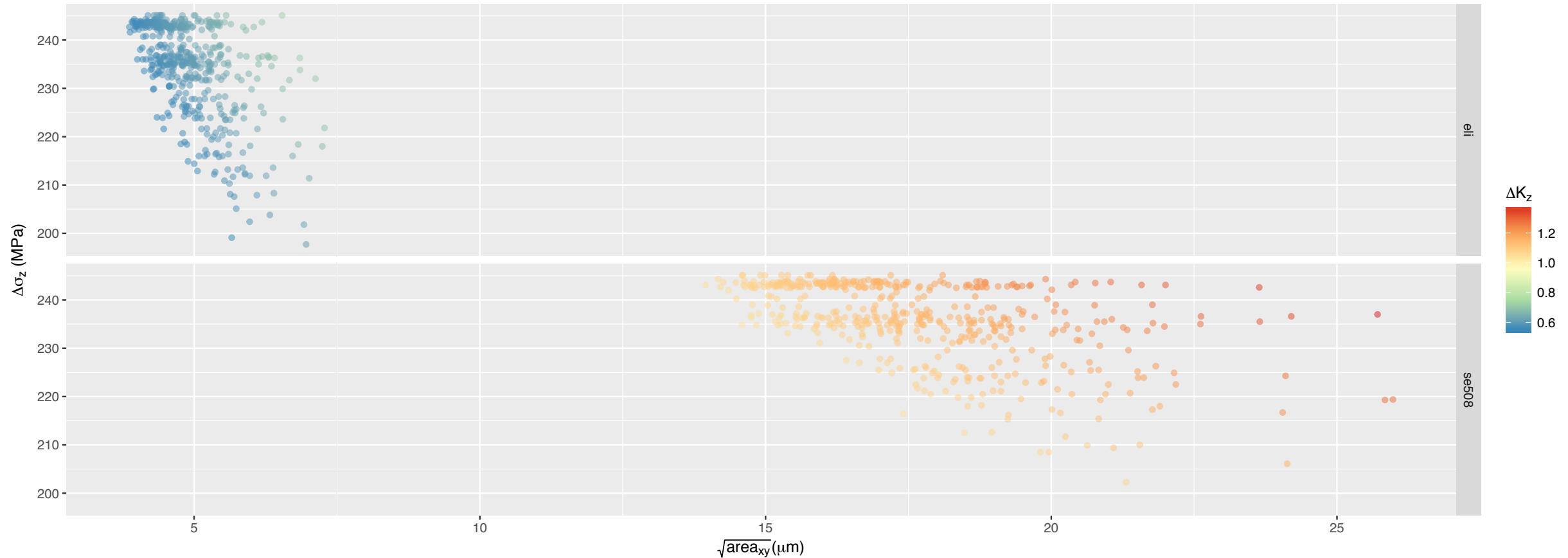
for 500 monte carlo runs with each material



“Fortune plot” for 500+500 runs

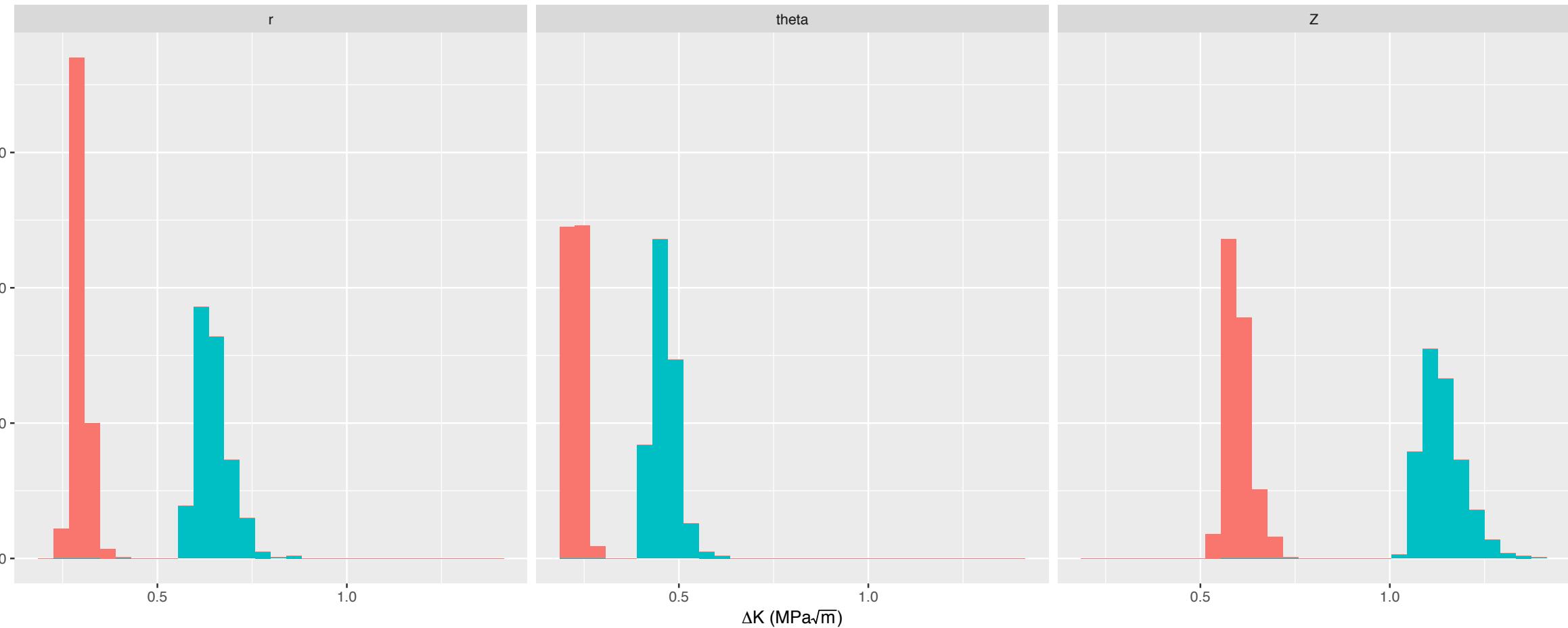
max. ΔK_z by cyclic stress and defect (inclusion) size

unluckiest combination at upper right: largest defect at highest cyclic stress



ΔK_{\max} for 500+500 runs

maximum delta stress intensity factor
for 500 monte carlo runs with each material



Limitations

- XCT results are currently limited to a single tubing configuration, and three sample volumes
- Resolution limit for XCT unconfirmed; comparison with conventional 2D analysis TBD
- K , ΔK are based on linear elastic fracture mechanics
- Muramaki 0.65 factor does not account for defect depth from surface
- No experimental confirmation completed (yet)
- Material properties for example FEA are unverified
- Code is all new and probably full of mistakes!
- Critical review and feedback will be greatly appreciated!

Introduction

Volumetric FEA methods

Sub- μm x-ray computed tomography

Monte-Carlo risk assessment

> Resources

More resources online: Nitinol Design Concepts

The screenshot shows the GitHub page for the 'confluentmedical/nitinol-design-concepts' repository. The page title is 'Nitinol Design Concepts'. It features a brief introduction about the project's purpose and a note that it will be moved to a virtual conference library. Below this is a detailed description of the project's goals and how it is used. A 'Design Tutorial' section is highlighted, followed by a 'Advanced Topics' section. At the bottom, there's information about maintenance, copyright, and links to other pages. Navigation links at the bottom include 'ZIP File', 'TAR Ball', and 'GitHub'.

Nitinol Design Concepts

Welcome! **SMST 2017 attendees!** Confluent Medical presentations will be posted to our virtual conference library at nitinol.com before the end of the conference.

This project includes tutorials and examples related to design and simulation of superelastic nitinol components. This work is provided by [Confluent Medical Technologies](#) as a resource for our customers, industry and community. If you want to know more about the background, or how you can contribute, read [about this project](#).

The material here includes a deeper dive into topics covered in our Nitinol University courses, as well as research supporting scientific presentations and publications. The [Design Tutorial](#) series provides an introduction to design and simulation of a nitinol component, following methods that are commonly applied in the medical device industry. The [Advanced Topics](#) series ventures into some more speculative territory, including new and emerging approaches that we find interesting.

Design Tutorial

This first series follows each step in the design and analysis of a realistic (but non-proprietary) user cut nitinol component, from designing the geometry using Solidworks to shape testing and fatigue cycling using Abaqus.

- [Design](#) | Create a 3D model of a laser cut Open Frame component using Solidworks.
- [Mechanical Properties](#) | Perform tensile testing to characterize mechanical properties for simulation.
- [Shape Setting](#) | Expand the laser cut component into a complex expanded shape using Abaqus finite element analysis.
- [Fatigue Simulation](#) | Apply fatigue loading conditions using Abaqus.

Advanced Topics

This project is maintained by [confluentmedical](#).

Copyright 2017 Confluent Medical Technologies
Creative content is licensed [CC BY-NC-SA](#), and code is licensed under [Apache 2.0](#).

Hosted on GitHub Pages - Themer by [readthedocs](#)

The screenshot shows the GitHub repository page for 'confluentmedical/nitinol-design-concepts'. The page displays basic repository statistics: 290 commits, 3 branches, 0 releases, and 2 contributors. A list of recent commits is shown, each with a commit message, author, and timestamp. The commits are dated from 14 minutes ago to 8 days ago.

confluentmedical / nitinol-design-concepts

Features Business Explore Pricing

Code Issues Pull requests Projects Releases Graphs

Nitinol design concepts and examples from Confluent Medical Technologies: <https://confluentmedical.github.io/nit...>

nitinol design-analysis computational-simulation design creative-commons

290 commits 3 branches 0 releases 2 contributors

Branch: master | New pull request | Find file | Generate download

commit	Author	Date
docs clarify axis labels	[]	Latest commit (diff 1M minutes ago)
100-open-frame-design	[] Renice index.html to README.html	8 days ago
110-material-characterization	[] Update and rename index.html to README.html	8 days ago
115-open-frame-shape-set	[] Correct link text and urls	4 days ago
120-open-frame-fatigue	[] add Apache 2.0 notice to code headers	6 days ago
120-mechanistic-analysis	[] renice links	4 days ago
125-advancing-fatigue-prediction	[] correct superscript for N ^o s	4 days ago
130-etc-methods	[] update link text	3 days ago
135-monte-carlo	[] clarify axis labels	14 minutes ago
_data	[] Create navigation.html	8 days ago
_includes	[] Create navigation.html	6 days ago
_layouts	[] adjust spacing in default layout	6 days ago
.RData	[] Initial commit for monte-carlo script and sample results	8 days ago

bit.ly/smst17ndc

Craig Bonsignore
Confluent Medical Technologies

craig.bonsignore@confluentmedical.com
@cbonsig

SMST2017

SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES CONFERENCE AND EXPOSITION