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Comparison of Reduced Order Numerical Residual Stress Predictions to Neutron Diffraction Measurements of Laser Powder Bed Fusion Parts

PRESENTED BY

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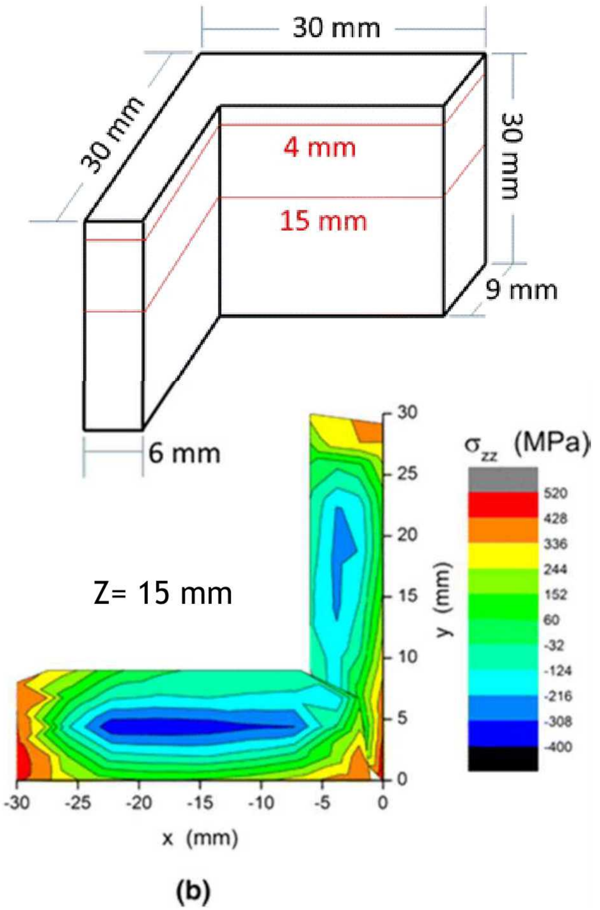
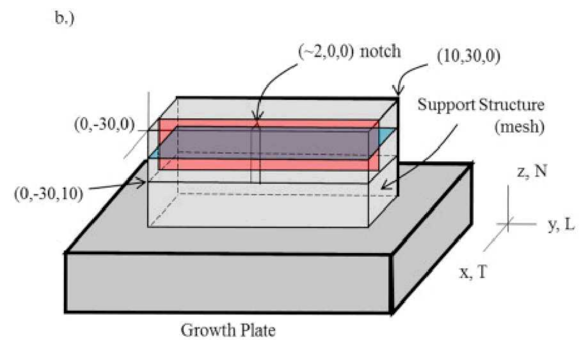
Outline

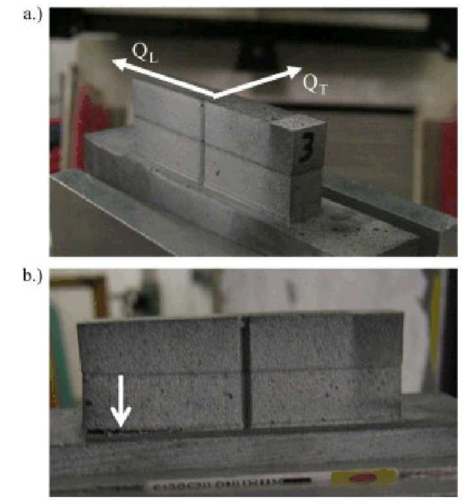
- Background
- Neutron Diffraction Measurements on AM Part
- Inherent Strain Method
- Multiscale Inherent Strain Method
- Lumped Laser Method
- Summary and Conclusions

High Thermal Gradients Produce High Residual Stresses

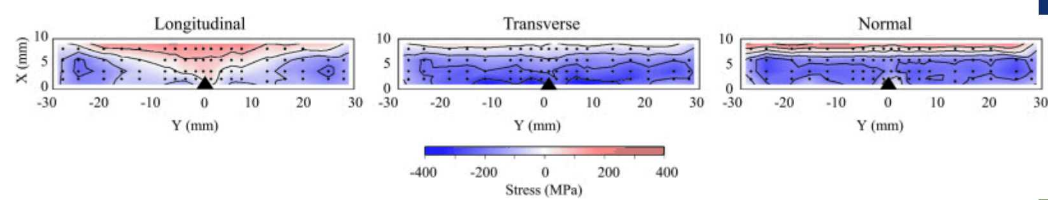


316L Stainless Steel Powder Bed
Wu *et al.* 2014 (LLNL, LANL)



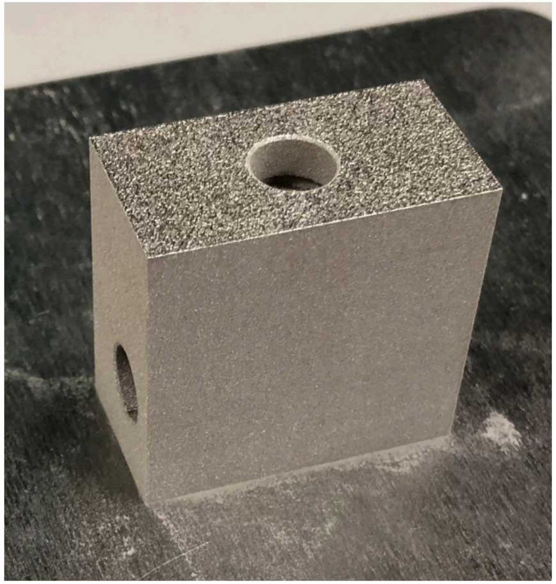


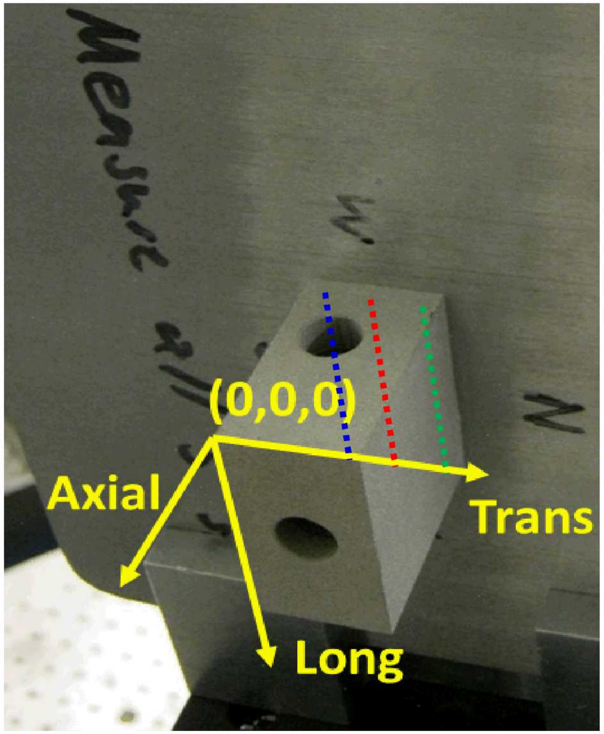
*Stress measured at blue plane

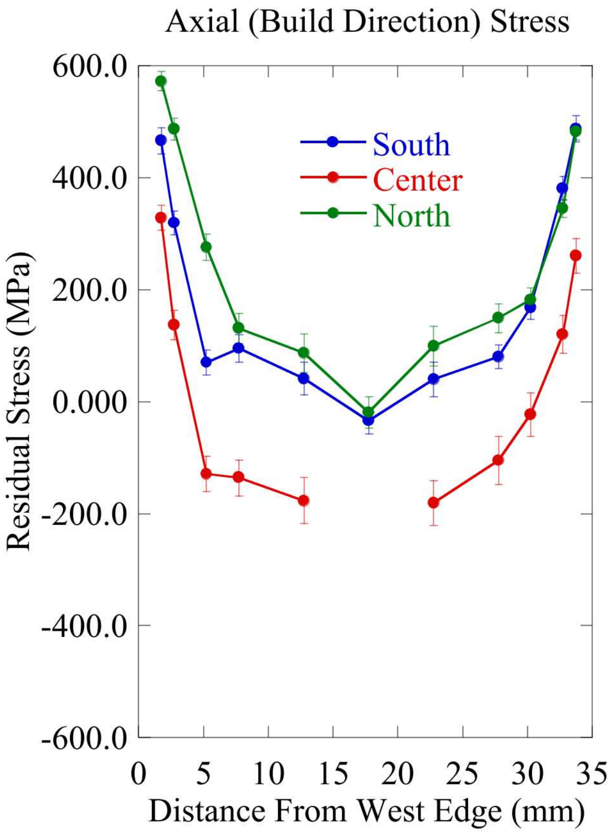


17-4 Stainless Steel Powder Bed
Brown *et al.* 2016 (LANL)

Neutron Diffraction (ND) Measurements on AM Part



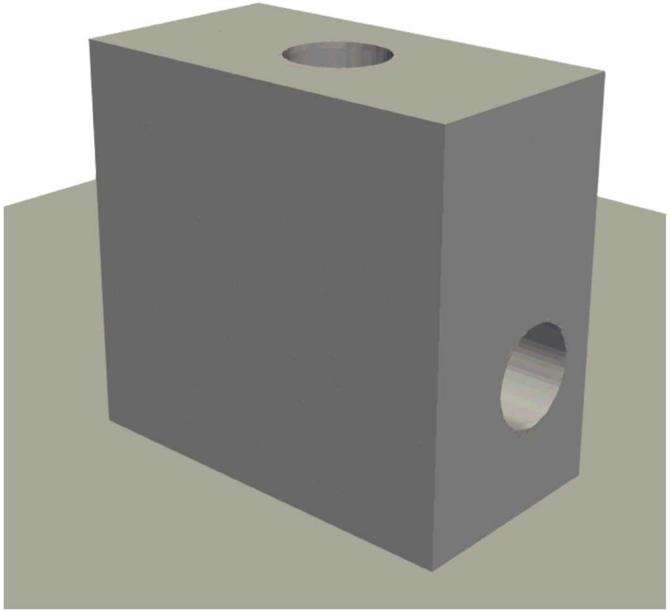




- 316L stainless steel part
- >1000 layers
- Internal channels
- Preliminary results from Don Brown, Bjorn Clausen, and Maria Strantza (LANL) using estimate for lattice parameter (values could change)
- Tensile on exterior, compressive on interior
- *Note, stresses shown with baseplate trimmed

Inherent Strain Method

- Part size is challenging for full solution
- Inherent strain method developed for weld stress prediction
  - (Ueda, Fukuda, Tanigawa 1979; Ueda, Kim, Yuan 1980, Hill and Nelson 1995)
- Volumetric strain is applied in layers over time
  - Quick approximation for distortion and stress
- Does not capture local variations due to different thermal gradients



$$\bar{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}$$

Bammann-Chiesa-Johnson (BCJ) Material Model

- Temperature and history-dependent viscoplastic internal state variable model
- Stress is dependent on damage ϕ and evolves according to

$$\dot{\sigma} = \left(\frac{\dot{E}}{E} - \frac{\dot{\phi}}{1-\phi}\right)\sigma + E(1-\phi)(\dot{\epsilon} - \dot{\epsilon}_p)$$

- Flow rule includes yield stress and internal state variables for hardening and damage

$$\dot{\epsilon}_p = f sinh^n\left(\frac{\frac{\sigma_e}{1-\phi} - \kappa}{Y} - 1\right)$$

- The isotropic hardening variable κ evolves in a hardening minus recovery form.

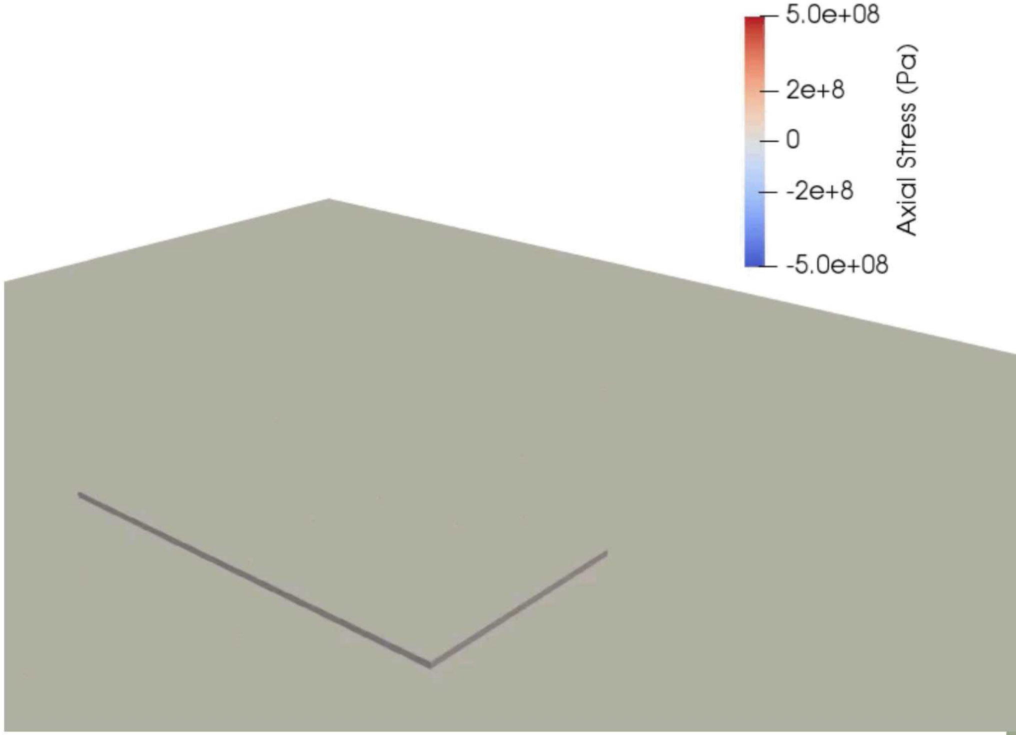
$$\dot{\kappa} = \kappa\frac{\dot{\mu}}{\mu} + (H(\theta) - R_d(\theta)\kappa)\dot{\epsilon}_p$$

Anisotropic Inherent Strain

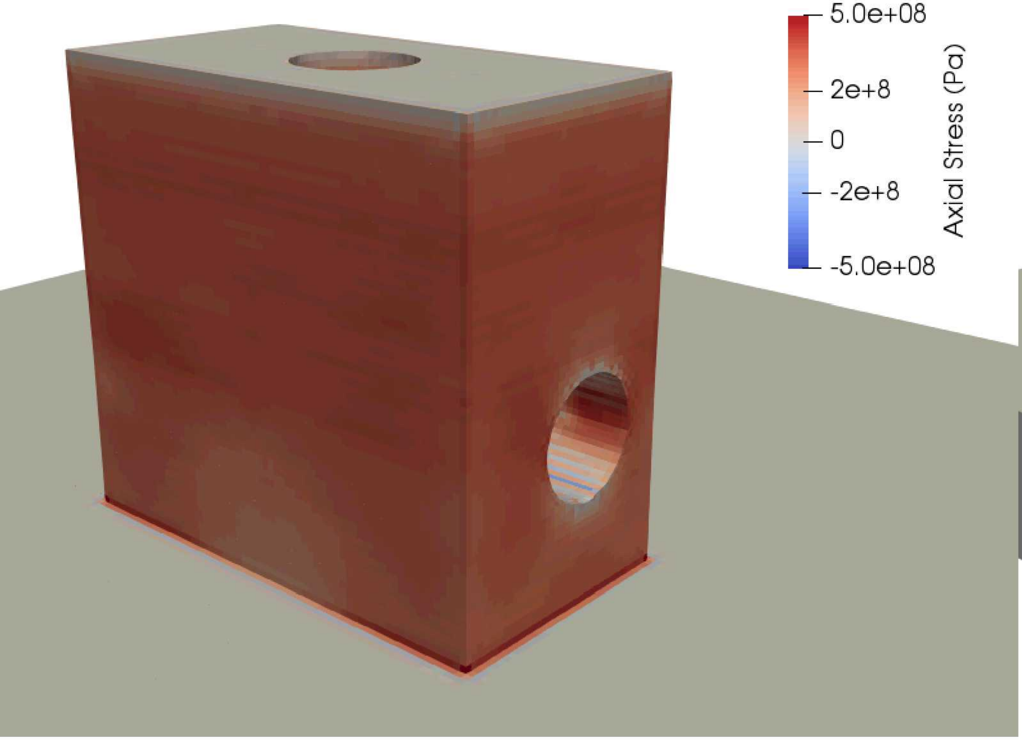
- Transverse (normal to build direction) strains are reduced and compressive

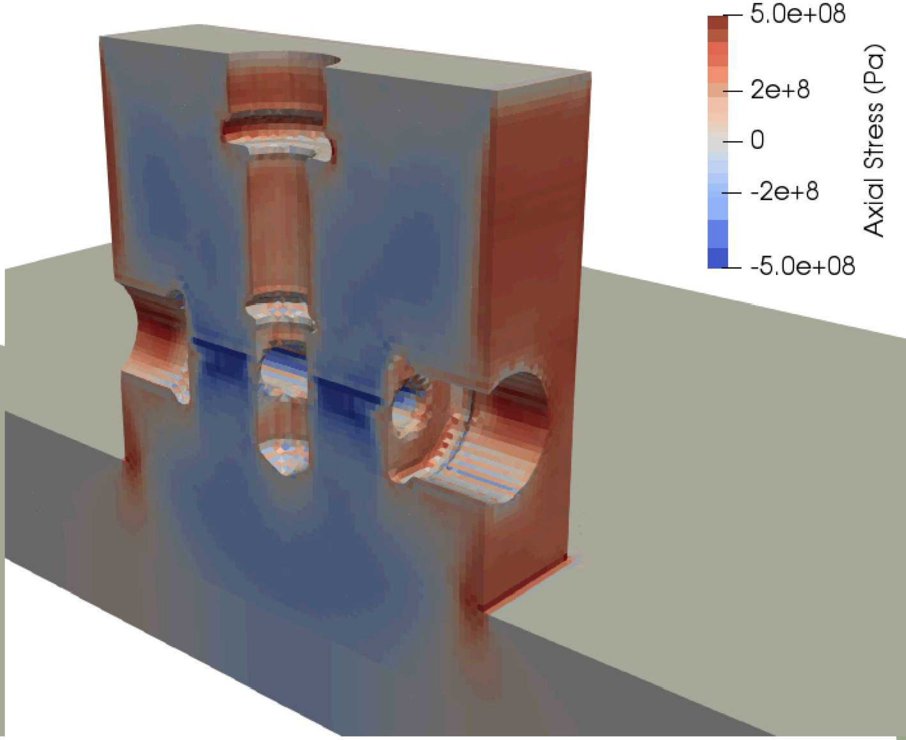
$$\bar{\varepsilon} = \begin{bmatrix} -0.02 & 0 & 0 \\ 0 & -0.02 & 0 \\ 0 & 0 & 0.05 \end{bmatrix}$$

Build Direction



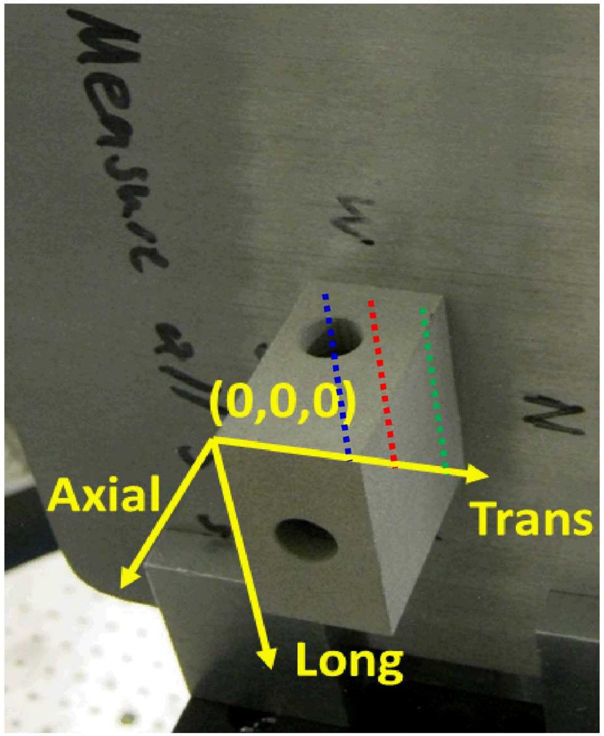
Anisotropic Inherent Strain Stress Contours

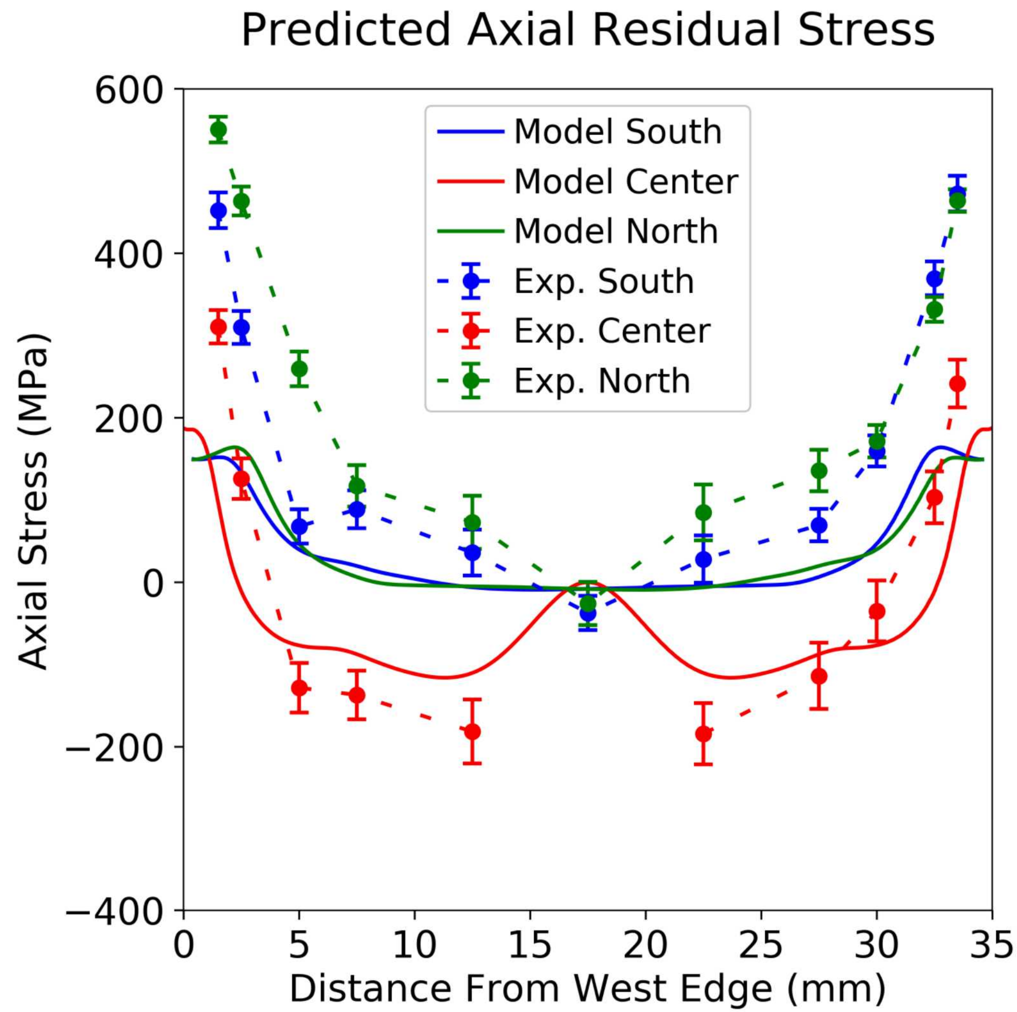




- Axial stress values appear similar to ND measurements
  - ~ 300 MPa exterior, ~ -200 MPa interior
- Wall time ~8 min on 60 cpus (~45X faster than real time 6 hr build)

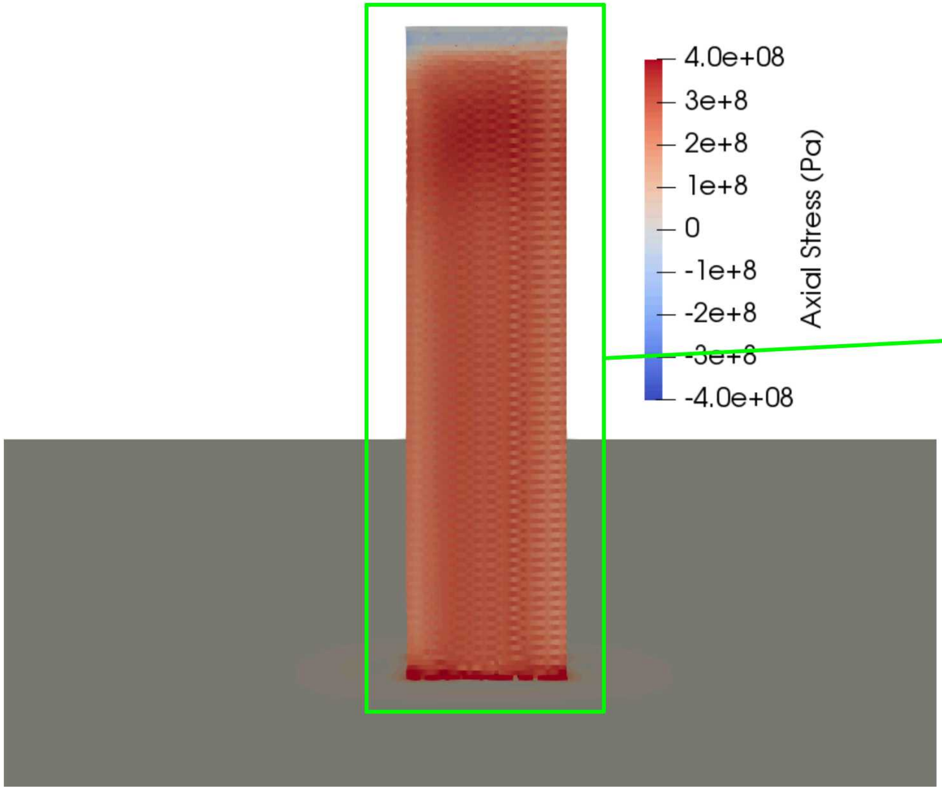
Residual Stress Predictions Show Similar Trends to ND Results





- Predicted Axial (Build Direction) Stress Shown for Blue, Red, and Green Dashed Lines

Multiscale Inherent Strain Method



$$\bar{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}$$

- Run full fine-scale solution on manageable part with same process settings – tensile dogbone gage section
- Upscale strain information to valve housing
- Could be different based on scan pattern

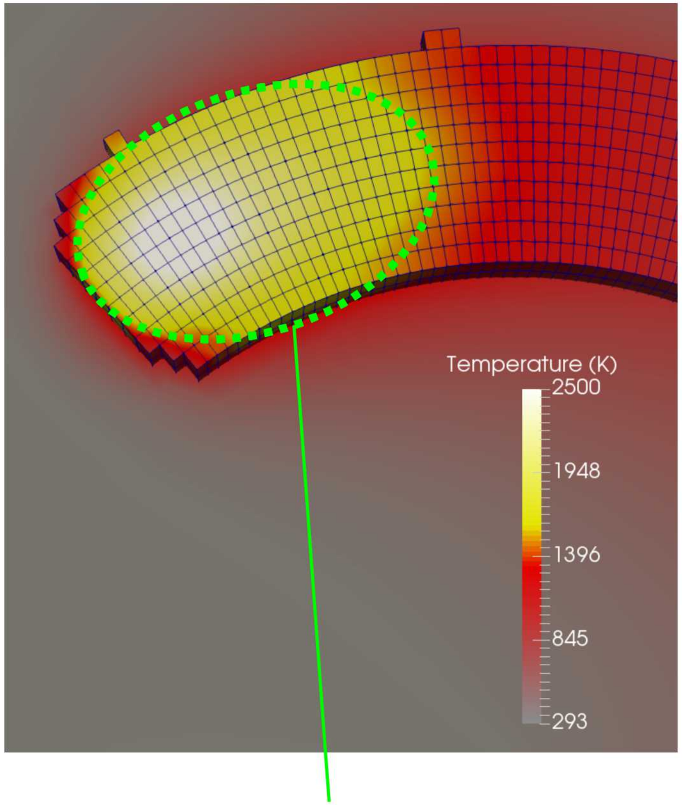
Thermal Approach

Pre-meshed part is initialized with "inactive" elements. Baseplate elements are active.

Laser heat source is scanned according to input path

Elements are activated by a thermal conductivity increase once they reach melt temperature

Conduction, convection, and radiation are considered.



Approximate Melt Pool

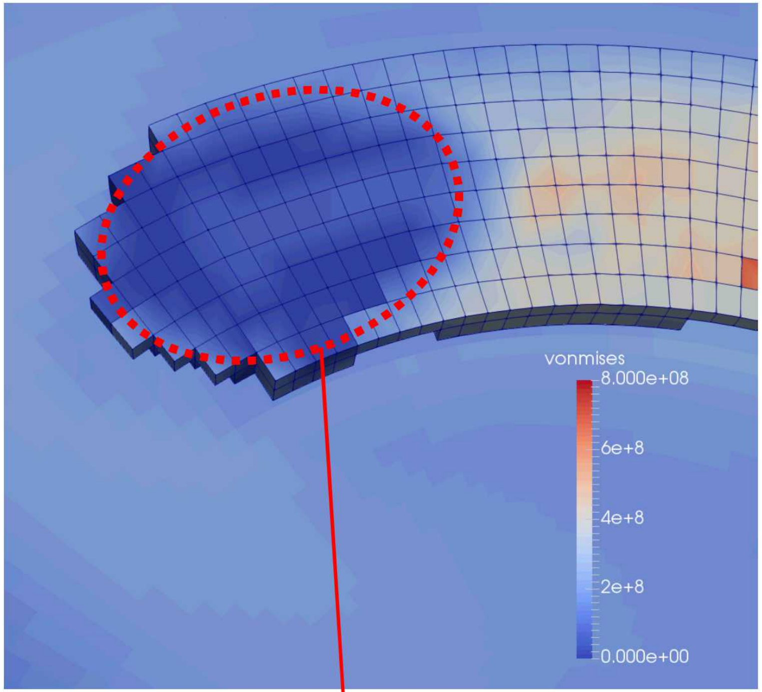
Solid Mechanics Approach

Pre-meshed part is initialized with "inactive" elements. Baseplate elements are active.

Thermal output file is read at every time step to provide temperatures

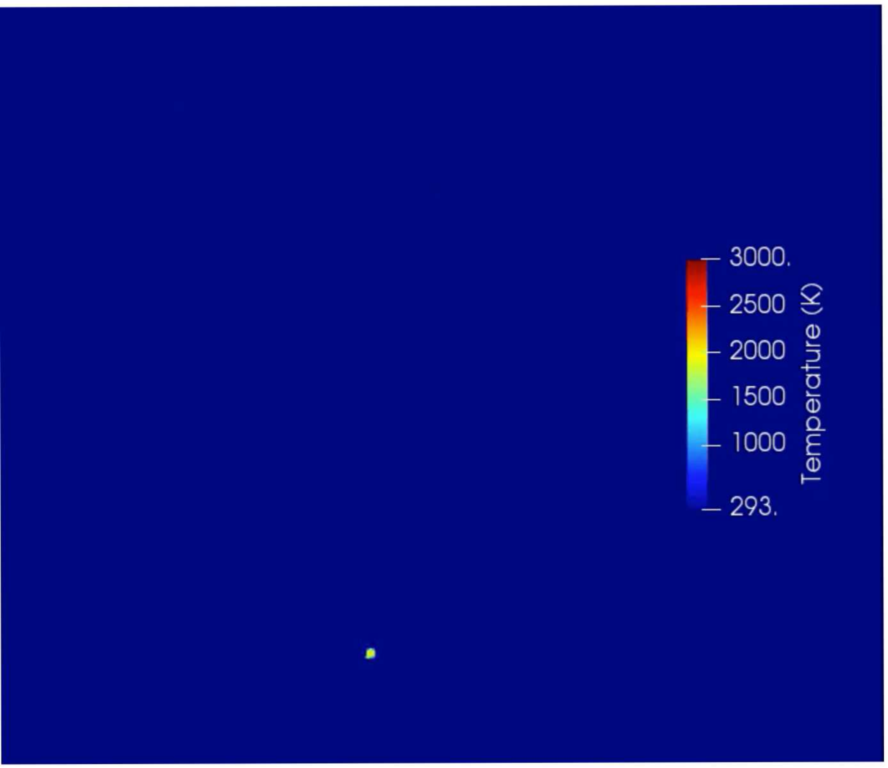
Elements are activated once they reach melt temperature

Residual stress builds as elements contract upon cooling and build thermal strain

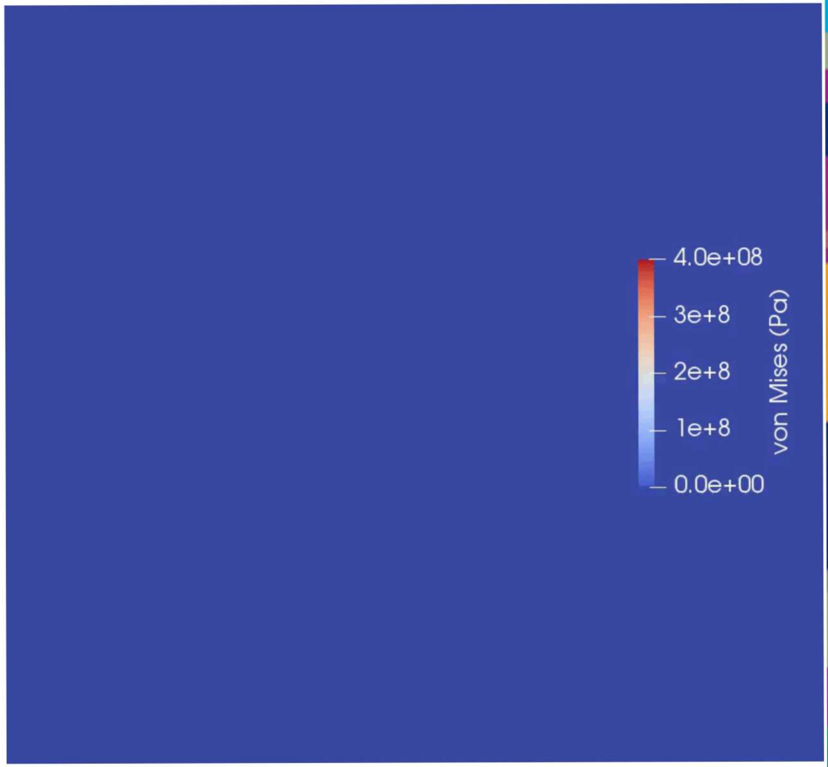


Approximate Melt Pool
(~zero stress)

Thermal and Structural Results

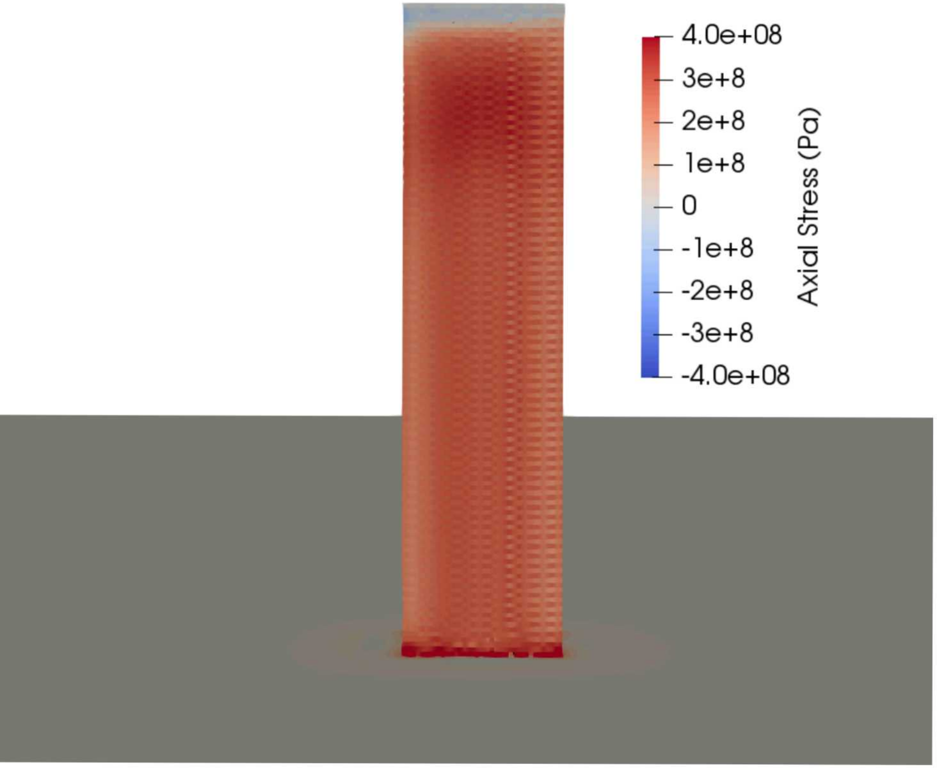


Thermal

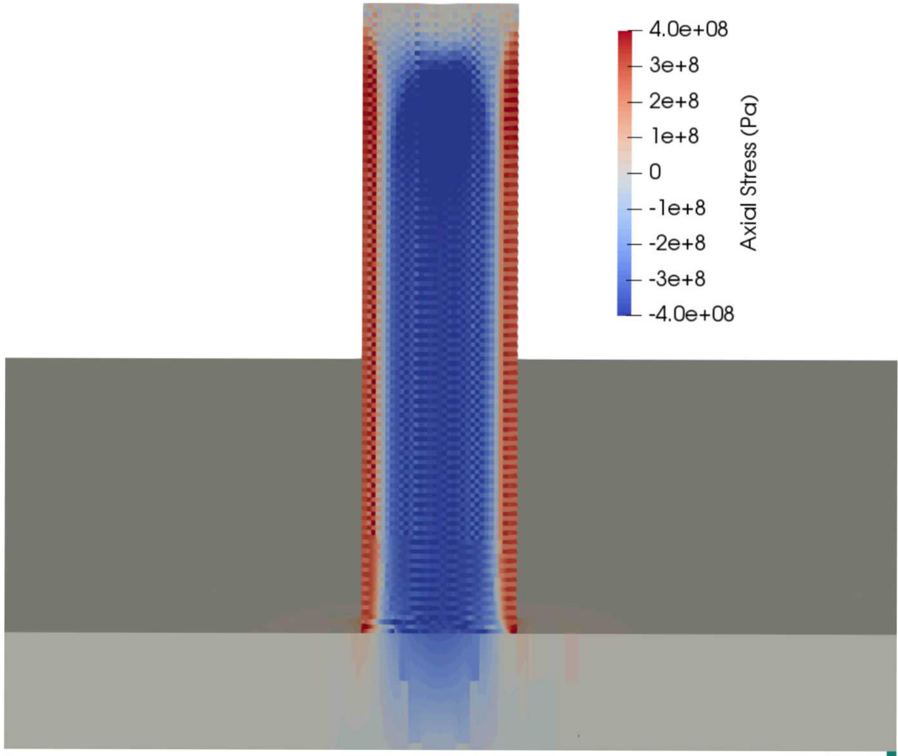


Structural

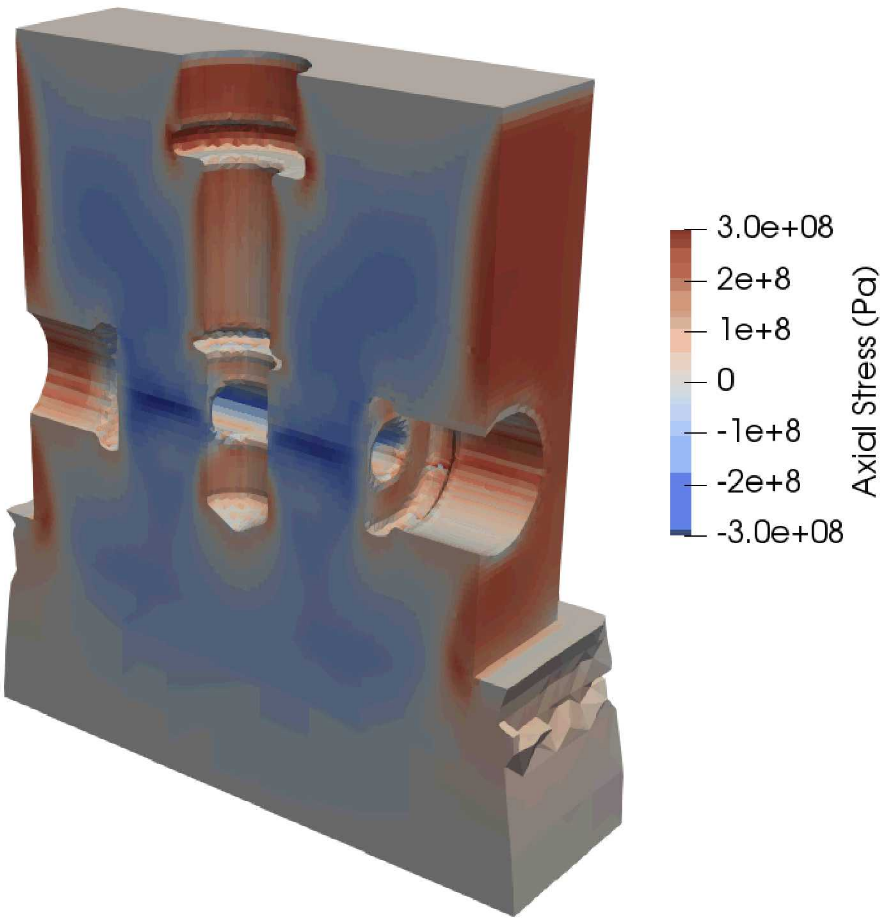
Significant Tensile and Compressive Residual Stresses Remain

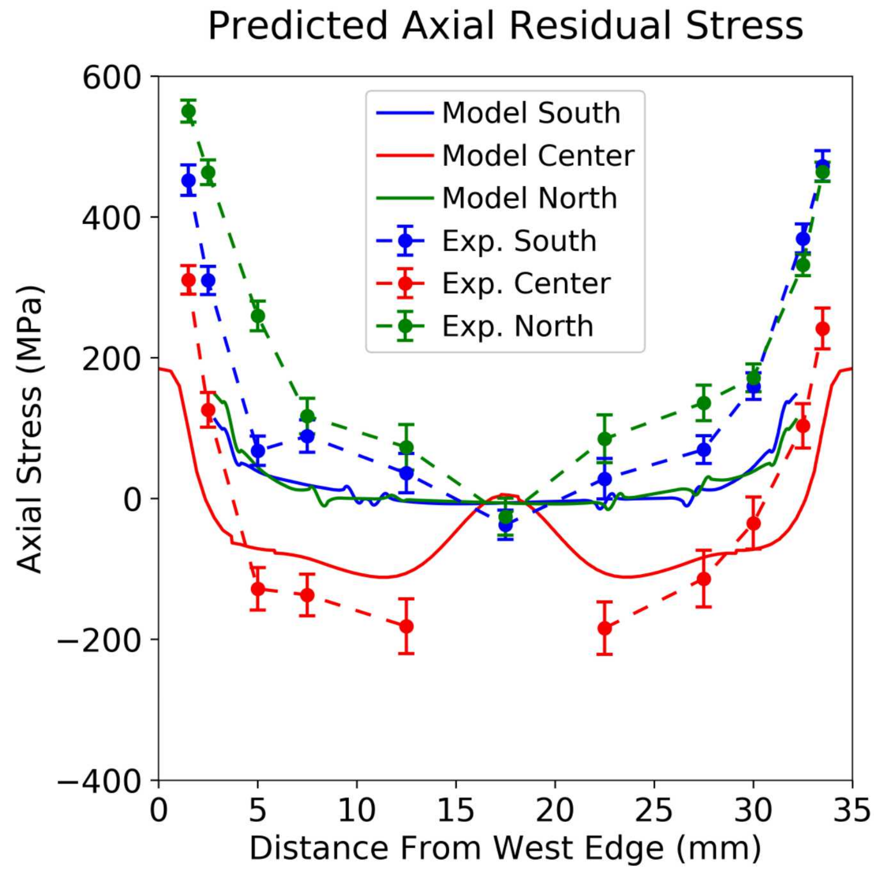


Mid-plane Cut View

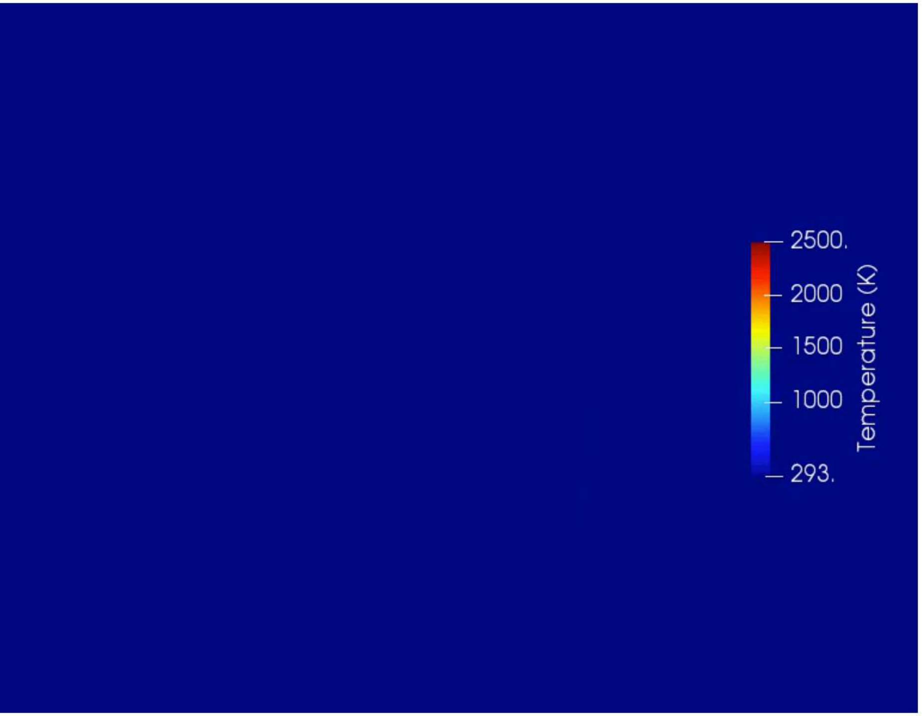


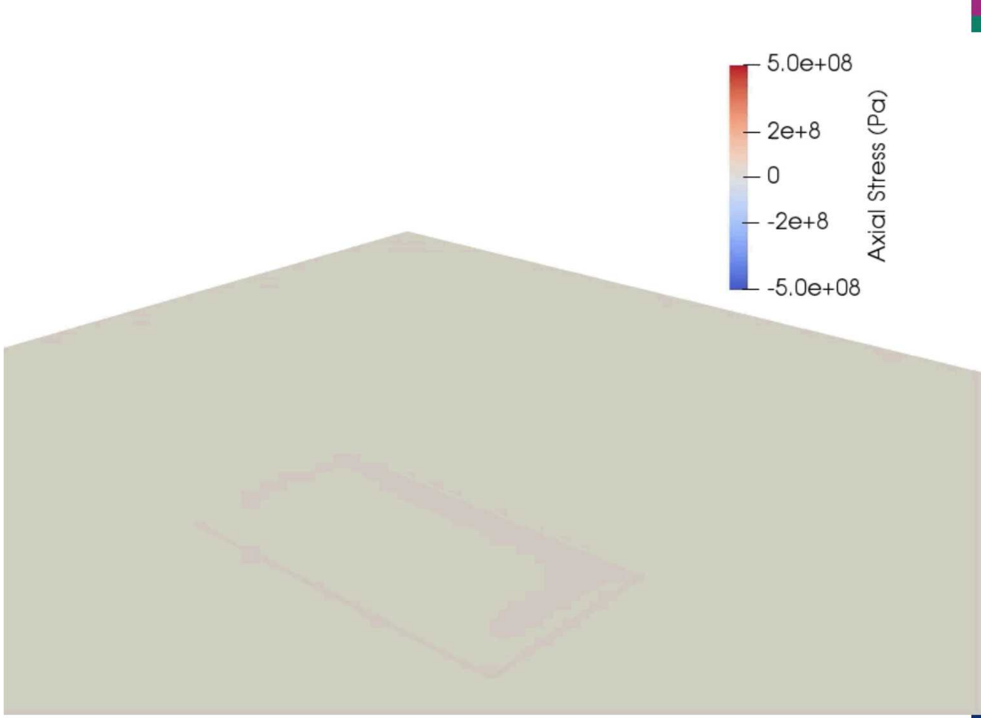
Results Show Higher Stresses and Distortion





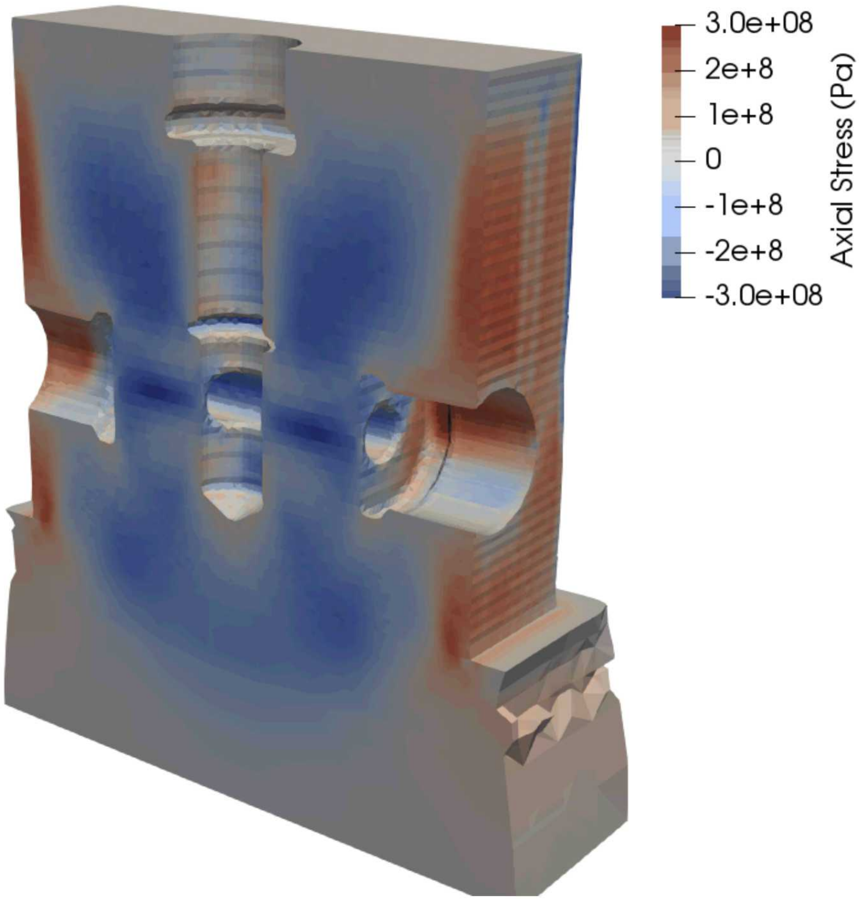
Lumped Laser Method

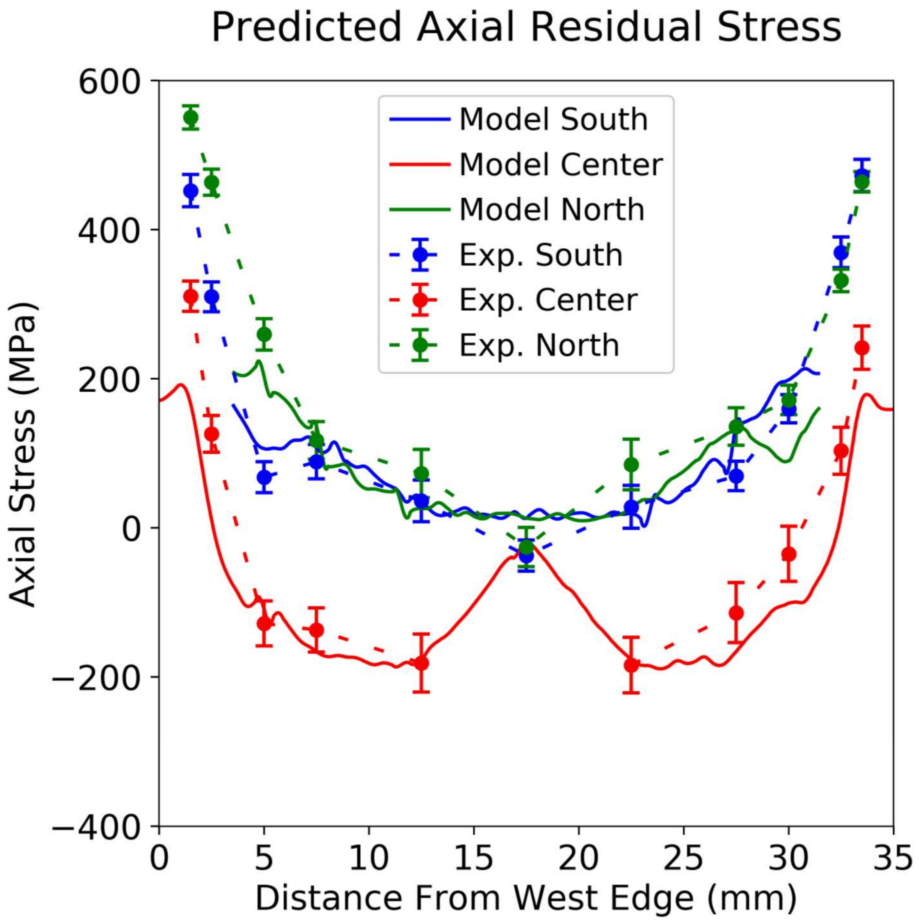




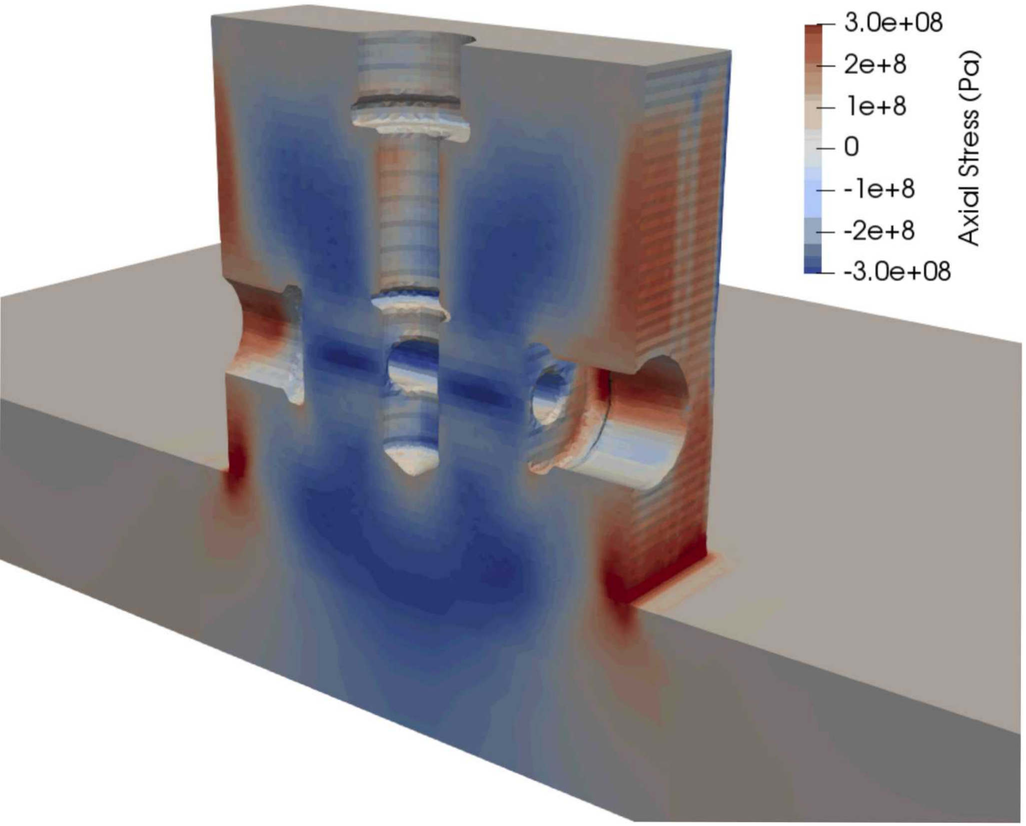
- Approach similar to Hodge *et al.* 2014 and 2016; Stender *et al.* 2018; Strantza , Ganeriwala *et al.* 2018
- ~3 mm laser diameter
- Laser radius to layer height ratio and total inter-layer cooling time held constant from actual conditions
- 0.84 mm layer height
- Laser speed unchanged – 1400 mm/s
- 40 layers
- Wall time ~6 hours on 100 cpus

Residual Stress Results

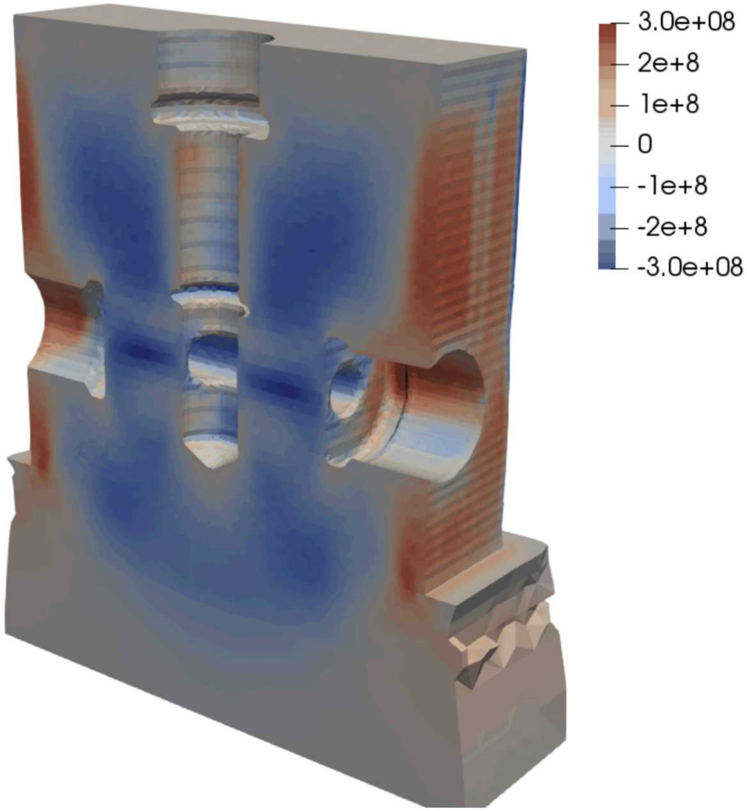




Importance of Baseplate Boundary Conditions

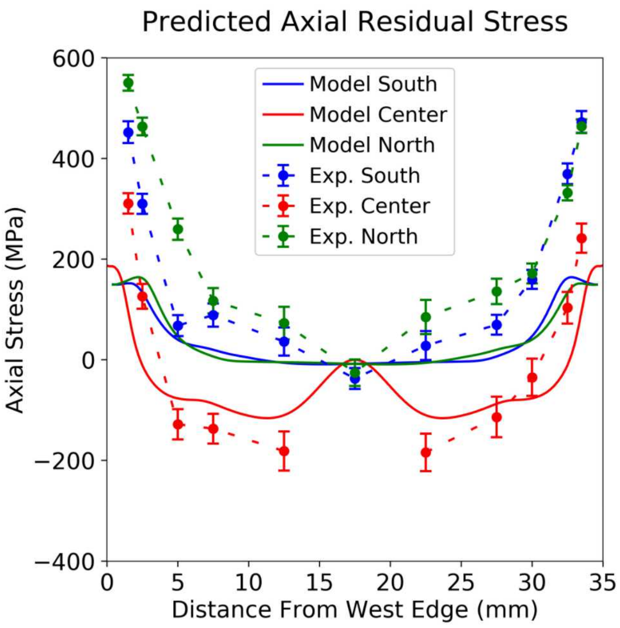


Full baseplate, fixed base

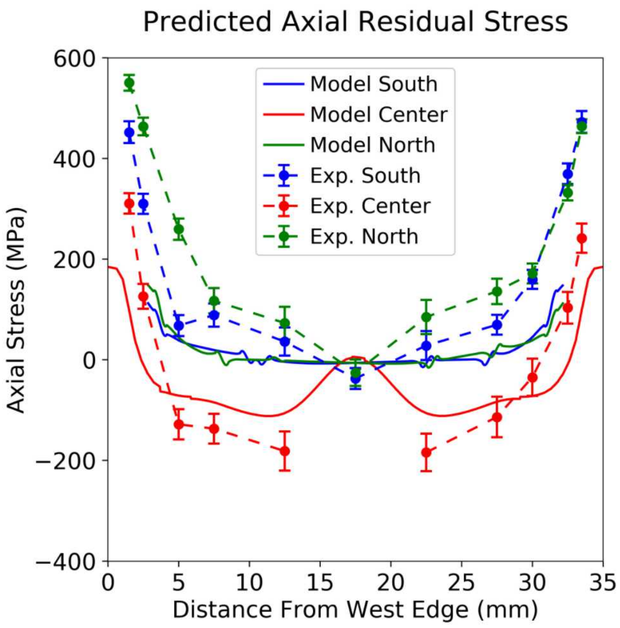


Trimmed baseplate, free base

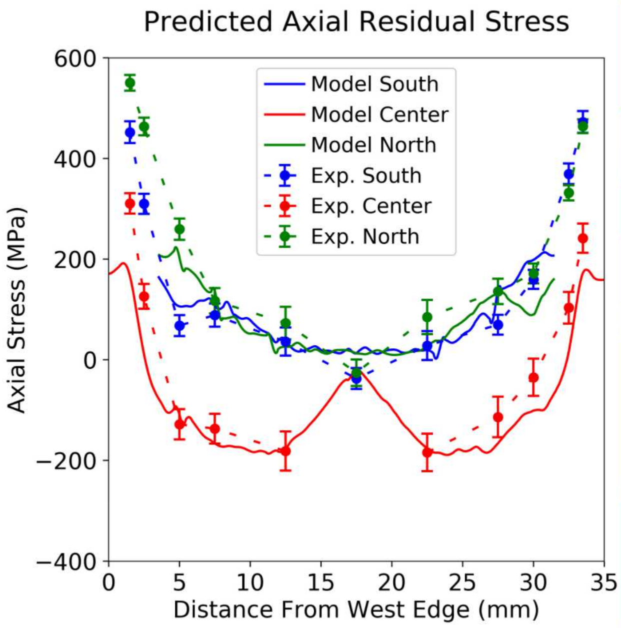
Comparison of Approximation Methods



Inherent Strain



Multiscale Inherent Strain



Lumped Laser

Conclusions

- Valve housing contains very high residual stresses
- Residual stress in valve housing can be predicted using efficient approximation methods

Future Work

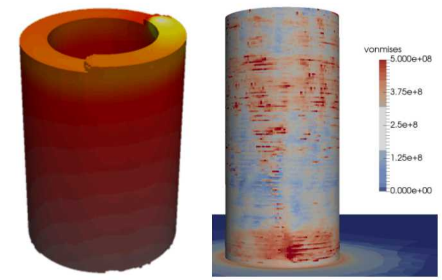
- Layer and mesh size dependence of inherent strain methods need to be understood
- Heat input in lumped laser model needs to be validated
- Examine different laser and layer sizes
- Average stresses over 2mm volume for direct comparison to ND results

Questions?

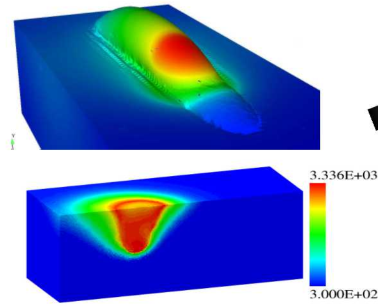
SNL Modeling Work

Codes
LAMMPS, SPPARKS, Sierra/Aria, Sierra/Adagio

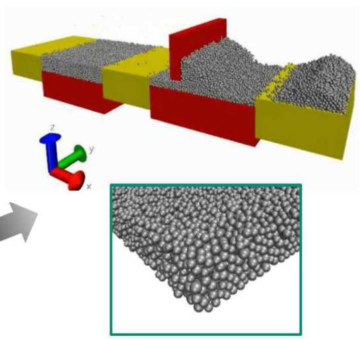
Part Scale Thermal & Solid Mechanics
Kyle Johnson, Kurtis Ford, Mike Stender, Lauren Beghini & Joe Bishop



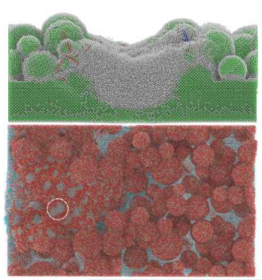
Mesoscale Thermal Behavior
Mario Martinez & Brad Trembacki



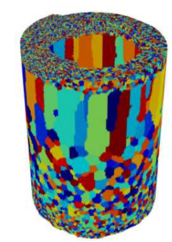
Powder Spreading
Dan Bolintineanu



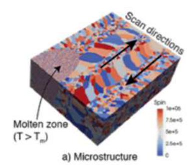
Powder Behavior
Mark Wilson



Part Scale Microstructure
Theron Rodgers



Mesoscale Texture/Solid Mechanics/CX
Judy Brown, Theron Rodgers and Kurtis Ford



10^{-6} 10^{-3} 1

Length Scale (m)