SAND2019-8816C

# Finite Element Models of Laser Weld Failure using Computed Tomography Images

*PRESENTED BY*

Kyle Karlson

Alyssa Skulborstad, Jon Madison, Thomas Ivanoff, Helena Jin, Sharlotte Kramer

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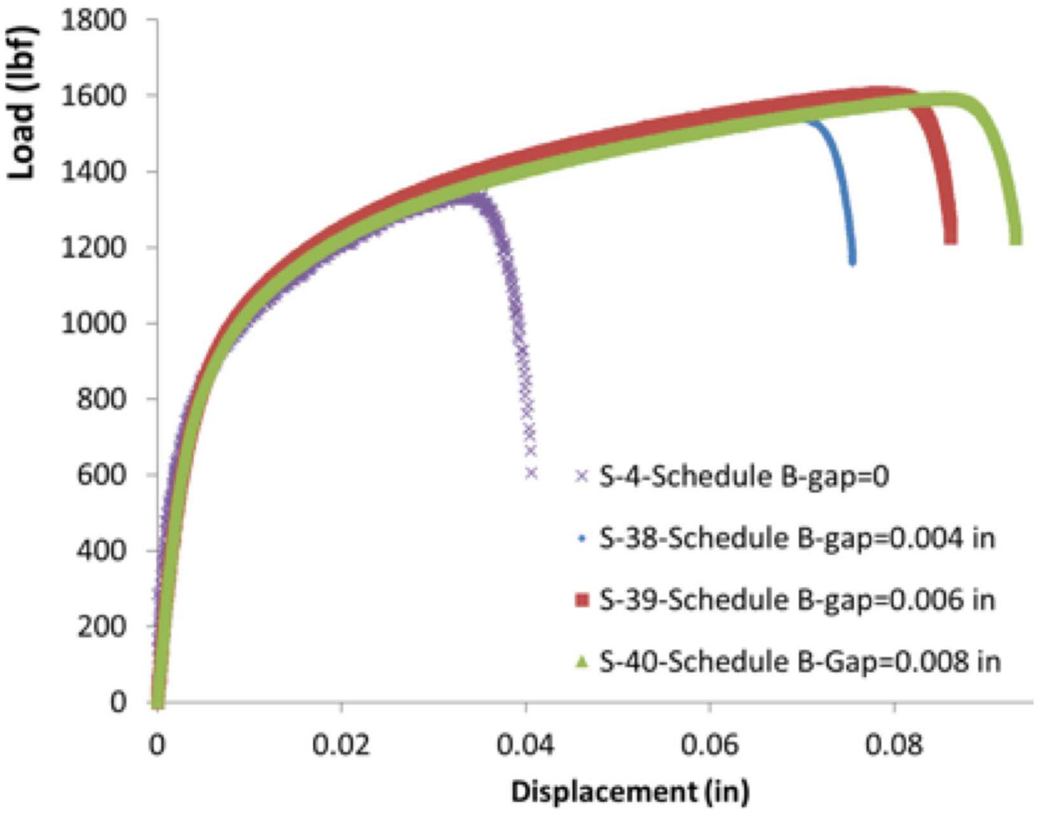
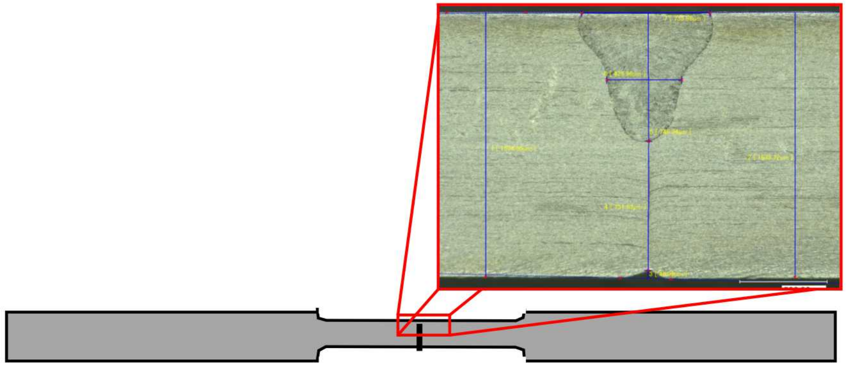
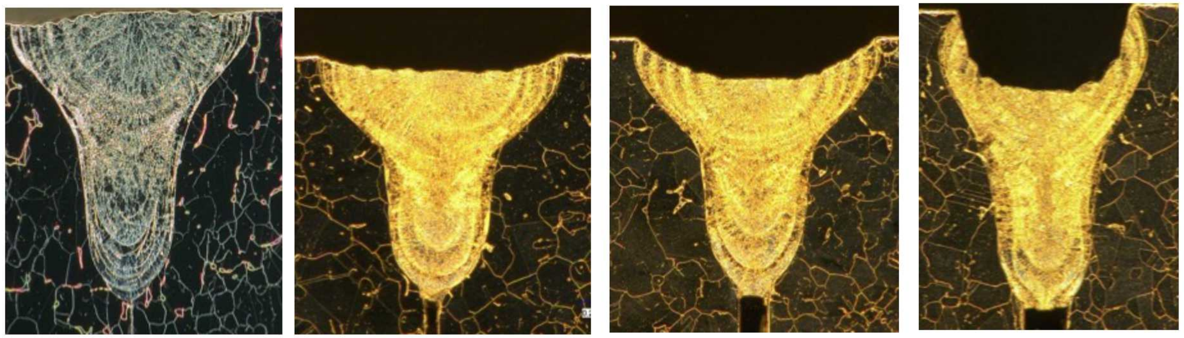
# Motivation for laser weld failure modeling

- We use laser welds to assemble components and create hermetically sealed volumes
- Laser welds exhibit large variability in structural performance
- We seek to model the welds and their variability to ensure components meet requirements



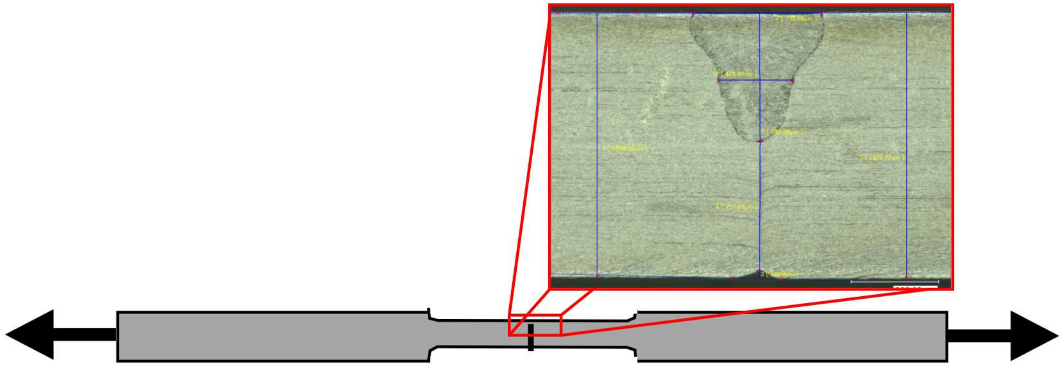



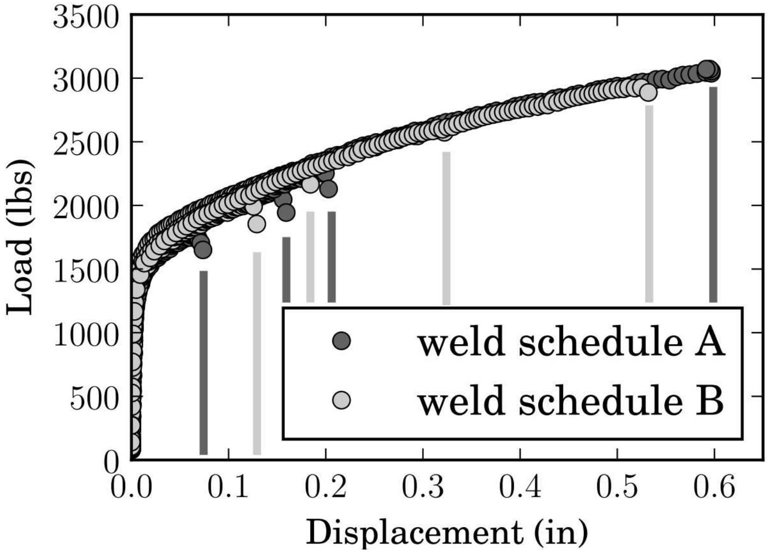


S-04 Gap=0 | S-38 Gap=0.004in | S-39 Gap=0.006in | S-40 Gap=0.008in

# Initial model – ignoring geometric details

Goal: Accurately model observed variability in laser weld failure in a manner that can be implemented in full system and component models.

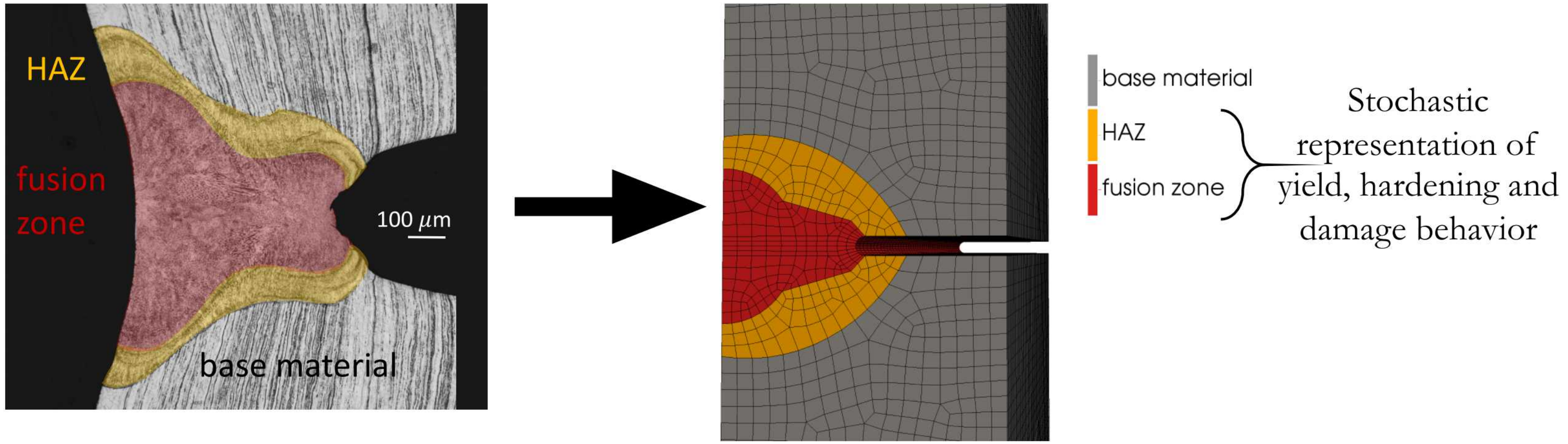





Peak Load Variability : 1700 – 3000 lbs

Failure Displacement Variability : 0.08” - 0.6”

Initial Modeling Plan: Resolve stresses in idealized laser weld geometries and lump observed variability into material property variability regardless of the source of the variability.




Propagate laser weld uncertainty through model of interest using Stochastic Reduced Order Model (SROM):

Statistical moments:

$$\max_{1\le r\le \bar{r}} \max_{1\le s\le d} \alpha_{s,r} |\tilde{\mu}_s(r) - \hat{\mu}_s(r)|$$

Cumulative distribution:

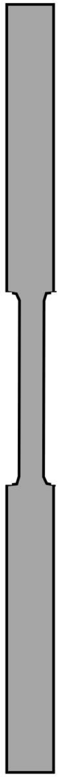
$$\max_{x} \max_{1\le s\le d} \beta_s |F_s(x) - F_s(x)|$$

Parameter correlations:

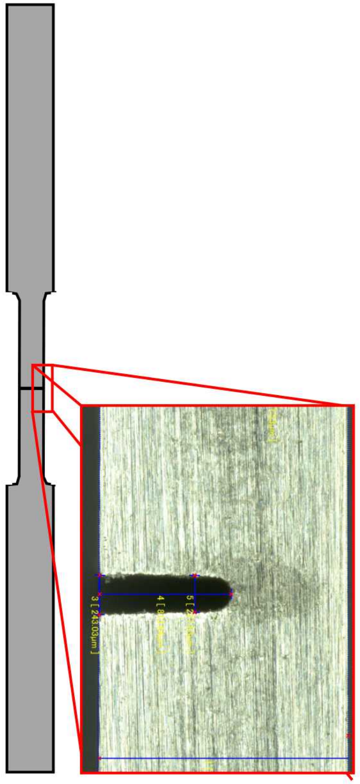
$$\zeta_{s,t} \max_{s,t} |\tilde{c}(s,t) - \hat{c}(s,t)|$$

# Calibrating and validating initial model

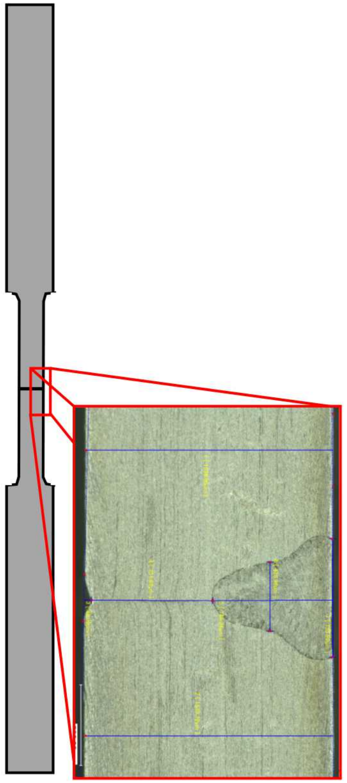
*10 specimens for each orientation*

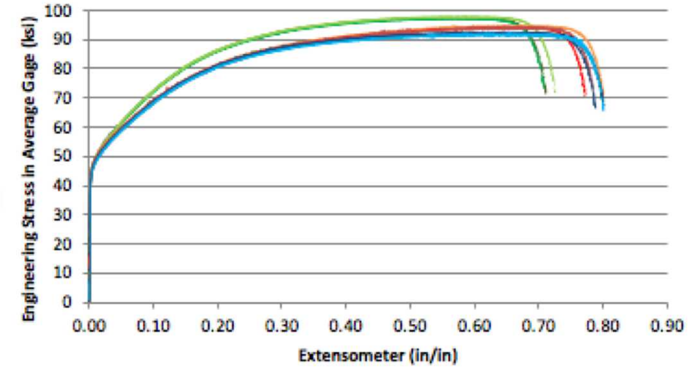


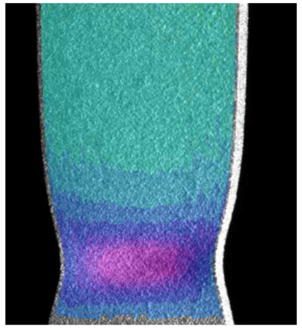
*10 specimens for each orientation*



*8 specimens for each orientation*





Yield condition:

$$Y_0 Y_T(\theta)\left[1+\sinh^{-1}\left\{\left(\frac{\dot{\epsilon}_{eq}}{f}\right)^{1/n}\right\}\right]+\kappa=\sigma_{eq}(\hat{\sigma}_{ij})$$

Hardening behavior:

$$\dot{\kappa}=\left[H\left(1+\frac{\zeta}{\kappa}\right)-R_d\kappa\right]\dot{\epsilon}_{eq}$$

$$\frac{d}{dt}\left(\frac{\zeta}{\mu}\right)=h_\zeta\left(\frac{\zeta}{\mu}\right)\dot{\epsilon}_{eq}$$

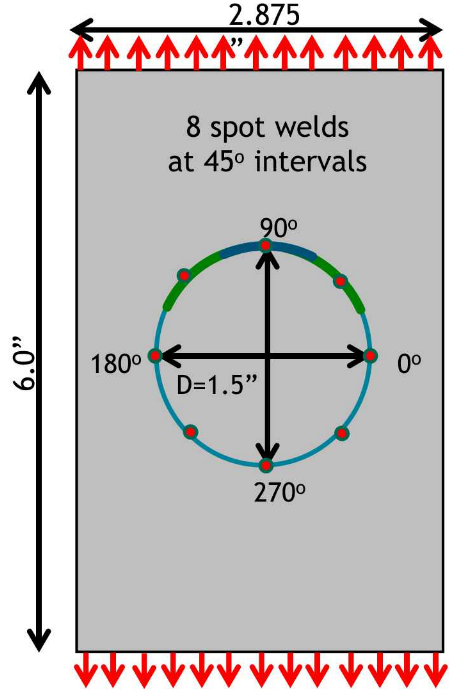
Weld failure:

$$\hat{\sigma}_{ij}=\sigma_{ij}/(1-\phi)$$

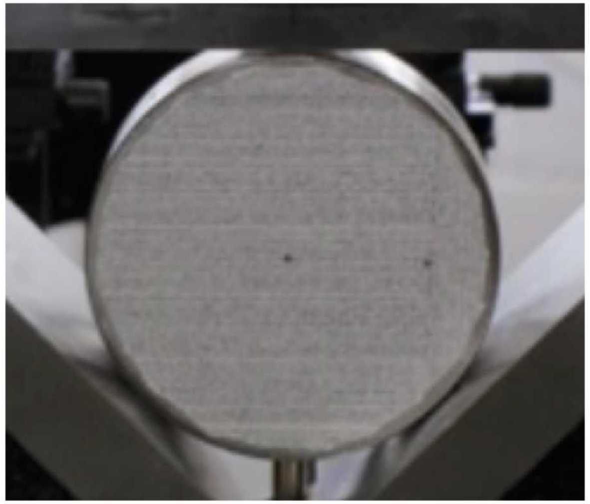
$$\dot{\phi}=(1-\phi)^2\dot{\eta}v_0$$

$$\dot{\eta}=\eta\dot{\epsilon}_p\left(n_3\left[\frac{|p|}{\sigma_f}\right]\right)$$

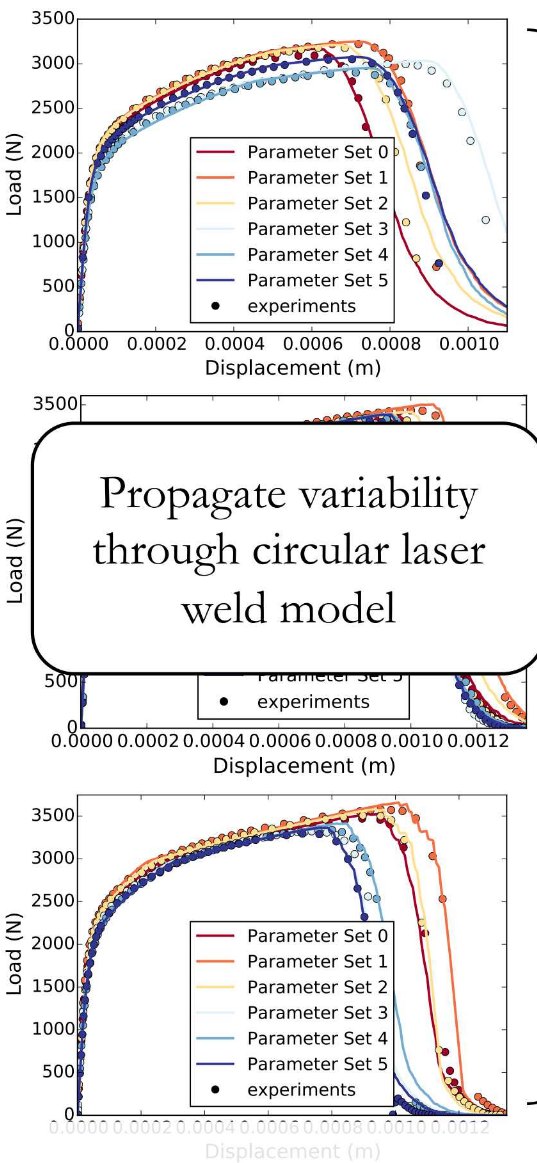
***Circular partial penetration weld loaded in tension***




***Sealed volume in a quasi-static crush: Tube with lids welded on both sides***

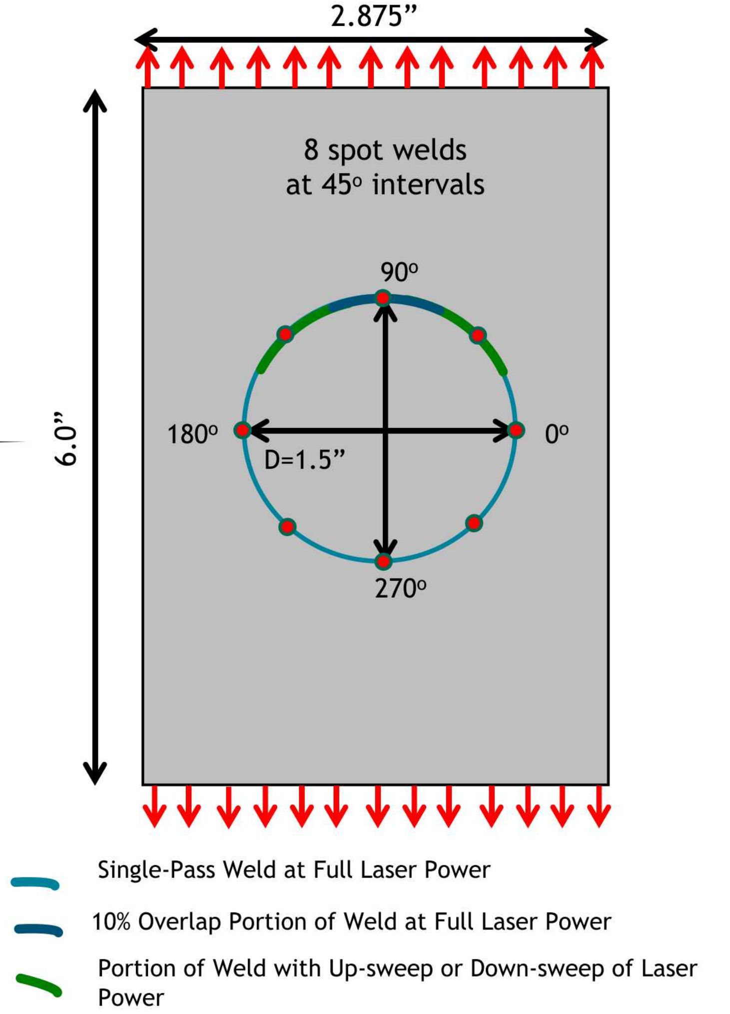


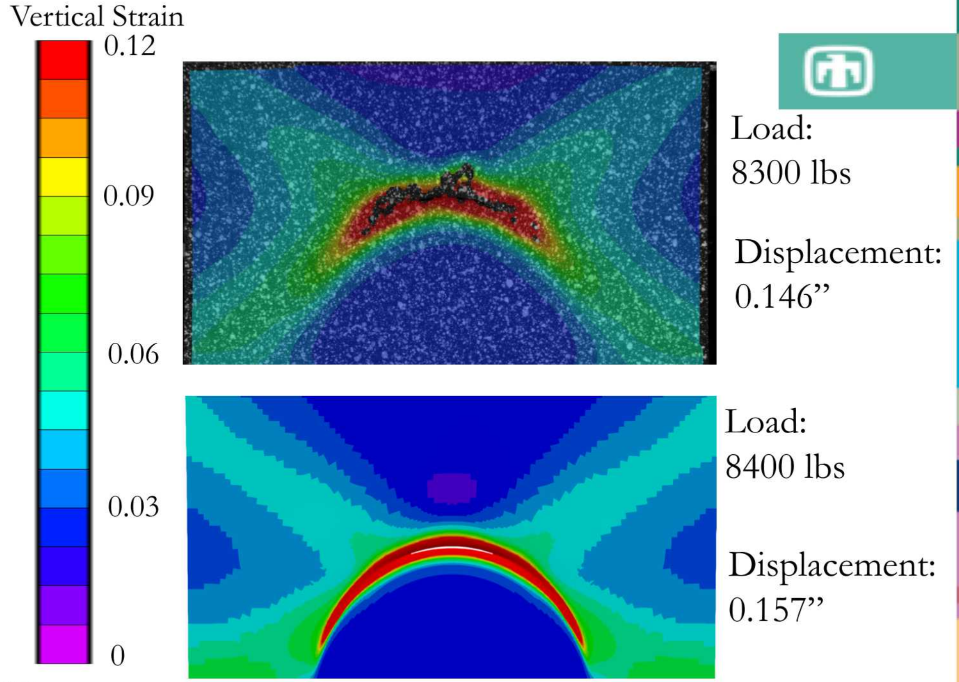
# Motivation for image-based modeling

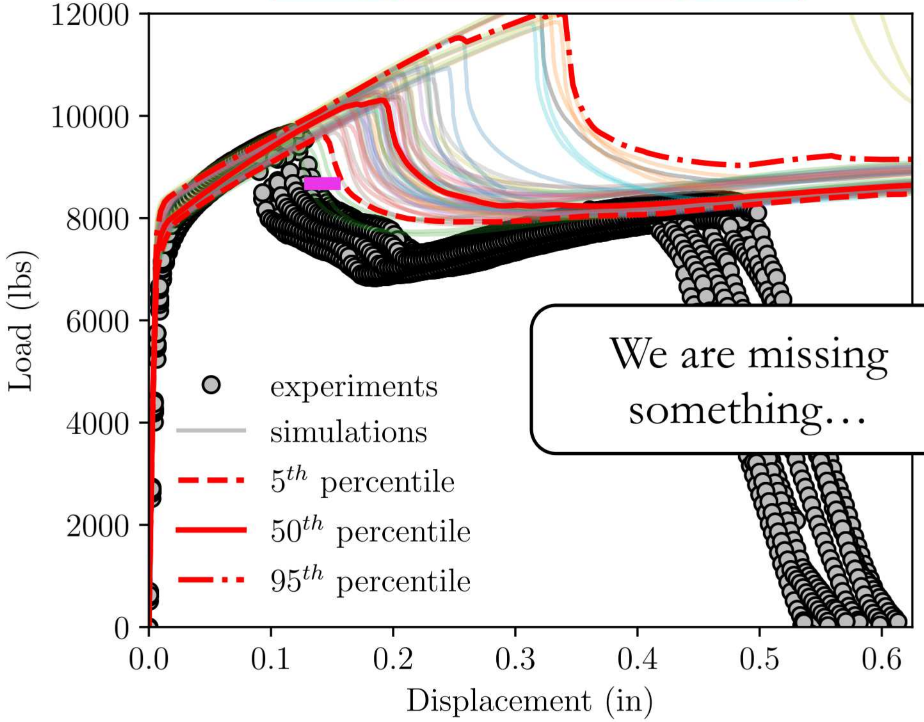



Propagate variability through circular laser weld model

*Schematic of Plate with Circular Partial Penetration Weld*

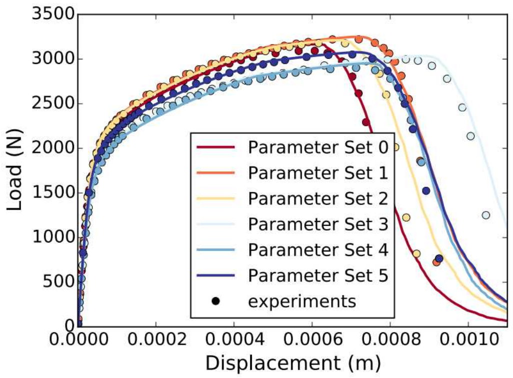


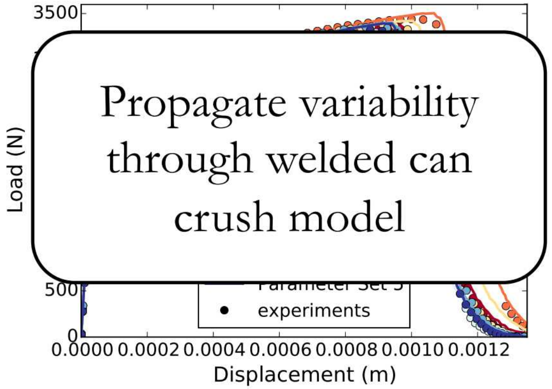



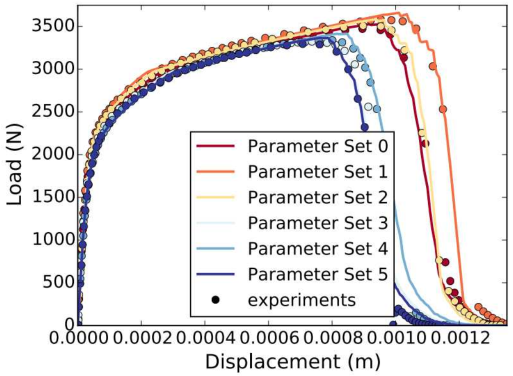

We are missing something…

# Motivation for image-based modeling

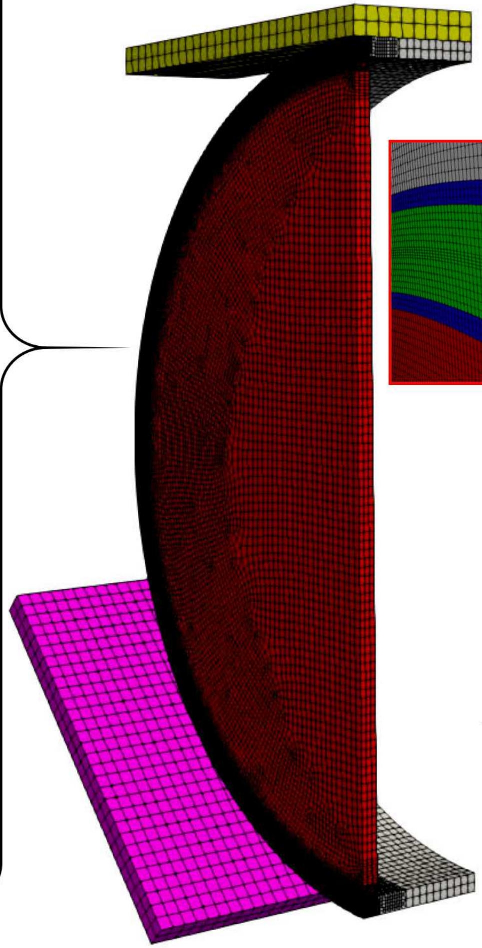


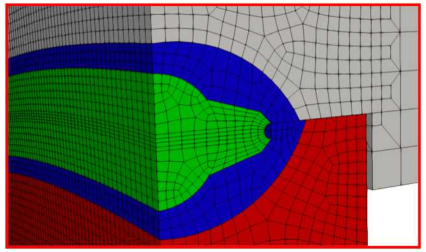



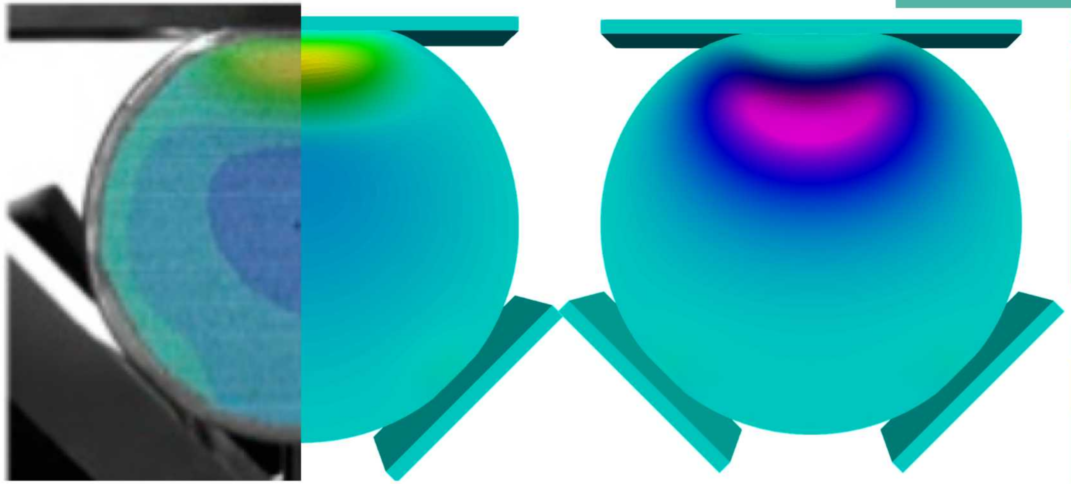

Propagate variability through welded can crush model




***Sealed volume in a quasi-static crush: Cylinder with lids welded on both sides***

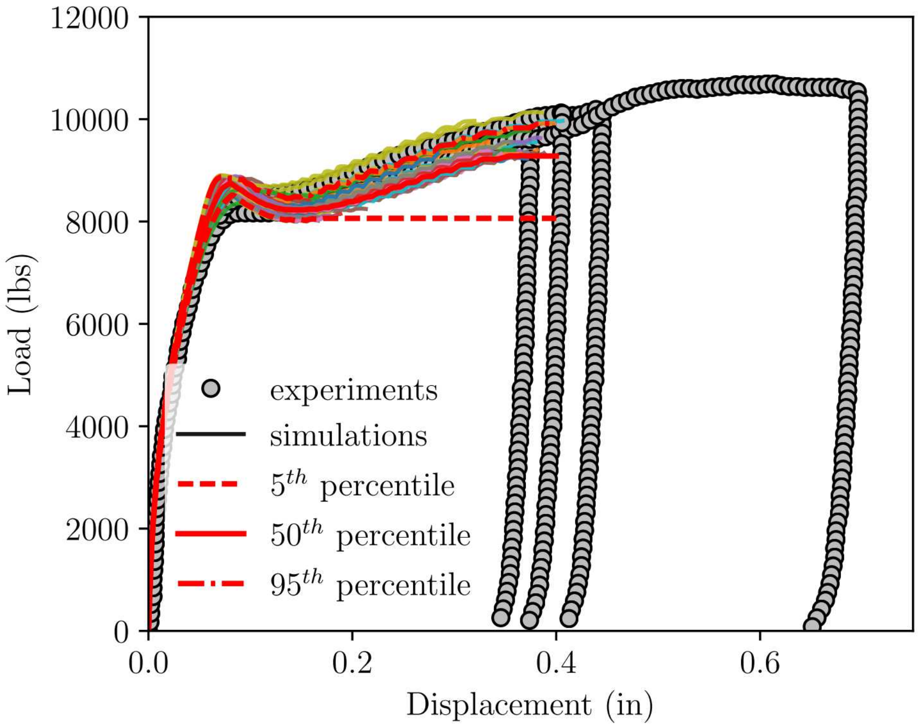






1 parameter set

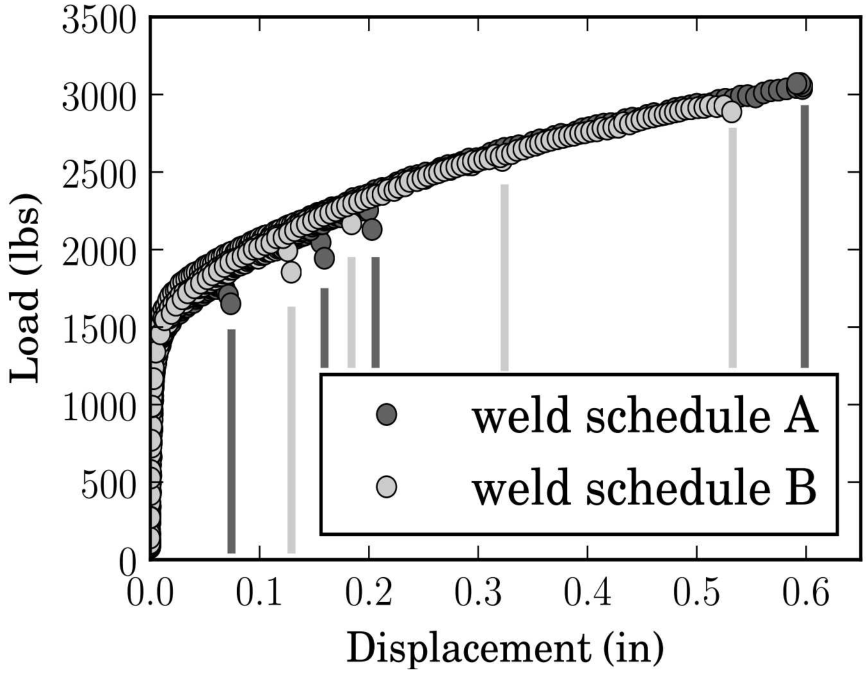
19 parameter sets



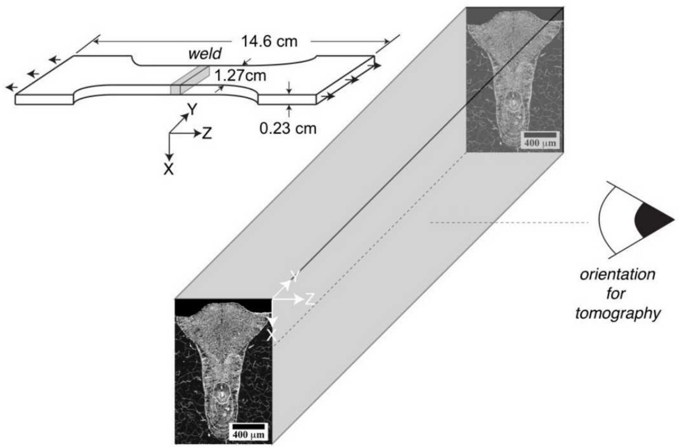

***All simulations DNF:***
No through cracks simulated!

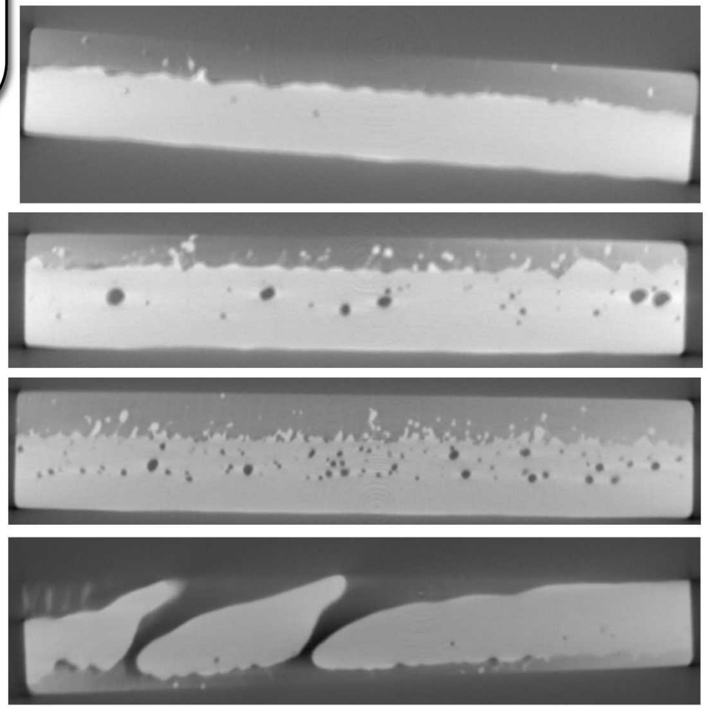
# Revisiting 304L SS laser weld modeling approach

- Lumping behavior into material model is not predictive
- ***New Goal***: Determine root cause of variability and revisit component and system scale laser weld modeling approach.




Possible causes for the observed variability:
- Small scale geometry
- Material/microstructure variability
- Residual stresses



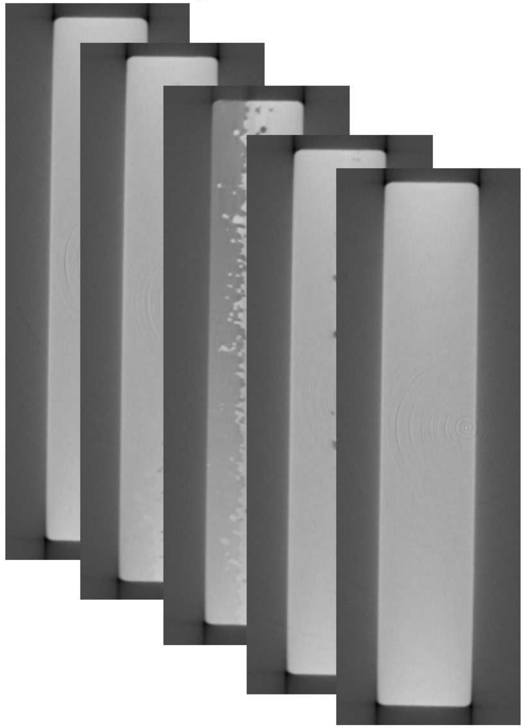
**Hypothesis**:
Small scale geometry is primary cause of variability.

# Investigating effects of laser weld geometry on 304L SS weld performance

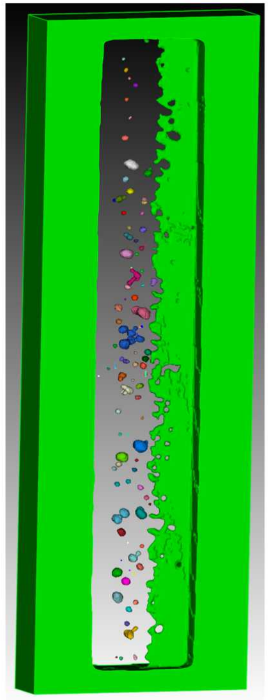
Plan to test hypothesis:

1. Mesh CT scans of laser weld specimens to get a high fidelity geometric model of test specimens.
2. Calibrate a quality material model to available base material data.
3. Run simulations where geometry is the only variable changed using base material properties and determine if models display similar trends in mechanical behavior variability.

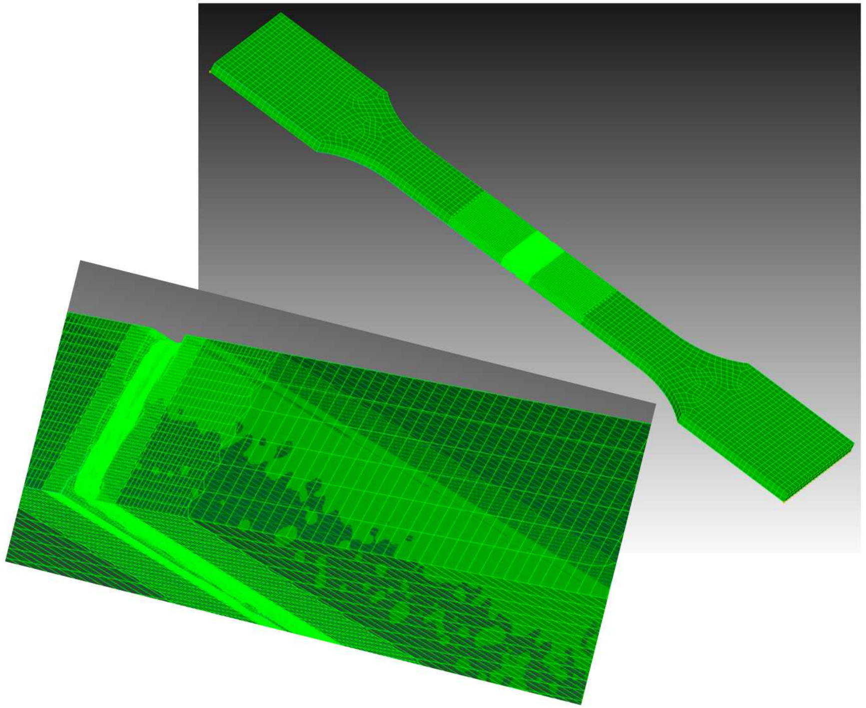
CT image Stack



Generate void and unwelded region mesh using python and Sculpt



Subtract voids and unwelded region from test part using Sculpt and Cubit



Generated meshes are on the order of 10 million elements with a minimum mesh size of ~17 microns, the size of the CT scan voxel.

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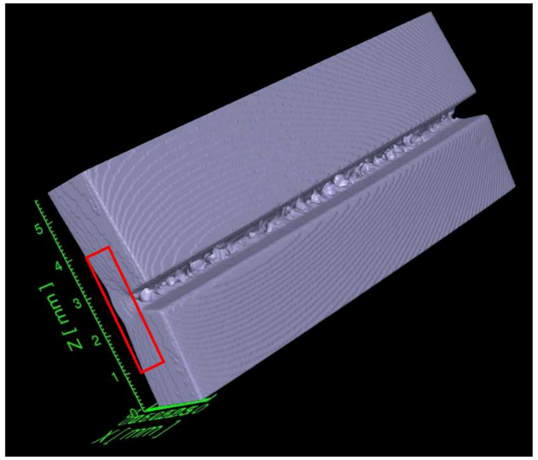


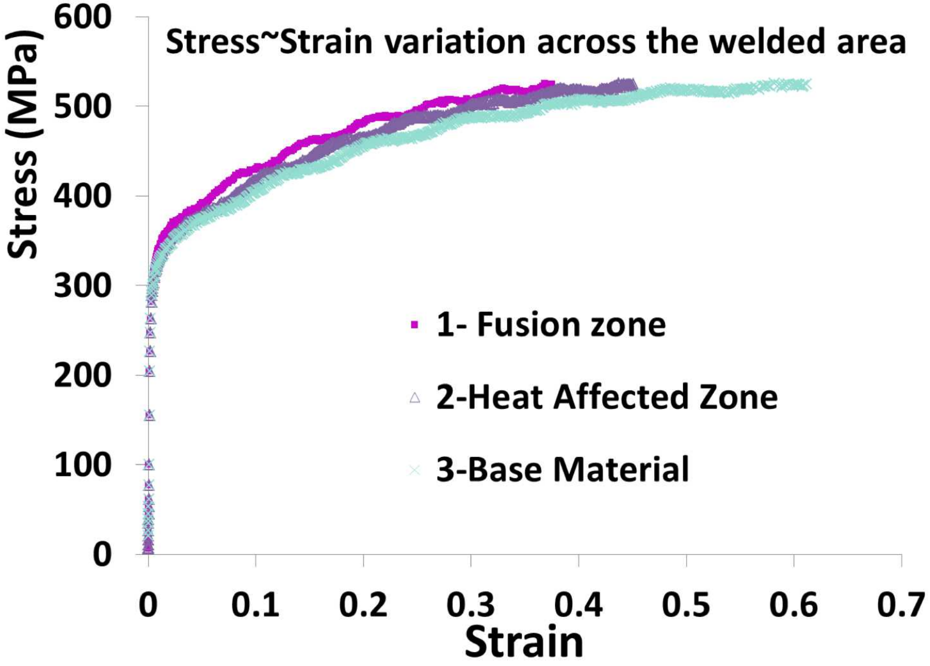


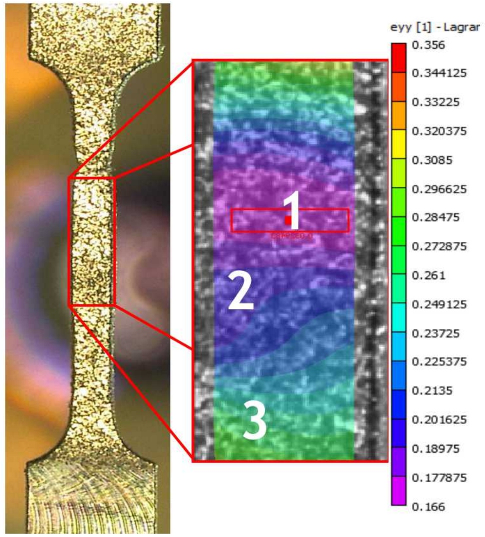

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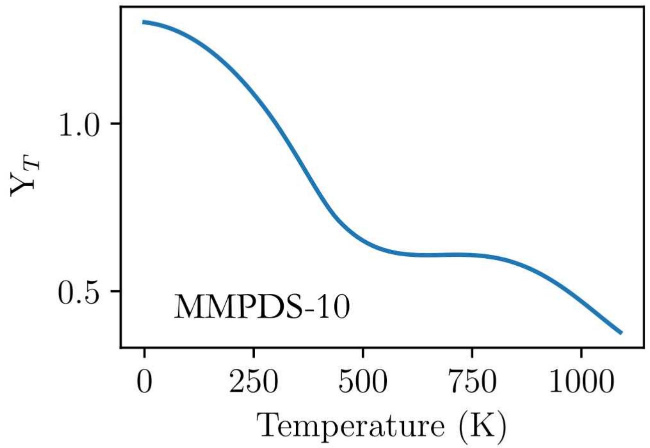
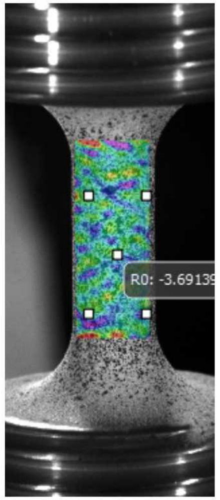
Hardening behavior:

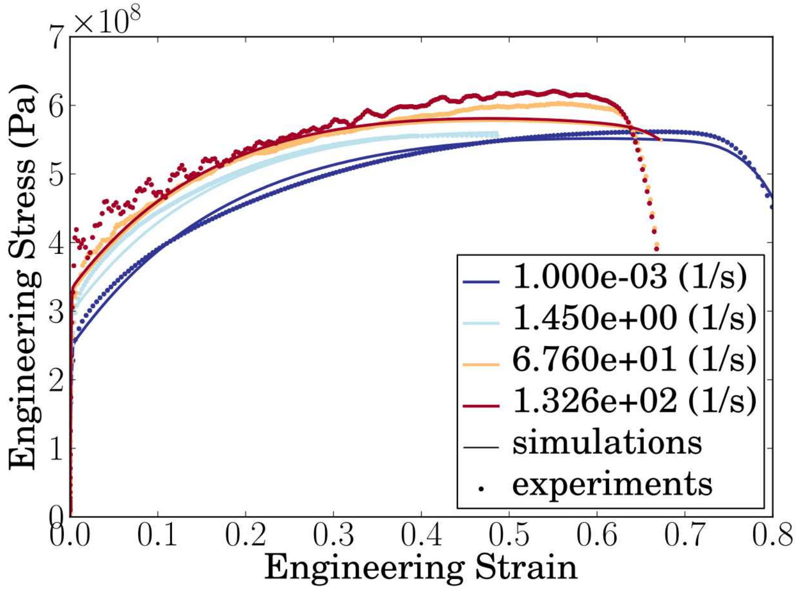
$$\dot{\kappa}=\left[H\left(1+\frac{\zeta}{\kappa}\right)-R_d\kappa\right]\dot{\epsilon}_{eq}$$

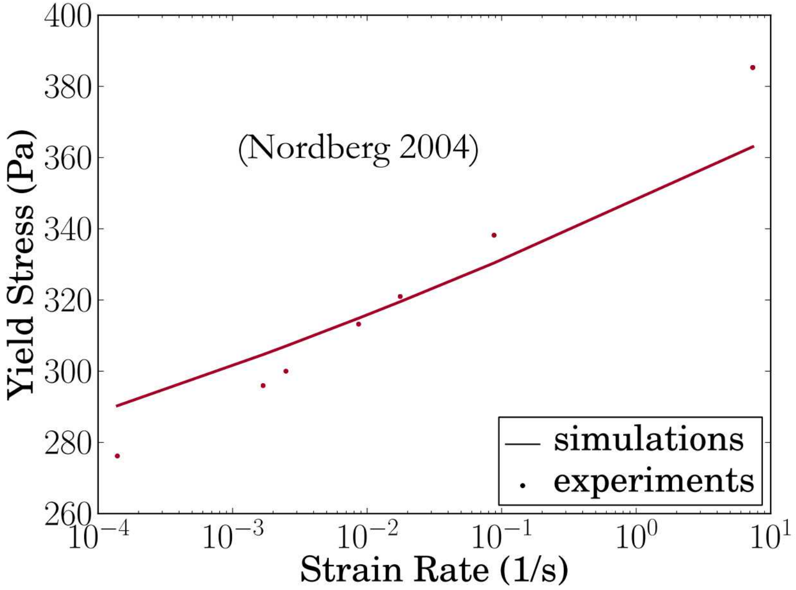
$$\frac{d}{dt}\left(\frac{\zeta}{\mu}\right)=h_\zeta\left(\frac{\zeta}{\mu}\right)\dot{\epsilon}_{eq}$$

***Temperature/rate dependent plasticity calibration***



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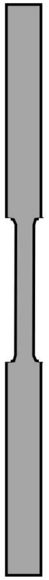
2. Calibrate a quality material model to available base material data.
3. Run simulations where geometry is the only variable changed using base material properties and determine if models display similar trends in mechanical behavior variability.

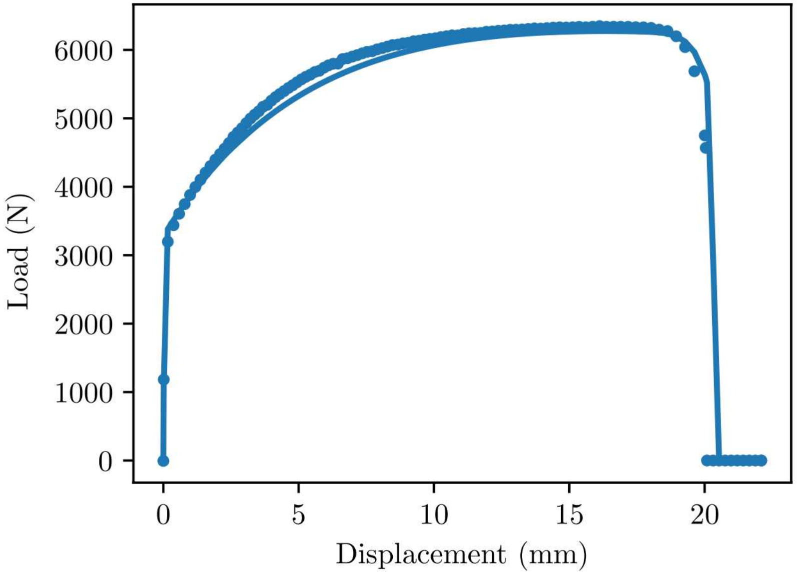
Material failure:

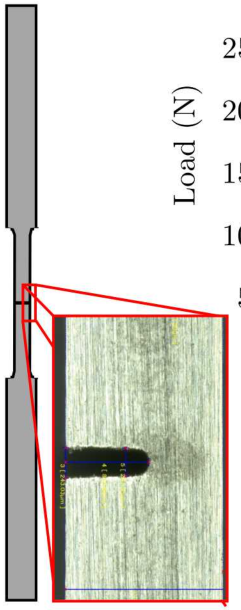
$$\dot{\phi} = \overbrace{\sqrt{\frac{2}{3}}\dot{\epsilon}_p \frac{1-(1-\phi)^{m+1}}{(1-\phi)^{m}} \sinh\left[\frac{2(2m-1)}{2m+1}\frac{\langle p\rangle}{\sigma_f}\right]}^{\text{void growth (Cocks and Ashby 1980)}} + (1-\phi)^2\dot{\eta}v_0$$

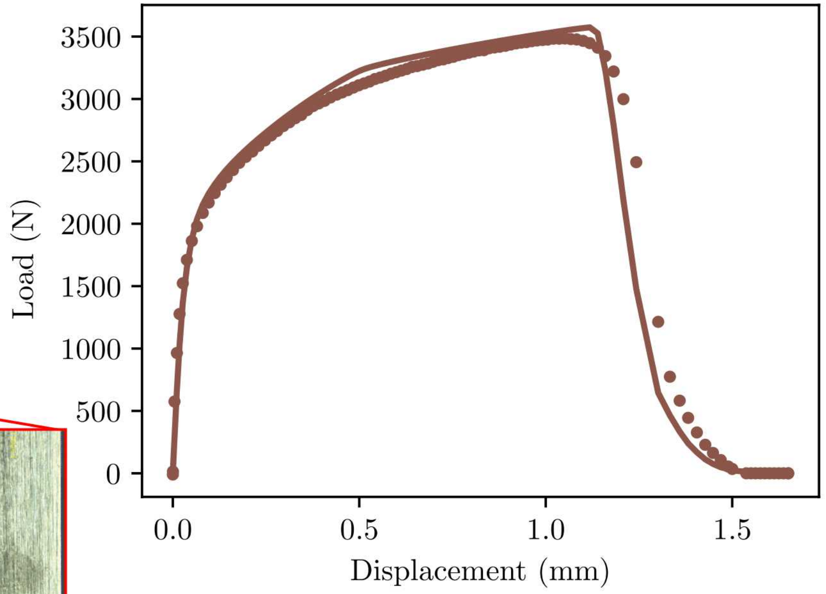
void nucleation $\longrightarrow$ $\dot{\eta} = \eta\dot{\epsilon}_p\left(N_1\left[\frac{4}{27}-\frac{J_3^2}{J_2^3}\right] + N_2\frac{J_3}{J_2^{3/2}} + N_3\left[\frac{|p|}{\sigma_f}\right]\right)$ (Horstemeyer 1999, Nashon 2008)

Elements deleted when $\phi = 0.75$








**Note:** Material is 304L sheet, not VAR 304L Bar

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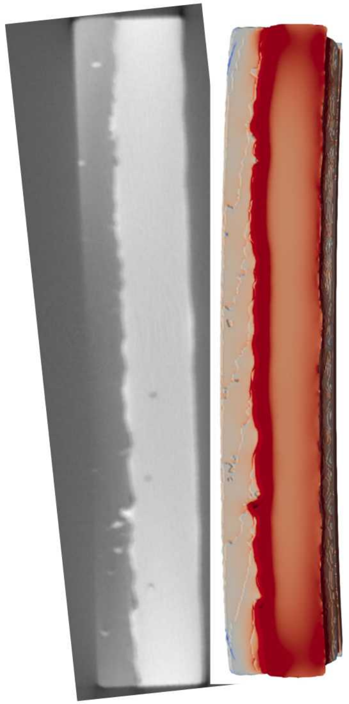
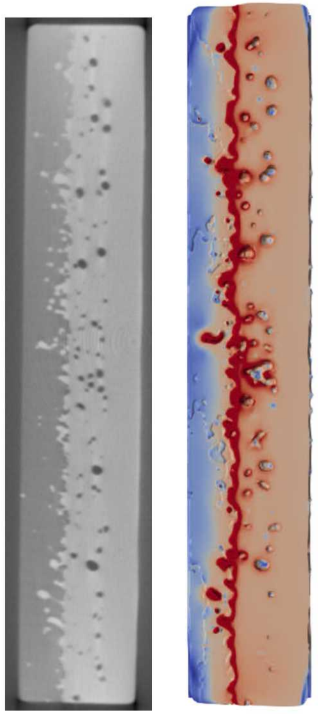
Adjust Calibration to S32 ($\phi_s$)

**Specimen S32 (low porosity, medium depth)**

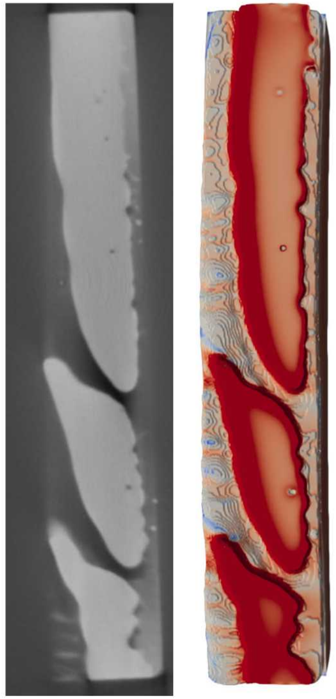


***Predict*** global behavior

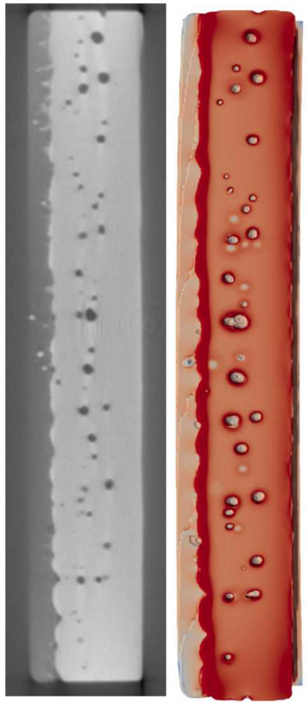
**Specimen S24 (high porosity, shallow weld)**



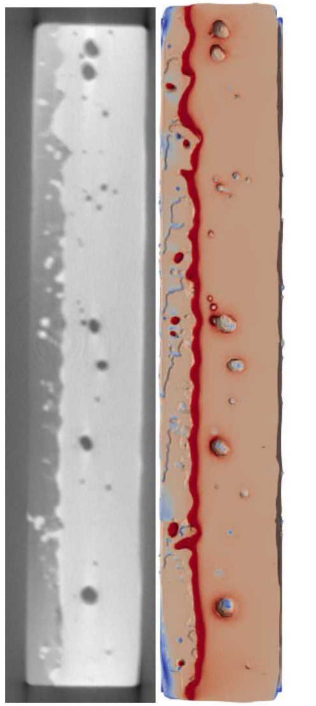
**Specimen S25 (abnormal geometry)**



**Specimen S26 (medium porosity, deep weld)**



**Specimen S33 (low porosity, deep weld)**



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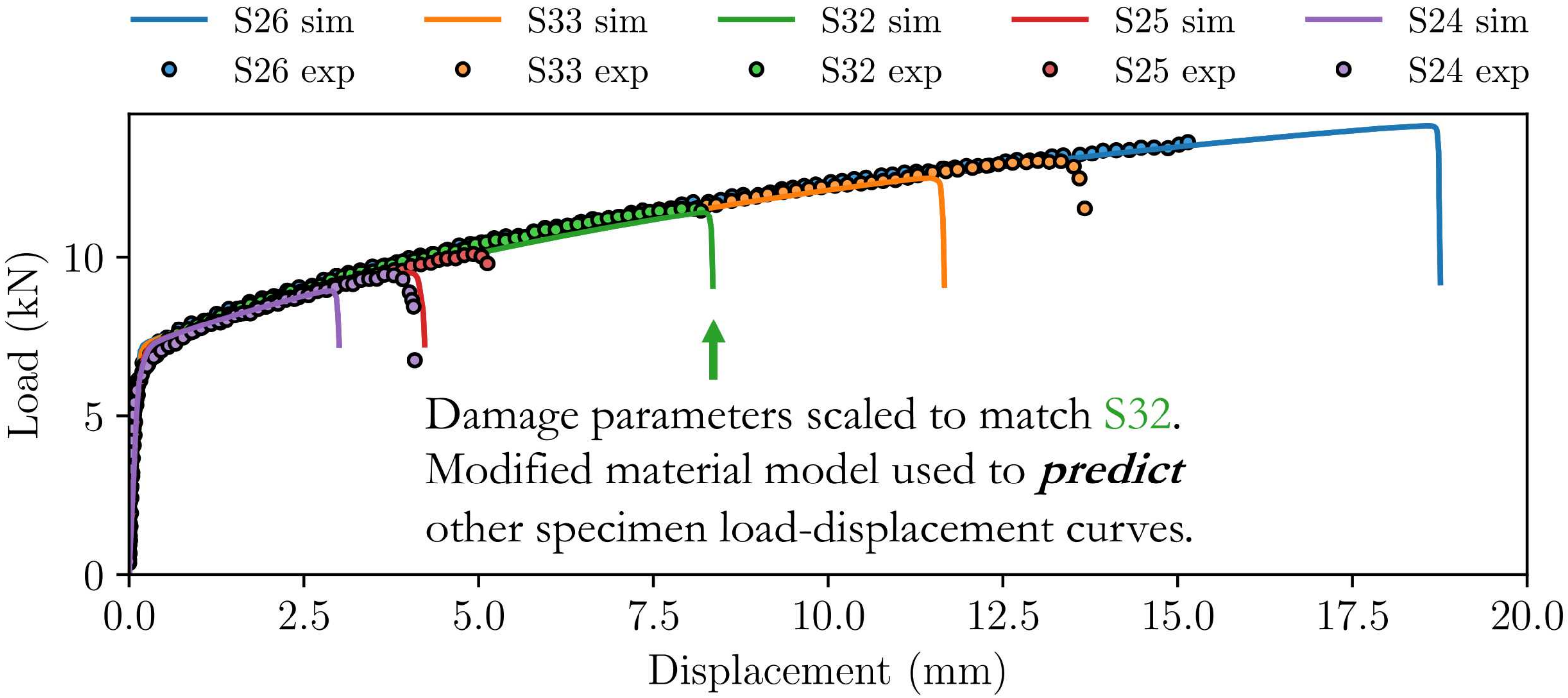
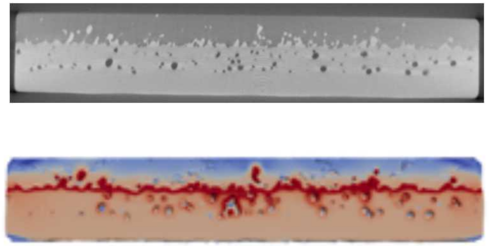



Specimen S24 (high porosity, shallow weld)



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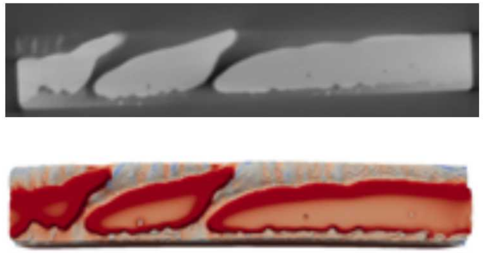
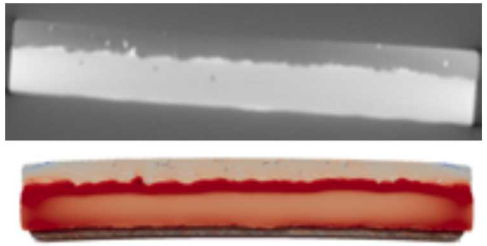
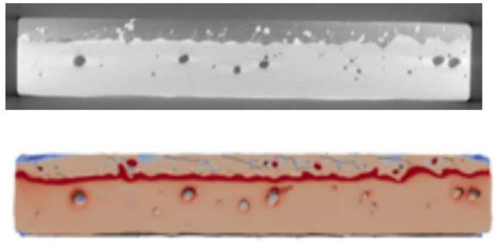


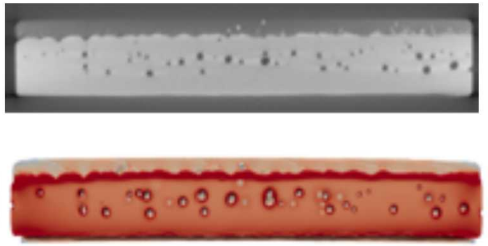
Specimen S32 (low porosity)



Specimen S33 (low porosity, deep weld)

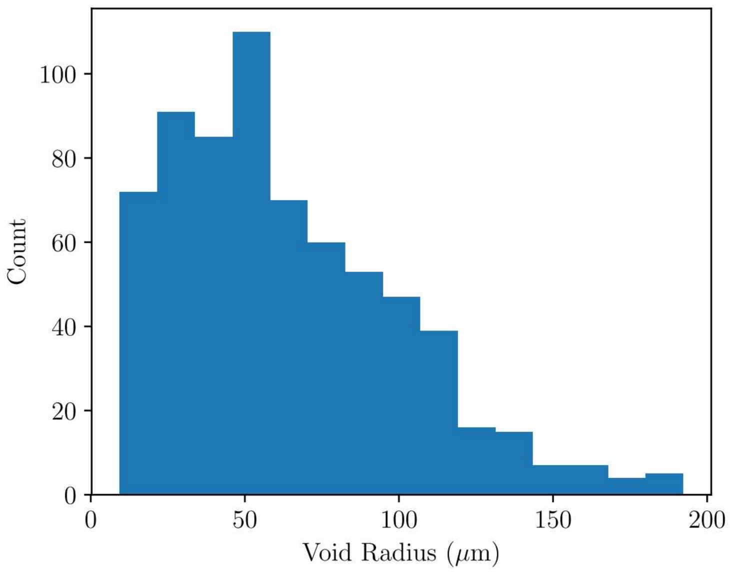


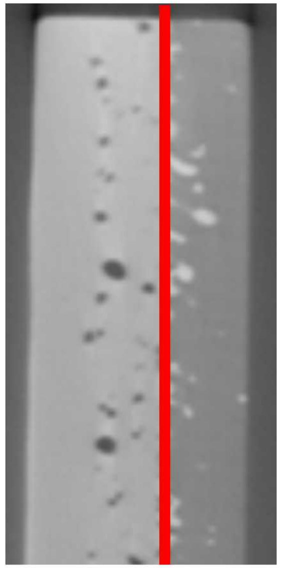
Specimen S26 (medium porosity, deep weld)

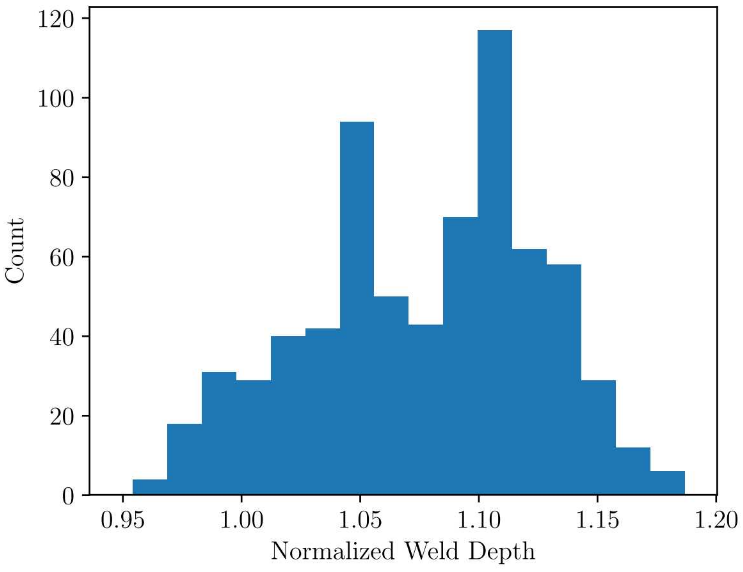


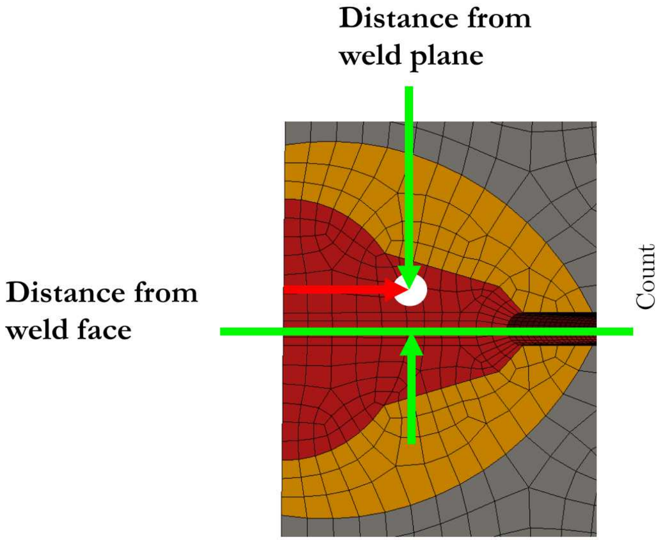
# Laser weld porosity and geometry models

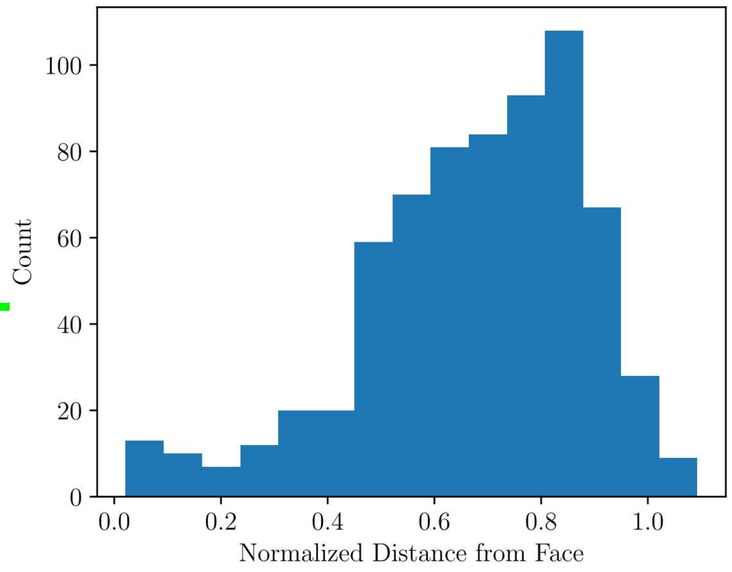
- Developed scripts to identify weld plane, weld root and weld face for locating voids
- Processed 13 CT scan data sets, 681 voids
- Assume uniform random distribution along weld length

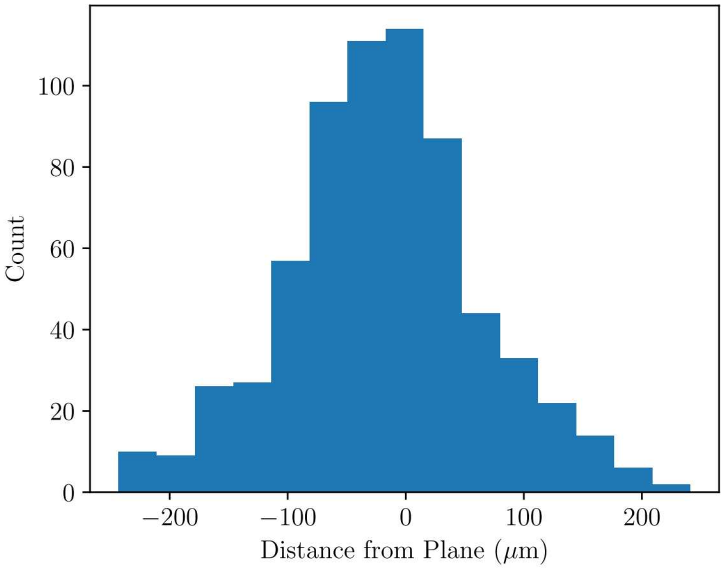




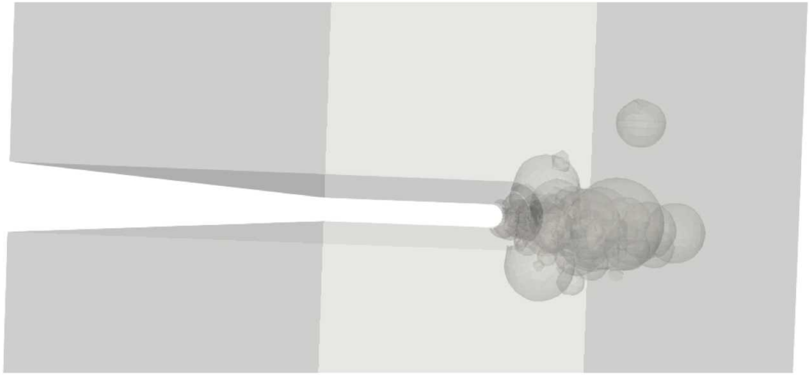



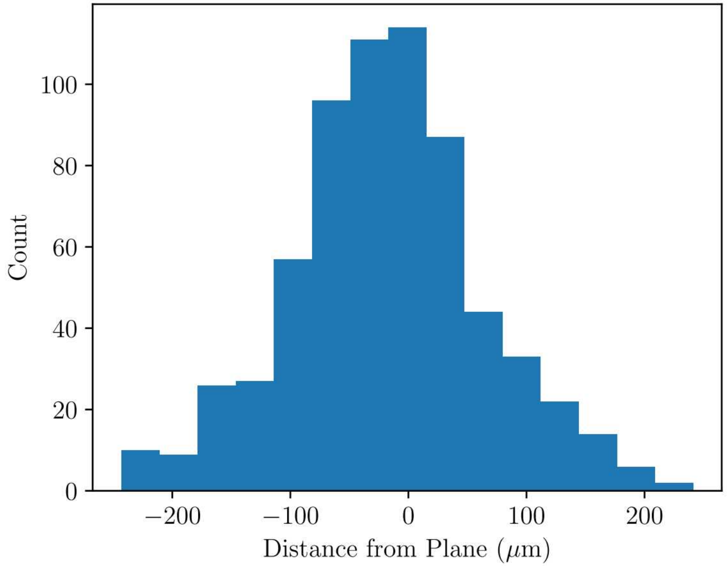



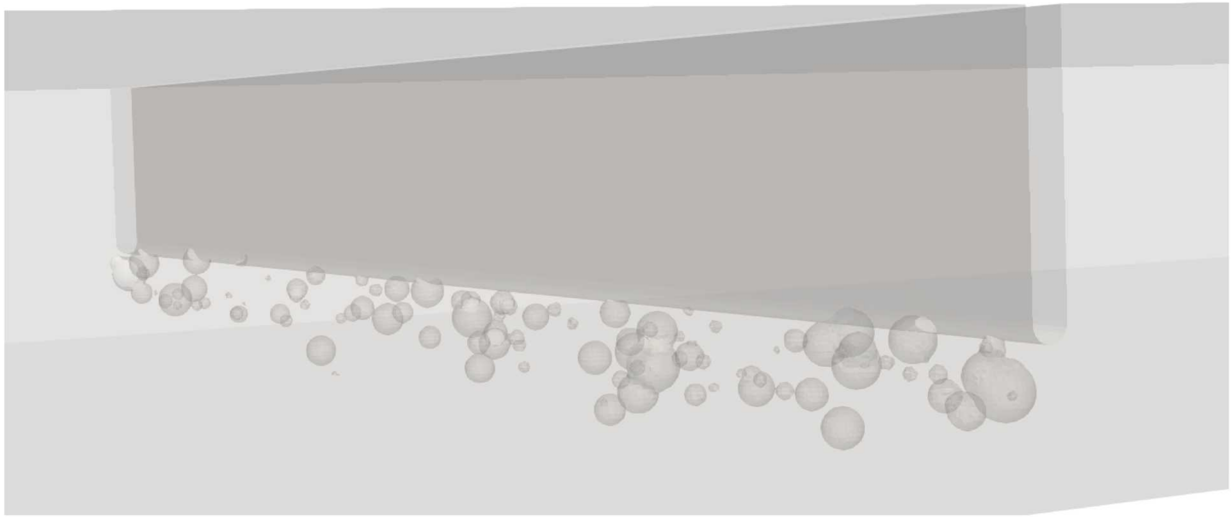
# Laser weld porosity and geometry models

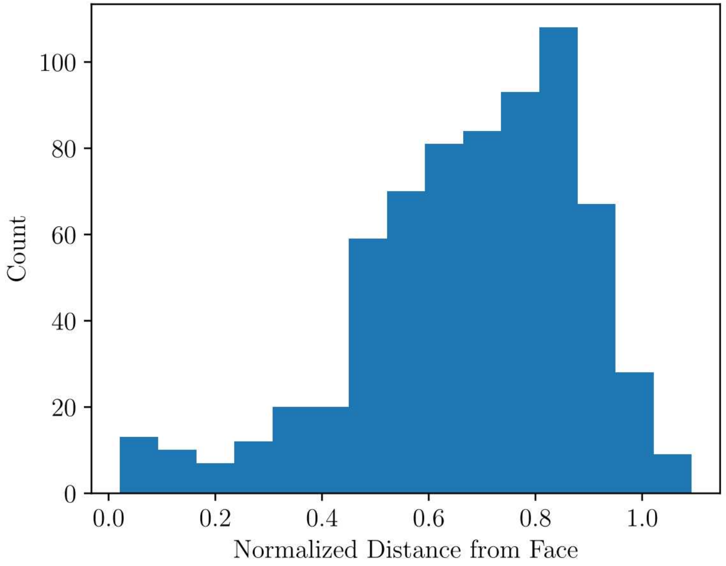
Side view of porosity realization 12



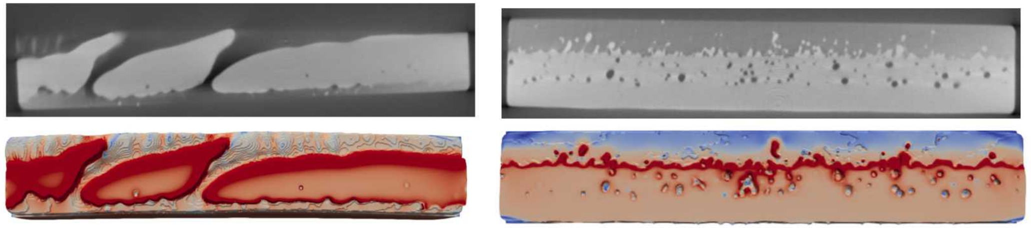



Bottom view of porosity realization 12



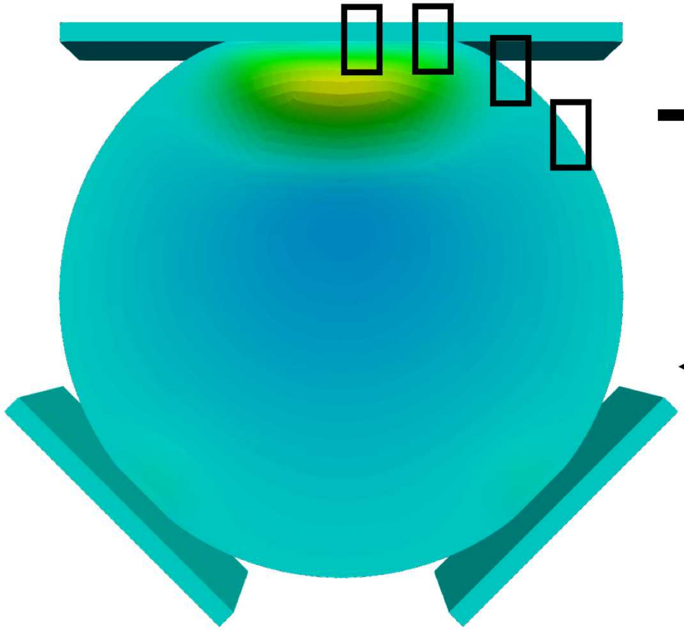


# Conclusions and future work

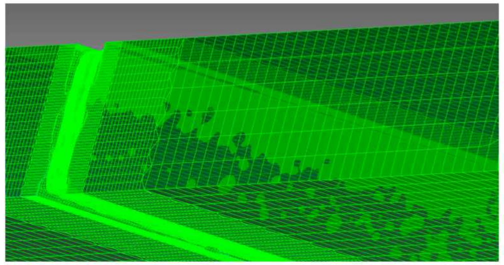


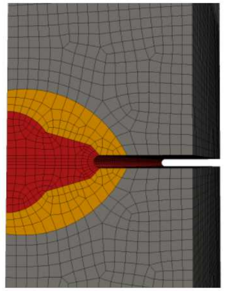
1. Weld geometry is primary driver of structural performance
   - CT Scan parts to predict as-built behavior – need more load states
   - Determine driver in variability – voids versus weld irregularity
2. Use porosity and geometry models developed from CT scans as RVE's to determine behavior in realistic loading scenarios
   - At rate/temperature in different loading conditions.

Extract boundary conditions from locations of interest using initial coarse model



Simulate the weld response with realizations of fine scale model





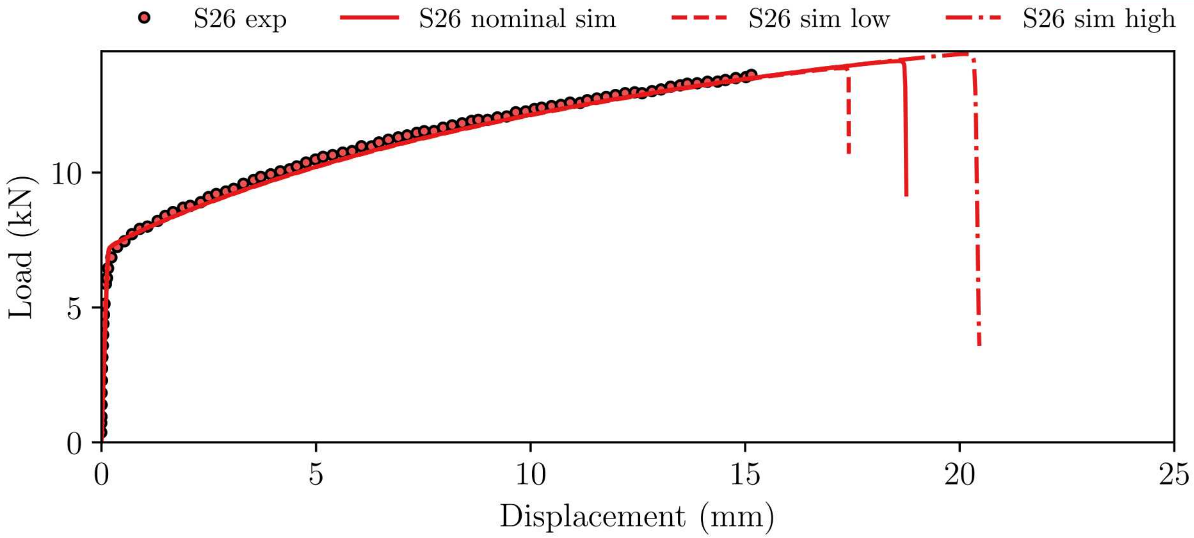
Calibrate coarse scale model to fine scale results

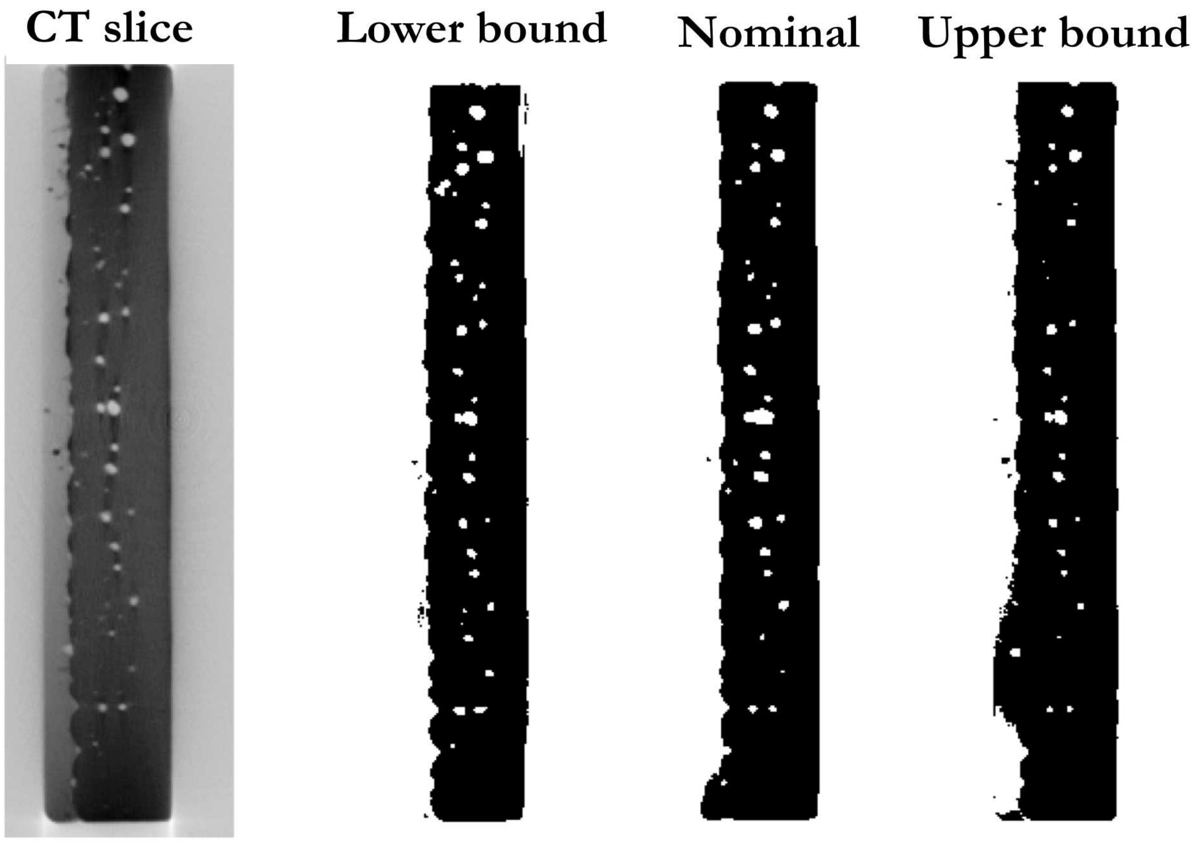
Re-run simulations with updated coarse scale model. Iterate if time allows.

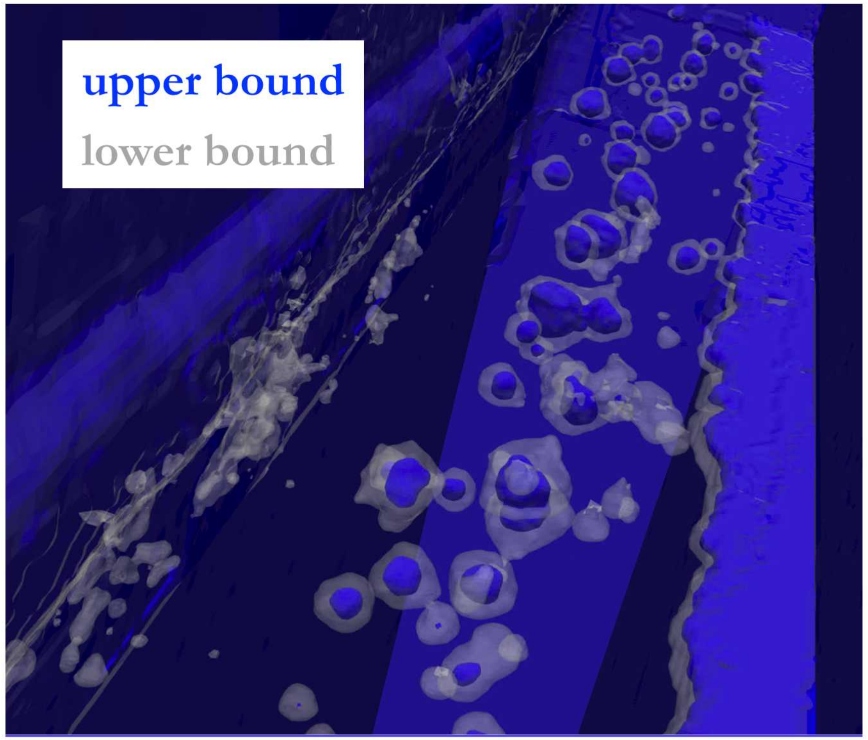
# Back up

# Uncertainty due to segmentation process

1. Still a work in progress - initial results suggest approximately 10% error due to uncertainty in segmentation process

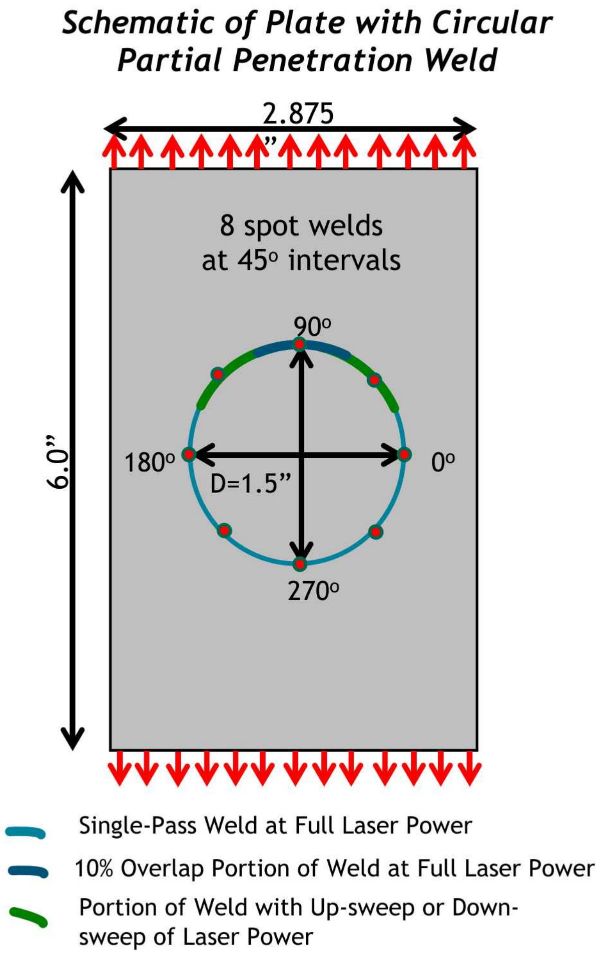


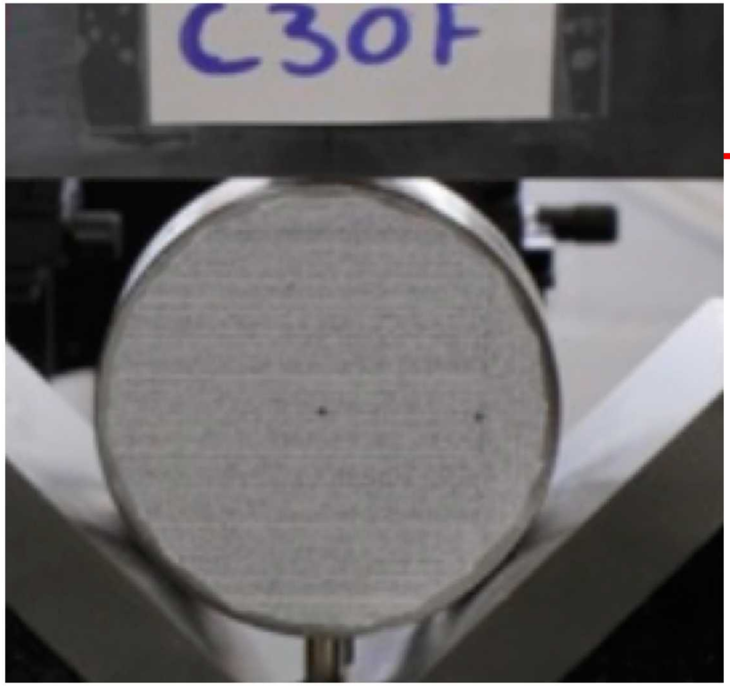
# Future work FY20: Validate new method against data from SAND2015-9012

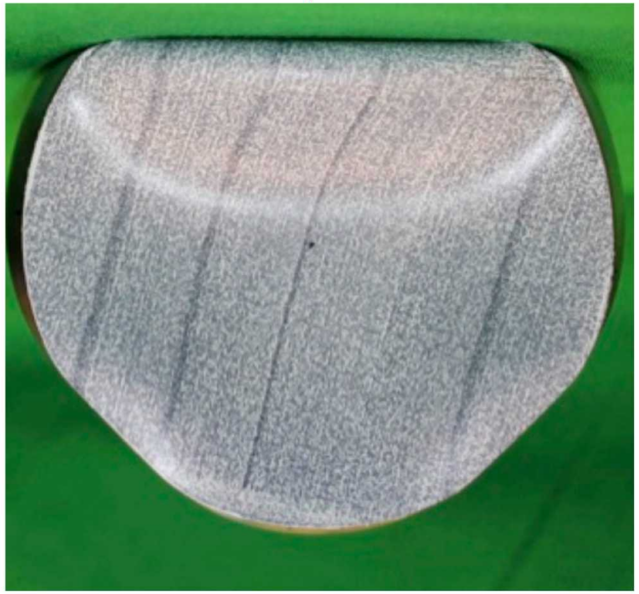
## *Circular laser weld loaded in tension*




*Simulations of actual CT scans possible.*

## *Sealed volume in a quasi-static crush*

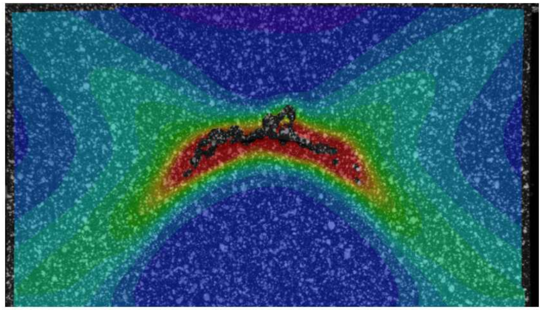


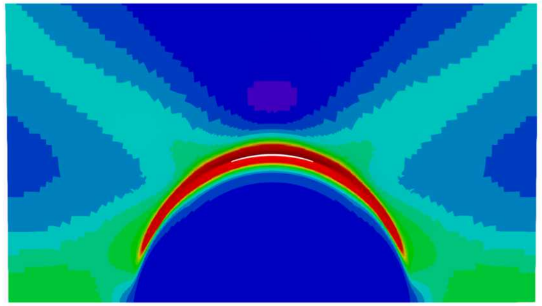



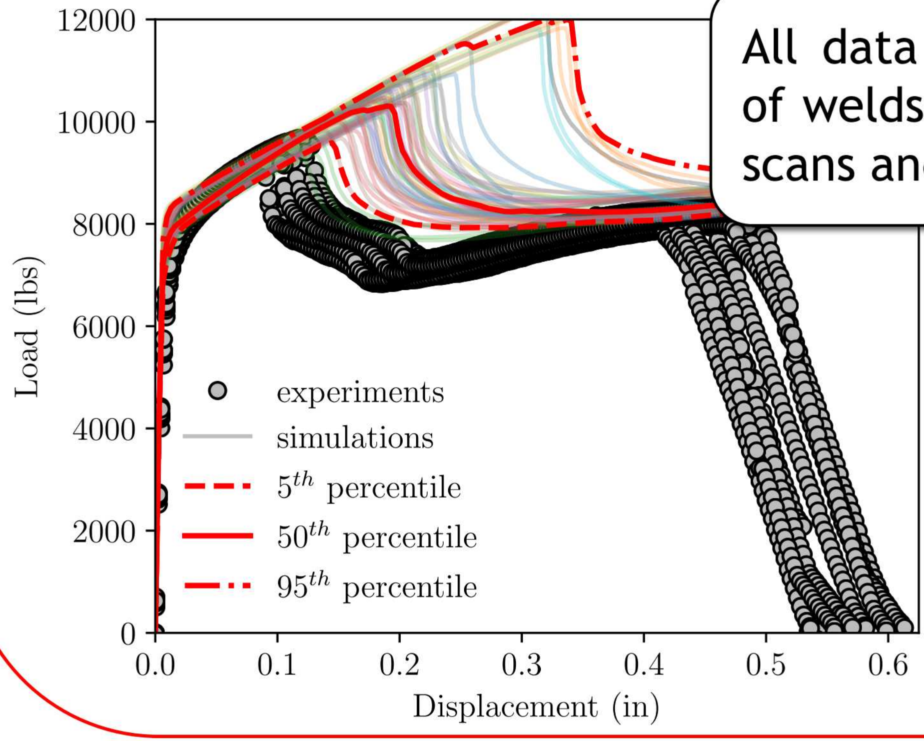
*Simulations of actual CT scans <u>seem</u> possible.*

# Future work FY20: Validate new method against data from SAND2015-9012

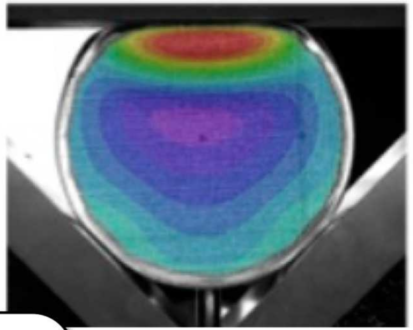
*Circular laser weld loaded in tension*



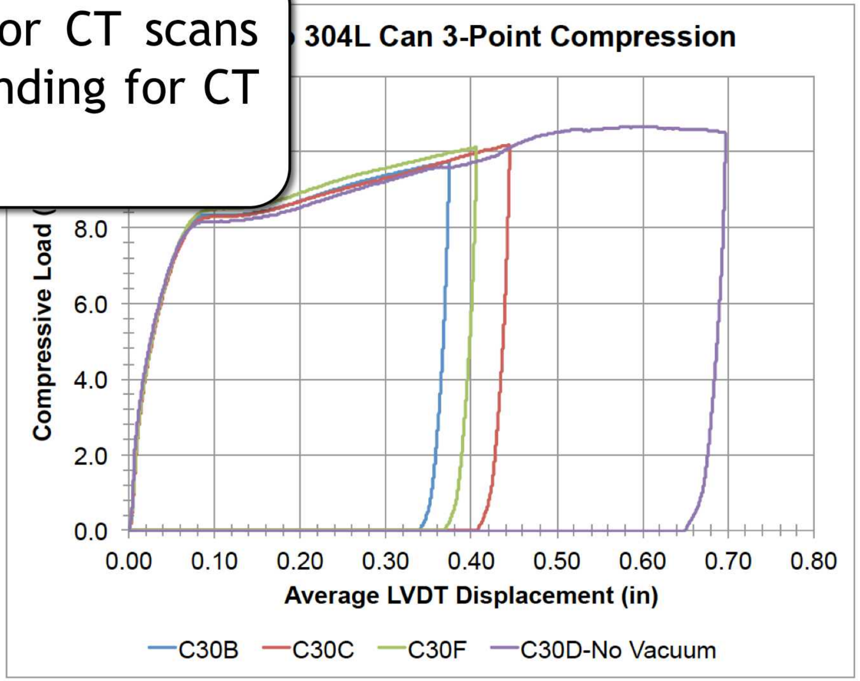





*Sealed volume in a quasi-static crush*

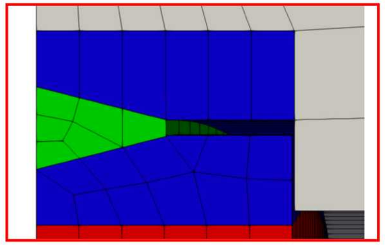


All data available except for CT scans of welds. Working to get funding for CT scans and data processing.

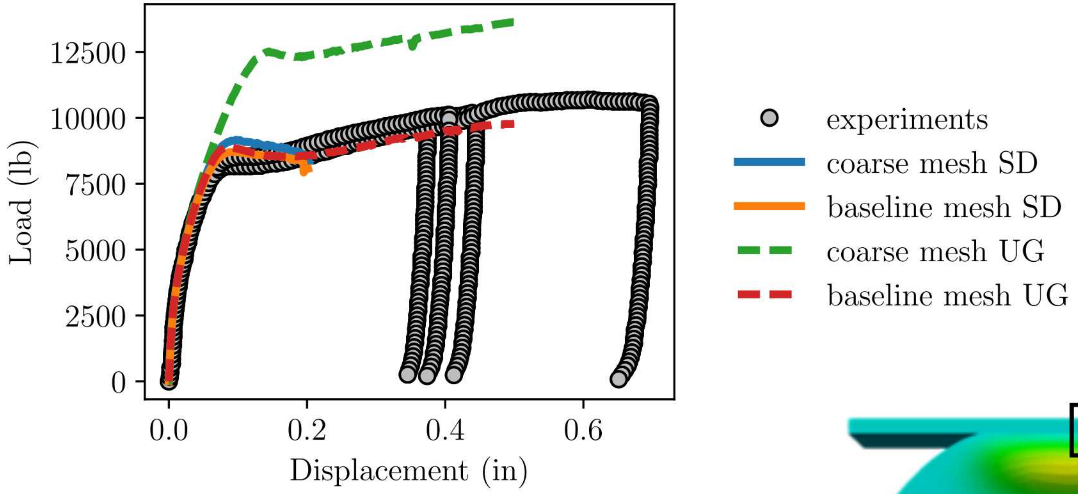


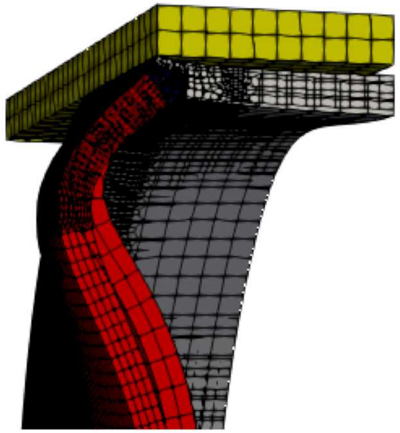
## Conclusions

- When attempting to make accurate predictions, small-scale geometry can really matter



- For highly ductile materials, the default element is not ***both*** cheap and predictive/converged. Choose one.



- Coupled, advanced surrogates for multiscale modeling may be an option for improved coarse-scale model predictions.

- Good models require a lot of great data.