



# Volume weighted probabilistic methods for nitinol lifetime prediction

**Craig Bonsignore**

Karthikeyan Senthilnathan

Ali Shamimi

Confluent Medical Technologies | Fremont California

## > Introduction

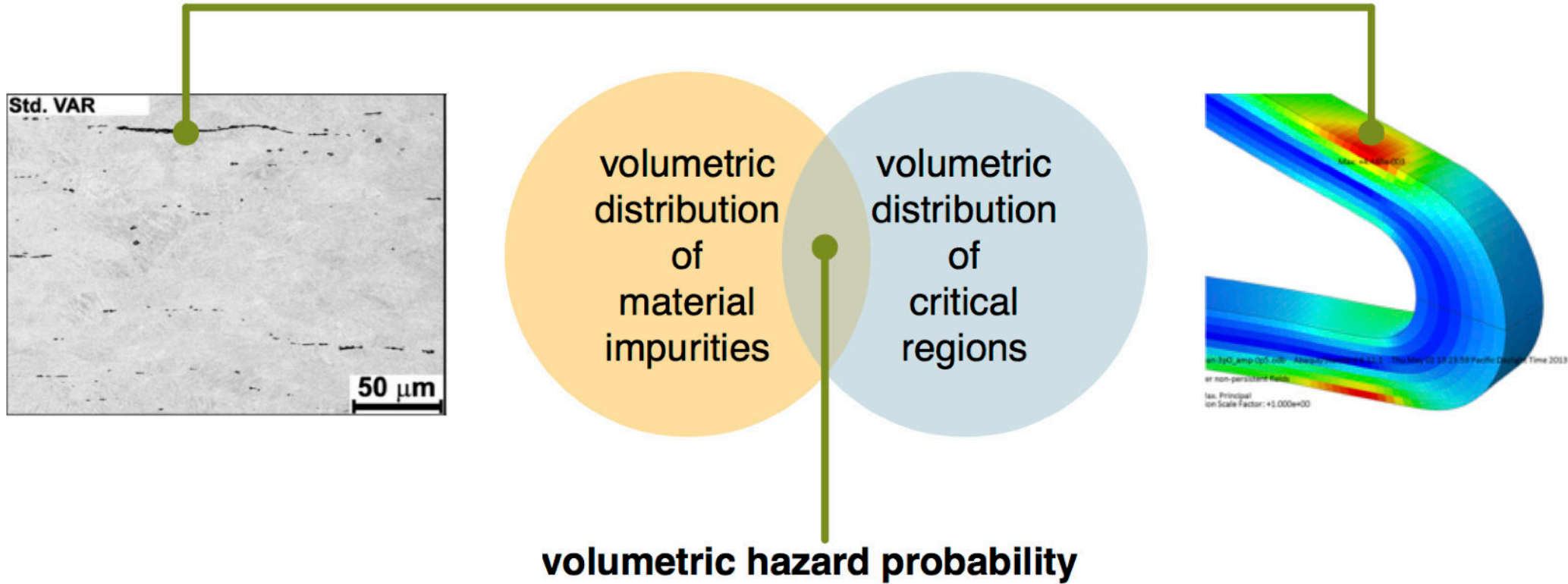
Volumetric FEA methods

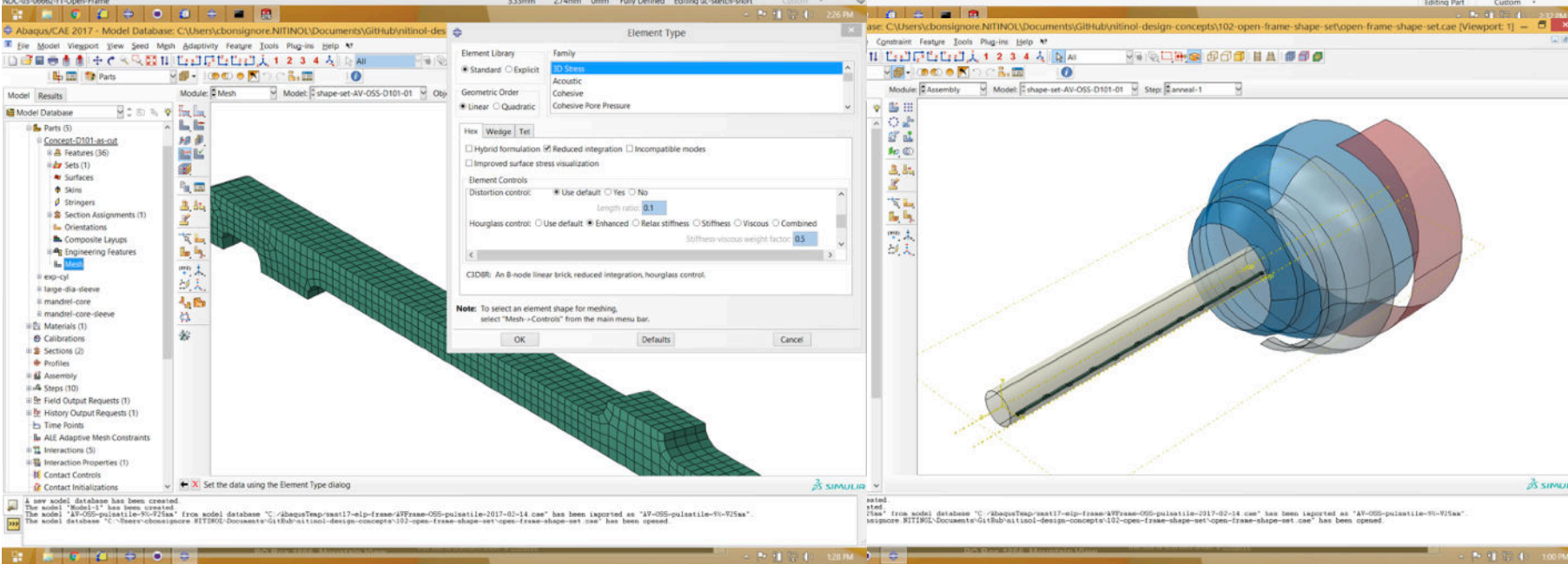
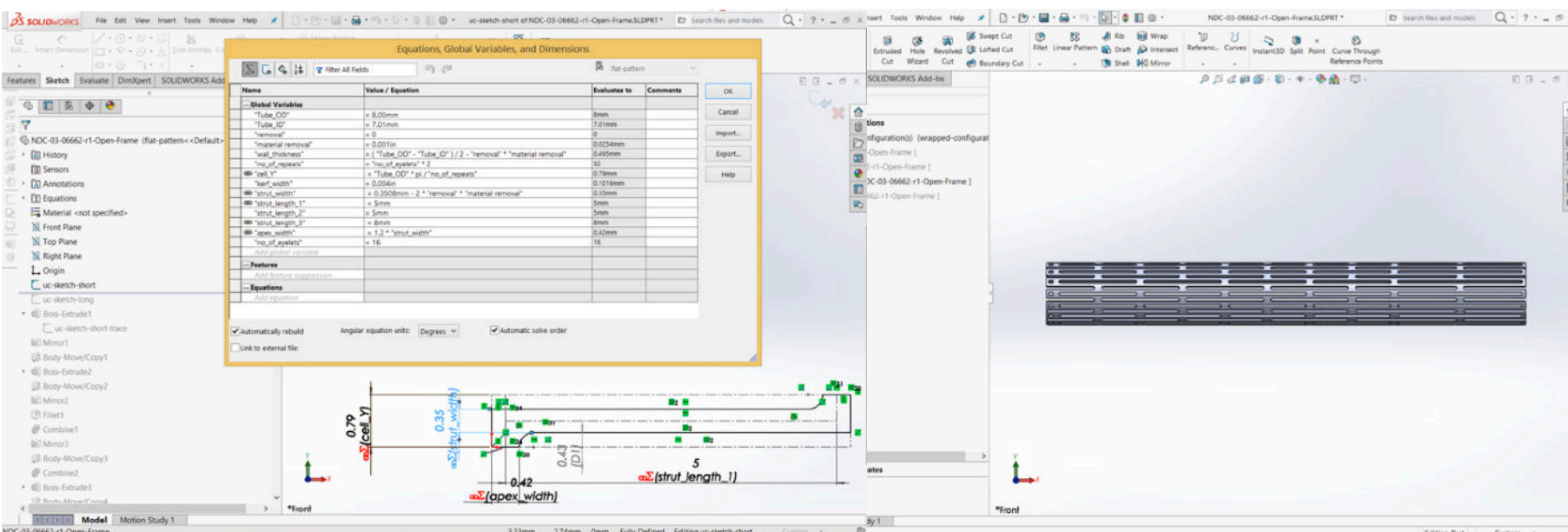
Sub- $\mu\text{m}$  x-ray computed tomography

Monte-Carlo risk assessment

Resources

# Motivation



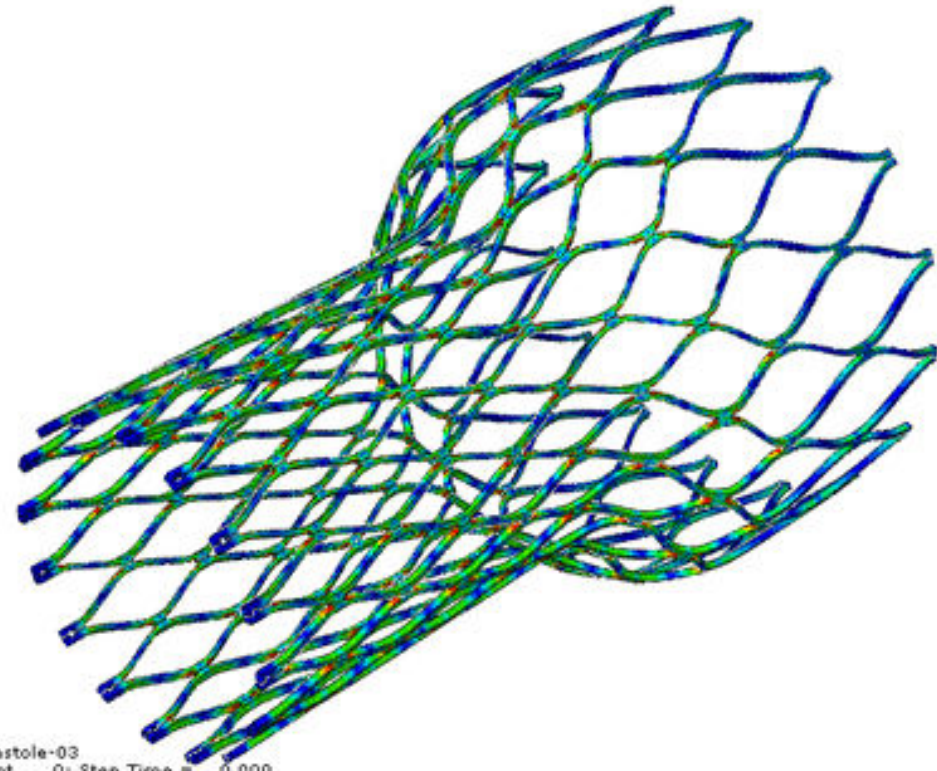
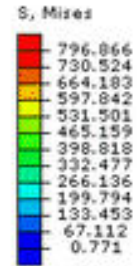


# SMST 2017

SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES CONFERENCE AND EXPOSITION

# cyclic fatigue condition

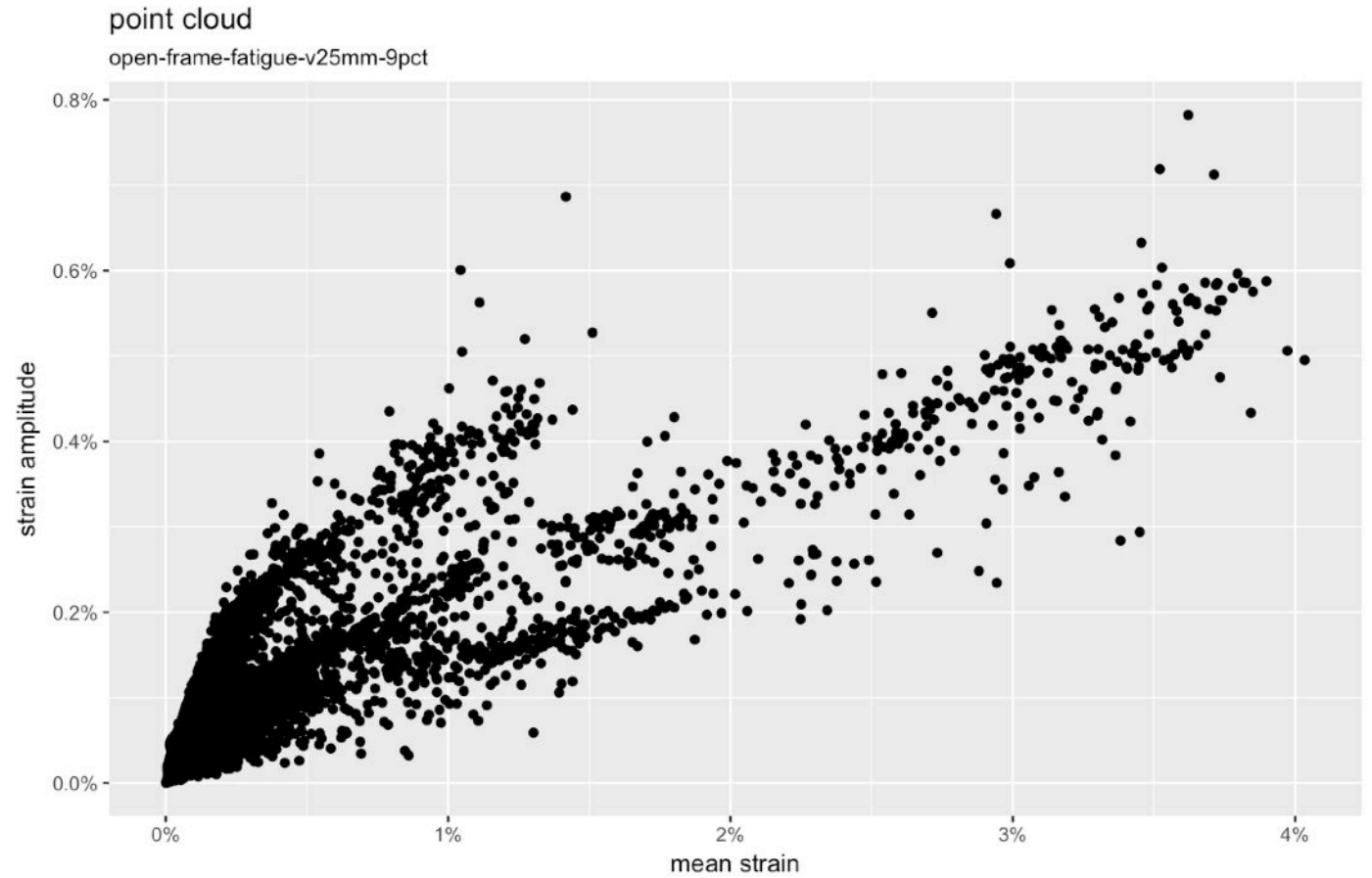
9% cyclic change in diameter



Step: diastole-03  
Increment 0: Step Time = 0.000  
Primary Var: S, Mises  
Deformed Var: U Deformation Scale Factor: +1.000e+00

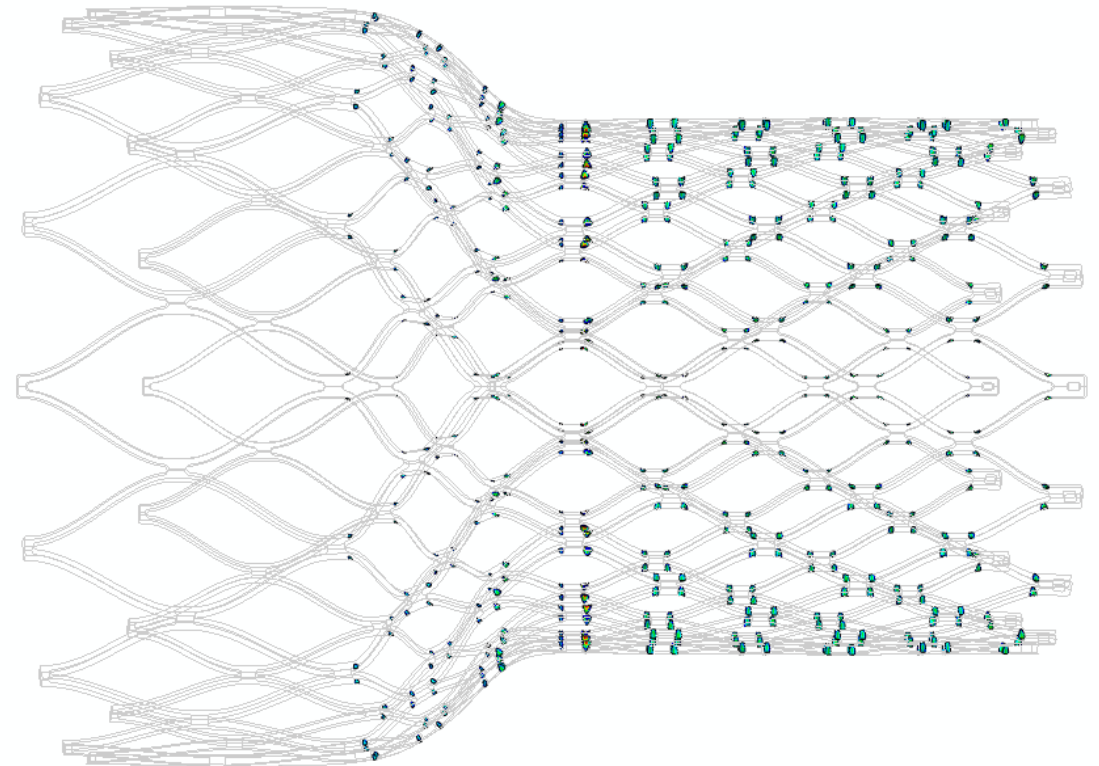
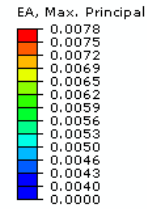
# typical point cloud

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- $\mu\text{m}$  x-ray computed tomography

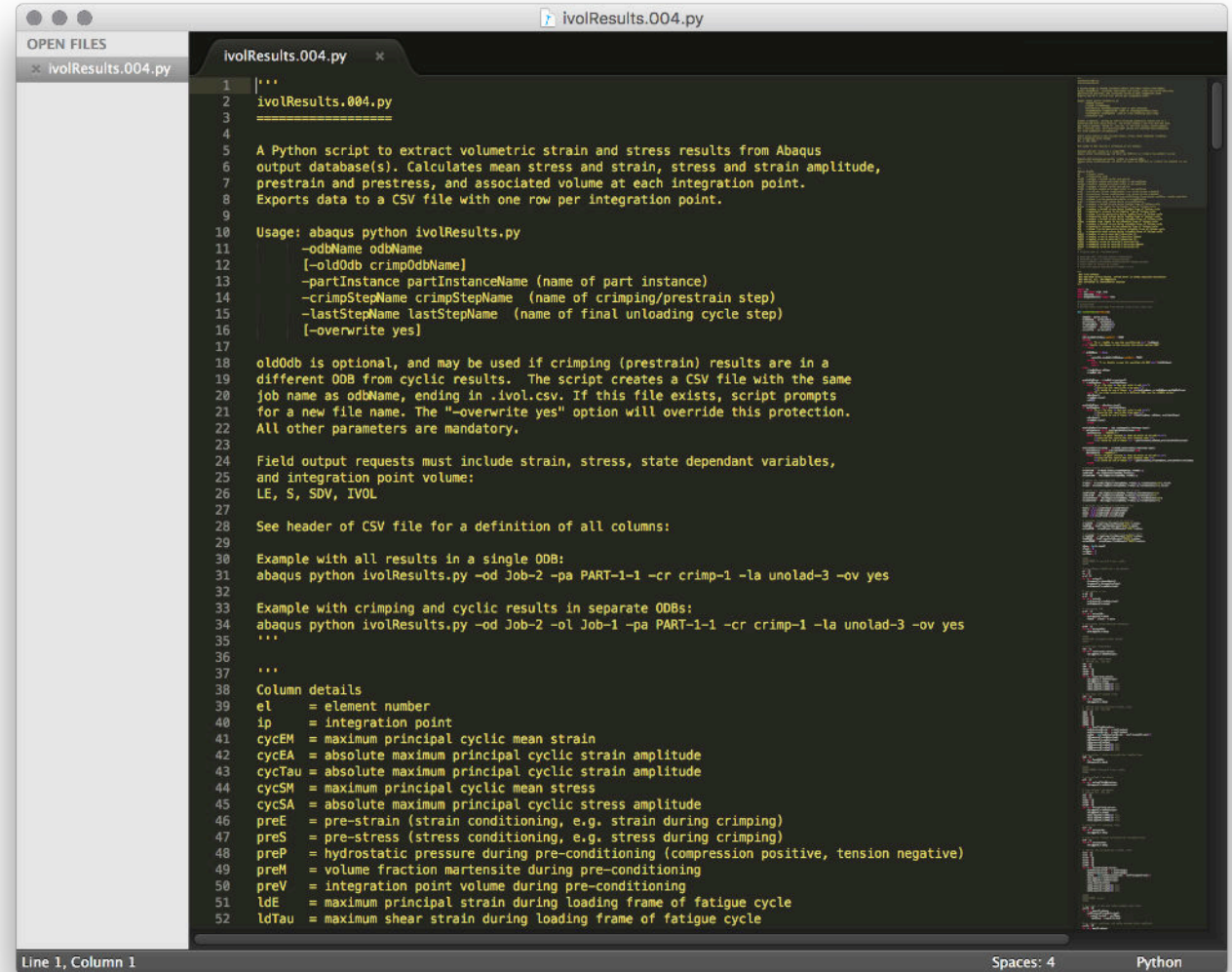
Monte-Carlo risk assessment

Resources



# Tools to extract volume data and more

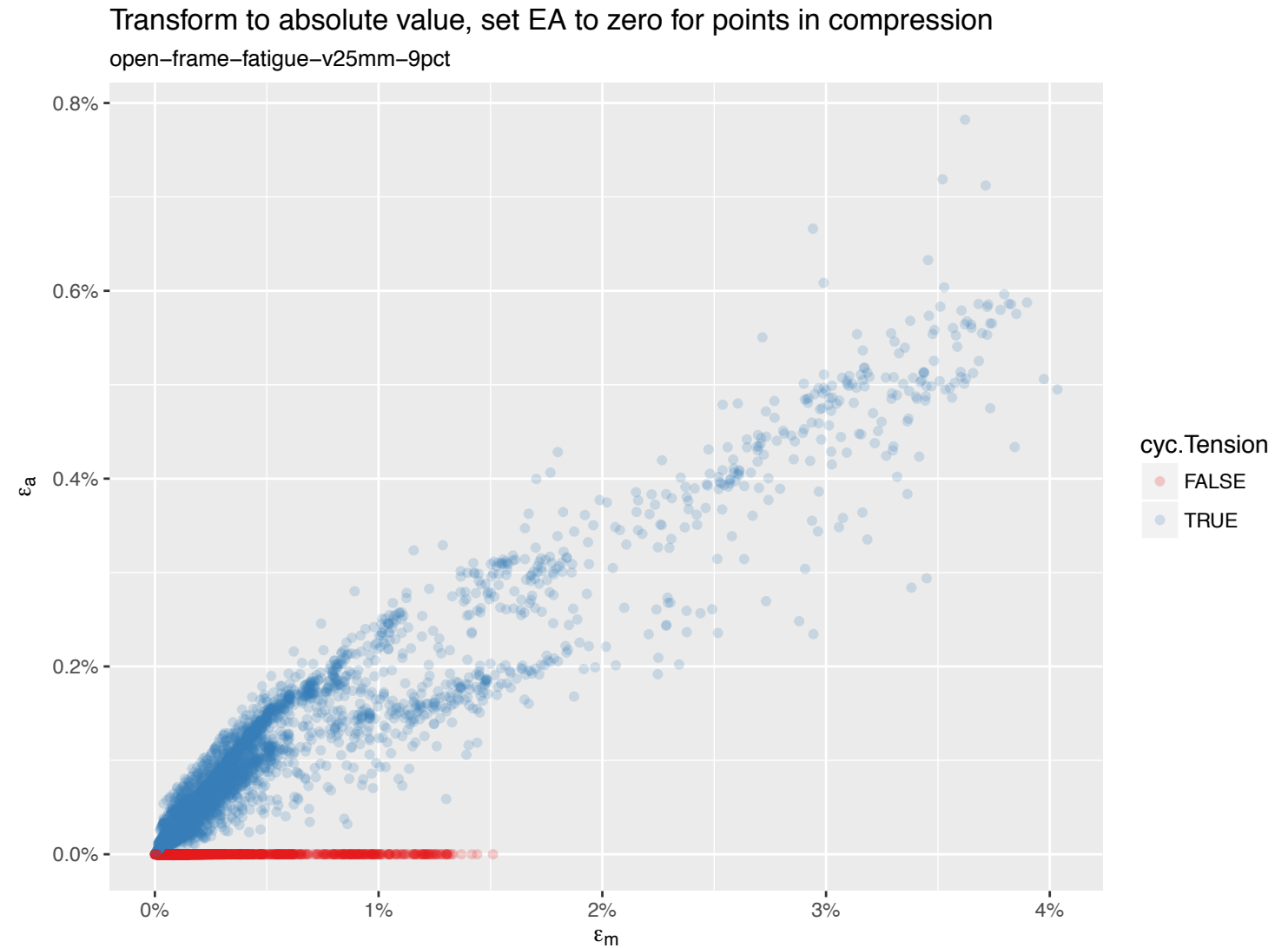
- integration point volume
- strain, stress at crimping step (pre-strain)
- hydrostatic pressure (tension vs. compression)
- volume fraction of martensite
- mean stress/strain
- stress/strain amplitude
- stress and strain components



```
1  """
2  ivolResults.004.py
3
4
5  A Python script to extract volumetric strain and stress results from Abaqus
6  output database(s). Calculates mean stress and strain, stress and strain amplitude,
7  prestrain and prestress, and associated volume at each integration point.
8  Exports data to a CSV file with one row per integration point.
9
10 Usage: abaqus python ivolResults.py
11         -odbName odbName
12         [-oldOdb crimpOdbName]
13         -partInstance partInstanceName (name of part instance)
14         -crimpStepName crimpStepName (name of crimping/prestrain step)
15         -lastStepName lastStepName (name of final unloading cycle step)
16         [-overwrite yes]
17
18 oldOdb is optional, and may be used if crimping (prestrain) results are in a
19 different ODB from cyclic results. The script creates a CSV file with the same
20 job name as odbName, ending in .ivol.csv. If this file exists, script prompts
21 for a new file name. The "-overwrite yes" option will override this protection.
22 All other parameters are mandatory.
23
24 Field output requests must include strain, stress, state dependant variables,
25 and integration point volume:
26 LE, S, SDV, IVOL
27
28 See header of CSV file for a definition of all columns:
29
30 Example with all results in a single ODB:
31 abaqus python ivolResults.py -od Job-2 -pa PART-1-1 -cr crimp-1 -la unolad-3 -ov yes
32
33 Example with crimping and cyclic results in separate ODBs:
34 abaqus python ivolResults.py -od Job-2 -ol Job-1 -pa PART-1-1 -cr crimp-1 -la unolad-3 -ov yes
35 """
36
37
38 Column details
39 el = element number
40 ip = integration point
41 cycEM = maximum principal cyclic mean strain
42 cycEA = absolute maximum principal cyclic strain amplitude
43 cycTau = absolute maximum principal cyclic strain amplitude
44 cycSM = maximum principal cyclic mean stress
45 cycSA = absolute maximum principal cyclic stress amplitude
46 preE = pre-strain (strain conditioning, e.g. strain during crimping)
47 preS = pre-stress (stress conditioning, e.g. stress during crimping)
48 preP = hydrostatic pressure during pre-conditioning (compression positive, tension negative)
49 preM = volume fraction martensite during pre-conditioning
50 preV = integration point volume during pre-conditioning
51 ldE = maximum principal strain during loading frame of fatigue cycle
52 ldTau = maximum shear strain during loading frame of fatigue cycle
```

# Typical point cloud

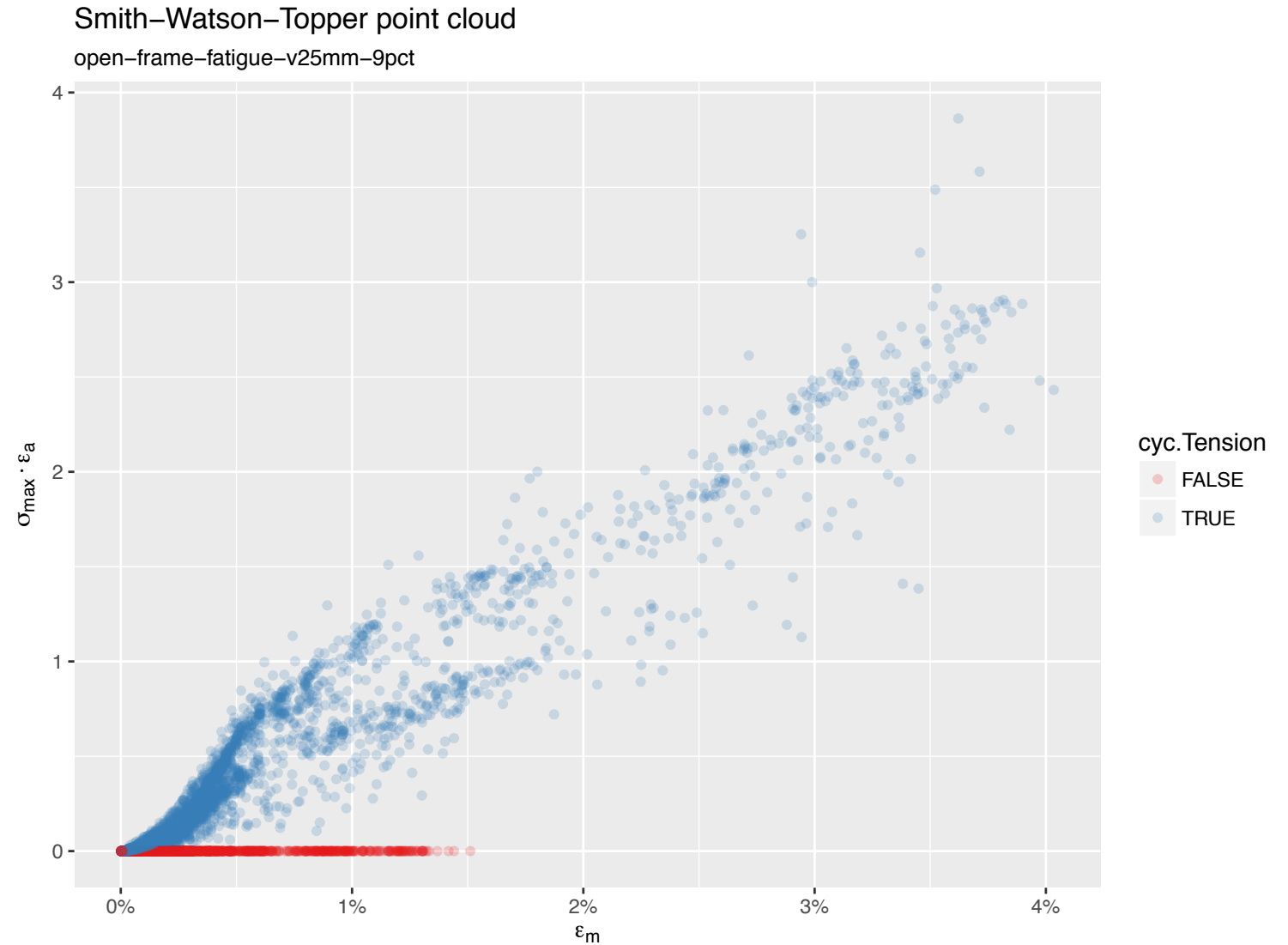
strain amplitude vs. mean strain



# SWT point cloud

Smith-Watson-Topper

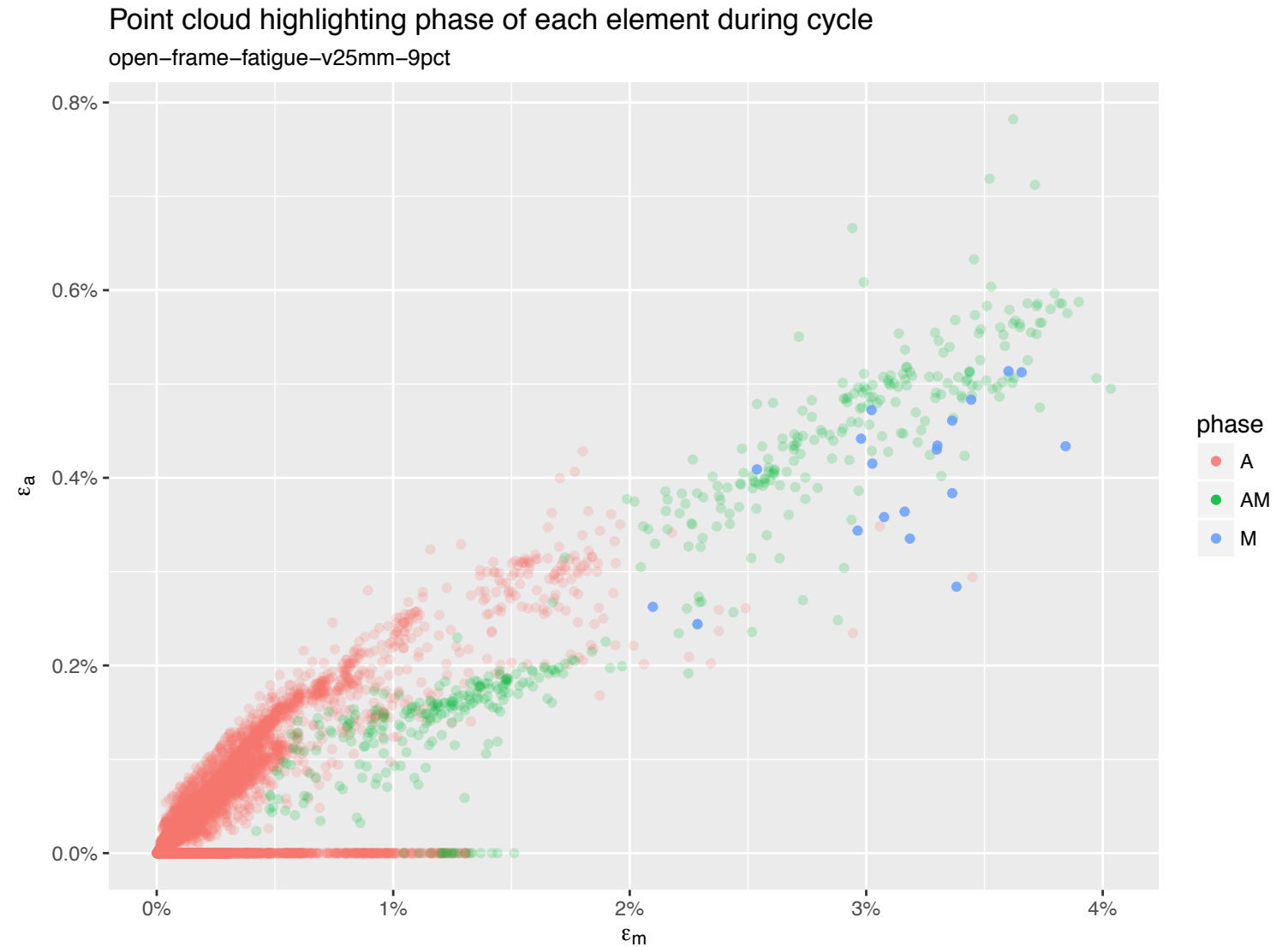
(maximum stress)·(strain amplitude)



# Phase map

During the fatigue cycle, elements may:

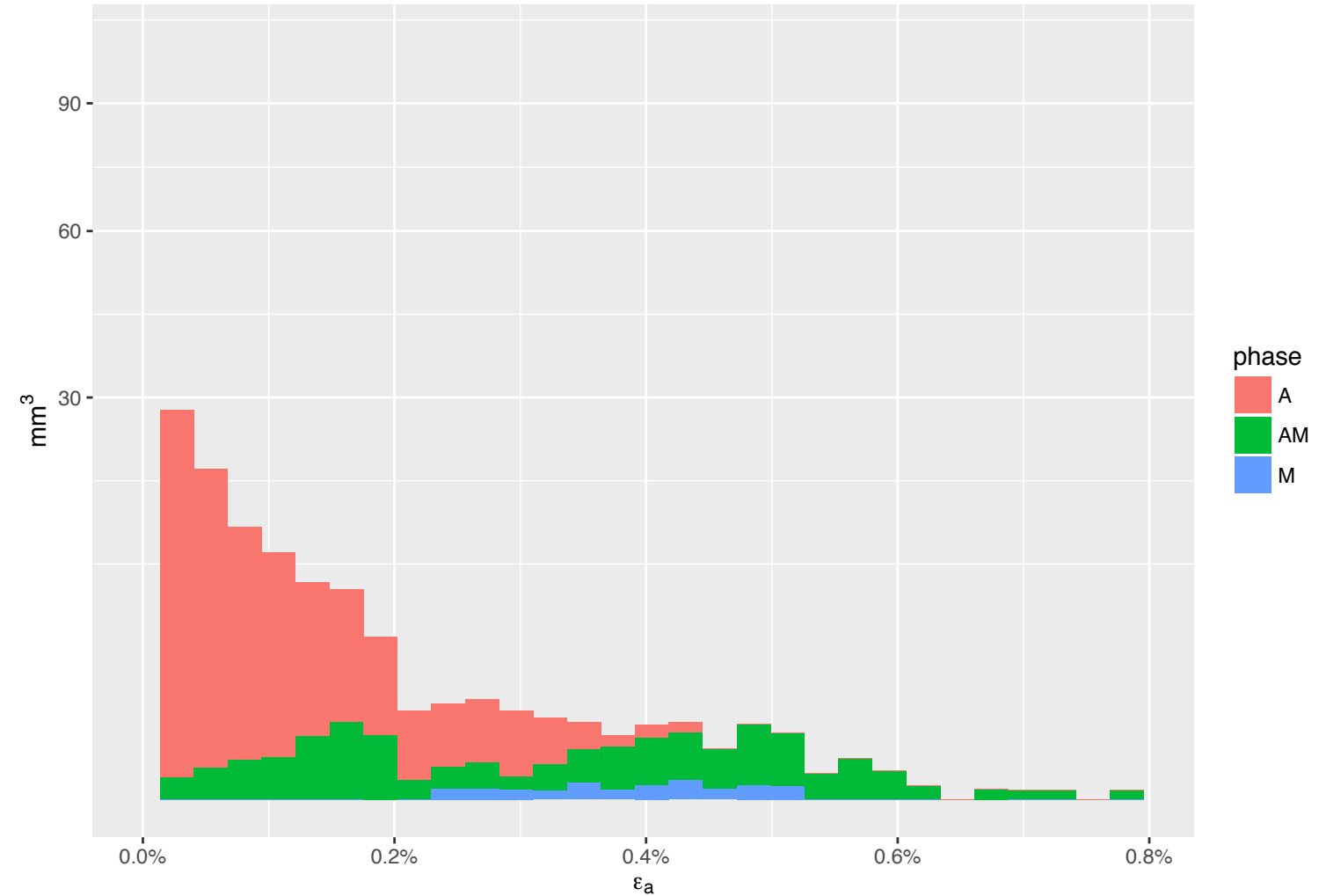
- Remain austenite throughout
- Remain martensite throughout
- Alternate A/M during cycle



# Volumetric histogram

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

Volume of material in each phase, by strain amplitude  
open-frame-fatigue-v25mm-9pct



Introduction

Volumetric FEA methods

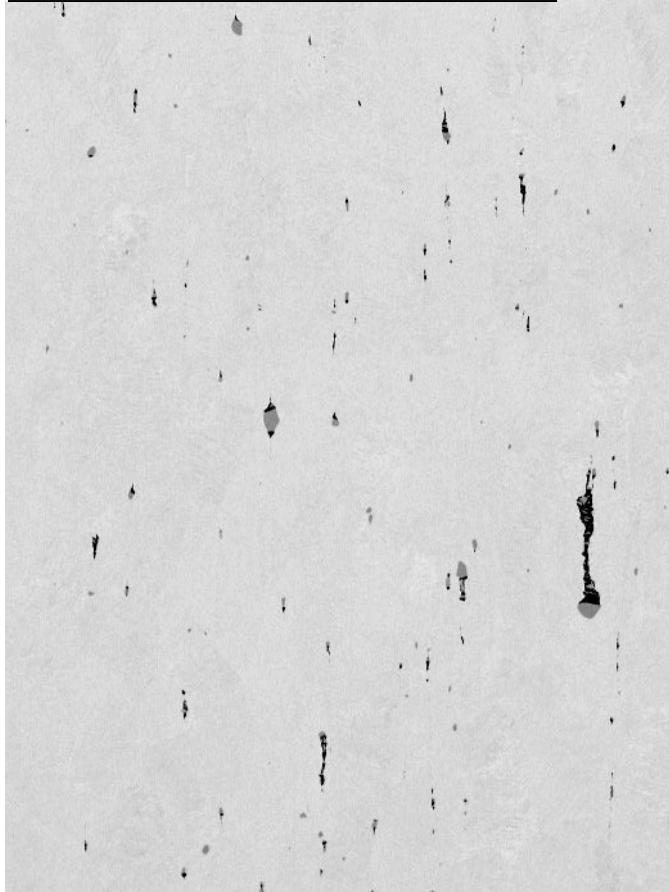
> **Sub- $\mu\text{m}$  x-ray computed tomography**

Monte-Carlo risk assessment

Resources

## Standard VAR (SE508)

264.46x198.35  $\mu\text{m}$  (1280x960); 8-bit; 1.2MB

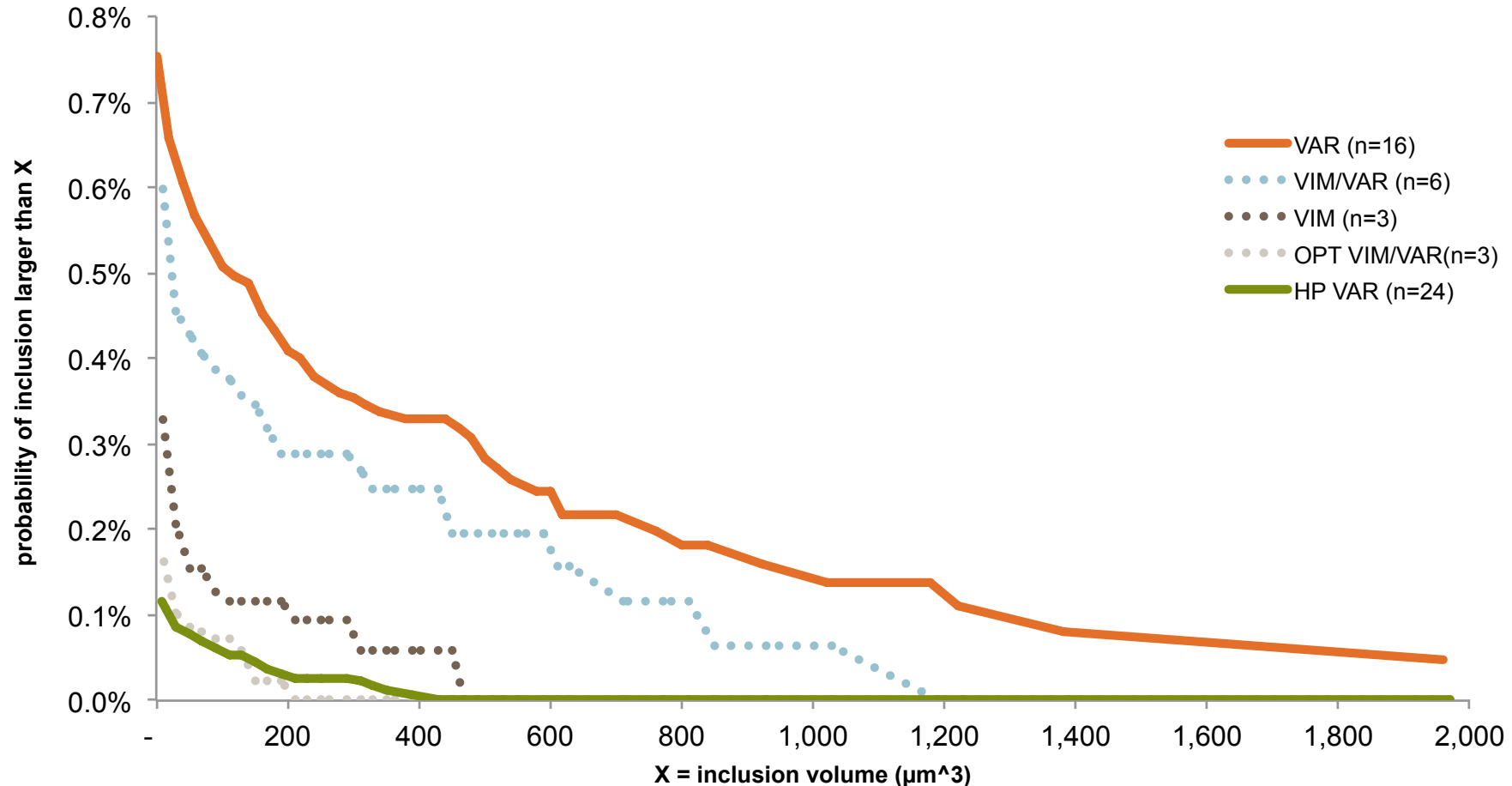


## High Purity VAR (SE508-ELI)

264.46x198.35  $\mu\text{m}$  (1280x960); 8-bit; 1.2MB



# Approximation of inclusion volumetric probability





# Durability performance benefit of high purity material

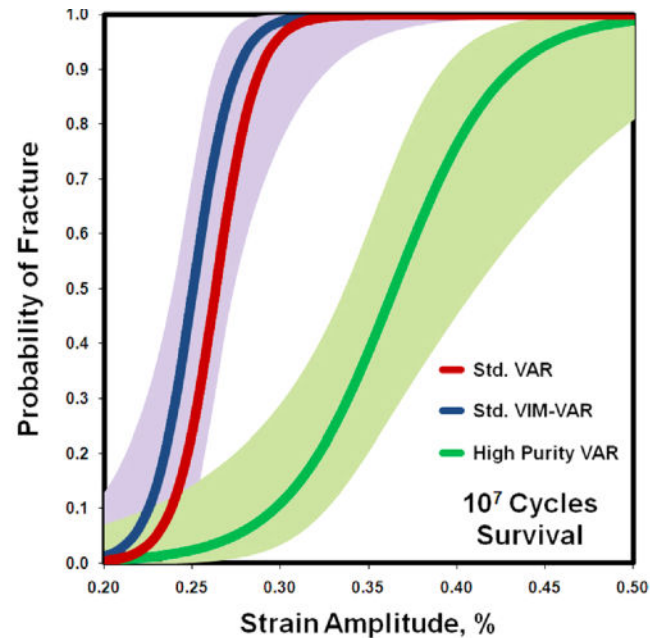


Fig. 8 – Probability of Nitinol wire fracture versus strain amplitude plots with the curve fit line shown bracketed by the 95th percentile upper and lower confidence interval bands.

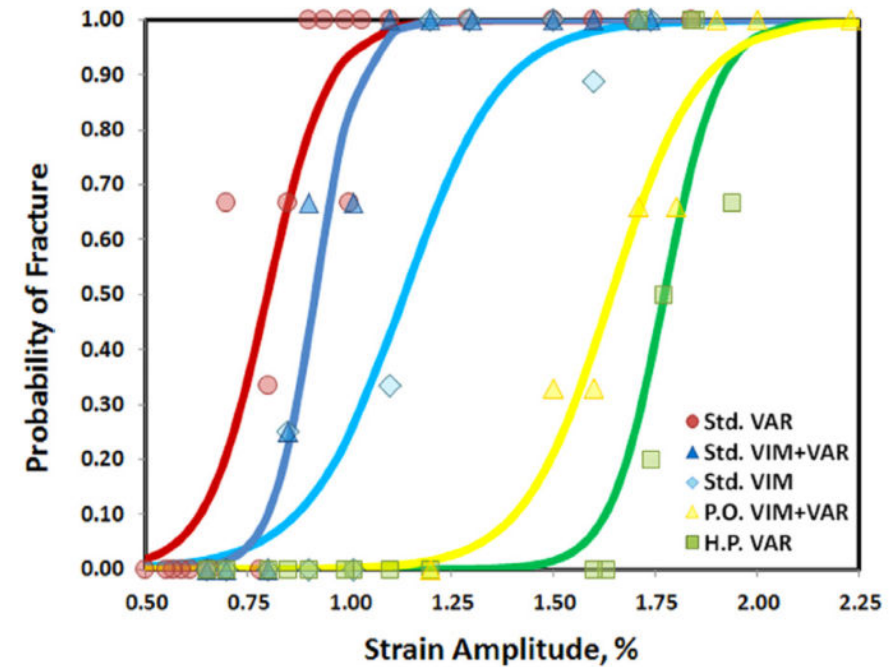
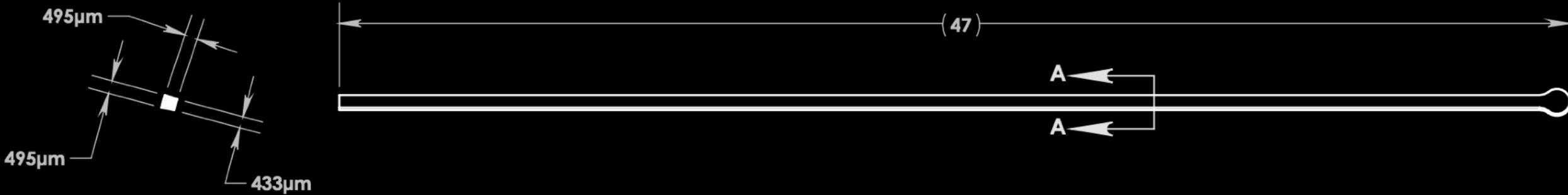
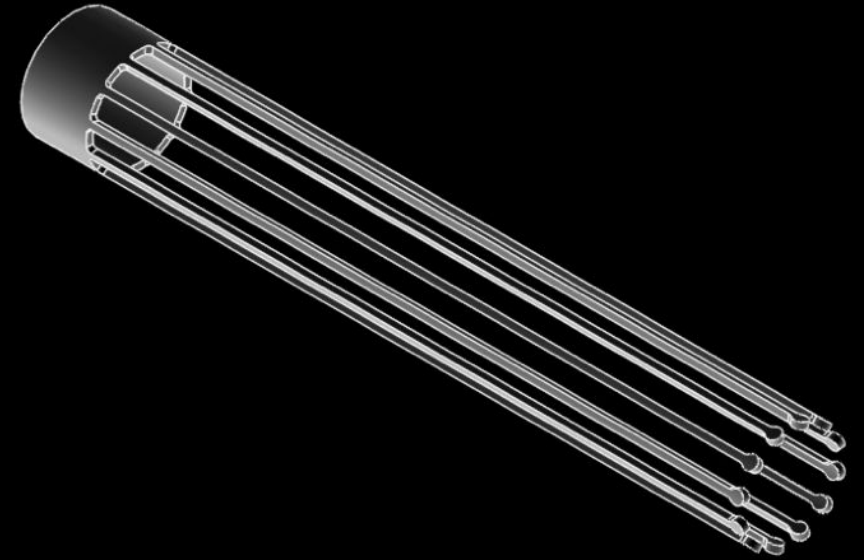


Fig. 9 – Probability of Nitinol diamond fracture at 10<sup>7</sup> cycles versus strain amplitude plots with a logit sigmoidal curve fit line for each data set.

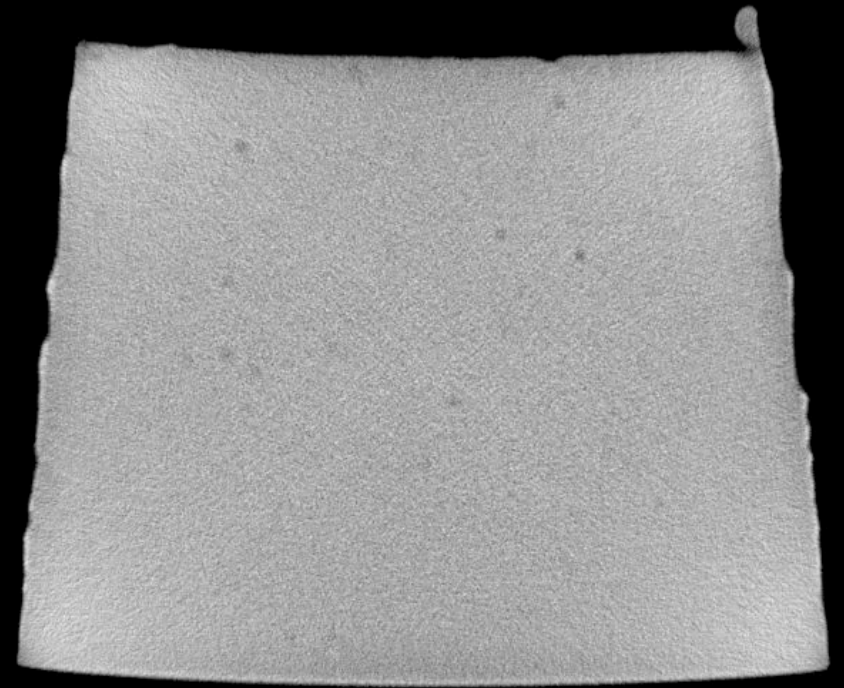
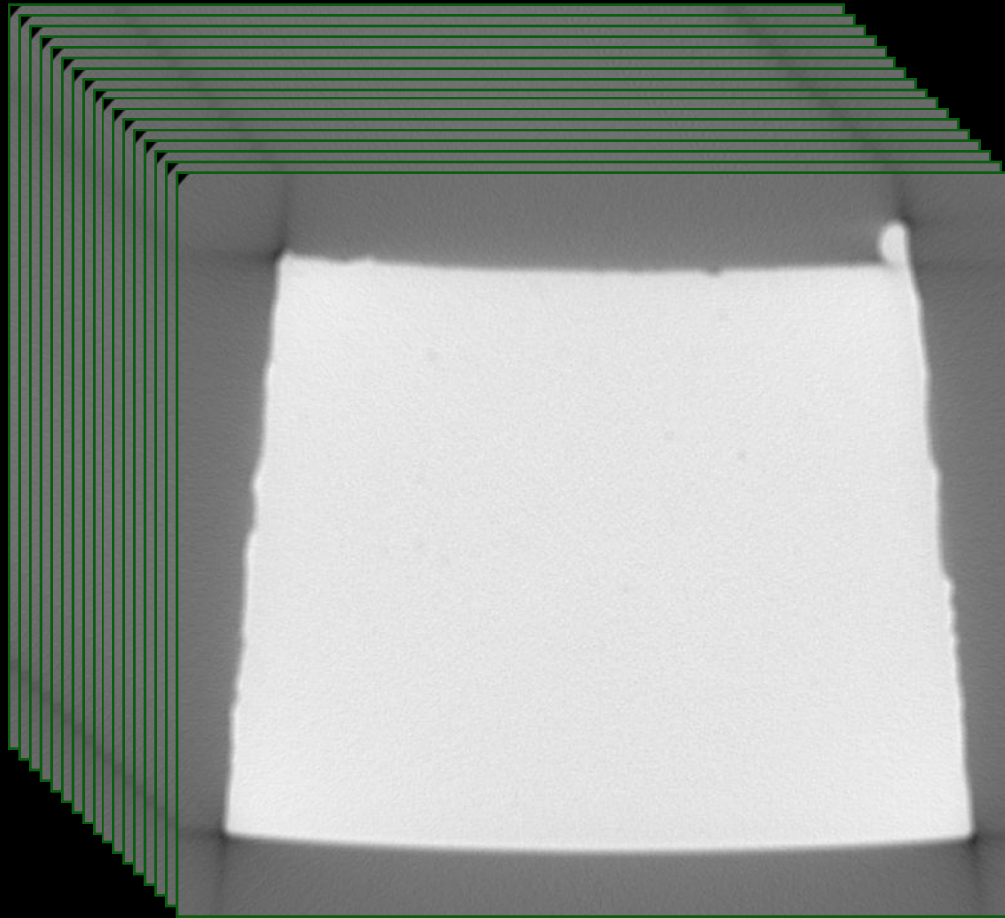
# X-ray computed tomography (XCT) test specimens

8.00x7.01 superelastic nitinol tubing  
0.5mm x 0.5mm x 50mm laser cut “matchstick” samples

scan01: SE508  
scan02: SE508ELI  
scan03: SE508ELI



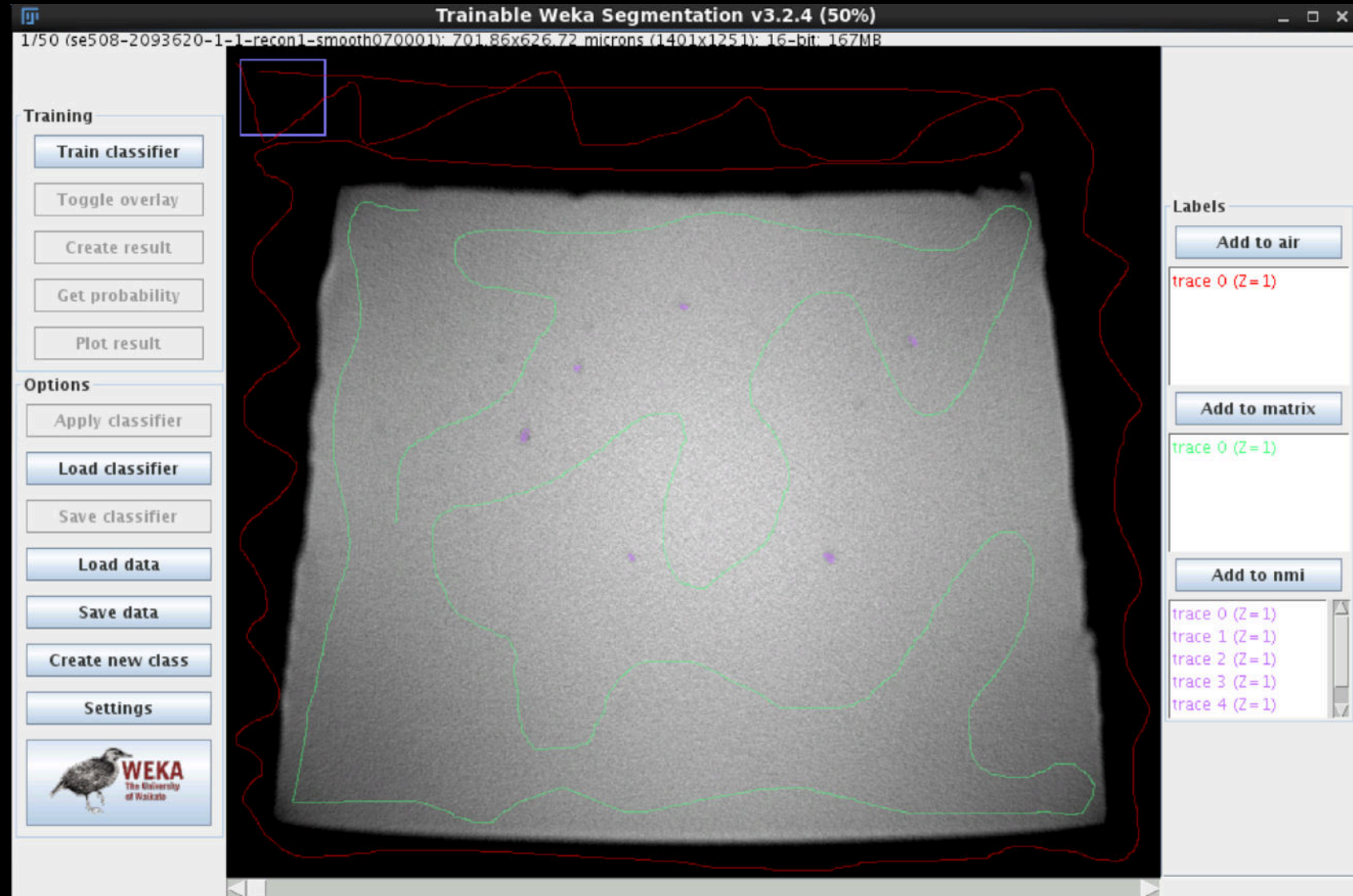
XCT scan output: 1,994 16-bit images ( $0.50\mu\text{m}^3$  voxel)



# Image segmentation by machine learning

Fiji [1] is just ImageJ [2]

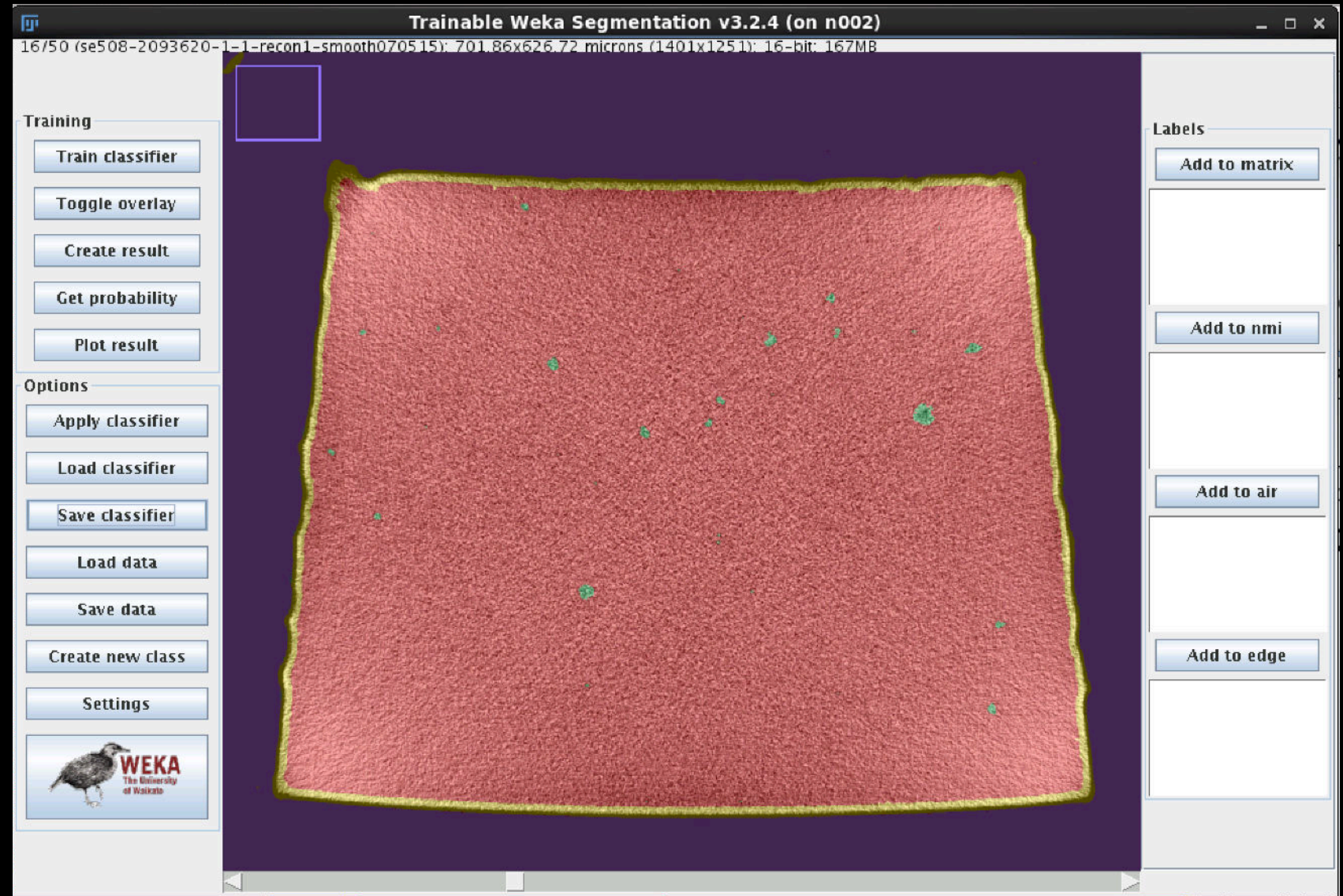
Trainable Weka Segmentation [3]



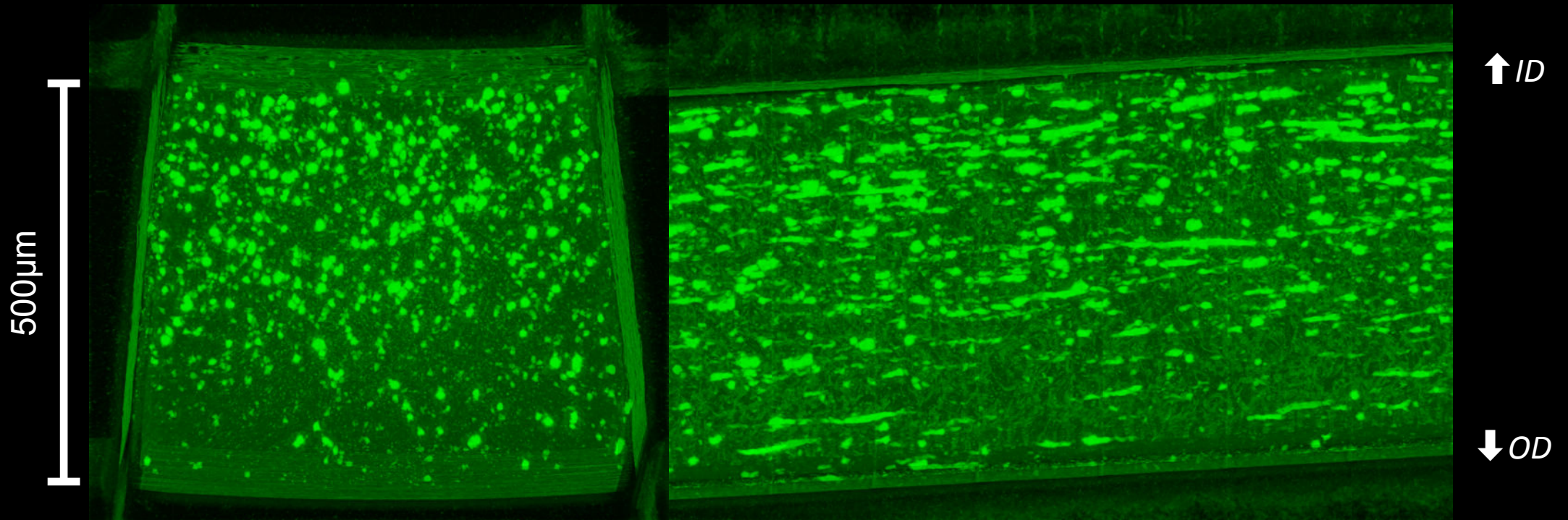
# Voxel Classification

Train classifier to identify probability of each voxel as:

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

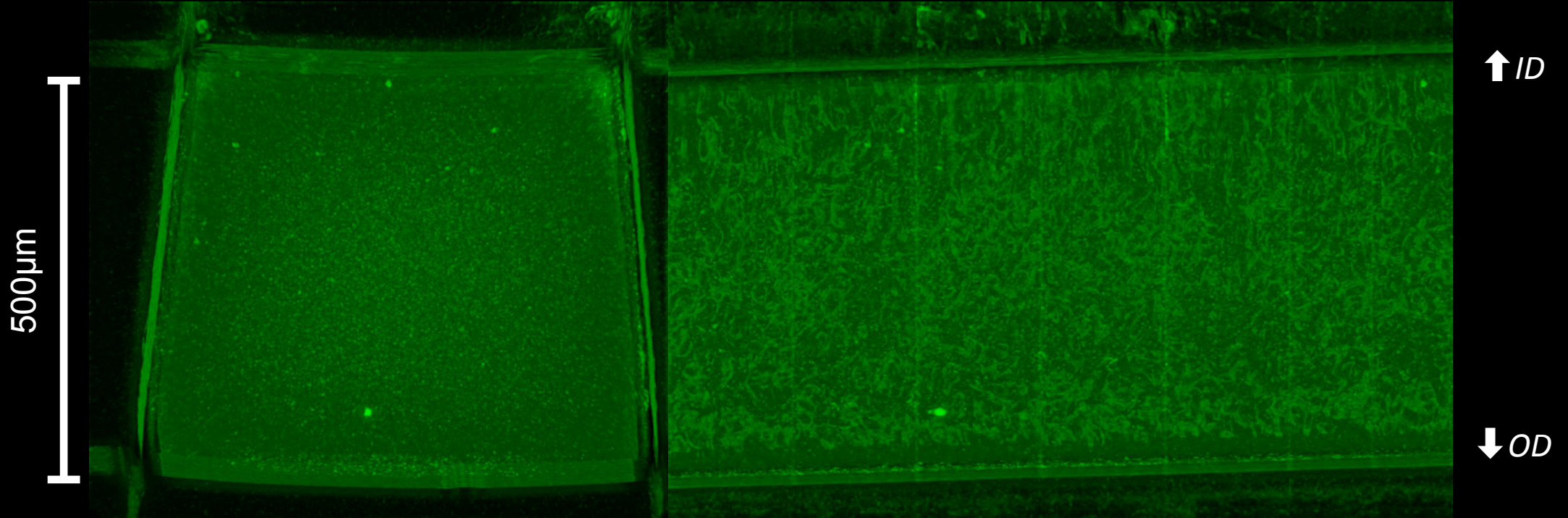


# SE508 maximum intensity projection of inclusion probability



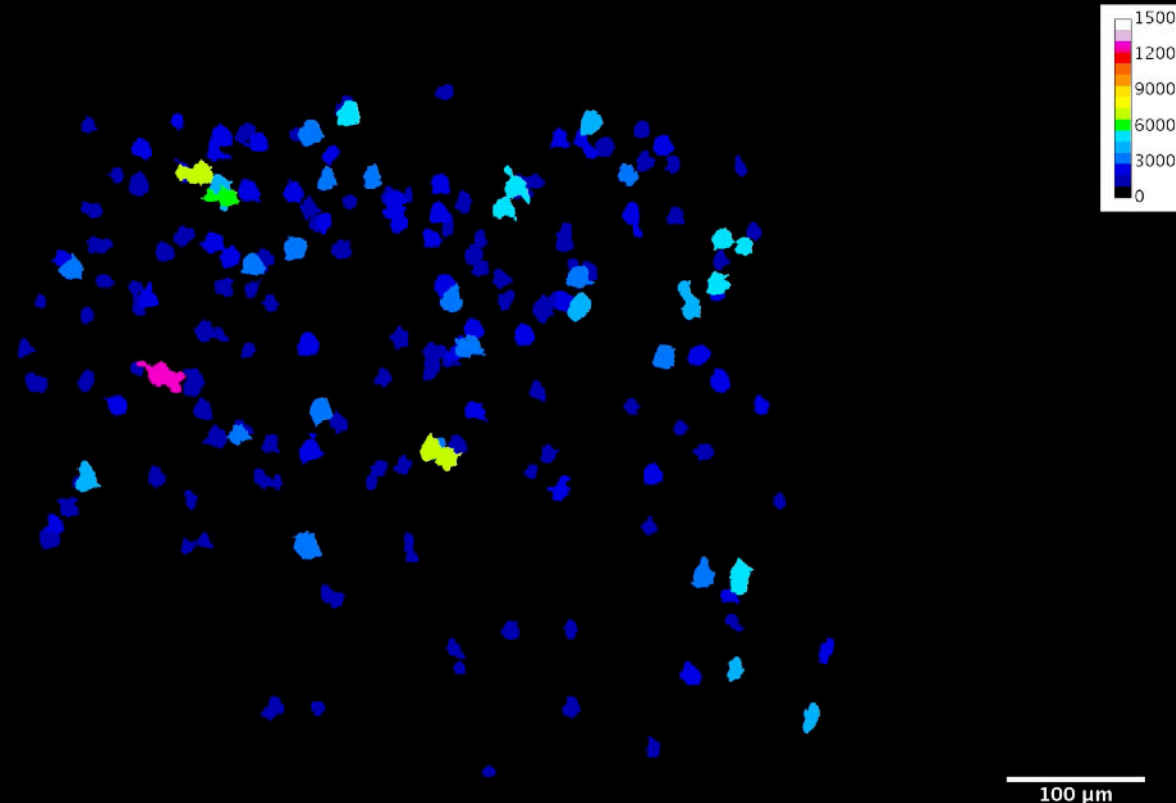
*visualization superimposes all inclusions through 500 $\mu$ m thickness*

# SE508-ELI maximum intensity projection of inclusion probability



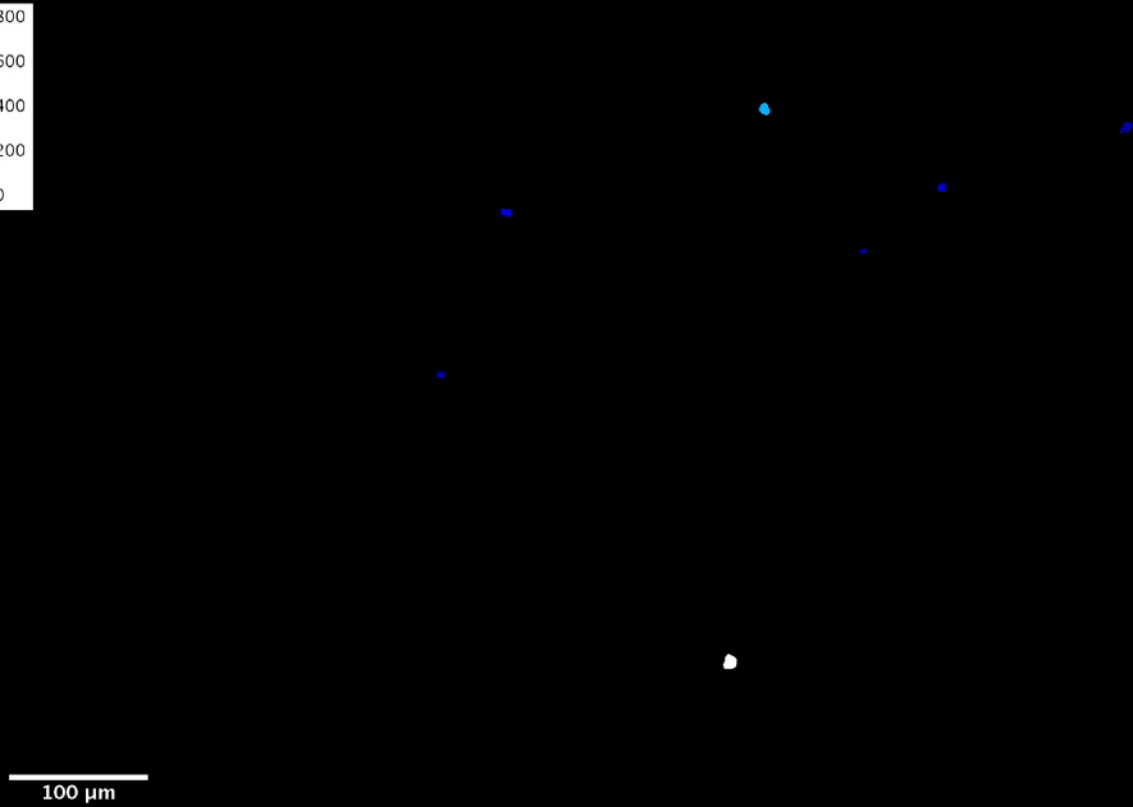
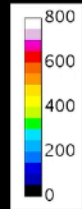
*visualization superimposes all inclusions through 500μm thickness*

# SE508 inclusion segmentation colored by volume

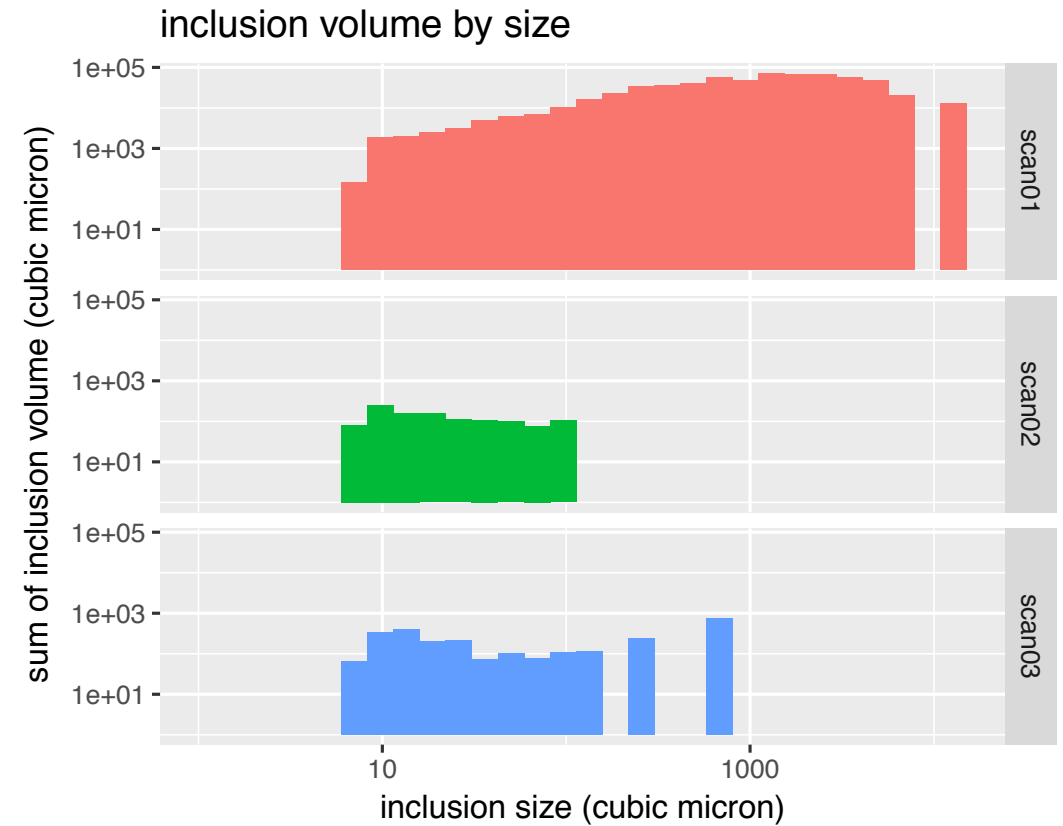
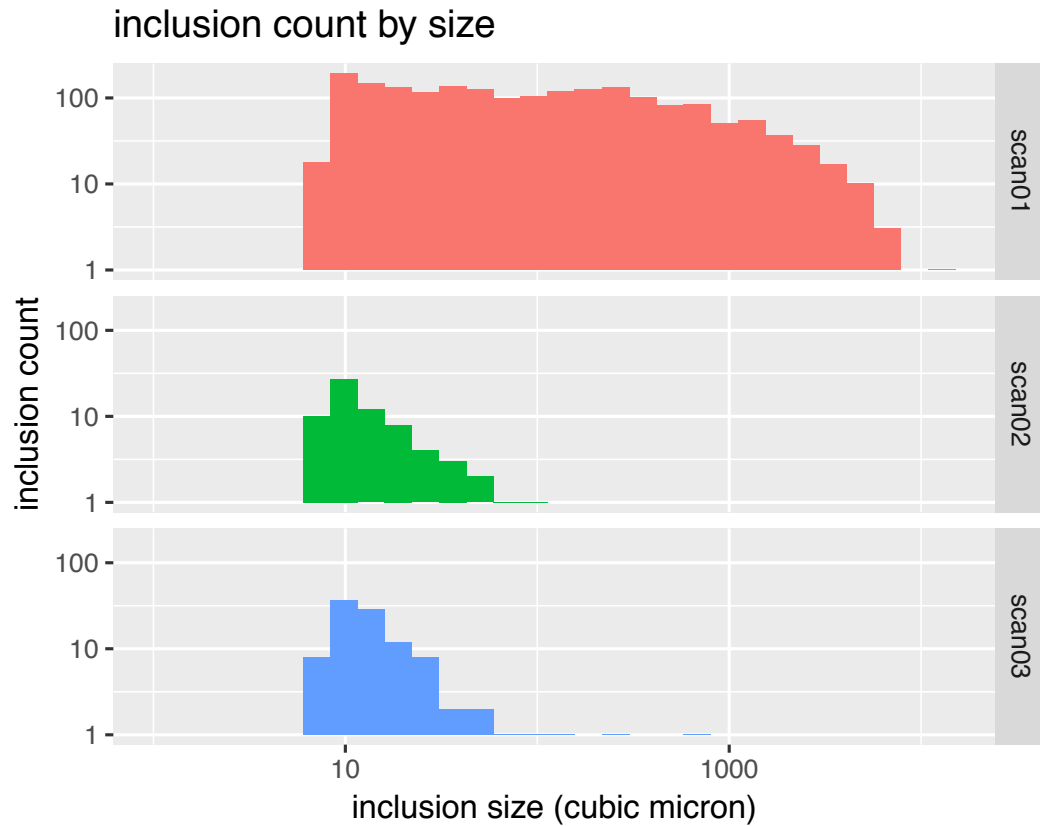




# SE508-ELI inclusion segmentation colored by volume

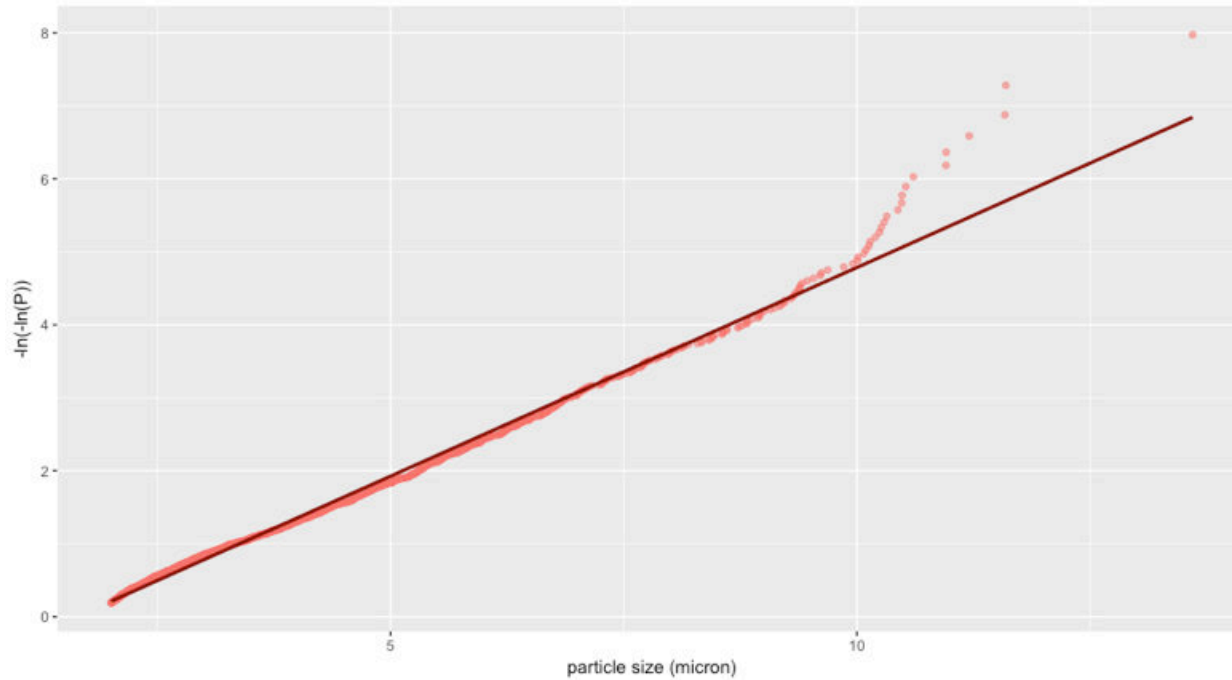


# Volumetric distribution of inclusions

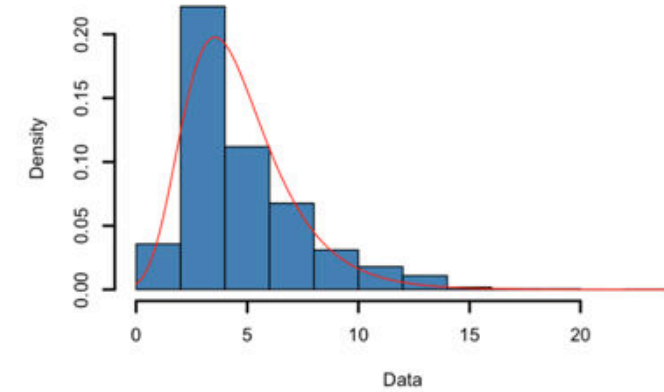


\* note log-log scales

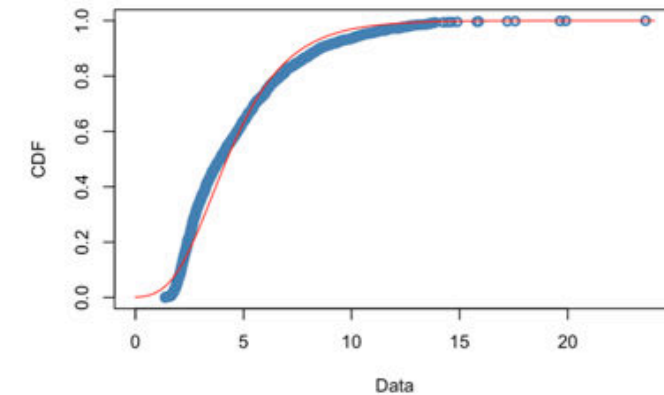
# √Area fit to Extreme Value Distribution per Urbano<sup>1</sup>



Empirical and theoretical dens.



Empirical and theoretical CDFs



# Inclusion density, Gumbel location and scaling parameters

SE508 Inclusion Distribution Parameters

plane	cutoff ( $\mu\text{m}^3$ )	inclusion density (1/mm <sup>3</sup> )	Gumbel $\mu$ ( $\mu\text{m}$ )	Gumbel $\sigma$ ( $\mu\text{m}$ )
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 ( $\mu\text{m}^3$ )	inclusion density (1/mm <sup>3</sup> )	Gumbel $\mu$ ( $\mu\text{m}$ )	Gumbel $\sigma$ ( $\mu\text{m}$ )
xy (transverse)	8	340	1.77	0.40
yz (longitudinal)	8	340	2.06	0.40
xz (longitudinal)	8	340	2.27	0.45

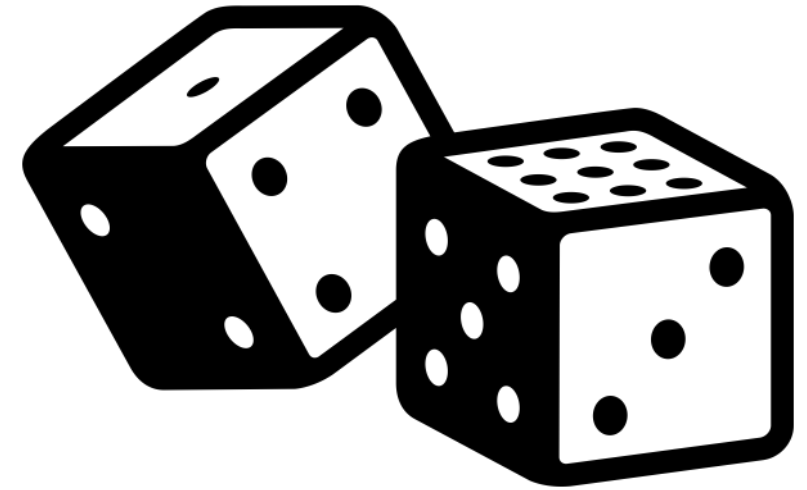


- Introduction
- Volumetric FEA methods
- Sub- $\mu\text{m}$  x-ray computed tomography
- > **Monte-Carlo risk assessment**
- Resources

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

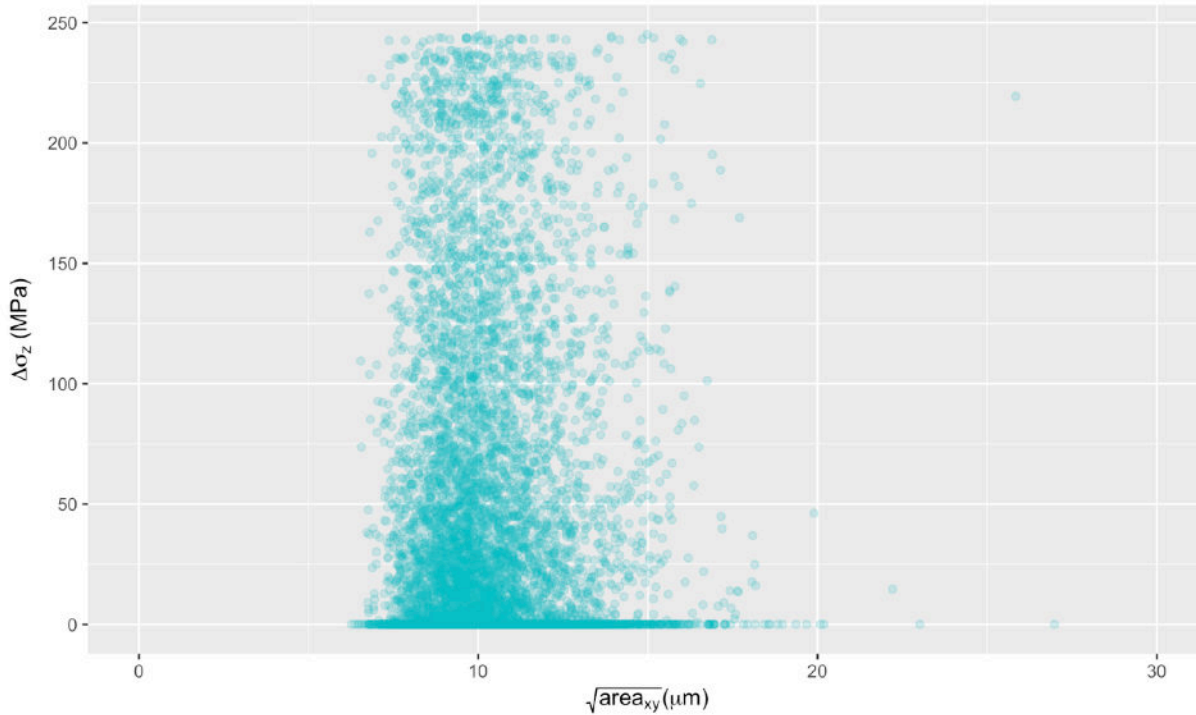
$$Q(p) = \mu - \sigma \ln[-\ln(p)]$$

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

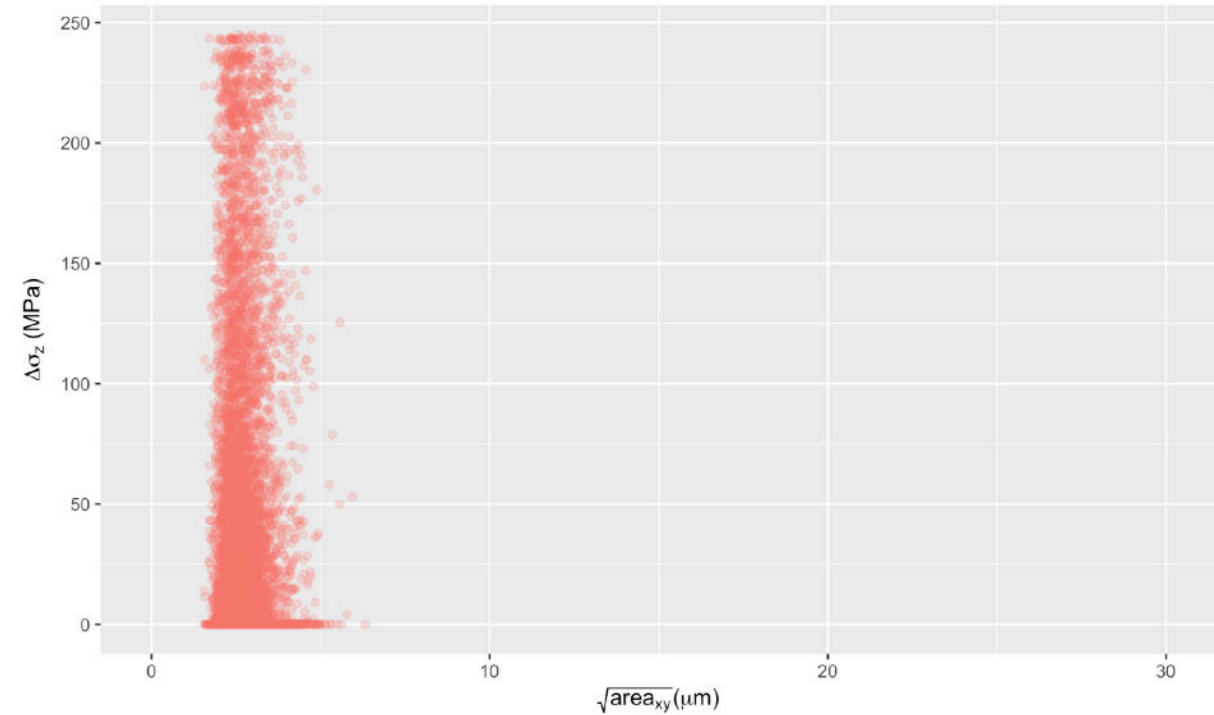


# “Fortune cloud”: $\Delta\sigma$ vs. $\sqrt{\text{area}}$ (single run SE508, ELI)

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 $\sqrt{area}$

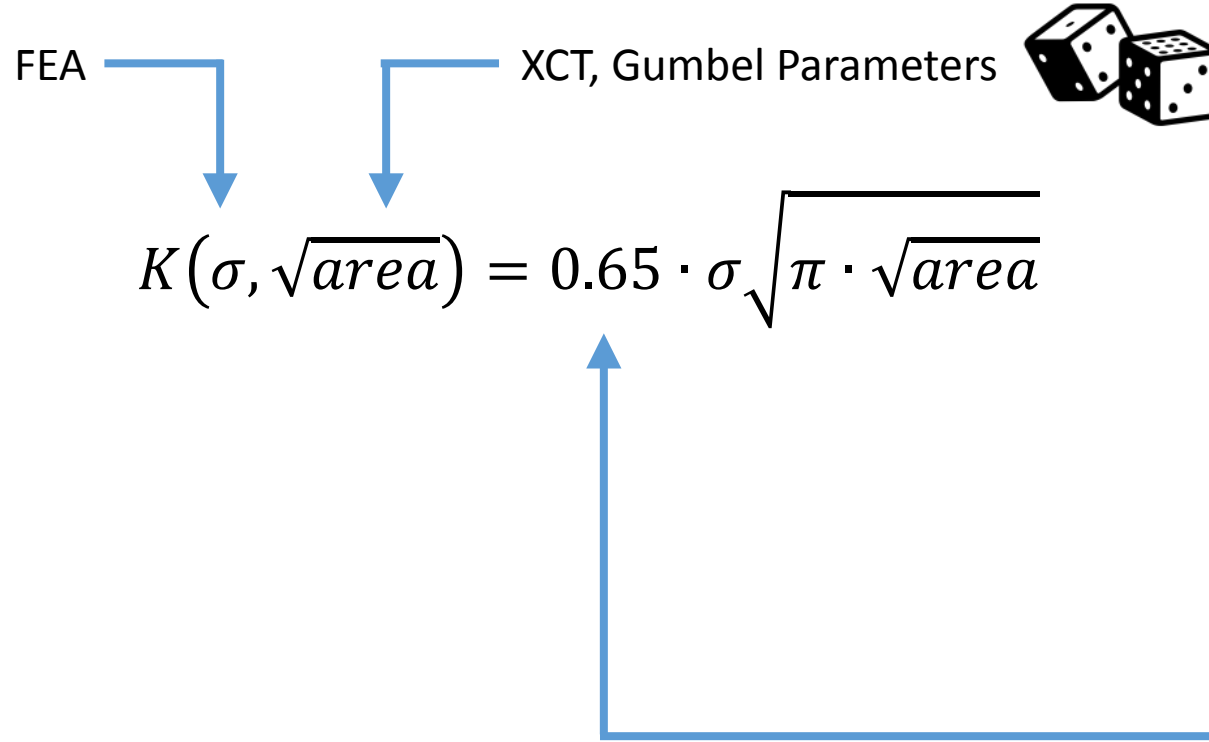
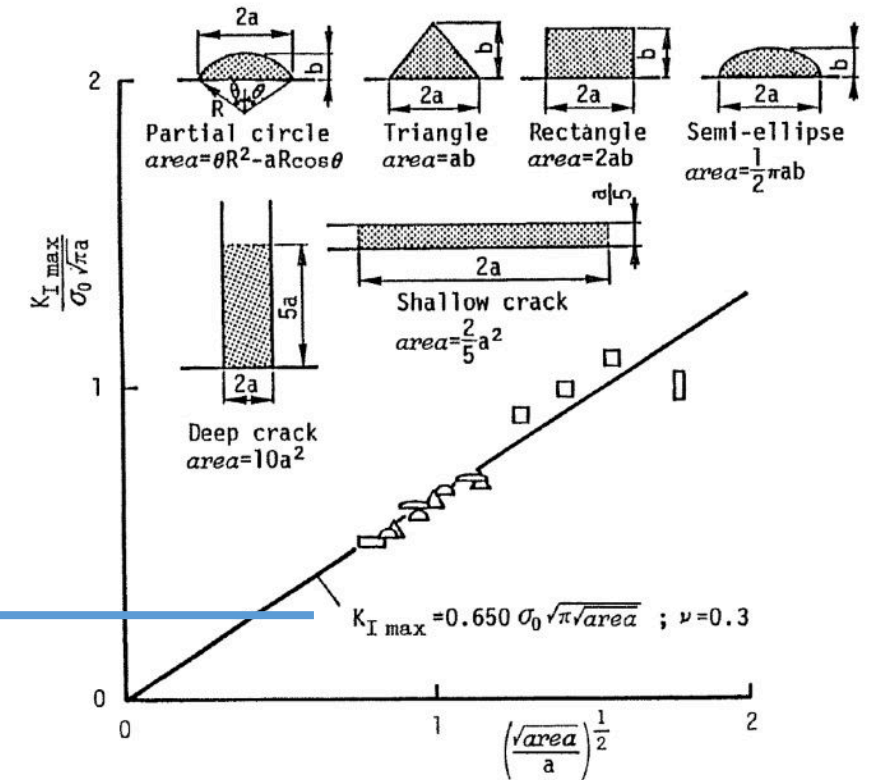


Figure 7 shows the relationship between the maximum stress intensity factor  $K_{I\max}$  and  $\sqrt{area}$  for surface cracks (elastic analysis) (24)(25). (See also (20)(66).)





# K and $\Delta K$ in each plane, at each integration point

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

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

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

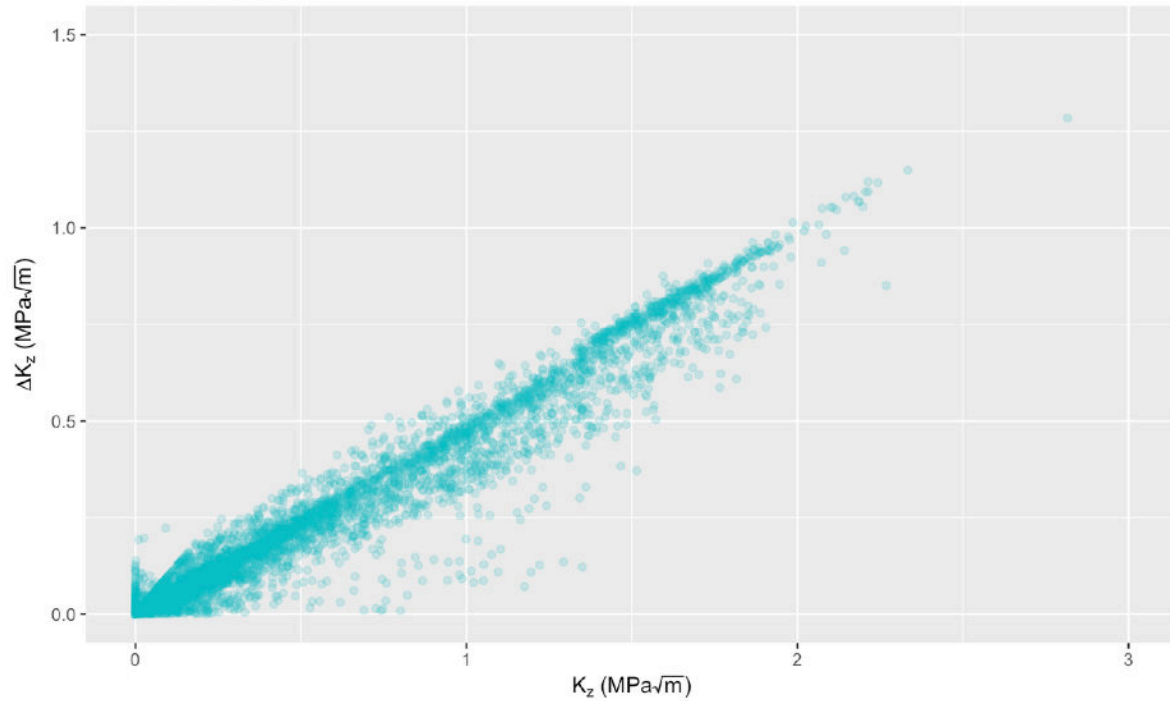
$$\Delta K_x = 0.65 \cdot \sqrt{\Delta\sigma_x \cdot \sqrt{area_{yz}}}$$

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

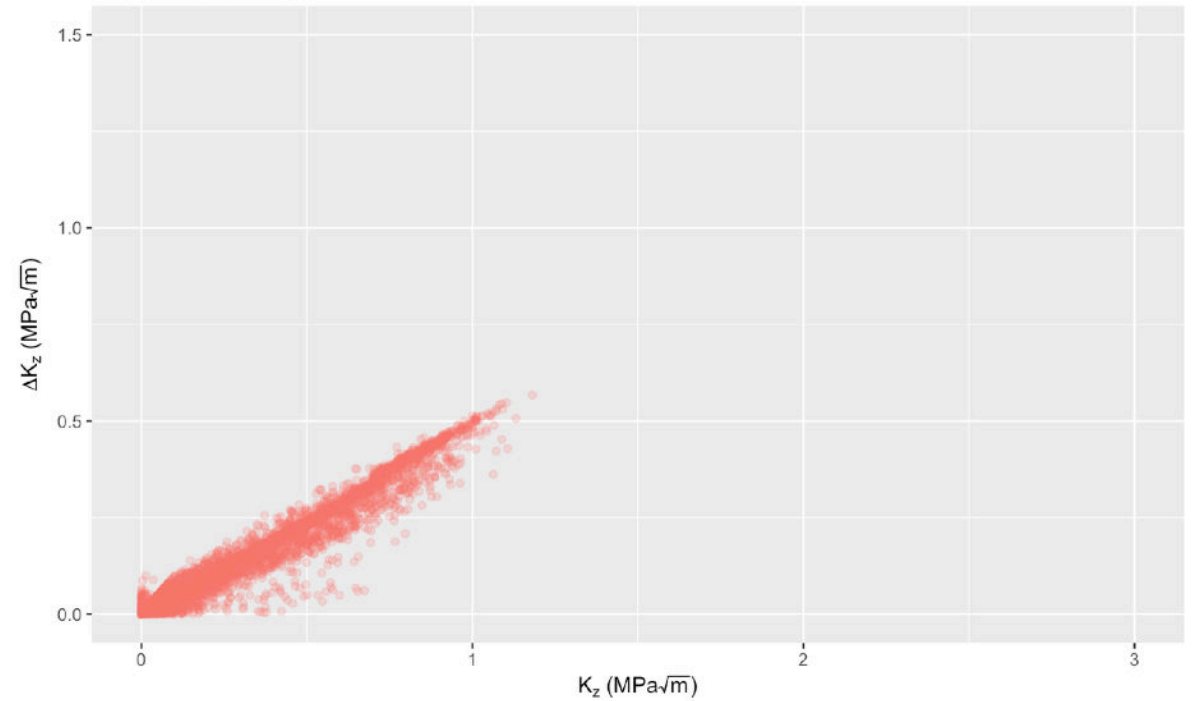
$$\Delta K_z = 0.65 \cdot \sqrt{\Delta\sigma_z \cdot \sqrt{area_{xy}}}$$

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

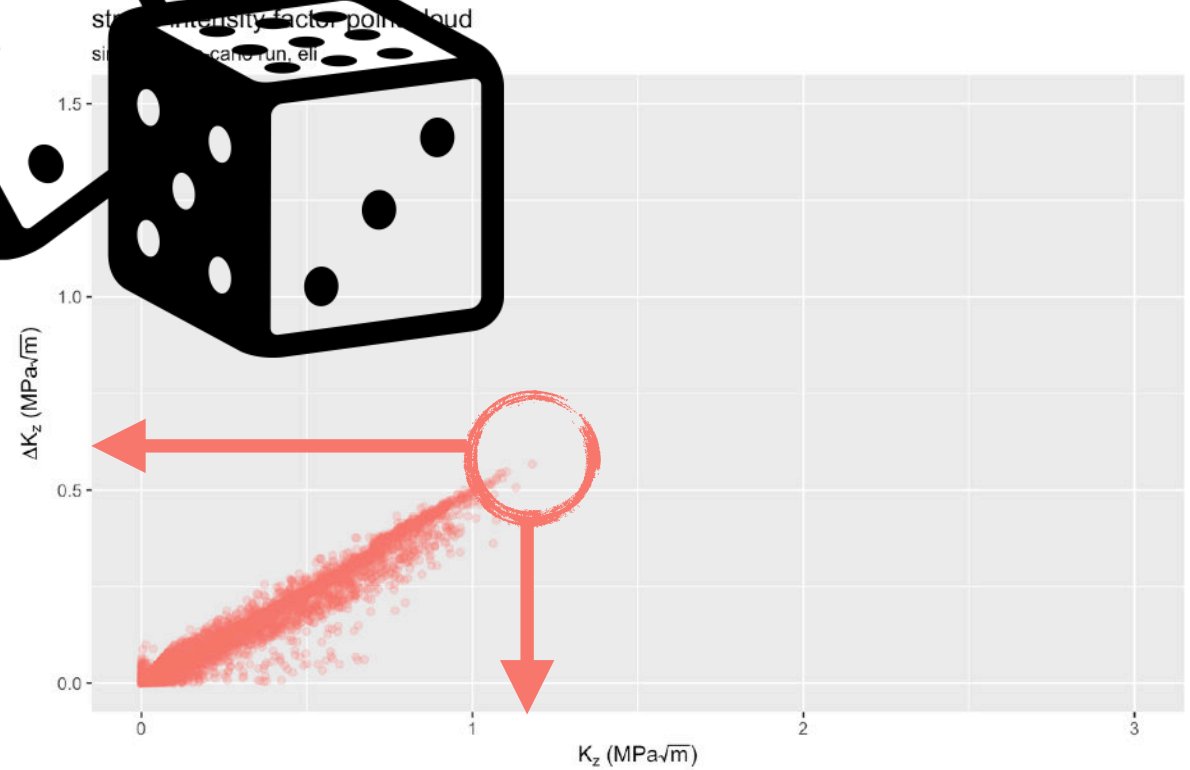
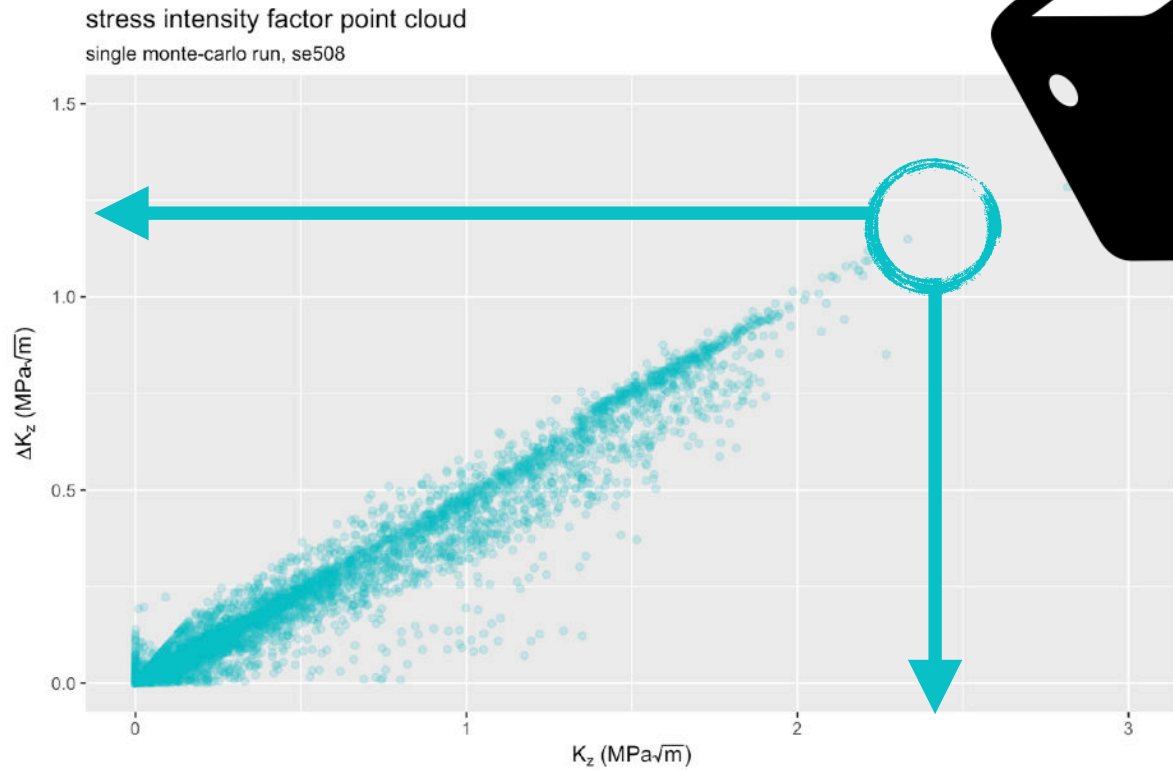
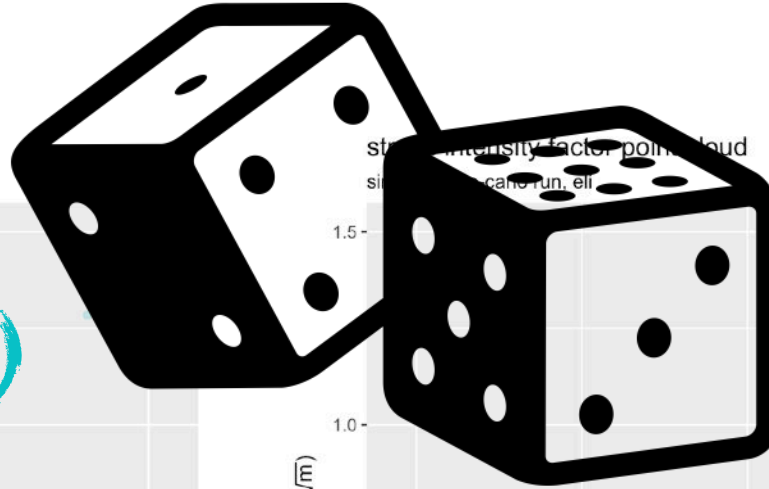
stress intensity factor point cloud  
single monte-carlo run, se508



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



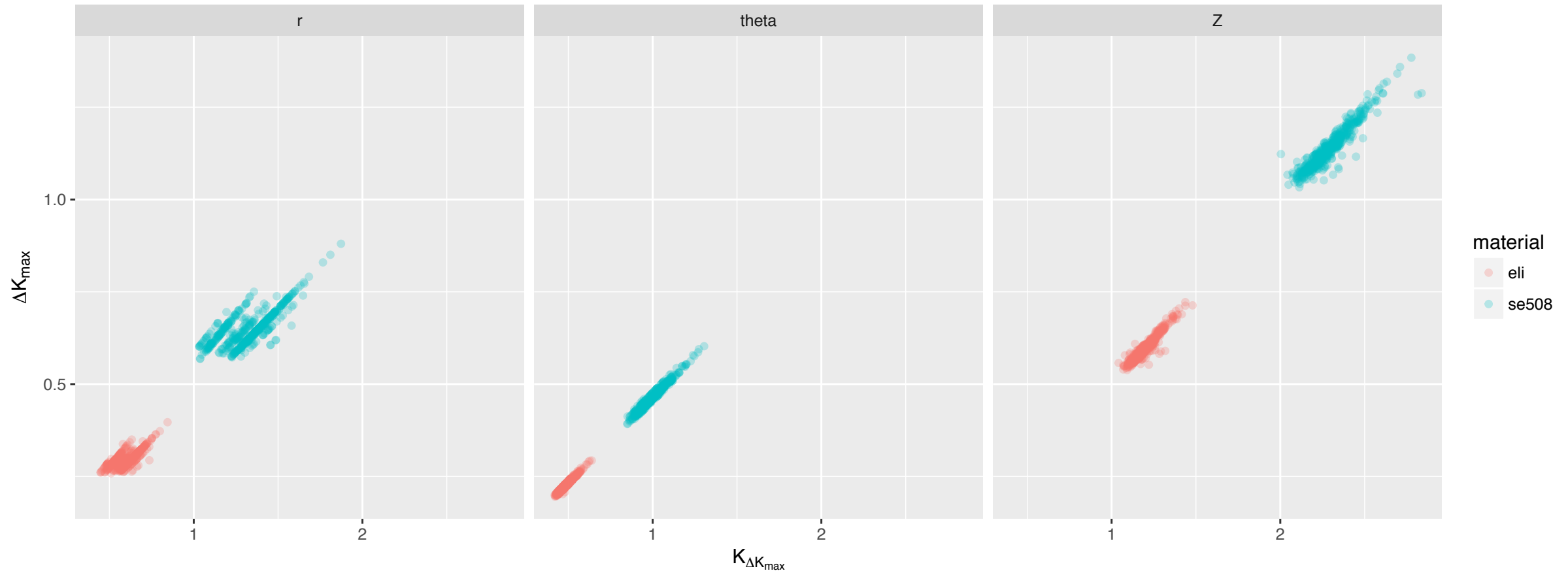
# Next: repeat many times, record $\Delta K_{\max}$ and $K$



# Maximum stress intensity factors for 500+500 runs

stress intensity factor: maximum  $\Delta K$  and corresponding K

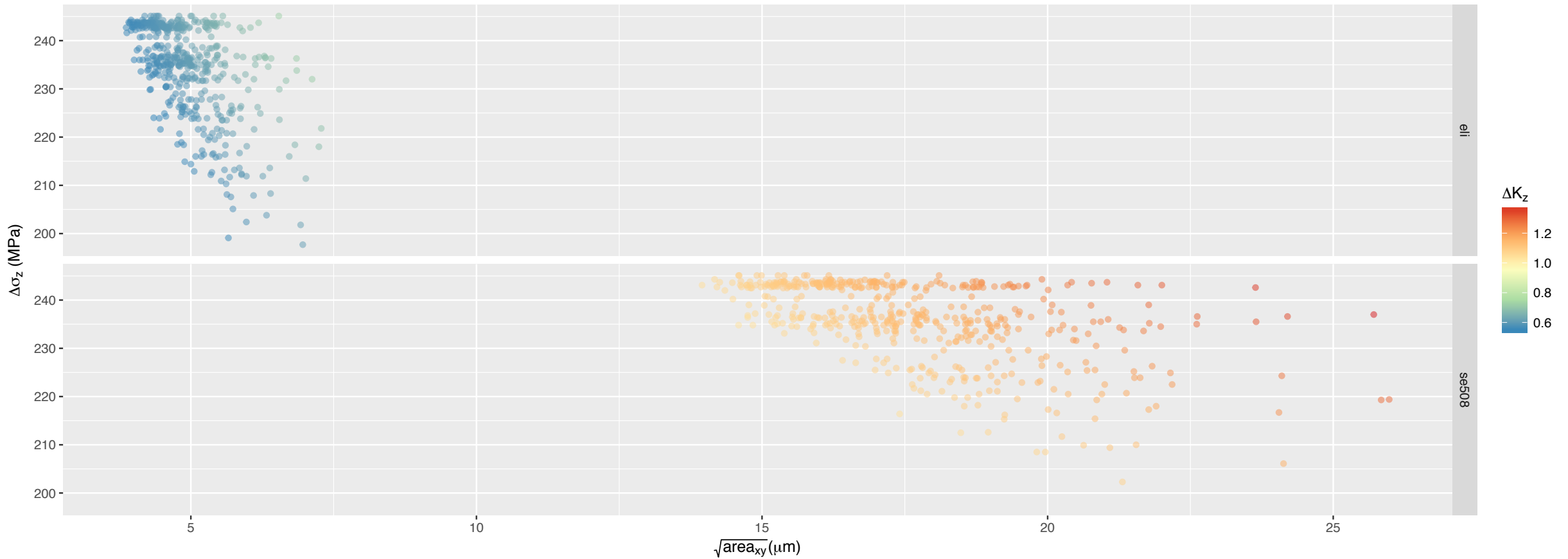
for 500 monte carlo runs with each material



# “Fortune plot” for 500+500 runs

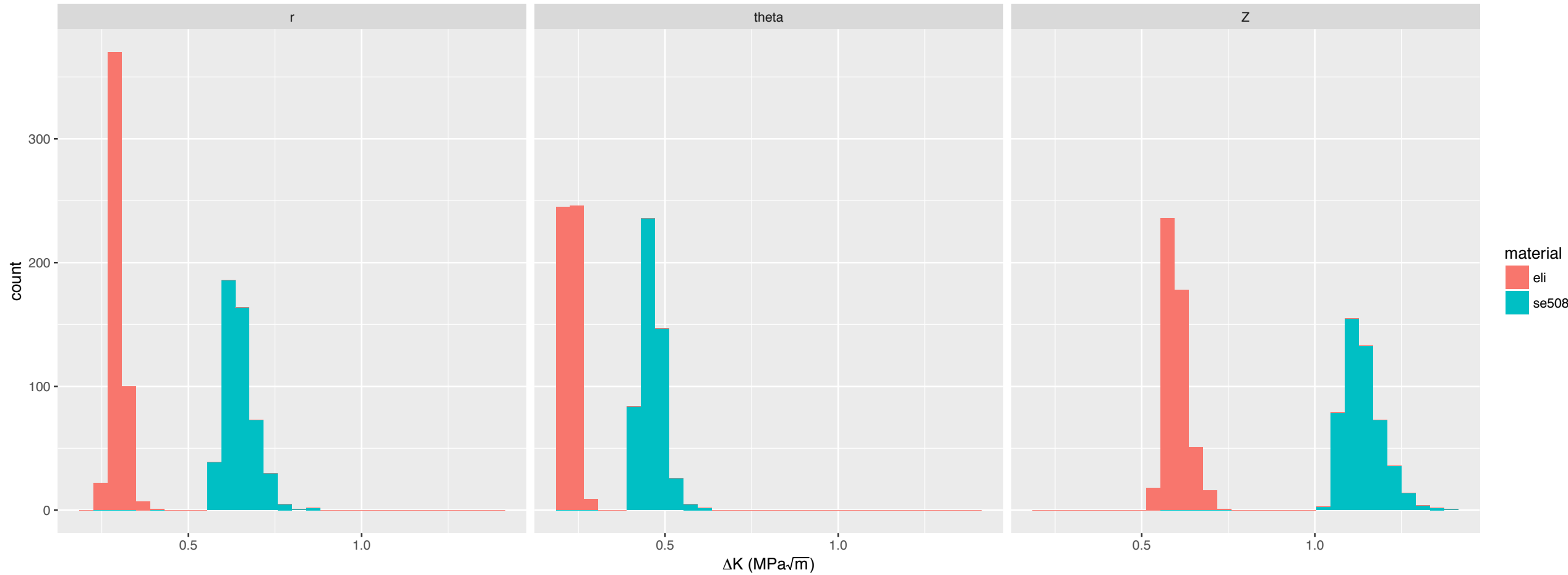
max.  $\Delta K_z$  by cyclic stress and defect (inclusion) size

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



# $\Delta K_{\max}$ 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
  - $K$ ,  $\Delta K$  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

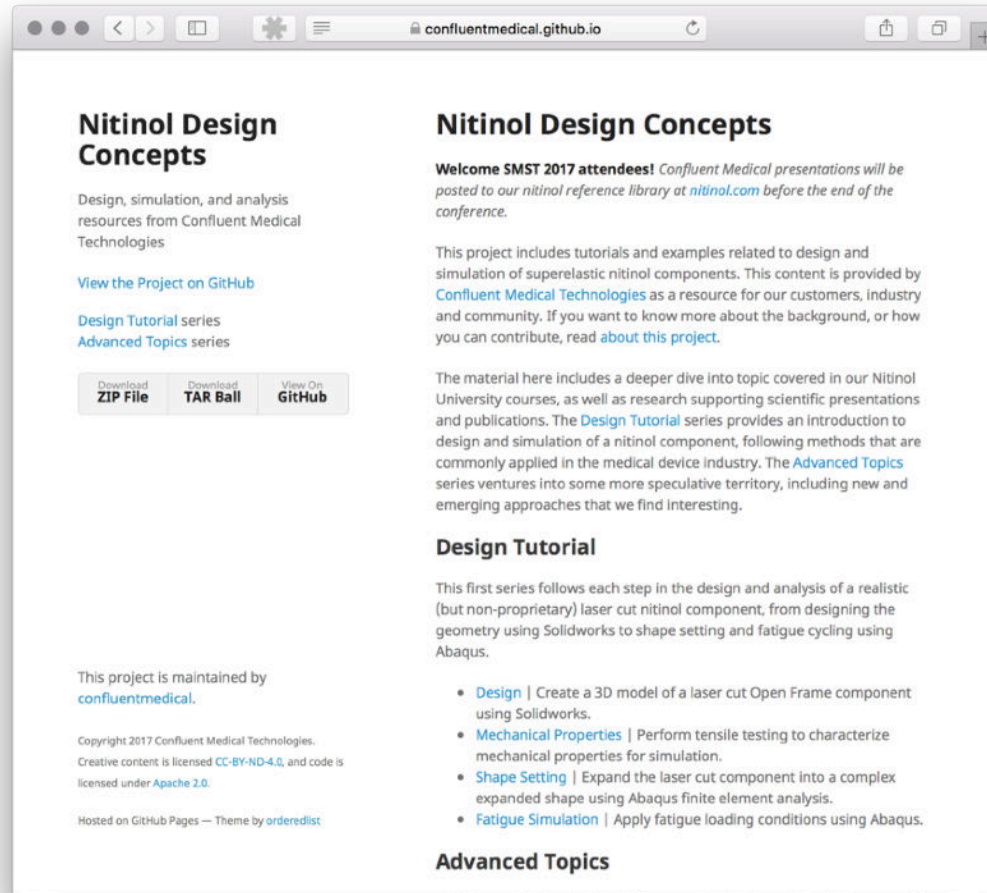
Sub- $\mu\text{m}$  x-ray computed tomography

Monte-Carlo risk assessment

> **Resources**



# More resources online: Nitinol Design Concepts



**Nitinol Design Concepts**

Design, simulation, and analysis resources from Confluent Medical Technologies

[View the Project on GitHub](#)

[Design Tutorial series](#)  
[Advanced Topics series](#)

[Download ZIP File](#) [Download TAR Ball](#) [View On GitHub](#)

**Nitinol Design Concepts**

Welcome SMST 2017 attendees! Confluent Medical presentations will be posted to our nitinol reference library at [nitinol.com](http://nitinol.com) before the end of the conference.

This project includes tutorials and examples related to design and simulation of superelastic nitinol components. This content 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 topic 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) laser cut nitinol component, from designing the geometry using Solidworks to shape setting and fatigue cycling using Abaqus.

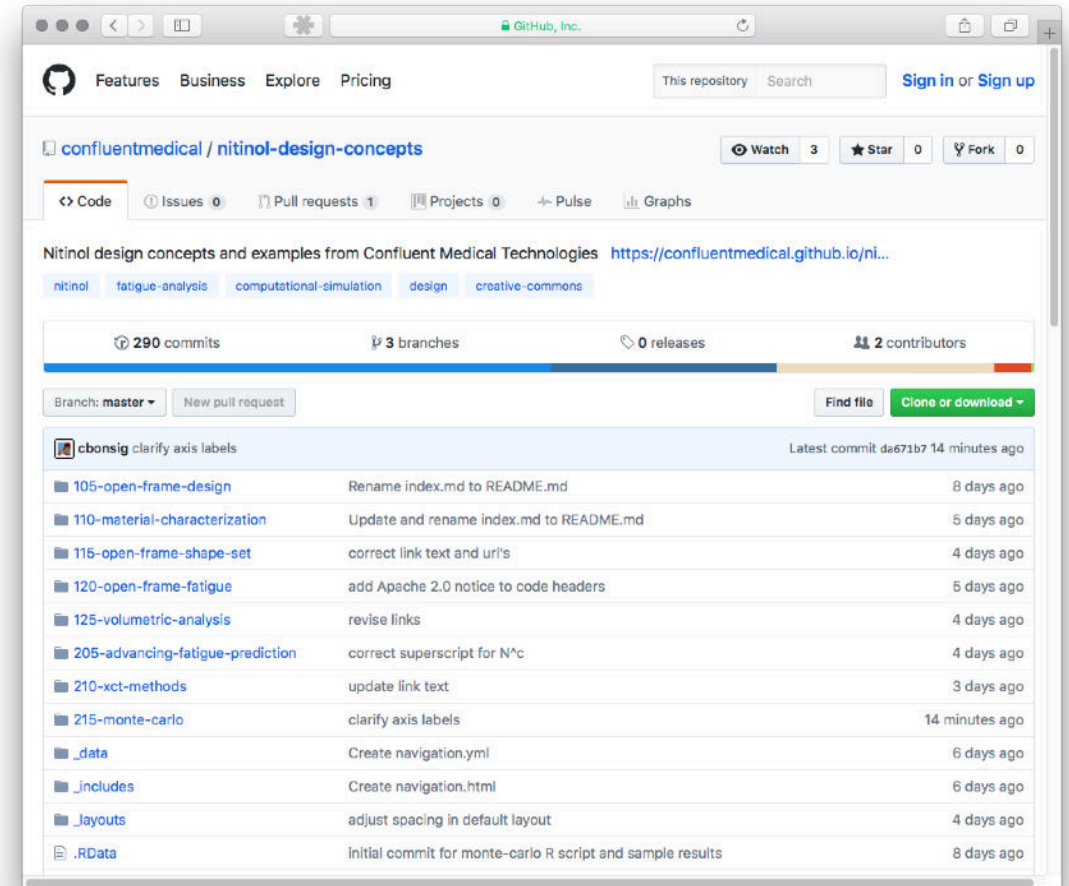
- [Design](#) | Create a 3D model of a laser cut Open Frame component using Solidworks.
- [Mechanical Properties](#) | Perform tensile testing to characterize mechanical properties for simulation.
- [Shape Setting](#) | Expand the laser cut component into a complex expanded shape using Abaqus finite 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-ND-4.0](#), and code is licensed under [Apache 2.0](#).

Hosted on GitHub Pages — Theme by [orderedlist](#)



confluentmedical / nitinol-design-concepts

290 commits 3 branches 0 releases 2 contributors

Branch: master New pull request Find file Clone or download

cbonsig clarify axis labels Latest commit da671b7 14 minutes ago

105-open-frame-design	Rename index.md to README.md	8 days ago
110-material-characterization	Update and rename index.md to README.md	5 days ago
115-open-frame-shape-set	correct link text and url's	4 days ago
120-open-frame-fatigue	add Apache 2.0 notice to code headers	5 days ago
125-volumetric-analysis	revise links	4 days ago
205-advancing-fatigue-prediction	correct superscript for N <sup>c</sup>	4 days ago
210-xct-methods	update link text	3 days ago
215-monte-carlo	clarify axis labels	14 minutes ago
_data	Create navigation.yml	6 days ago
_includes	Create navigation.html	6 days ago
_layouts	adjust spacing in default layout	4 days ago
.RData	initial commit for monte-carlo R script and sample results	8 days ago

SMST2017

SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES CONFERENCE AND EXPOSITION



[bit.ly/smst17ndc](http://bit.ly/smst17ndc)

**Craig Bonsignore**

Confluent Medical Technologies

[craig.bonsignore@confluentmedical.com](mailto:craig.bonsignore@confluentmedical.com)

@cbonsig

**SMST2017**

SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES CONFERENCE AND EXPOSITION