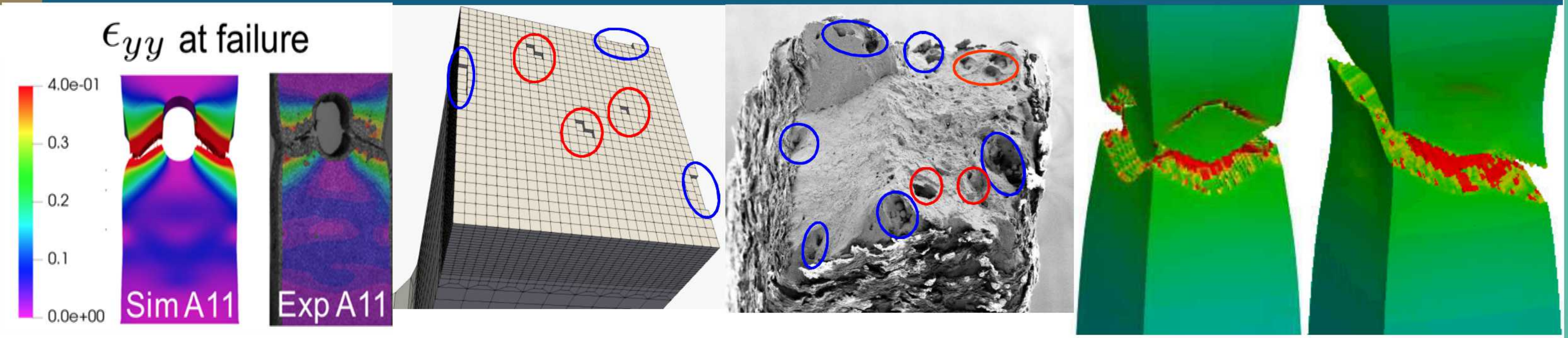
SAND2019-6056C

Sandia Fracture Challenge 3 (SFC3): Sandia Team Q's Approach



PRESENTED BY

C. Alleman, G. Bergel, J. Foulk, **K. Karlson**, K. Manktelow, J. Ostien, M. Stender, A. Stershic, M. Veilleux

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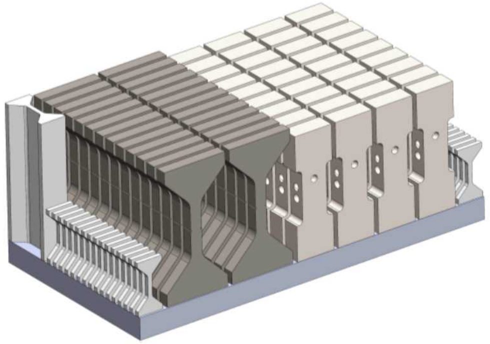
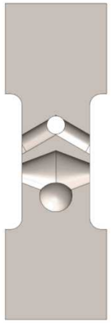
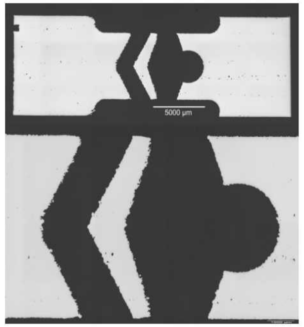
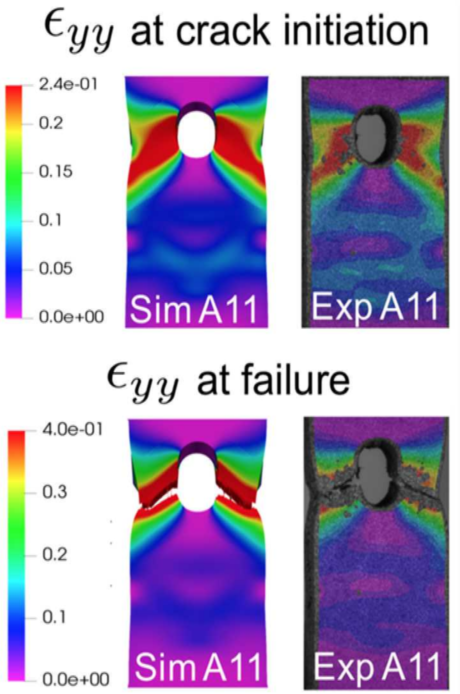
Overview of approach

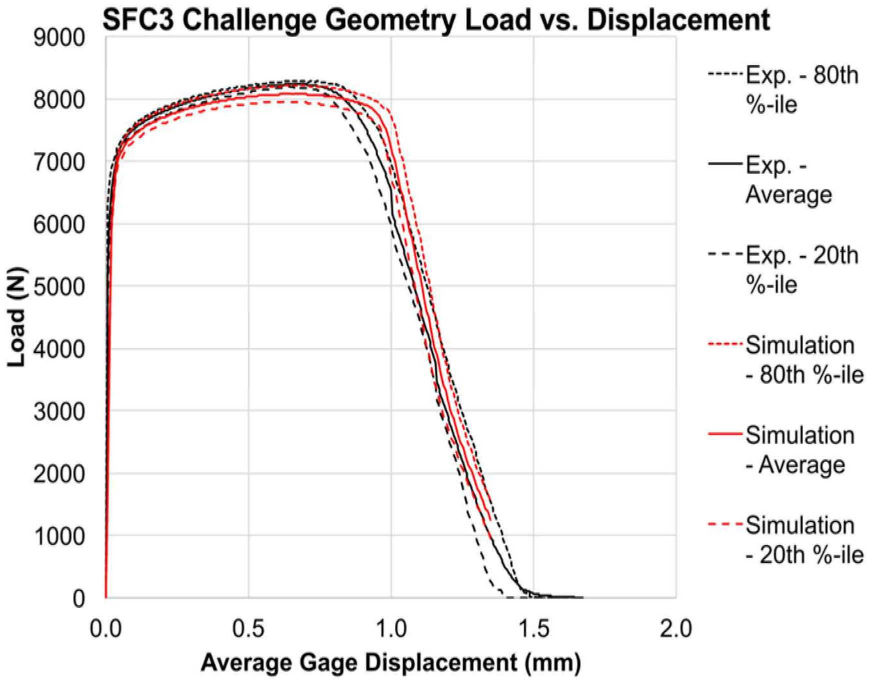
- Examined test procedures, geometries, and findings to build a modeling methodology
- Constitutive components: plastic anisotropy (SFC1), rate-dependence, and damage evolution (SFC2)
- Iterative and rapid parameterization of input physics through MatCal (SFC2) and Dakota
- Inclusion of variability through Kolmogorov-Smirinov test statistics and sensitivity studies



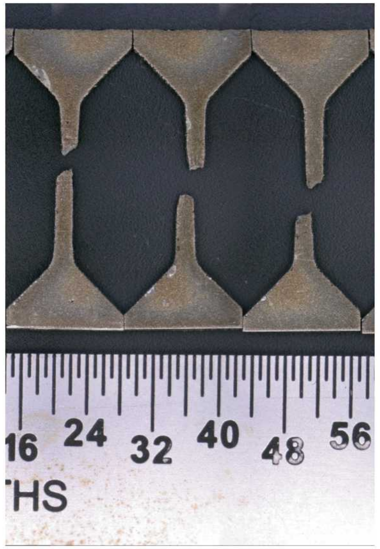


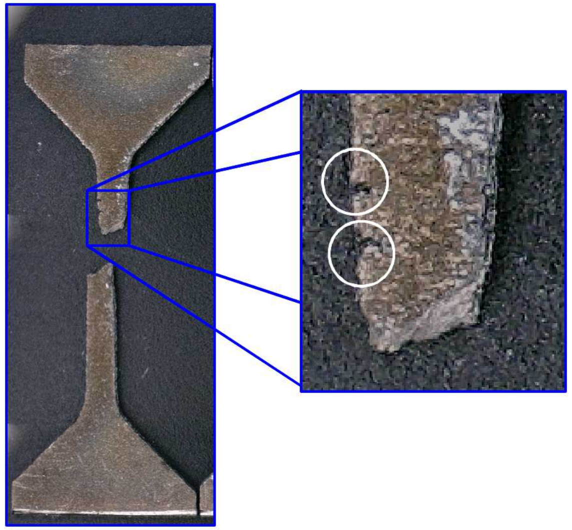




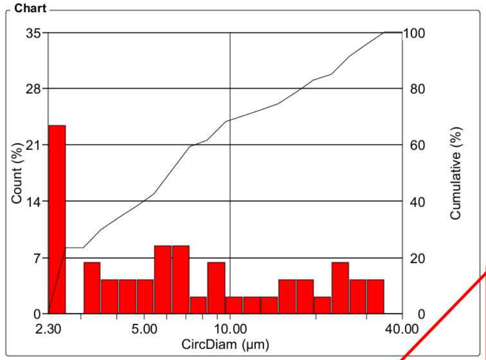


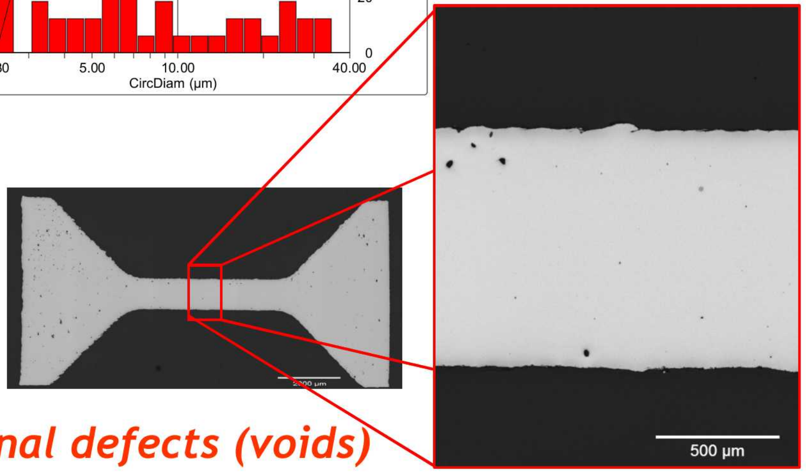
Reviewing tensile data



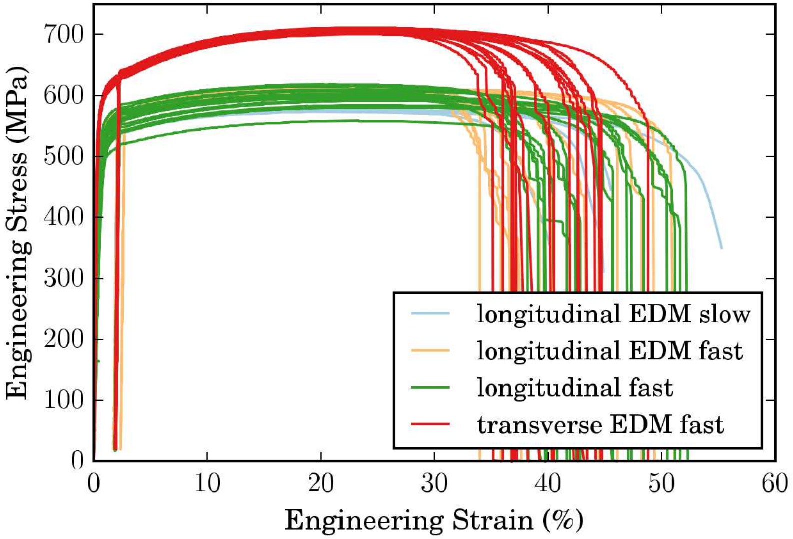


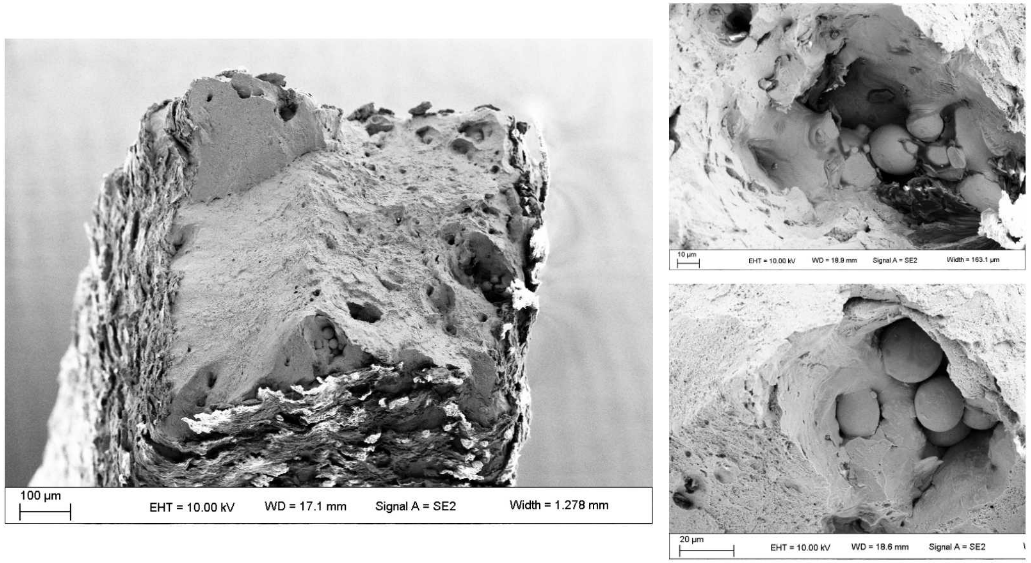
surface defects (cracks)



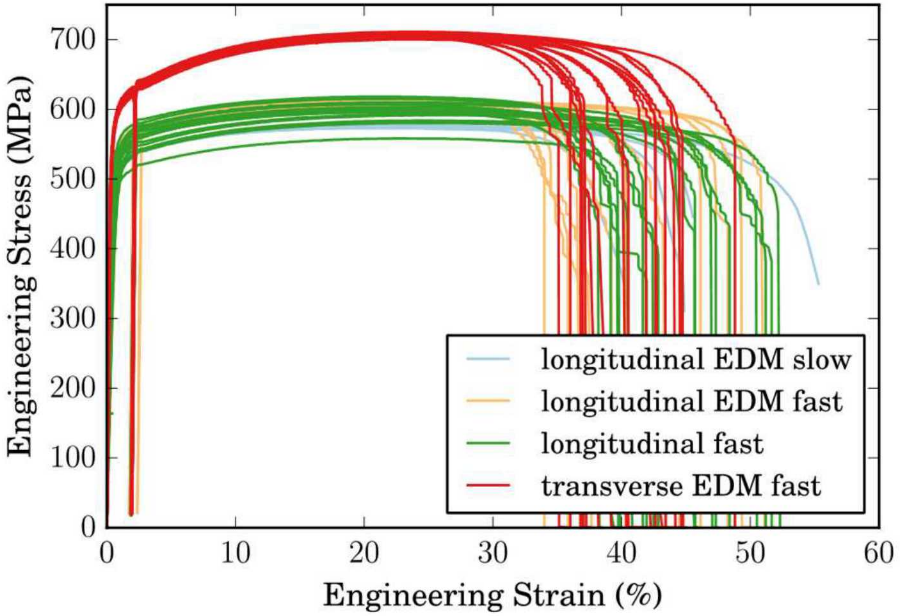


internal defects (voids)





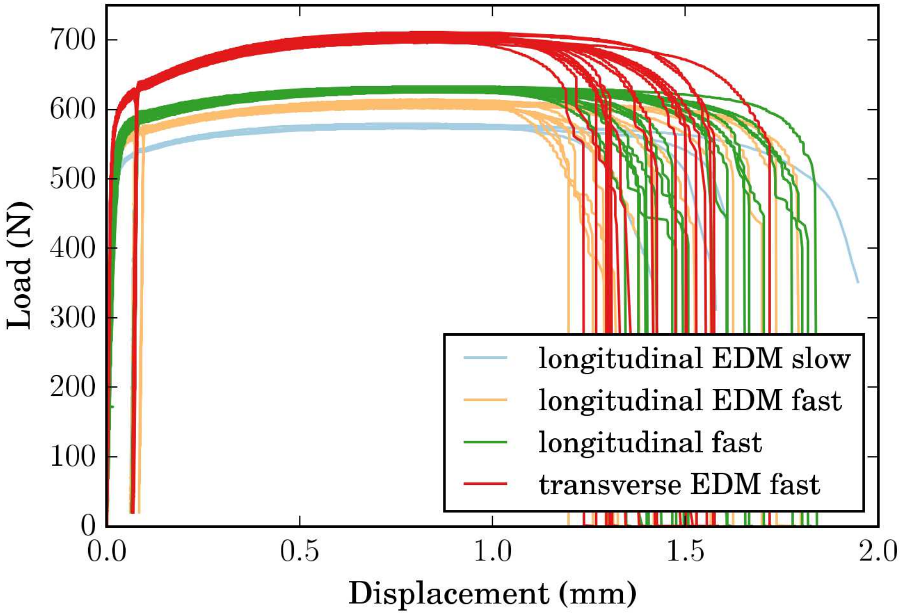
Modeling assumptions and calibration



Modeling methodologies

- Temperature and rate dependent plasticity
- Plastic anisotropy
- Geometric variability, surface defects/voids
  - Explicit representation of geometries
  - Inclusion of surface defects
- Void nucleation, growth

Modeling assumptions and calibration



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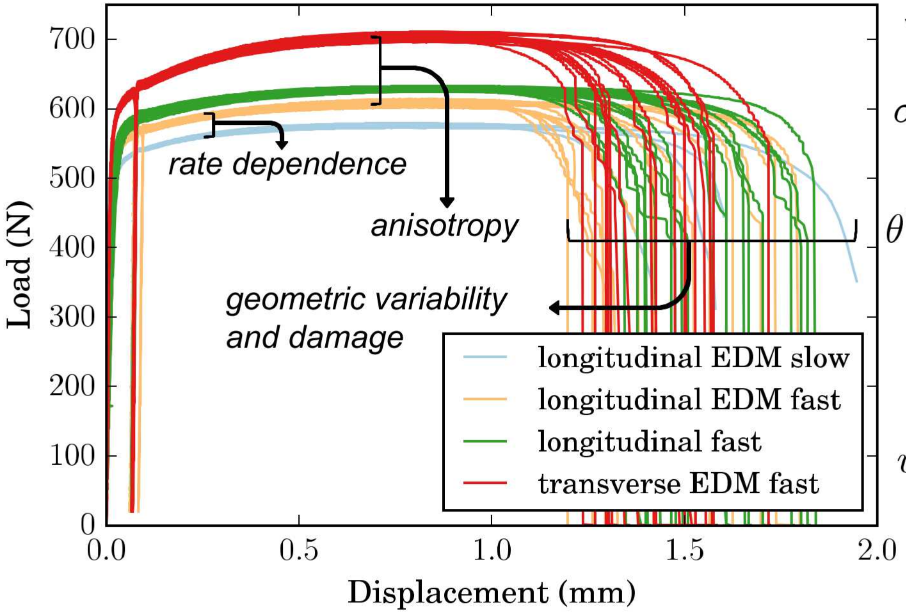

$$\mathcal{F} := \theta^2(\hat{\sigma}_{ij}) - \sigma_f^2 = 0$$

$$\sigma_f = Y_0 \left\{ 1 + \sinh^{-1}\left[\left(\frac{\dot{\epsilon}_p}{f}\right)^{1/n}\right]\right\} + A(\epsilon_p)^b$$

$$\begin{aligned}\theta^2(\hat{\sigma}_{ij}) = & F(\hat{\sigma}_{22} - \hat{\sigma}_{33})^2 + G(\hat{\sigma}_{33} - \hat{\sigma}_{11})^2 \\ & + H(\hat{\sigma}_{11} - \hat{\sigma}_{22})^2 + 2L\hat{\sigma}_{23}^2 \\ & + 2M\hat{\sigma}_{31}^2 + 2N\hat{\sigma}_{12}^2\end{aligned}$$

$$\begin{aligned}\dot{v_v} = & \sqrt{\frac{2}{3}}\dot{\epsilon}_p \frac{1}{\eta}(1+\eta v_v)\left[(1+\eta v_v)^{m+1} - 1\right] \\ & \cdot \sinh\left[\frac{2(2m-1)}{2m+1}\frac{\langle p \rangle}{\sigma_f}\right] - (v_v - v_0)\frac{\dot{\eta}}{\eta}\end{aligned}$$

$$\dot{\eta} = \eta\dot{\epsilon}_p\left(N_1\left[\frac{4}{27} - \frac{J_3^2}{J_2^3}\right] + N_3\left[\frac{|p|}{\sigma_f}\right]\right)$$

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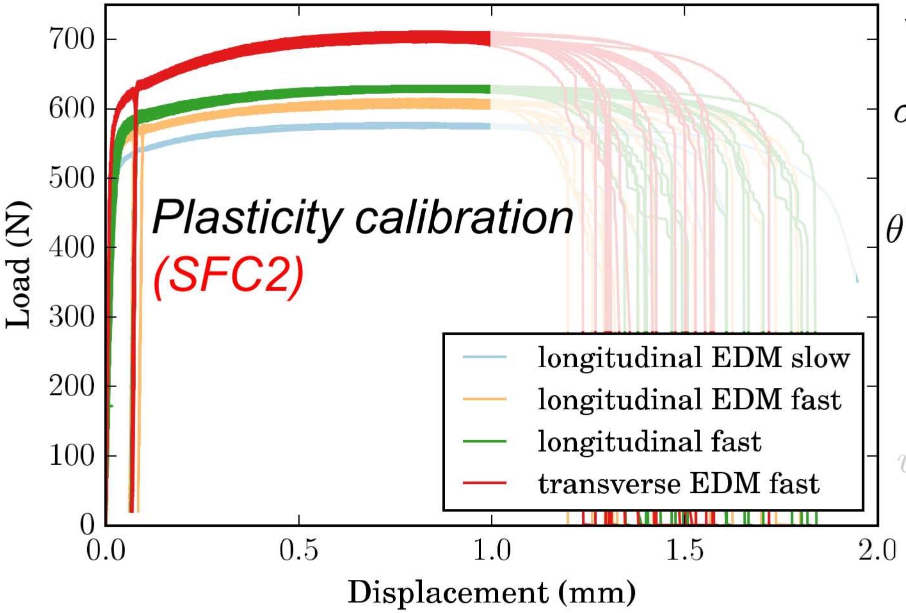

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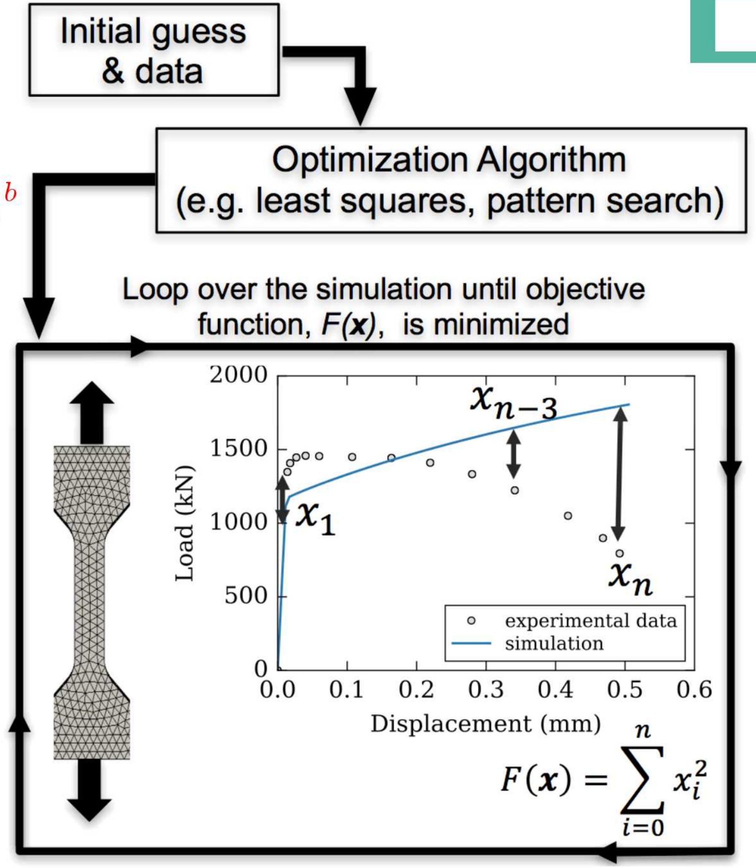

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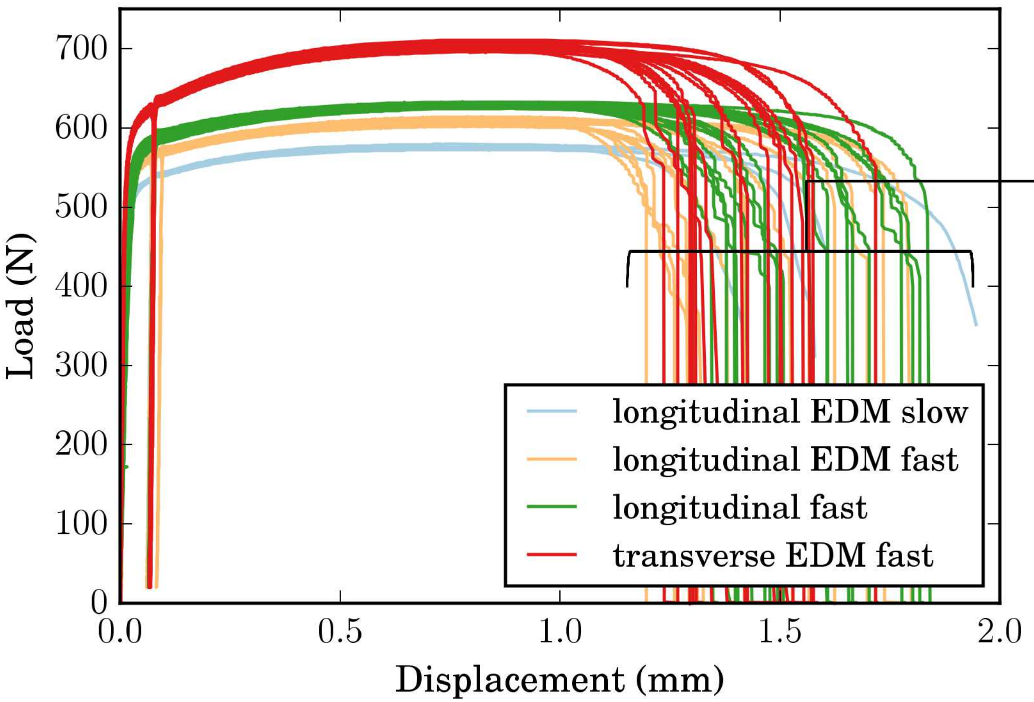
- **Sierra/SM** for FEA
- **Dakota** for Optimization Algorithm
- **MatCal** for file and model management

With **14 unknown parameters**, calibrate using an iterative approach with increasing complexity :
(1) rate dependence (2) hardening (3) anisotropy (4) damage

Learning through targeted studies

- Method 1 – constitutive model can account for observed variability
- Method 2– explicit modeling of defects required to accurately capture variability



variability of interest

Learning through targeted studies

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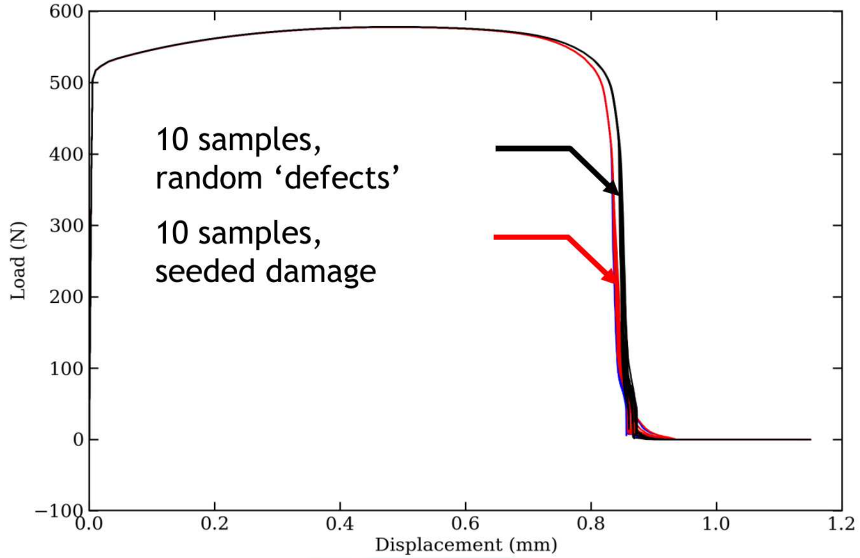

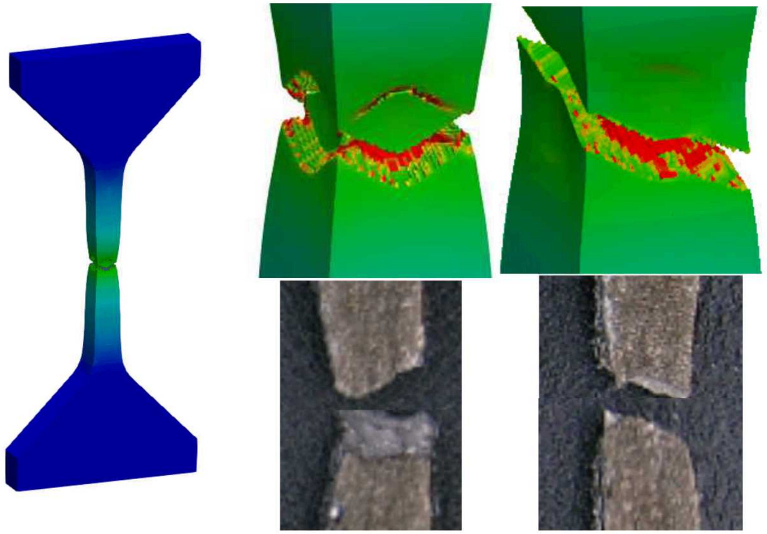

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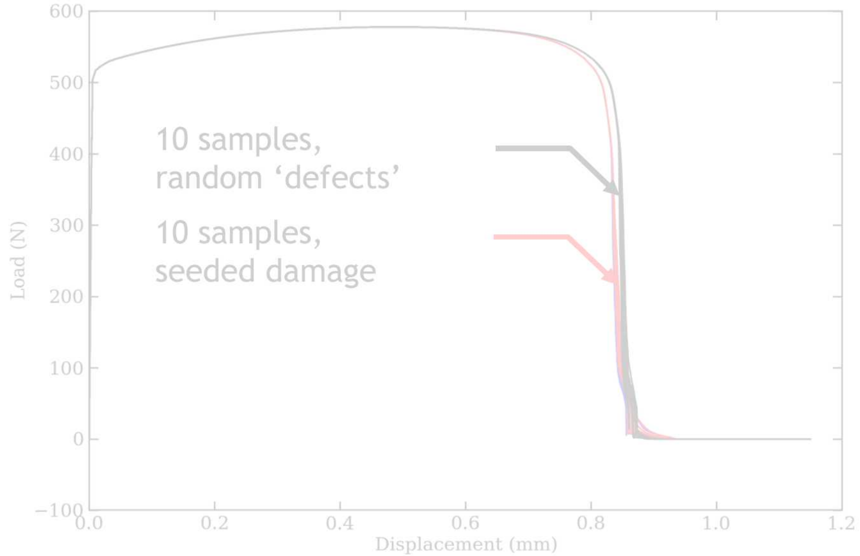

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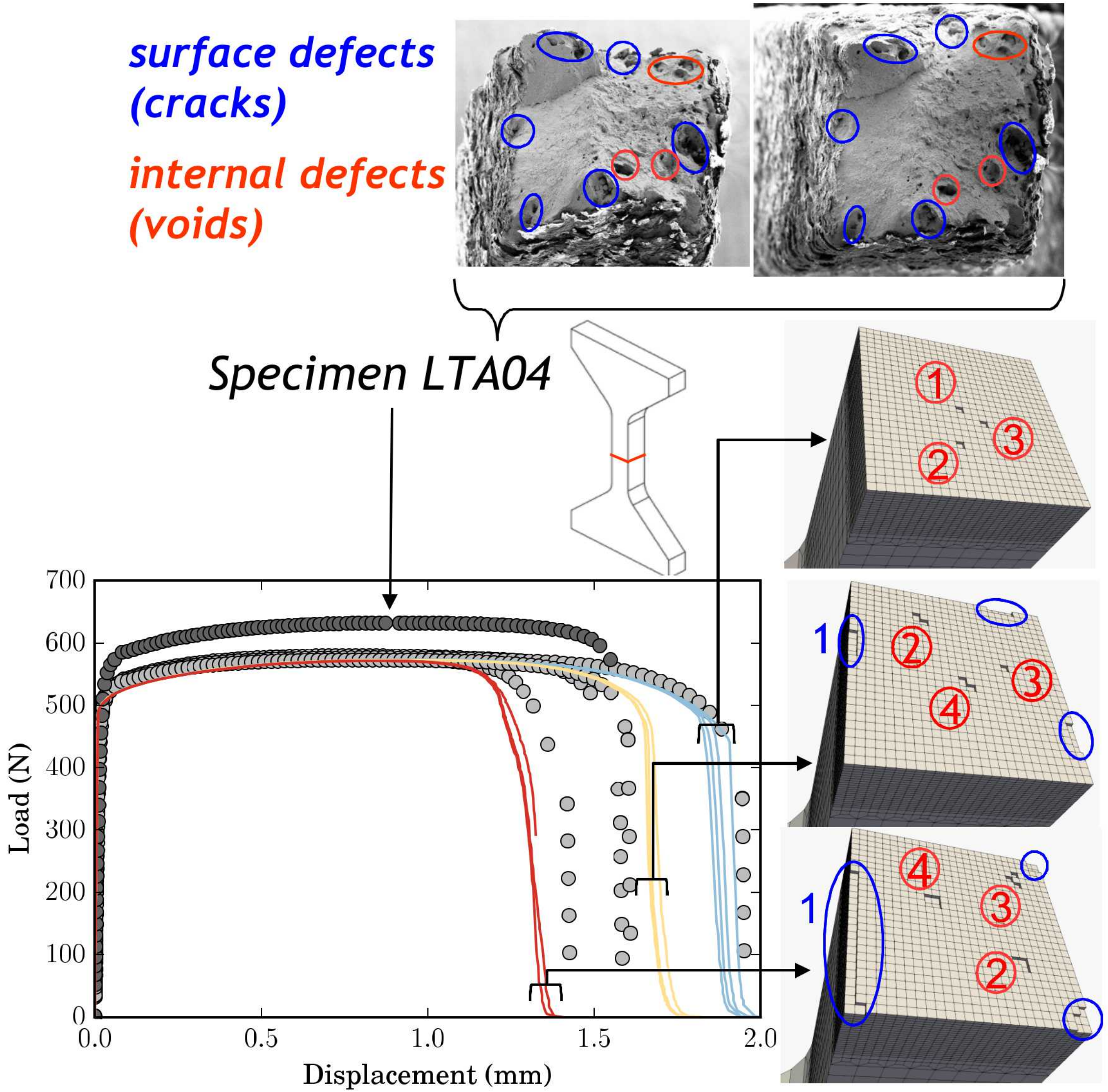
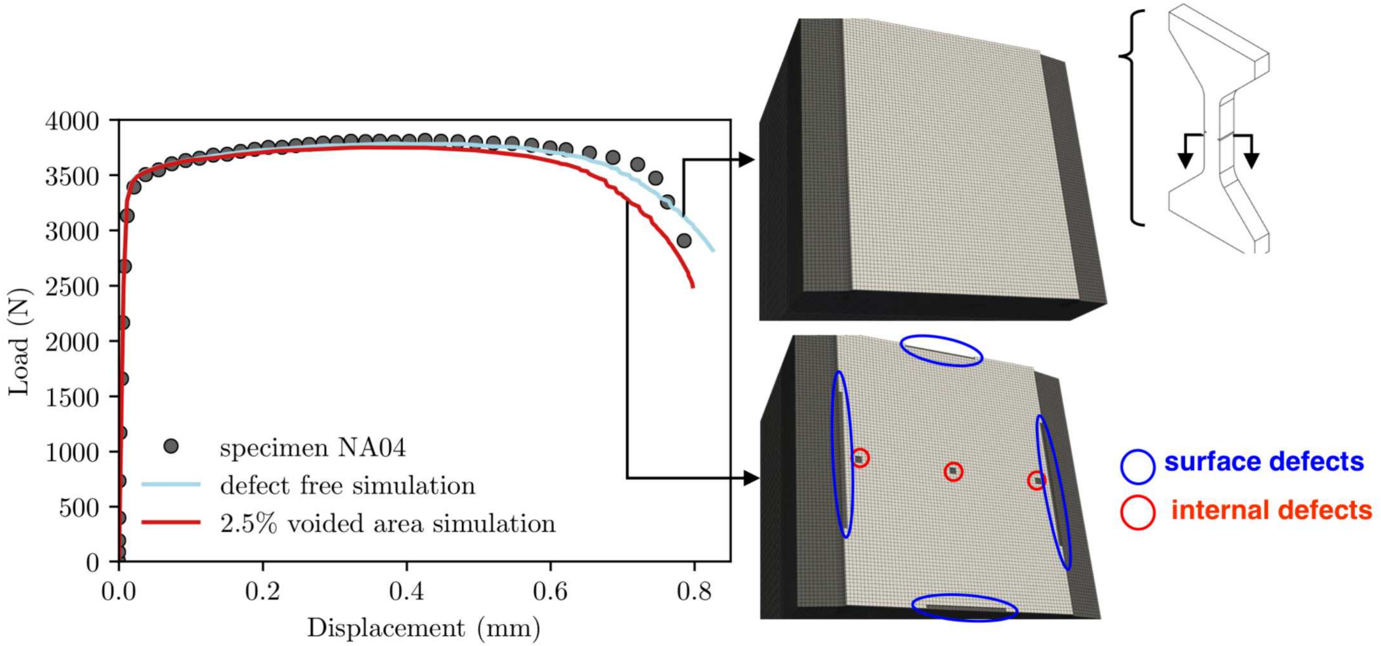
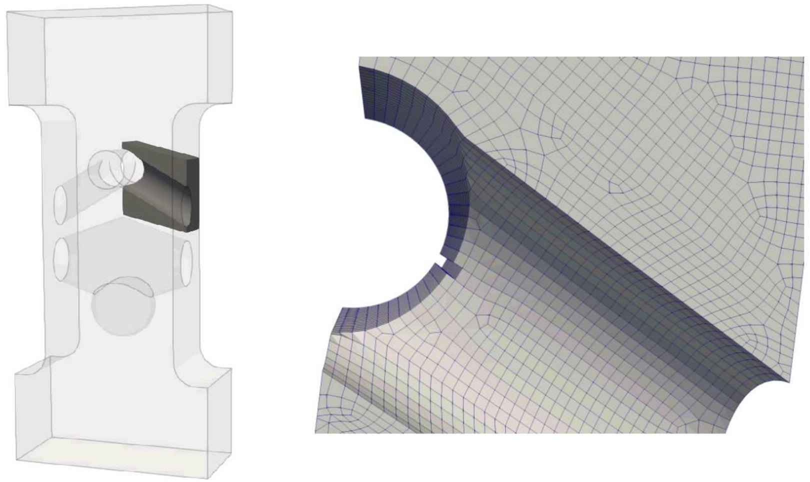


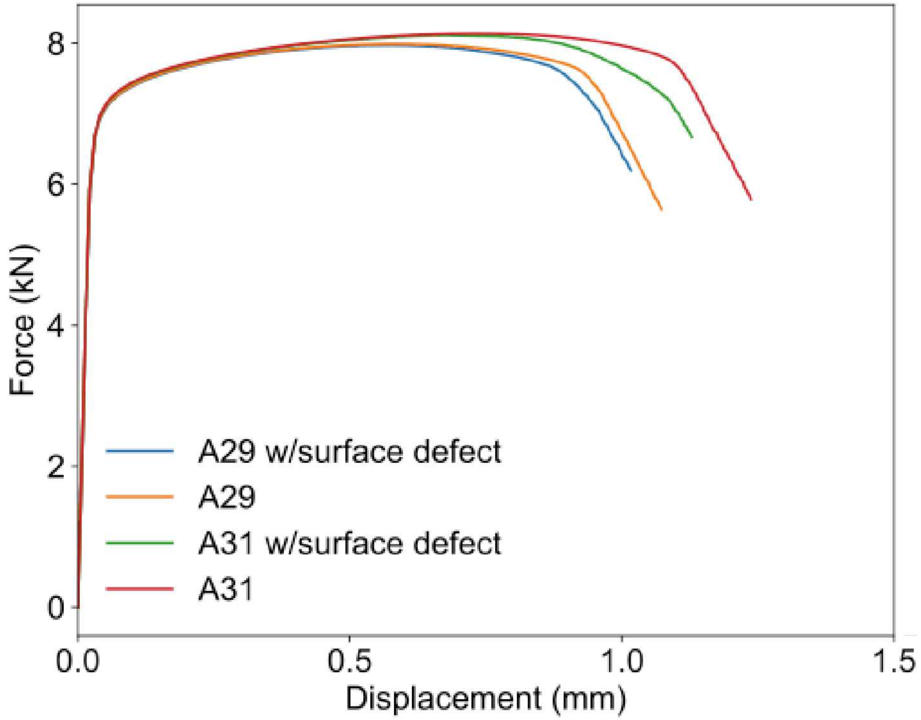
Seeding large defects in notched and challenge geometries

- Notched specimen



- Challenge specimen

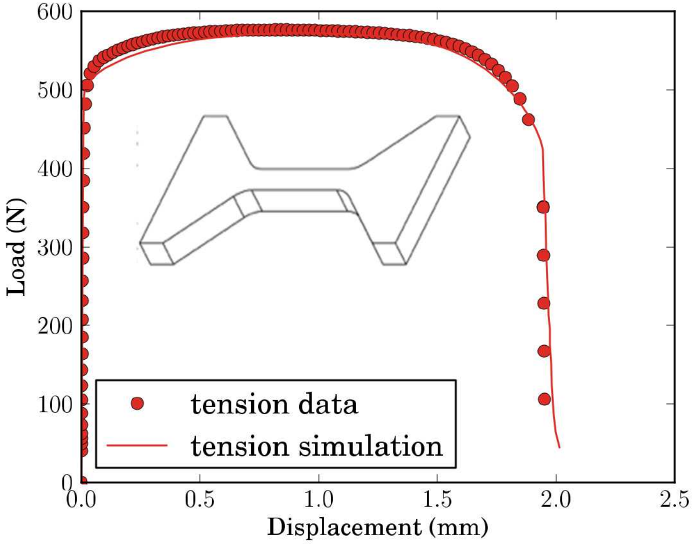


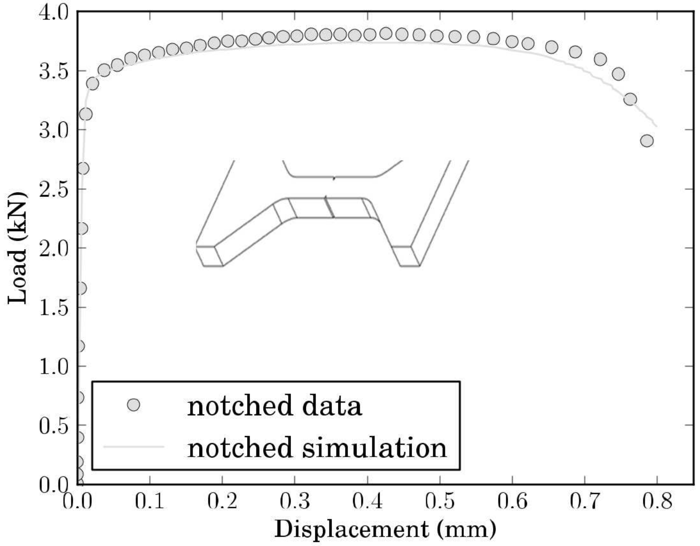


- Defects have small effect on load displacement curves
- Not enough data to develop defect model

Calibrate damage and account for variability

- Calibrated damage material constants to the uniaxial and notched specimens with largest displacements
- Calibrated material model to all data sets individually to obtain parameter variability





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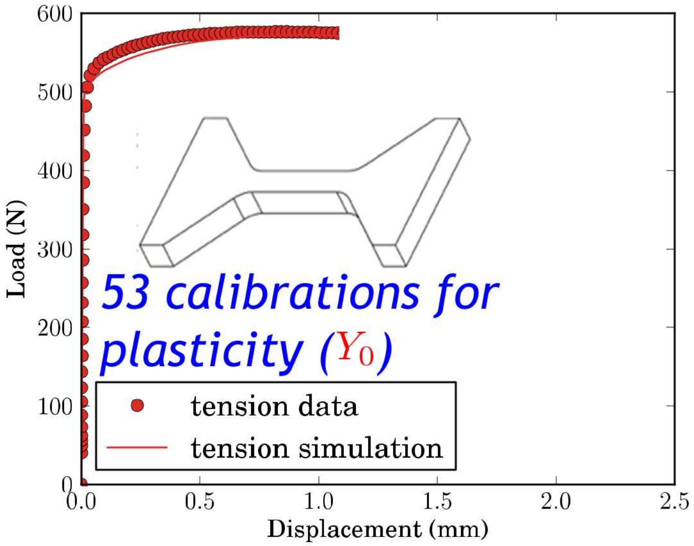

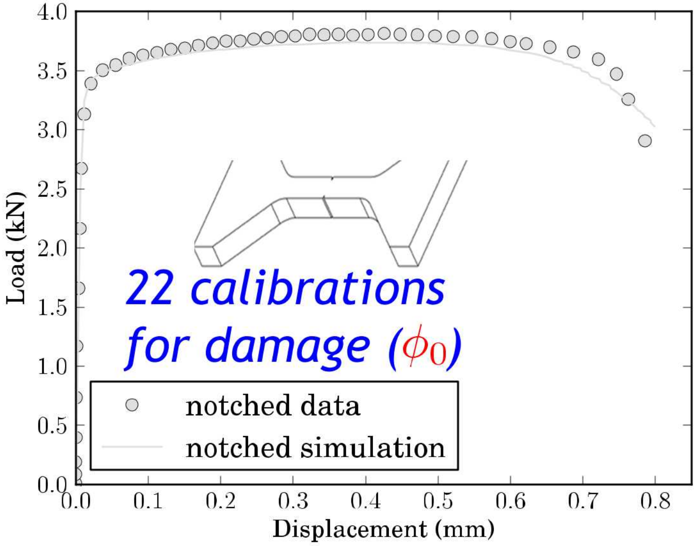

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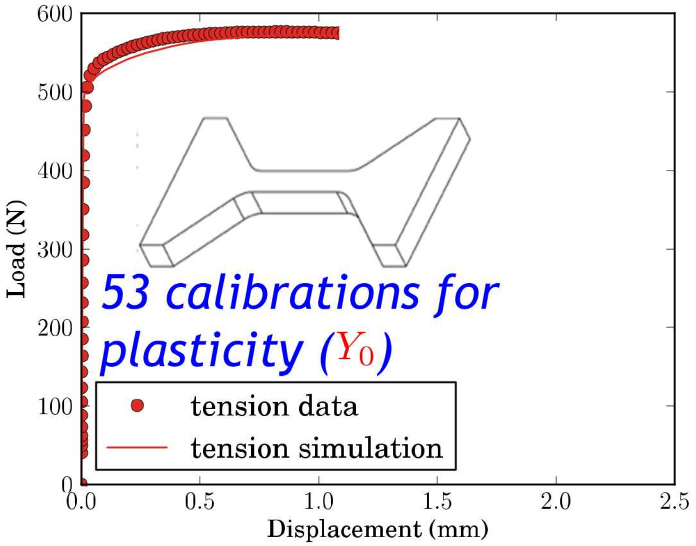
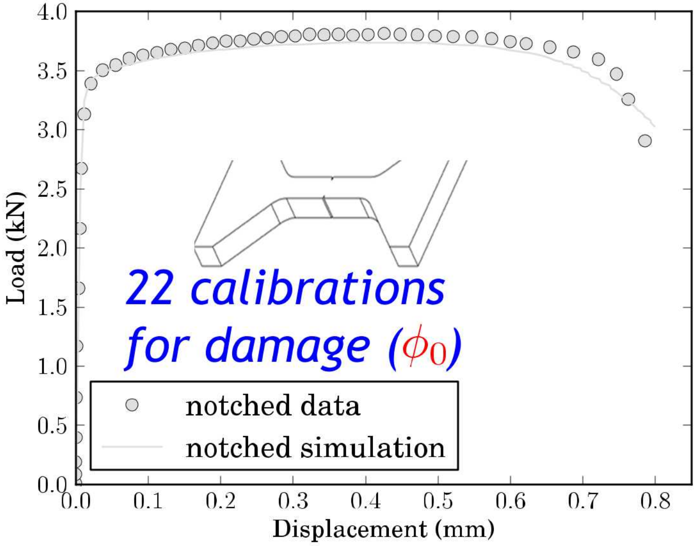
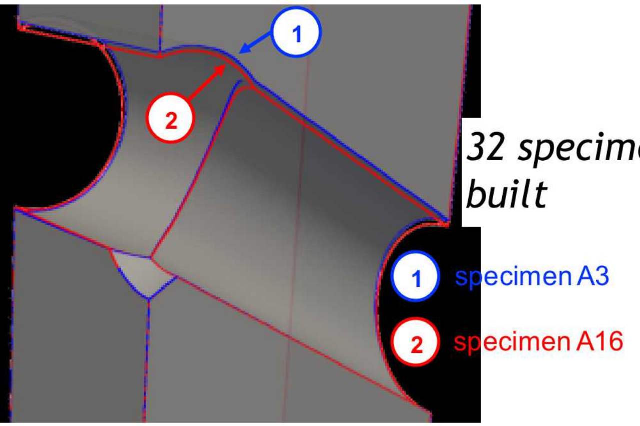
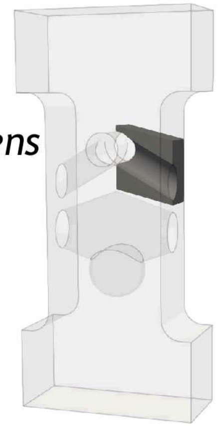
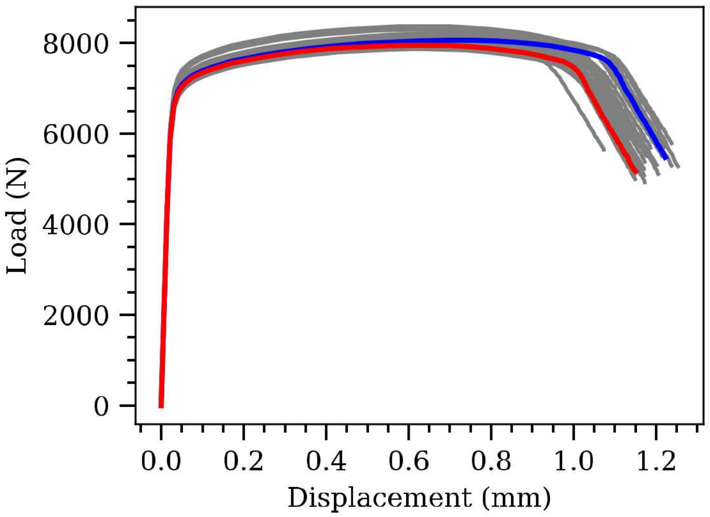






32 specimens built





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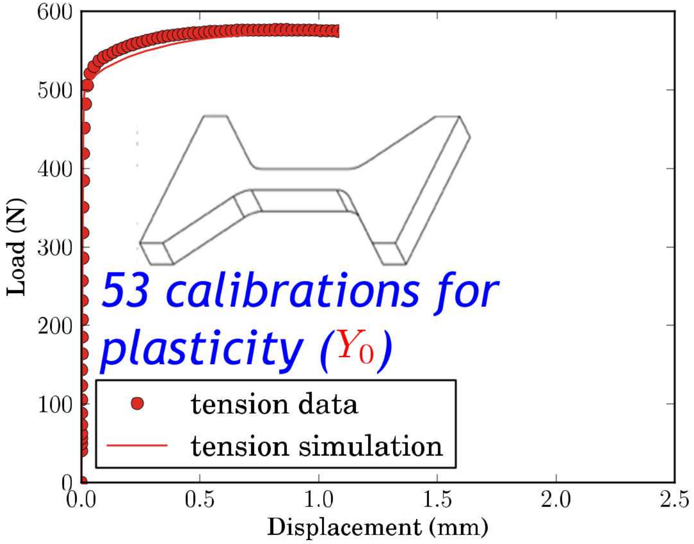

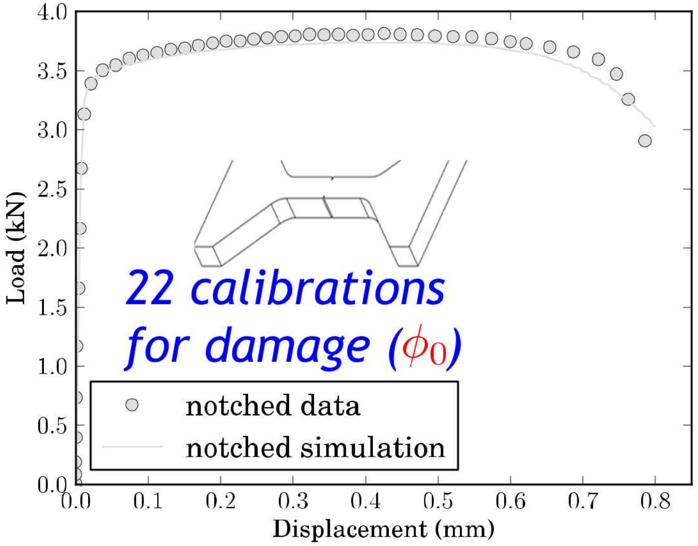

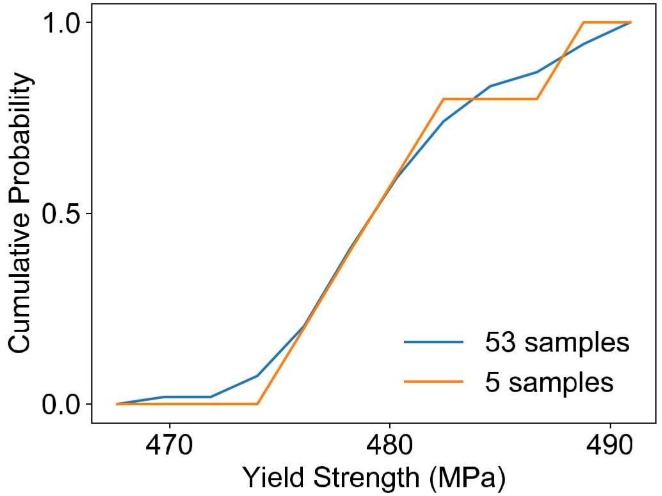

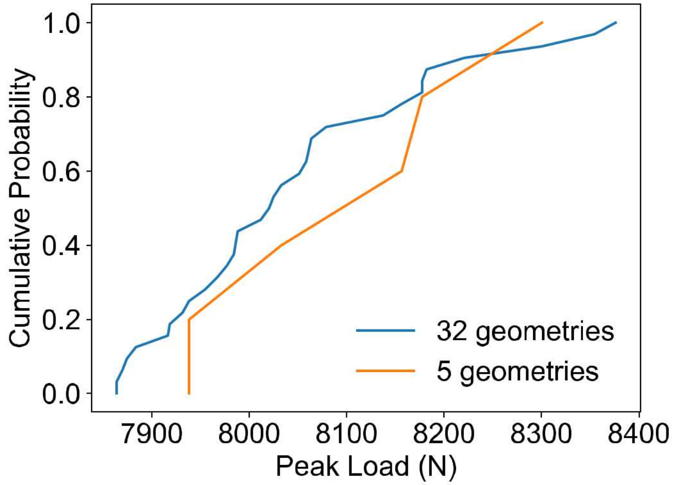

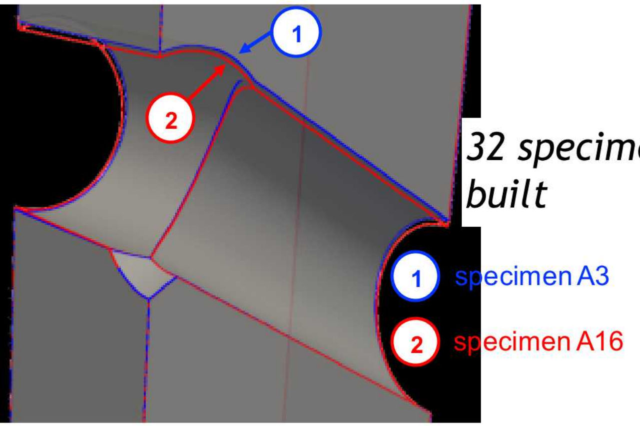

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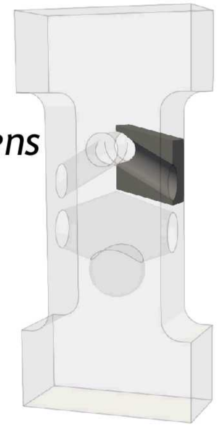
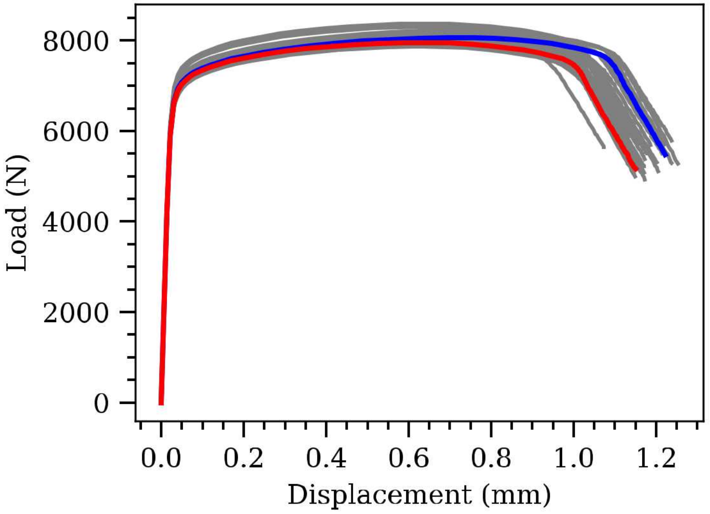


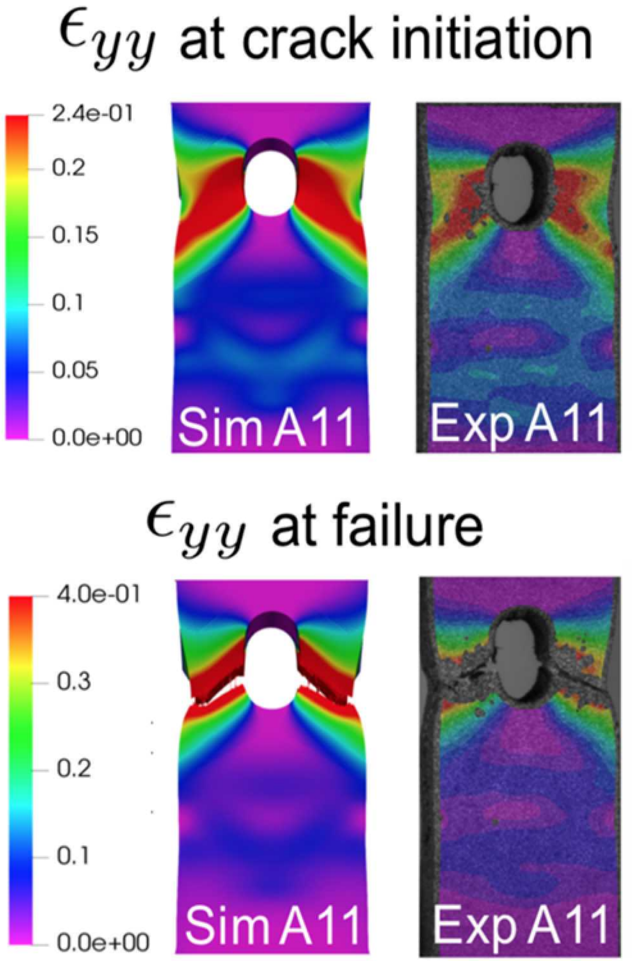


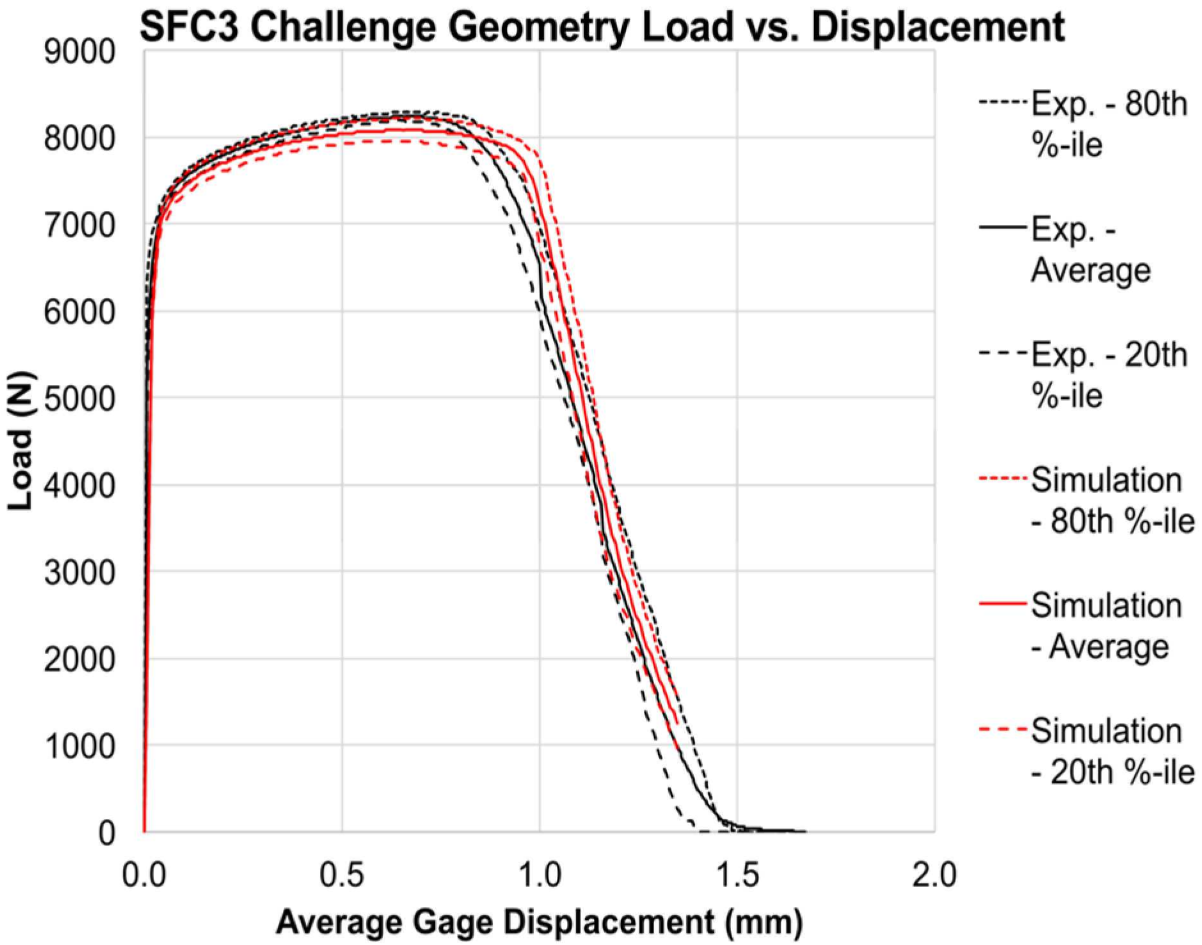
*The **Kolmogorov-Smirnov** test statistic used to optimally obtain a reduced set of representative simulations.*

*Reduced ~**42000** simulations to **125** simulations total*

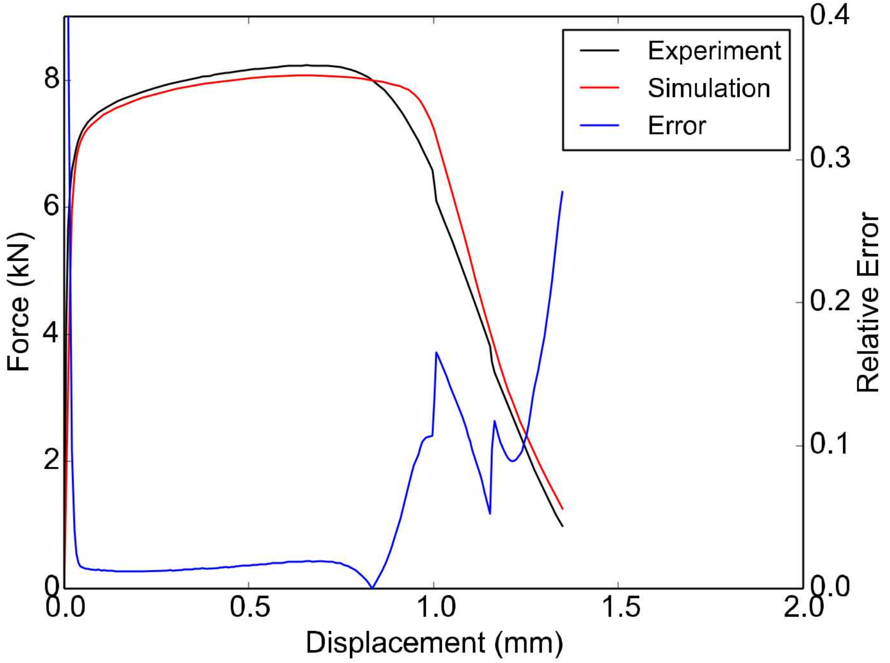
Blind predictions

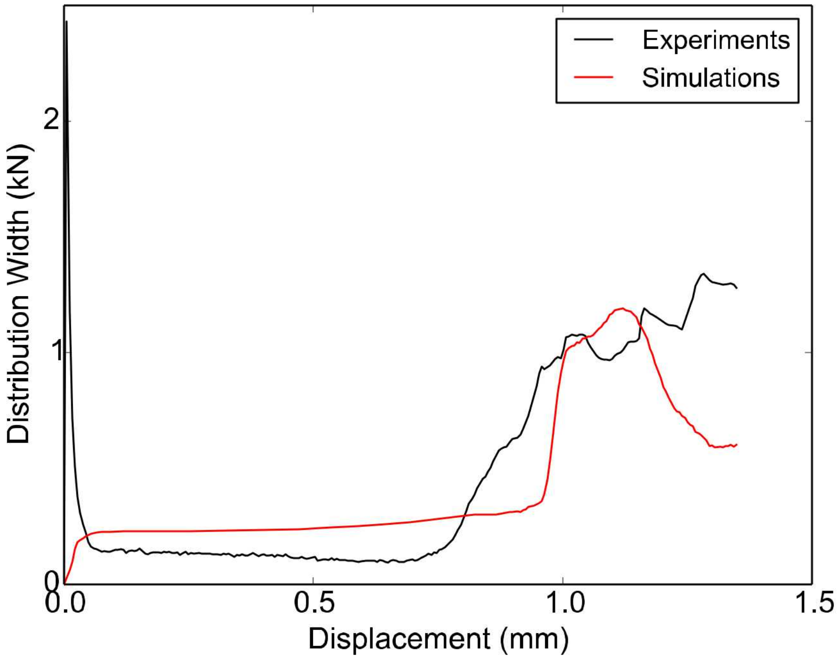
- Load displacement prediction shows good agreement to experimental results
- Local measurements (strains) are accurate at higher displacements

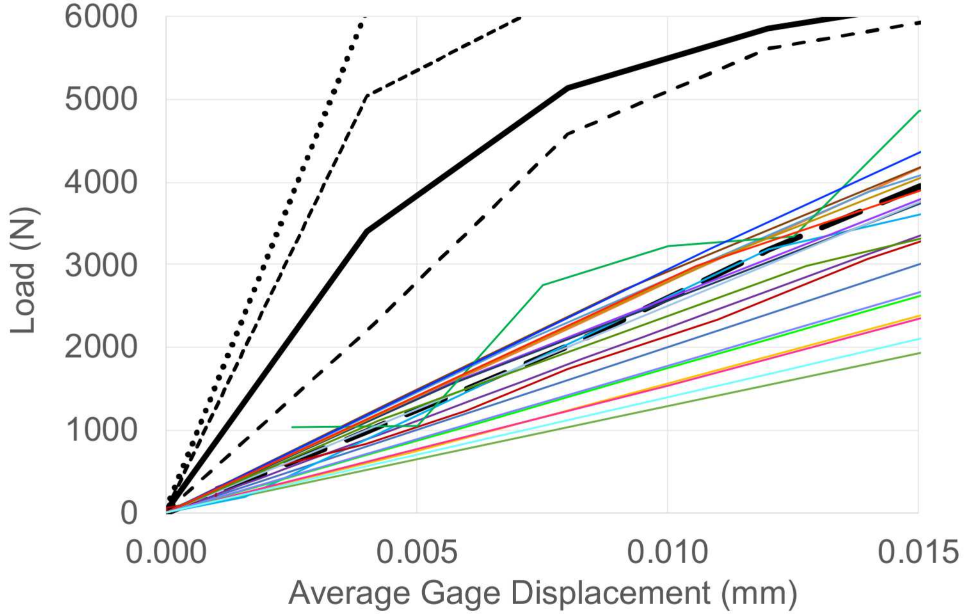




Global load displacement errors

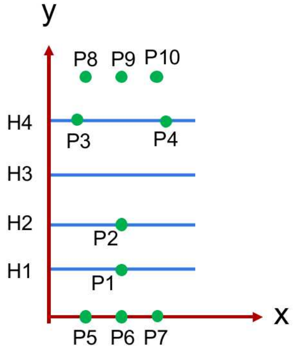






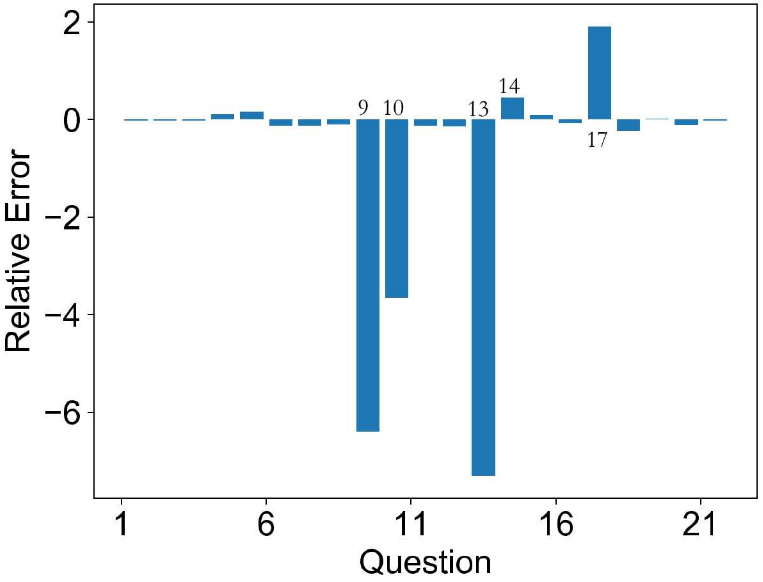
- Elastic slope of average experiments is 4 times that of simulations and varies by a factor of 6

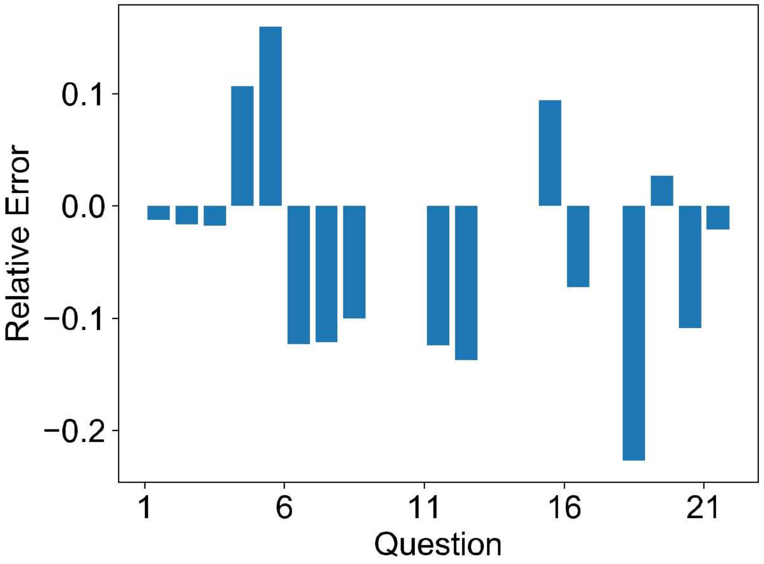
Error for all QoIs



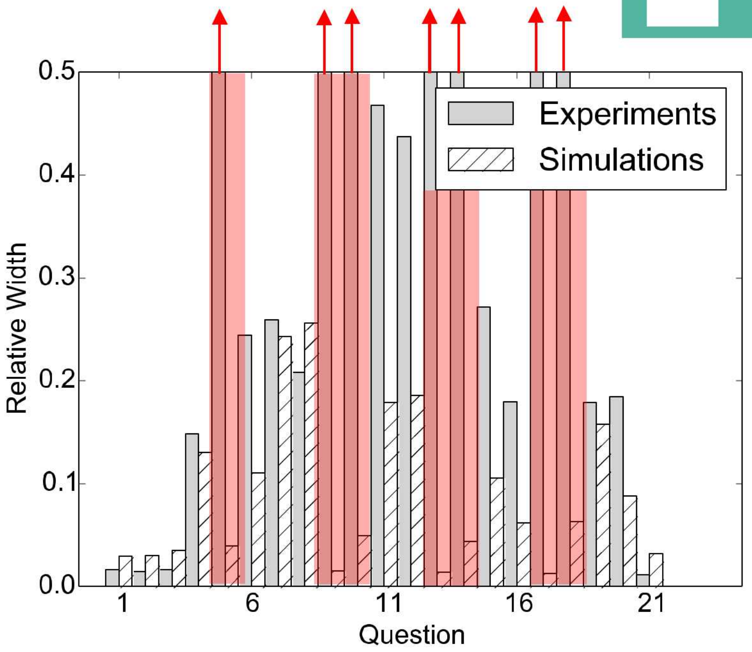
No.	Question
1	Q1 Force @ D = 0.25 mm
2	Q1 Force @ D = 0.50 mm
3	Q1 Force @ D = 0.75 mm
4	Q1 Force @ D = 1.00 mm
5	Q2/P1 ϵ_{YY} @ 75% PL
6	Q2/P1 ϵ_{YY} @ 90% PL (Pre)
7	Q2/P1 ϵ_{YY} @ Peak Load
8	Q2/P1 ϵ_{YY} @ 90% PL (Post)
9	Q2/P2 ϵ_{YY} @ 75% PL
10	Q2/P2 ϵ_{YY} @ 90% PL (Pre)
11	Q2/P2 ϵ_{YY} @ Peak Load
12	Q2/P2 ϵ_{YY} @ 90% PL (Post)
13	Q2/P3 ϵ_{YY} @ 75% PL
14	Q2/P3 ϵ_{YY} @ 90% PL (Pre)
15	Q2/P3 ϵ_{YY} @ Peak Load
16	Q2/P3 ϵ_{YY} @ 90% PL (Post)
17	Q2/P4 ϵ_{YY} @ 75% PL
18	Q2/P4 ϵ_{YY} @ 90% PL (Pre)
19	Q2/P4 ϵ_{YY} @ Peak Load
20	Q2/P4 ϵ_{YY} @ 90% PL (Post)
21	Q2 Maximum Load

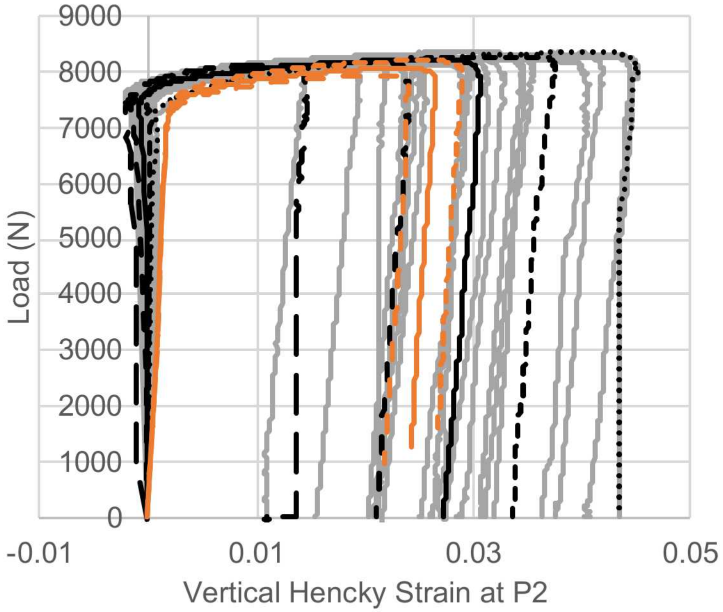
Number	Average	Range	Range/Average
9	-0.000276	0.000817	2.96
10	-0.000761	0.001325	1.74
13	-0.000348	0.001525	4.38
14	0.007084	0.007041	0.99
17	0.000751	0.001452	1.93
18	0.012887	0.006902	0.54





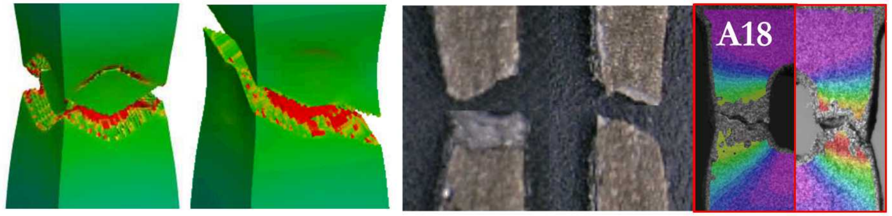
Experiments show negative strain at 75% peak load for some specimens at pts 2, 3 and 4. No simulations results show this.



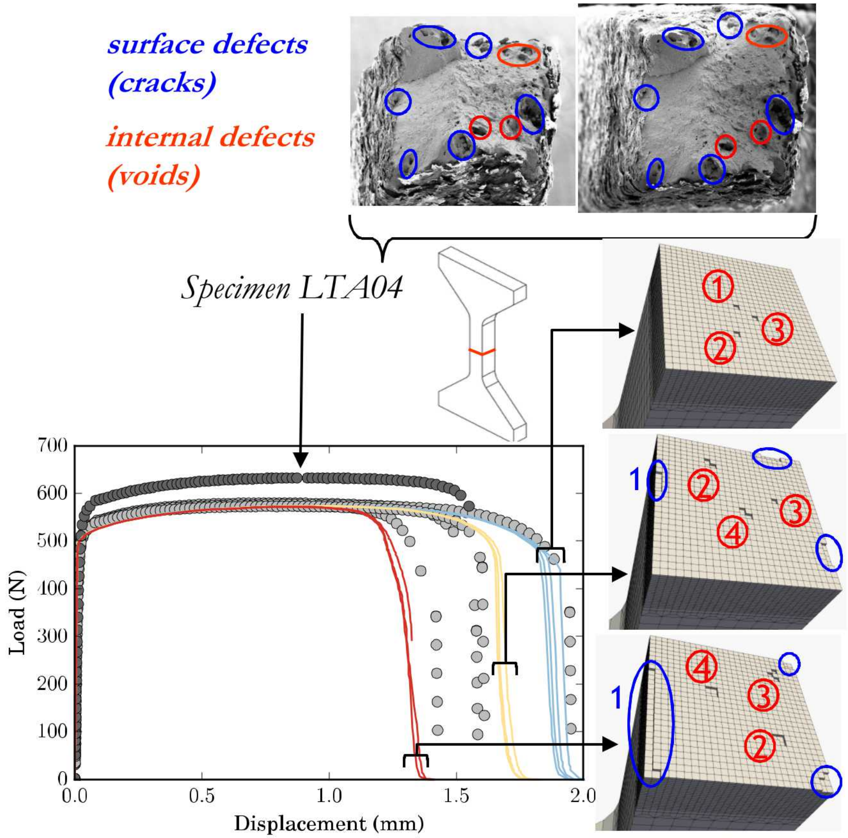


Lessons learned

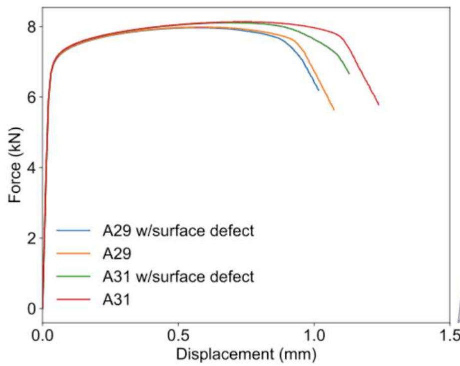
- Local deformation sensitive to local defect structures

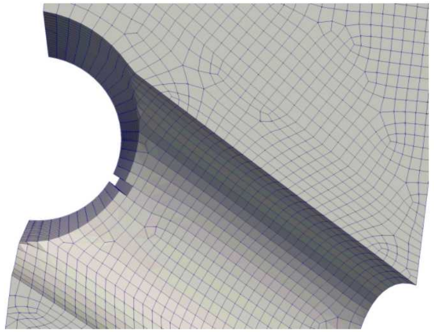


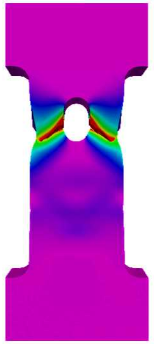
- Global measures can be sensitive to small, local geometric inconsistencies and defects



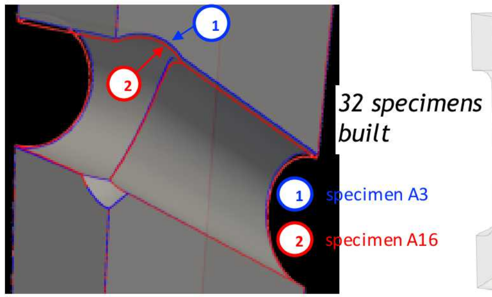
- Stress concentrations, however, overwhelm surface defects to mitigate differences in the global response

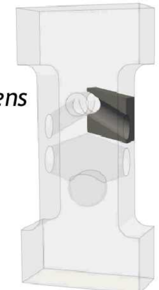


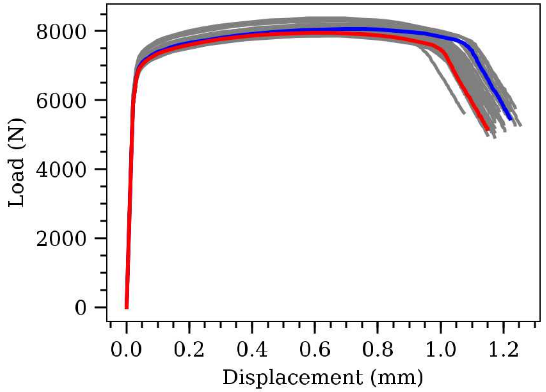


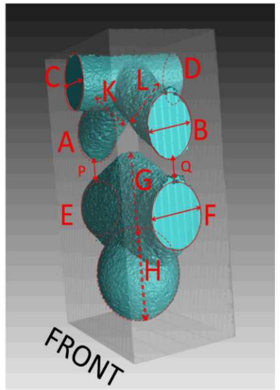


- The geometric character of dominant stress concentrations drives the global response



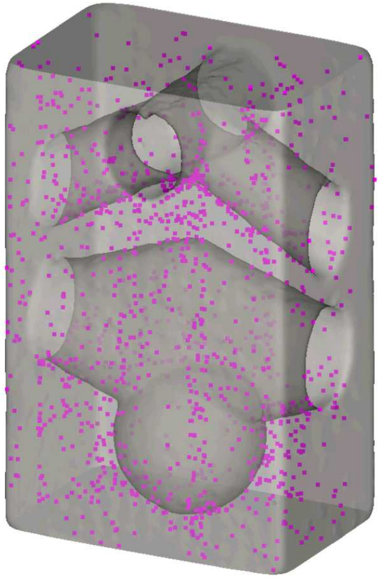


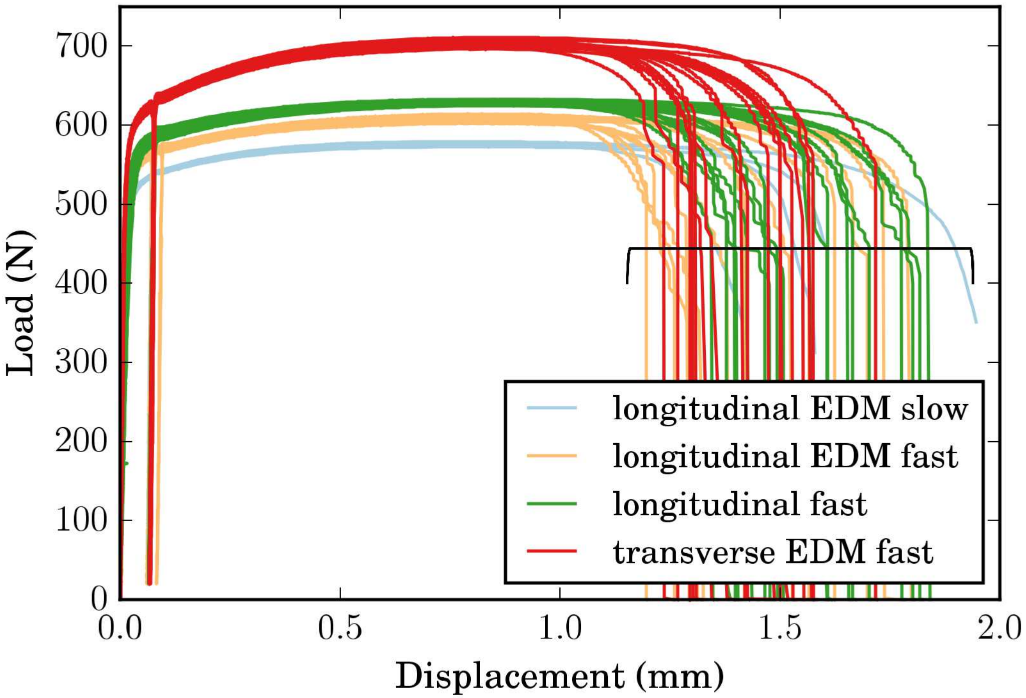


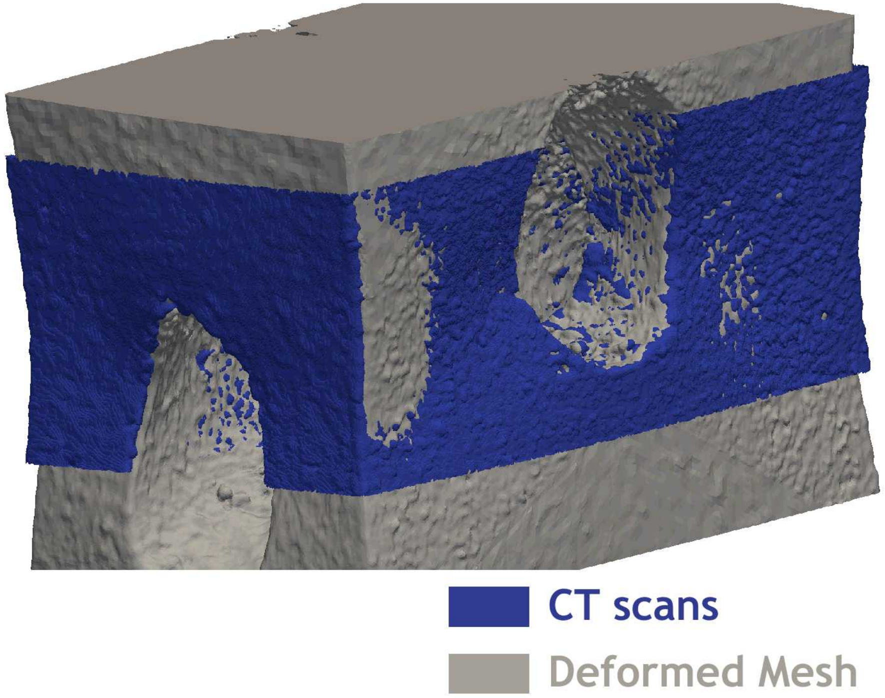


Current/future work: overview

- Improve local strain predictions by including porosity and voids
- Underlying assumption: voids primary driver for observed variability
  - Ignoring surface roughness
  - Assuming oxides or other impurities/imperfections can be homogenized in material model
- Requires three steps:
  - Calibrate void-free material model
  - Develop stochastic void model
  - Validate the void model and void-free material model

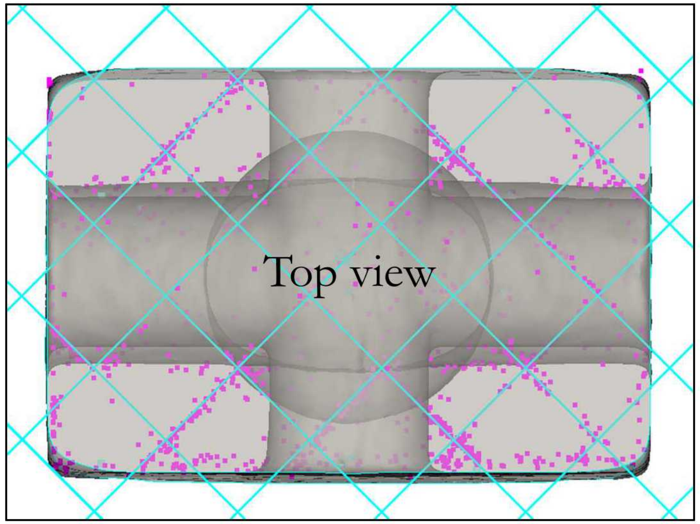


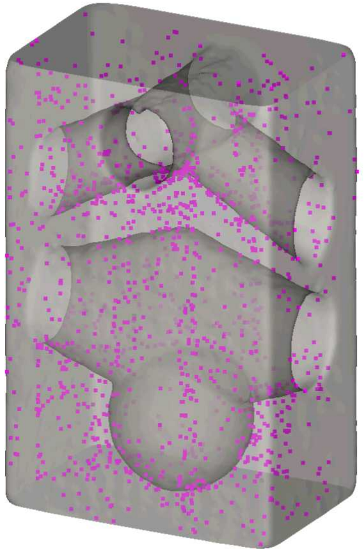




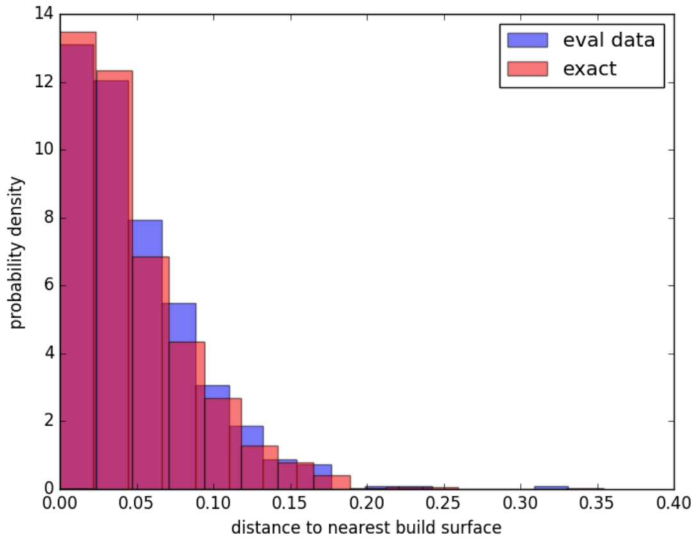
Current/future work: Adding stochastic void model

Specimen B10 CT scan data

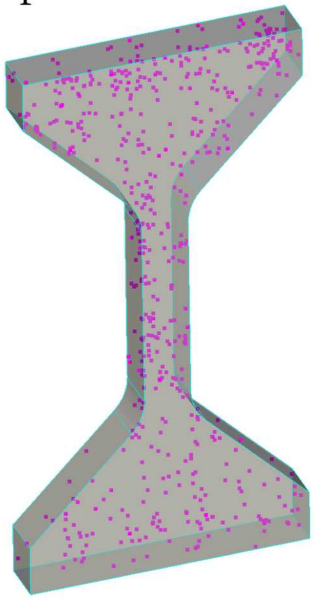




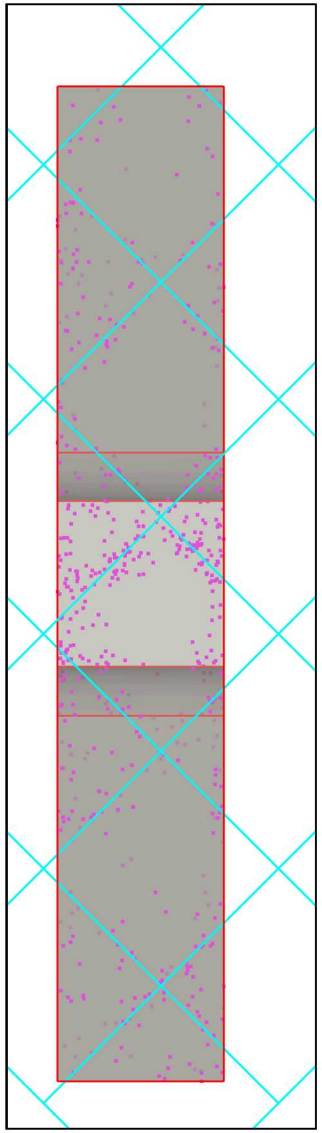
Distance to nearest surface



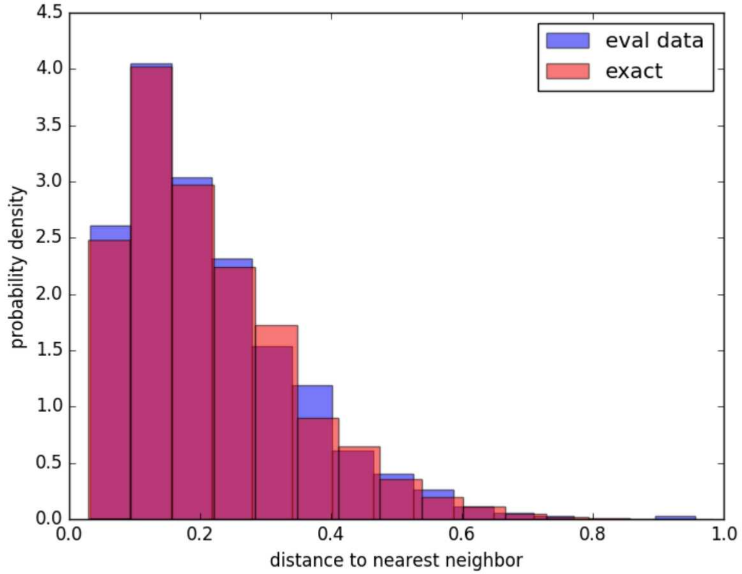
Tension specimen with void ***realization*** matching experimental CDFs

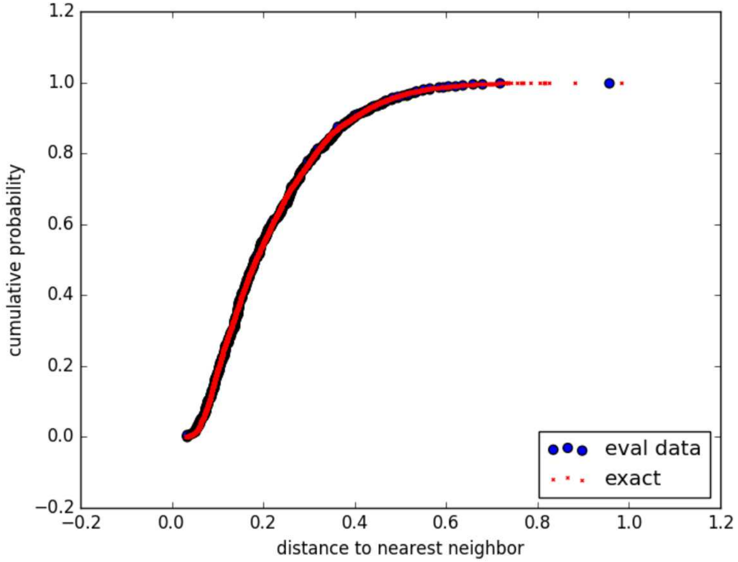


Top view



Distance to nearest neighbor





Current/future work: Void-free material model calibration

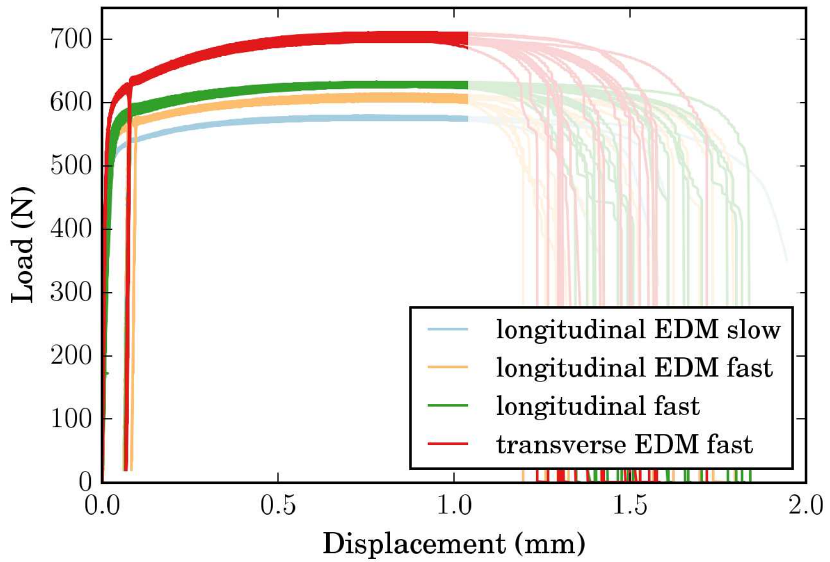
- Calibrate plasticity to pre-peak load uniaxial, tension data; literature rate dependence data (Nordberg 2004); and new notched data: machined 5 mm and 15 mm notches

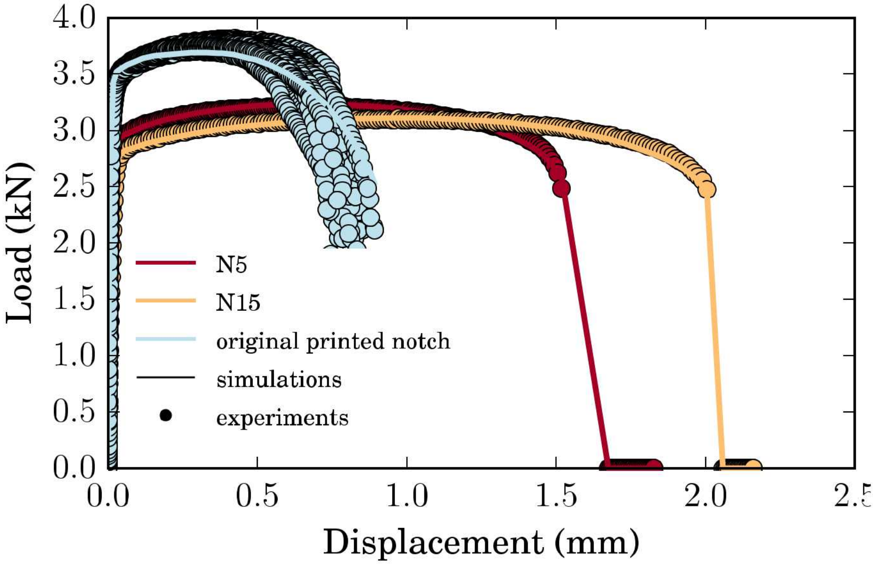
- Calibrate damage to all notched data using genetic algorithm
  - Printed, 5 mm notch, 15 mm notch

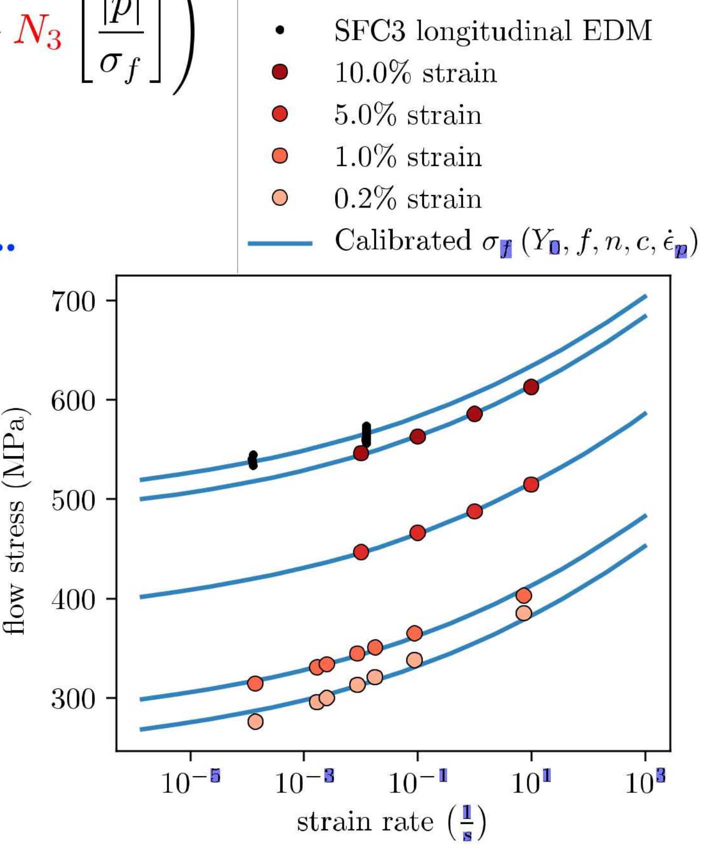
- Same assumptions as during challenge but additional nucleation term

$$\dot{\eta} = \eta \dot{\epsilon}_p \left(N_1 \left[\frac{4}{27} - \frac{J_3^2}{J_2^3} \right] + N_3 \left[\frac{|p|}{\sigma_f} \right] \right) \longrightarrow \dot{\eta} = \eta \dot{\epsilon}_p \left(N_1 \left[\frac{4}{27} - \frac{J_3^2}{J_2^3} \right] + N_2 \frac{J_3}{J_2^{\frac{3}{2}}} + N_3 \left[\frac{|p|}{\sigma_f} \right] \right)$$

Current best damage set, still going…

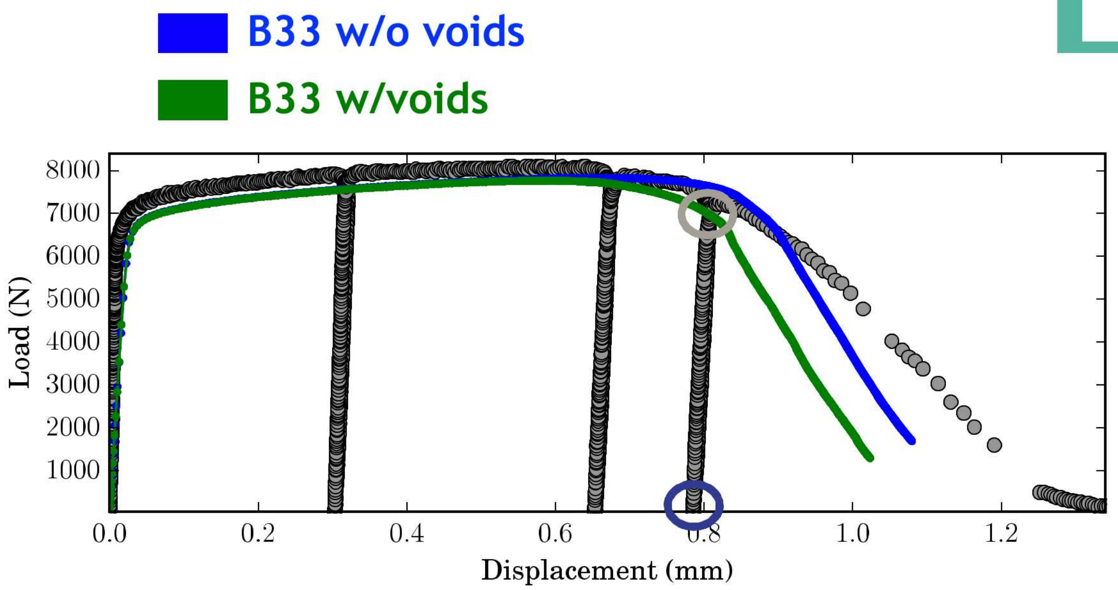


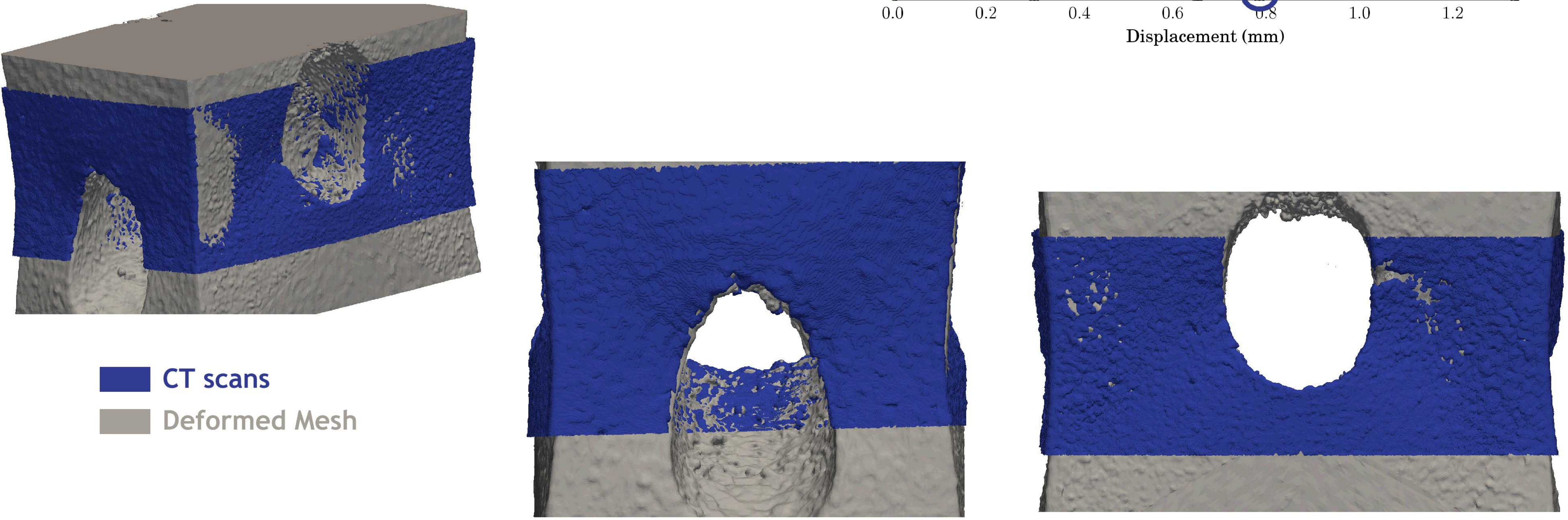




High Fidelity Validation

- Material model seems fairly accurate
    - Global load-displacement accurate
    - Local deformation very similar
- The model unloads too quickly after 0.9 mm displacement

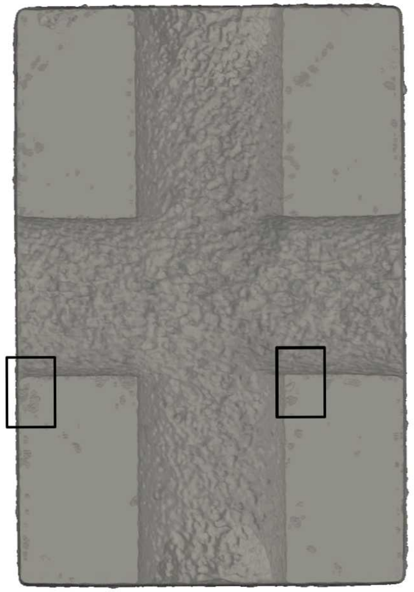




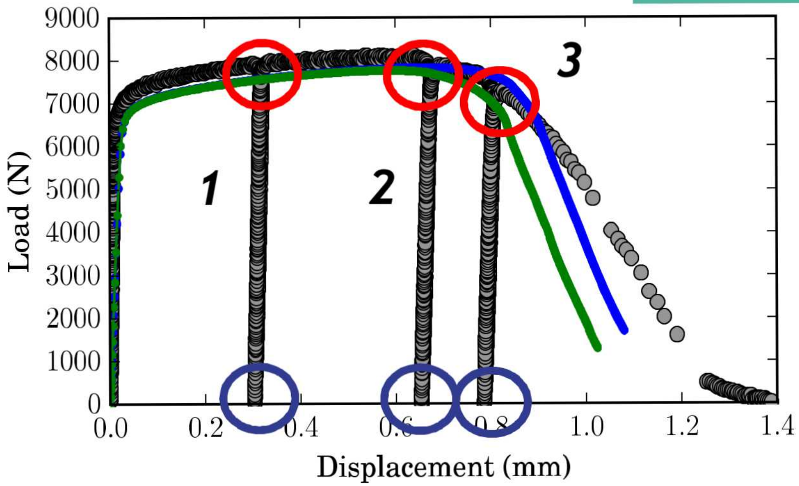
High Fidelity Validation

- Material model predicts crack growth in two areas well

Top Row



Bottom Row

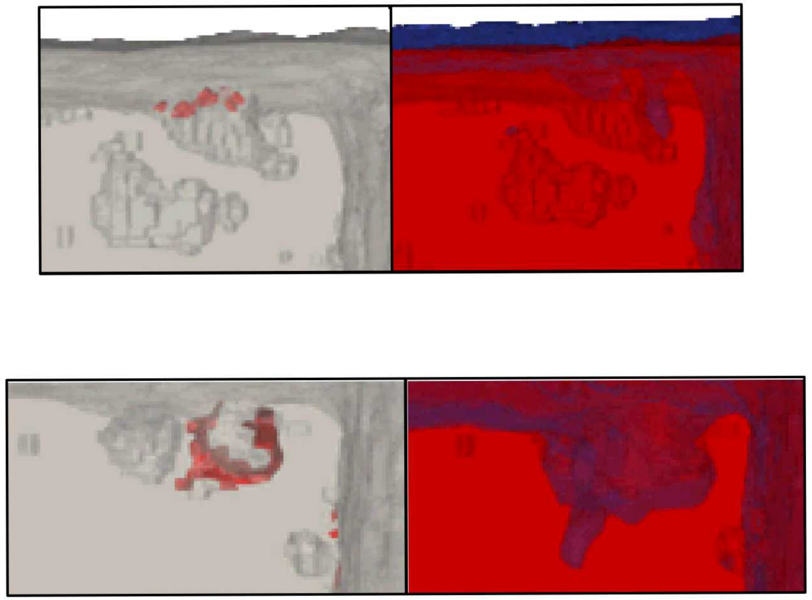


CT scans

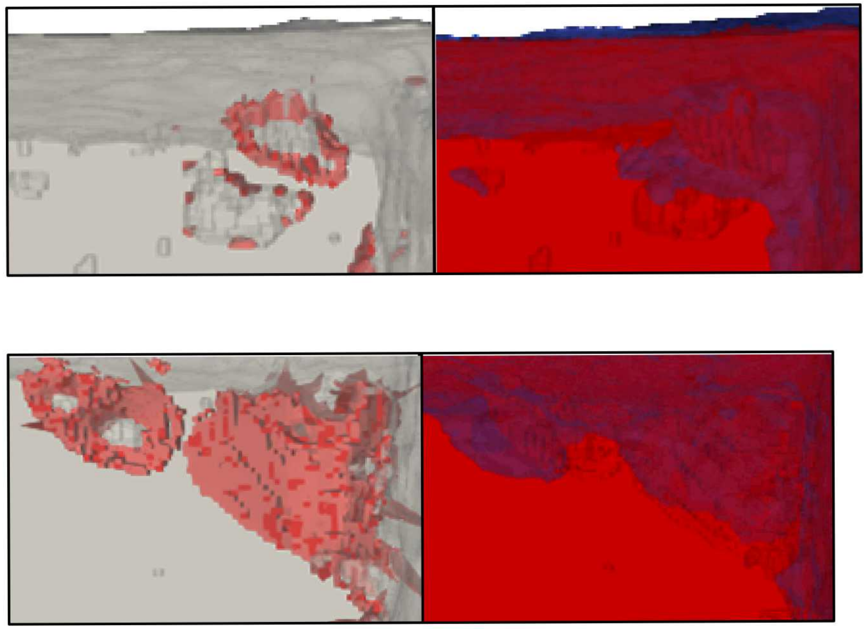
Deformed Mesh with Crack

Deformed Mesh without Crack

1



2



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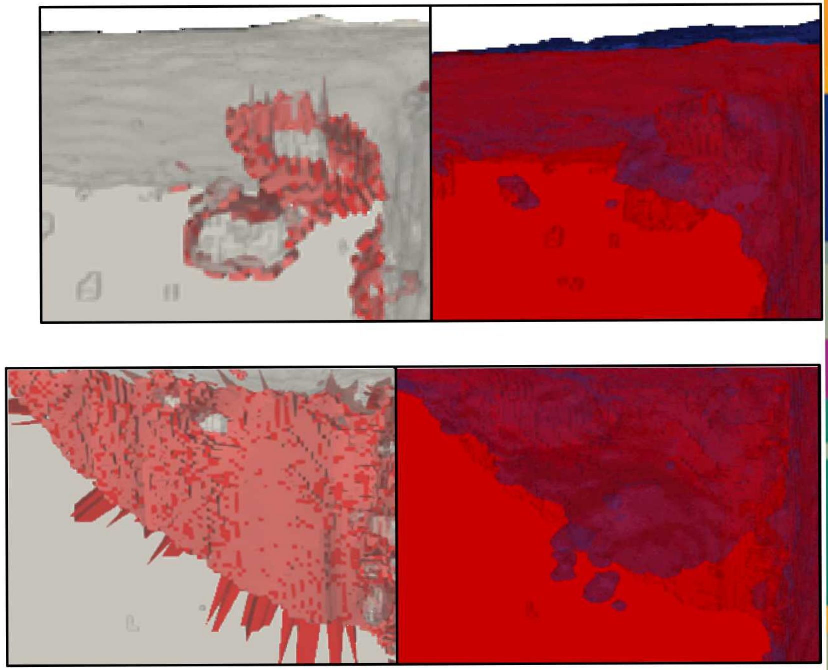
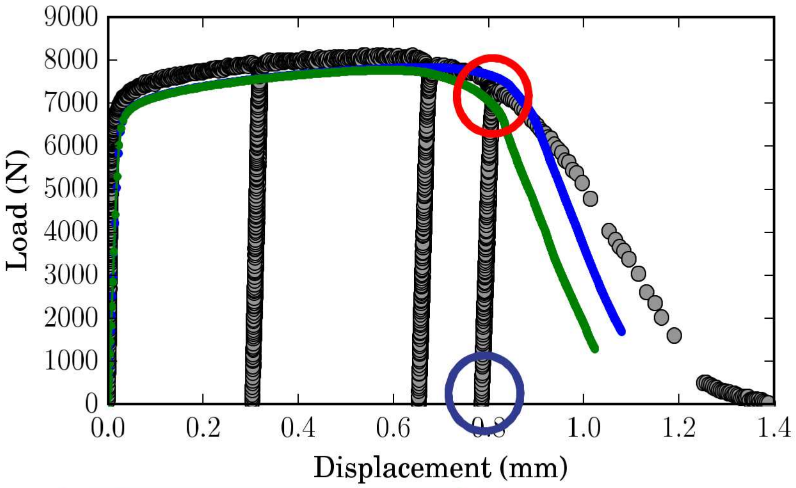
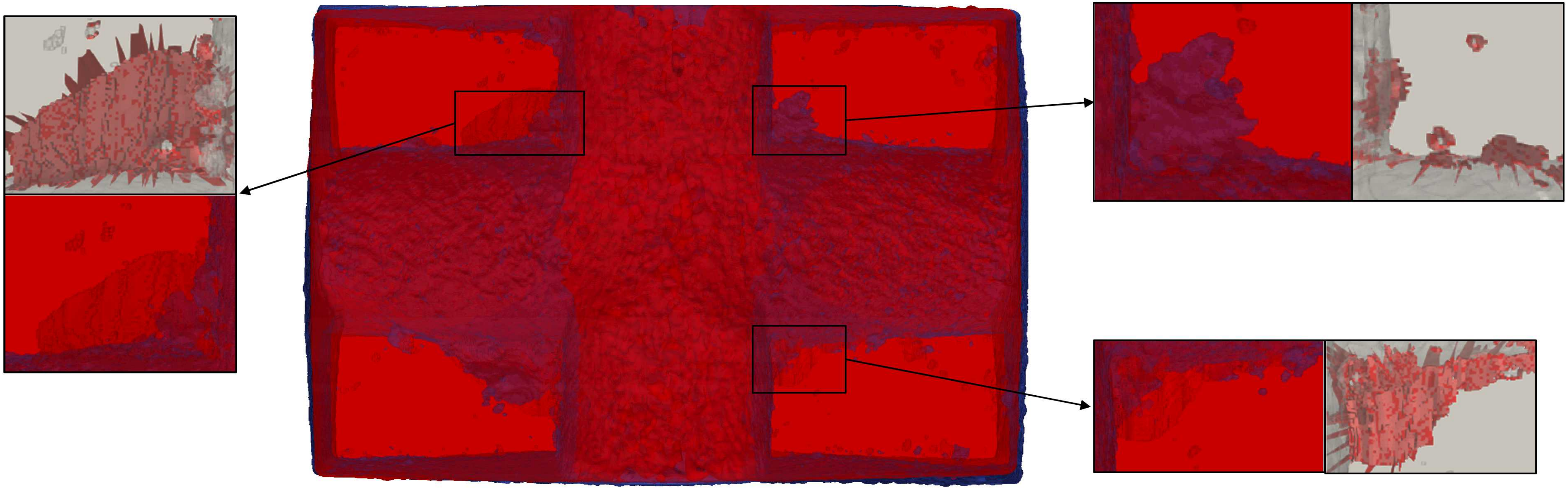


High Fidelity Validation

- In the three other stress concentrations there are clear short comings
  - Cause could be material model, mesh or boundary conditions
- Approaching best that model can do without more information

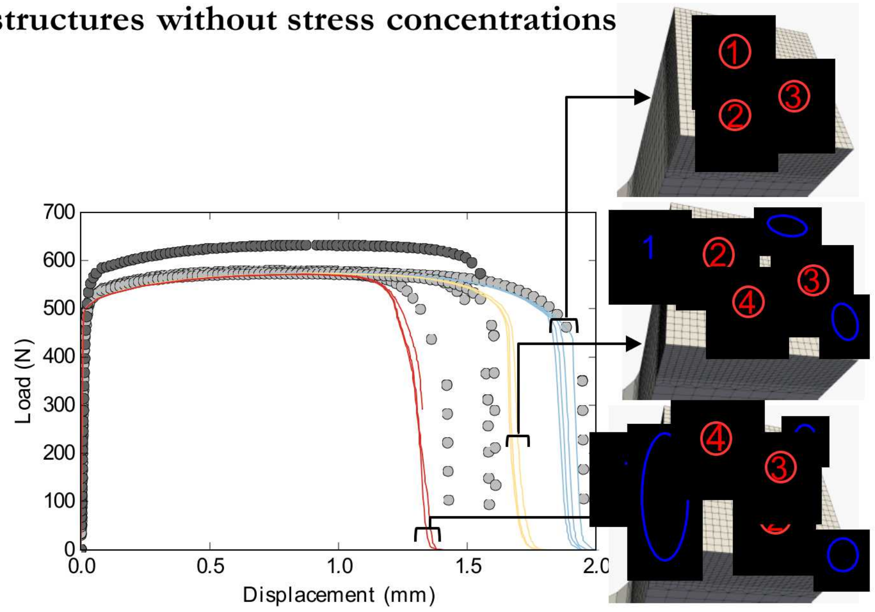


CT scans
Deformed Mesh with Crack
Deformed Mesh without Crack

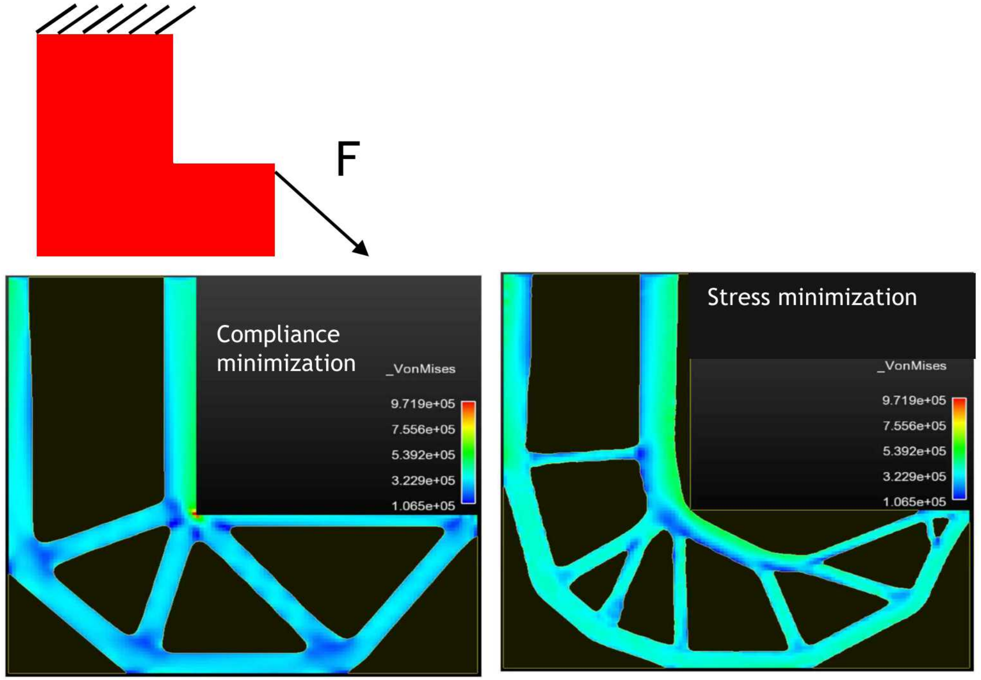


Goal: Assess structural variability of AM topology optimized parts

From SFC3, we suspect that in AM materials defects drive the response of small structures without stress concentrations



Plato Topology Optimization



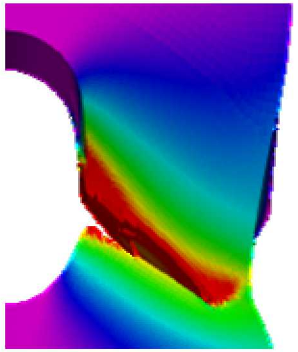
Possible paths forward:

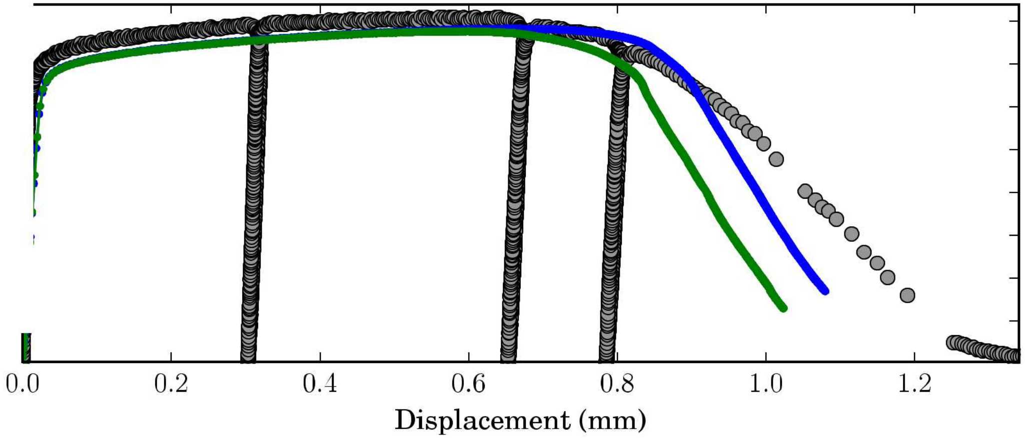
- Reduce material sensitivity to surface defects through post-processing
- Experimentally measure defects in every AM part manufactured and develop an acceptance criteria
- **Develop statistical defect model and explicitly simulate defects**

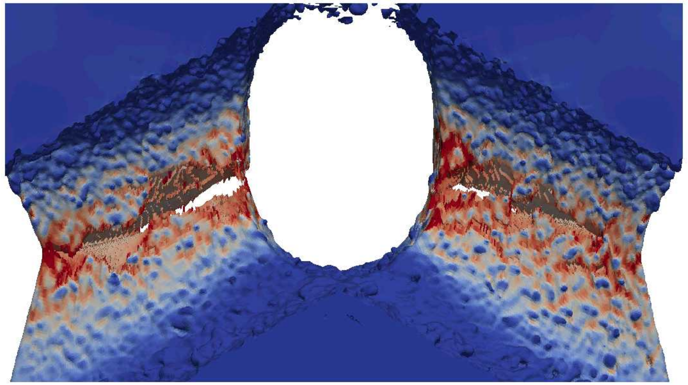
References:

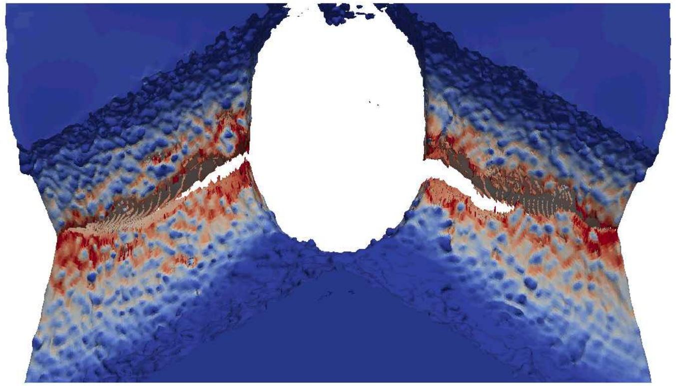
Nordberg, H.: Note on the sensitivity of stainless steels to strain rate. Research Report 04.0-1, AvestaPolarit Research Foundation and Sheffield Hallam University (2004)

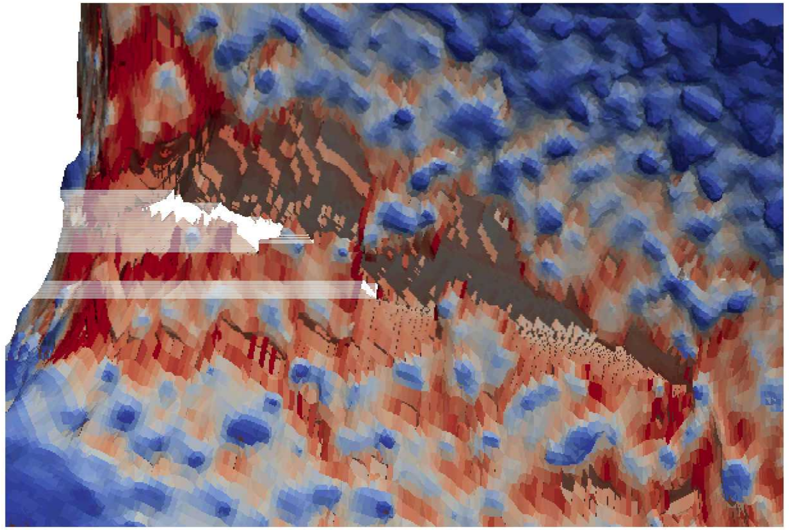
High Fidelity Validation

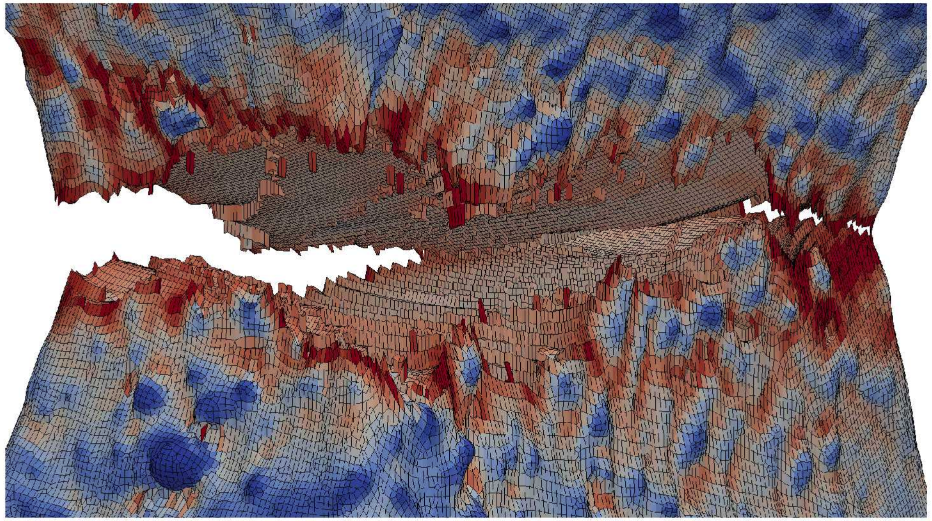






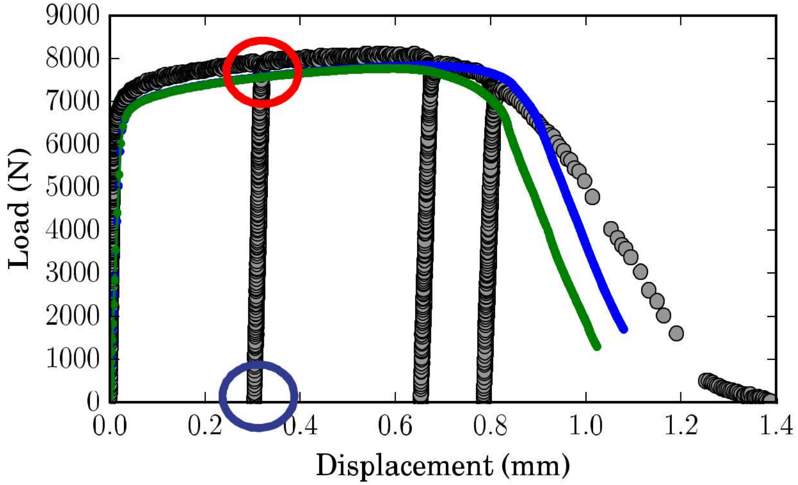


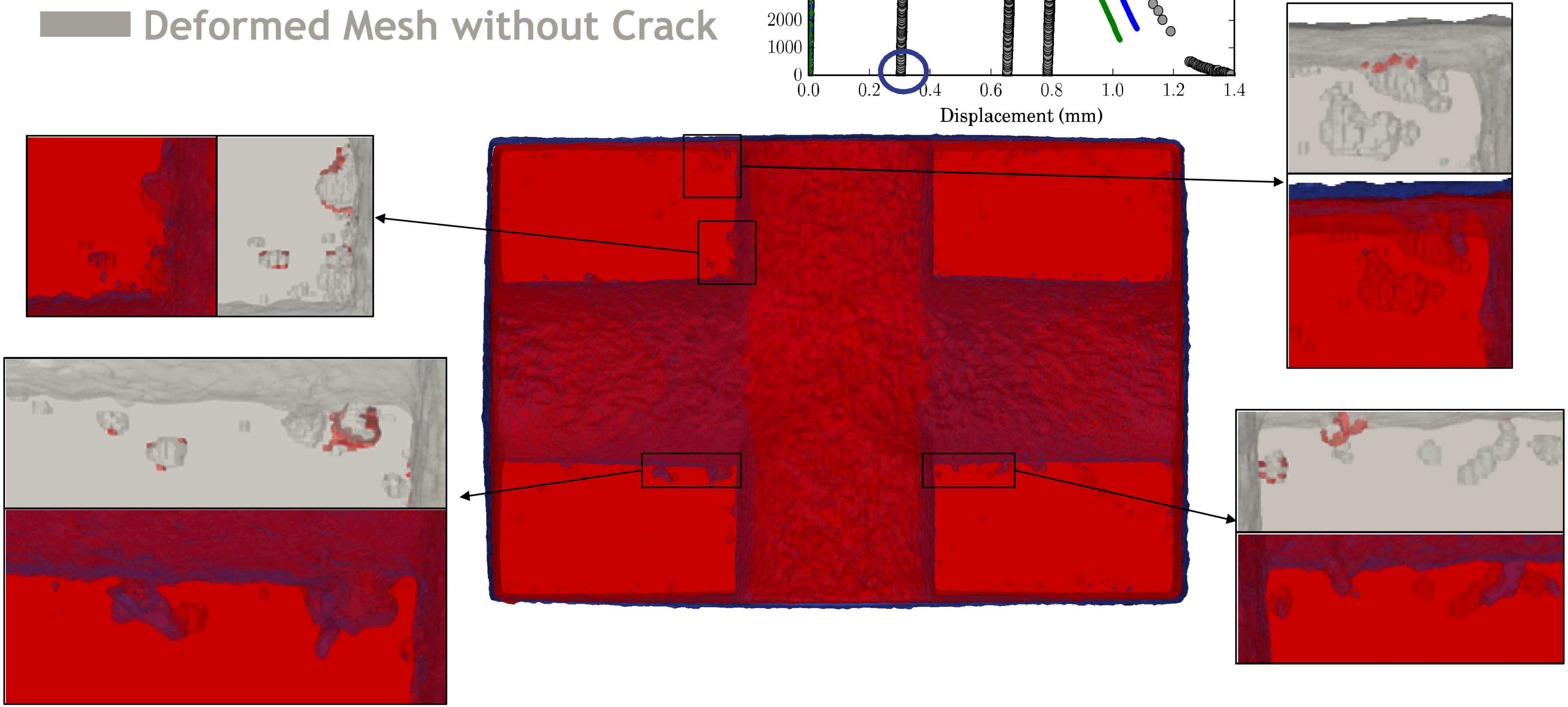




High Fidelity Validation

- CT scans
- Deformed Mesh with Crack
- Deformed Mesh without Crack





High Fidelity Validation

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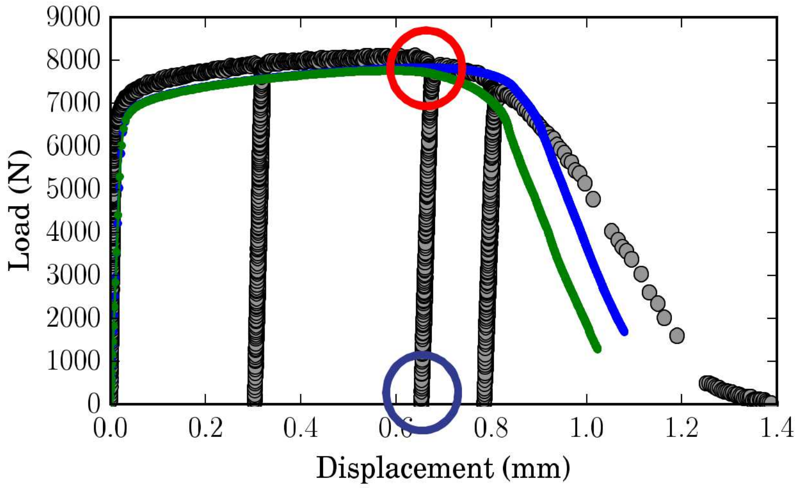

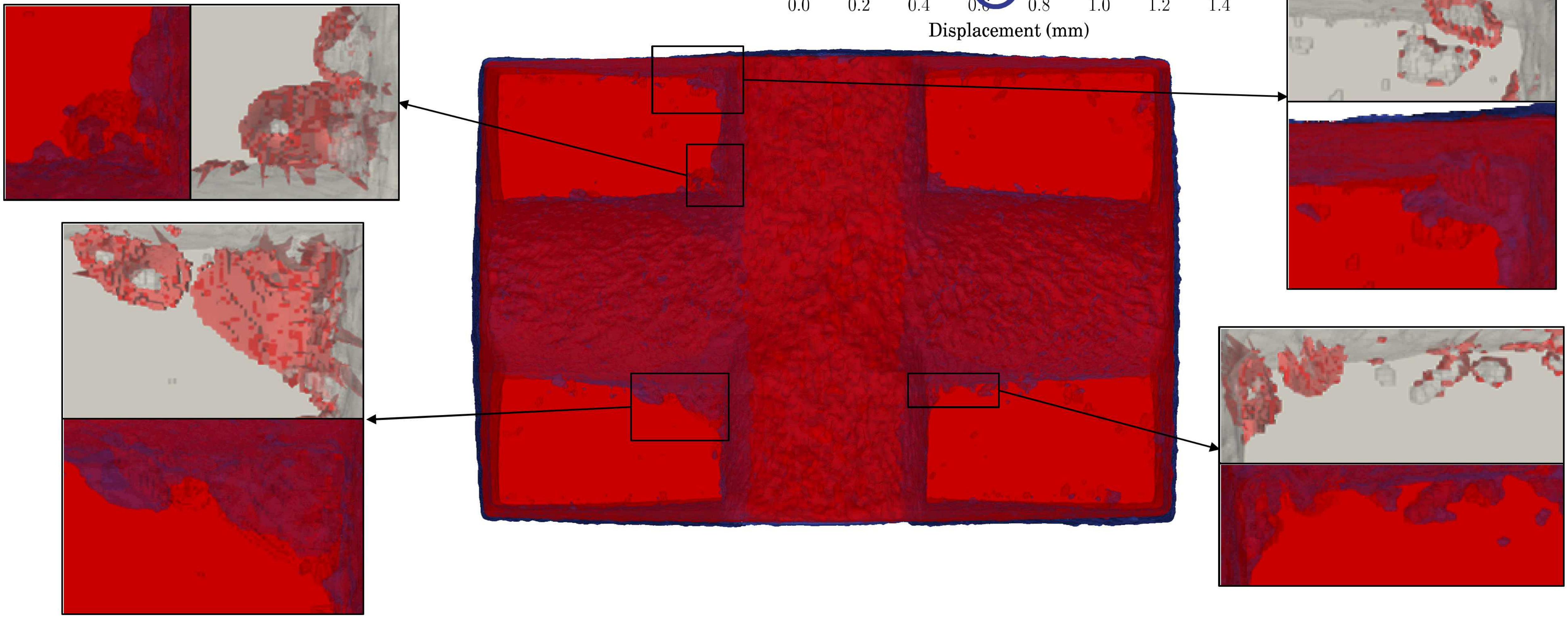

High Fidelity Validation

CT scans

Deformed Mesh with Crack

Deformed Mesh without Crack