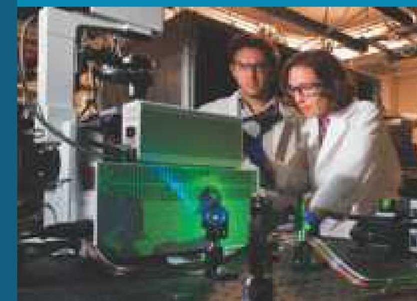
SAND2019-2839C

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



PRESENTED BY

Kyle Johnson[1], Don Brown[2], Bjørn Clausen[2], Maria Strantza[2], Bradley Jared[1], Kurtis Ford[1], and Joe Bishop[1]

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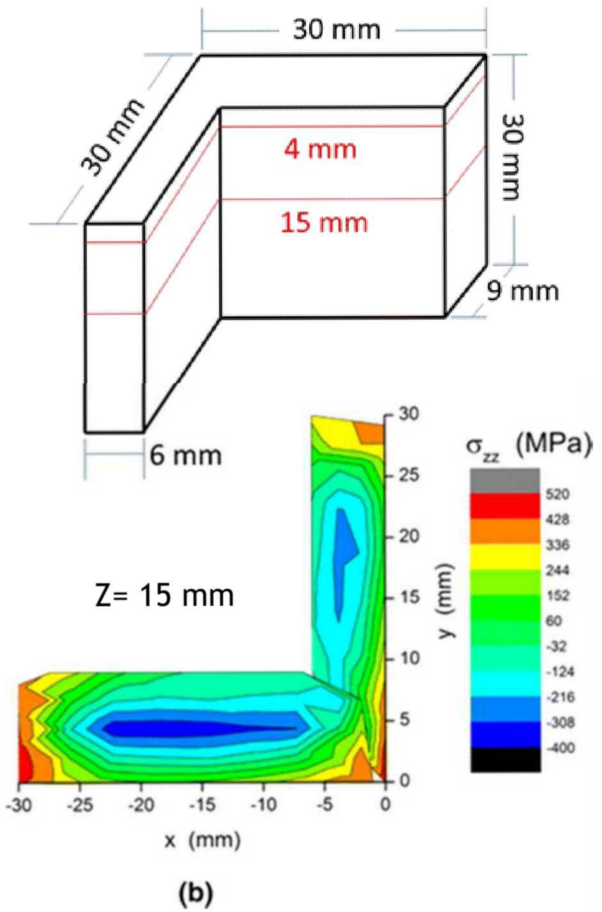
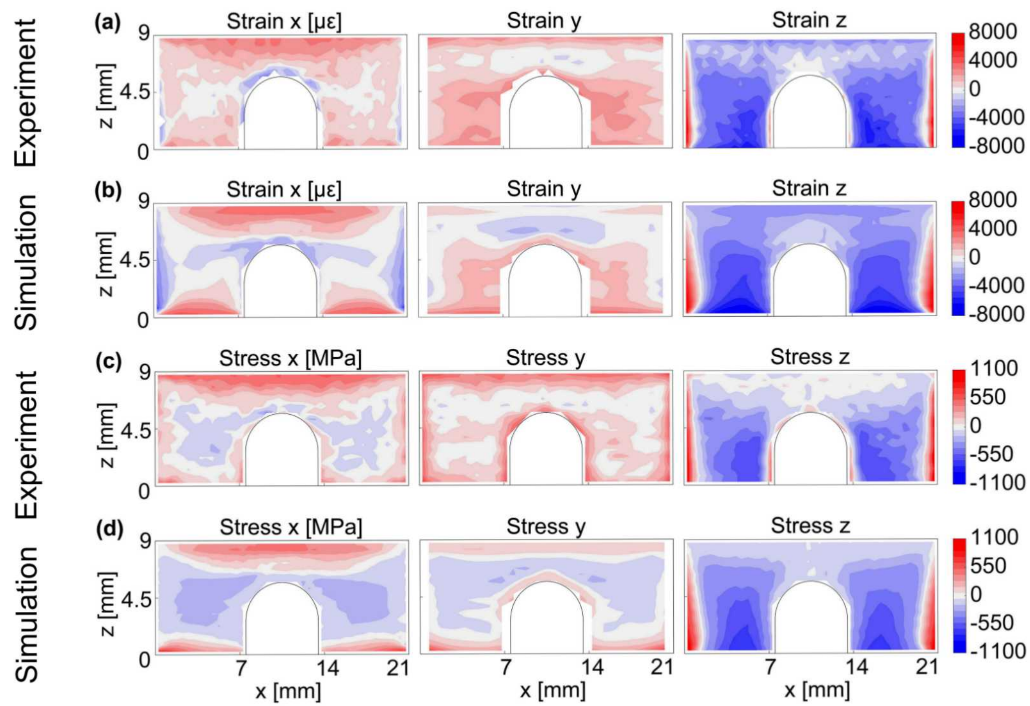
Outline

- 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

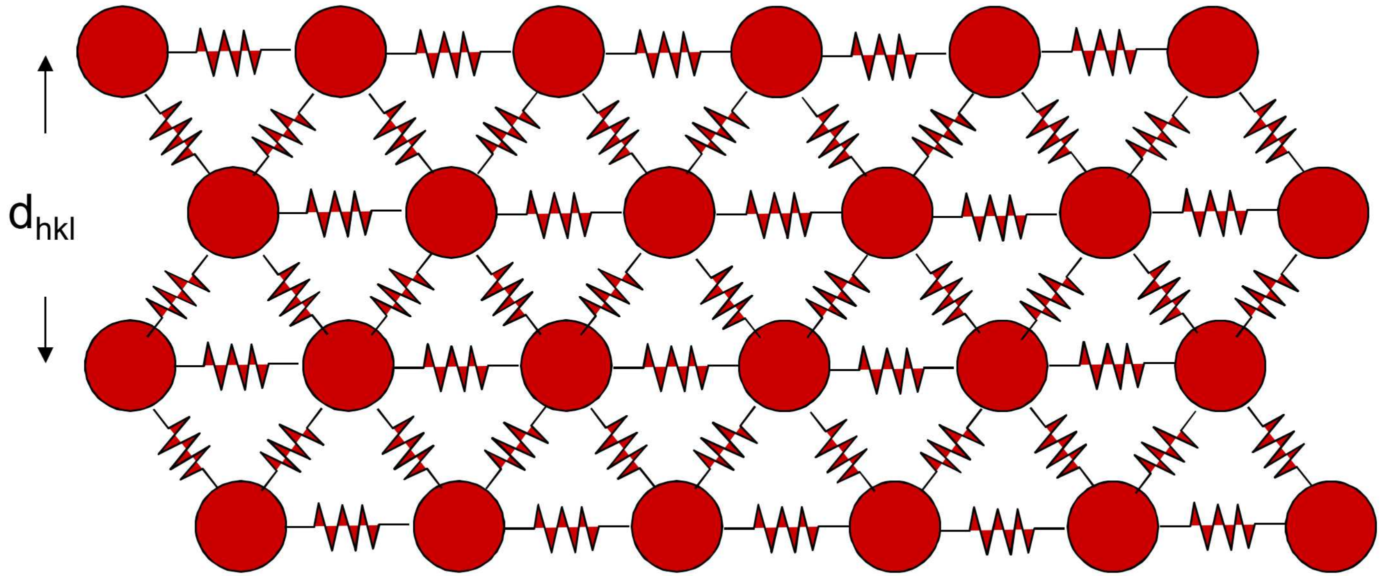


316L Stainless Steel Powder Bed
Wu *et al.* 2014



Ti-6Al-4V Powder Bed
Strantza *et al.* 2018

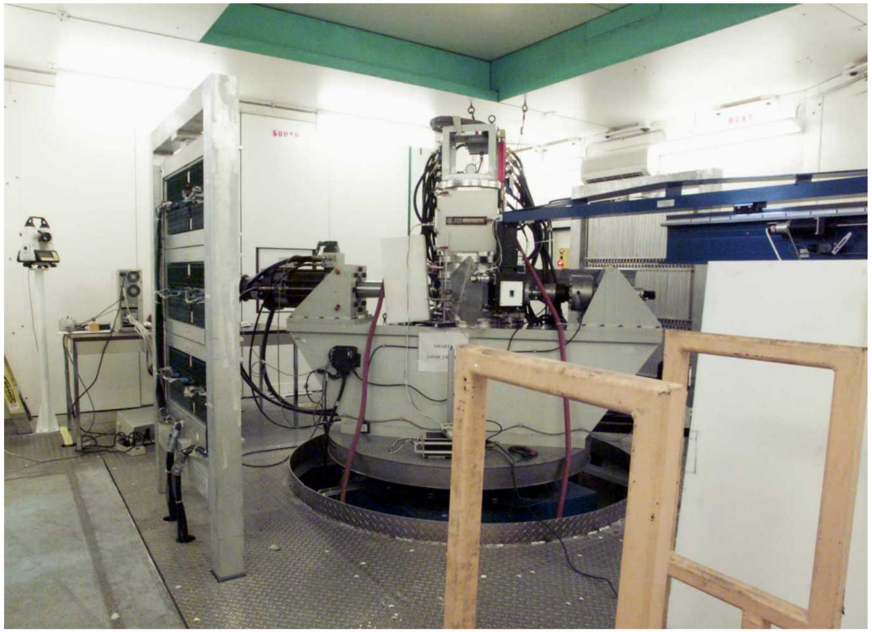
Stress is Calculated From the Elastic Lattice Strain

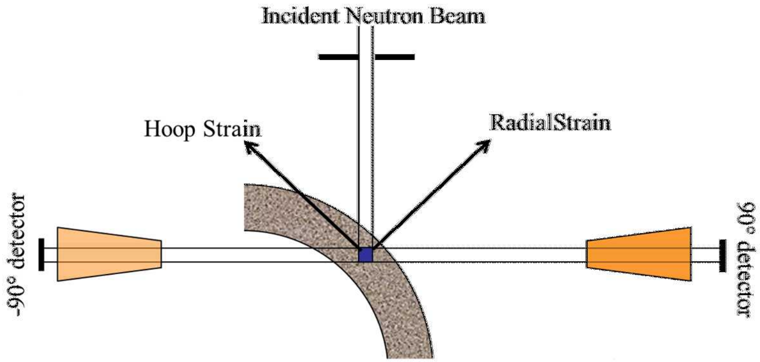


- We measure the spacing between atoms very accurately, ~10 ppm.
- Calculate lattice strains from change in atomic spacing due to stress.
  - Lattice strain : $\varepsilon = \dfrac{d_{hkl} - d_0}{d_0}$
- If we know the spring constants, we can calculate the stresses from the strains.
  - $\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$ $\quad \sigma_i = \dfrac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_i + \nu\left(\varepsilon_j + \varepsilon_k\right)\right],\ i, j, k \in L, T, N$
- It is important to note that the lattice strain is necessarily proportional to the stress on the grain set, not the macroscopic stress.

Sample Dimensions and Objectives Drive Measurement Type

Neutrons: SMARTS

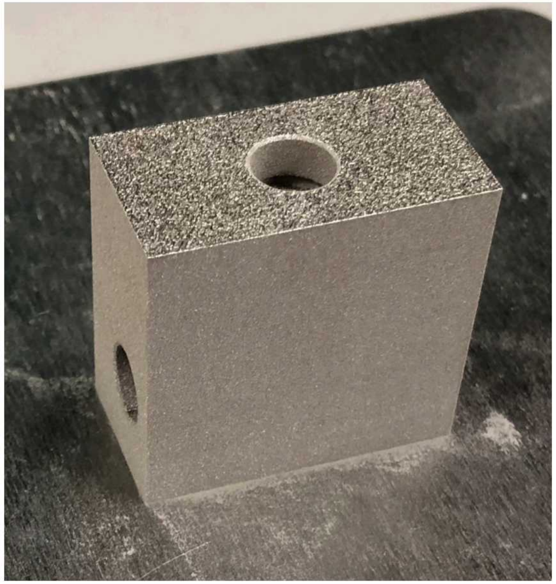


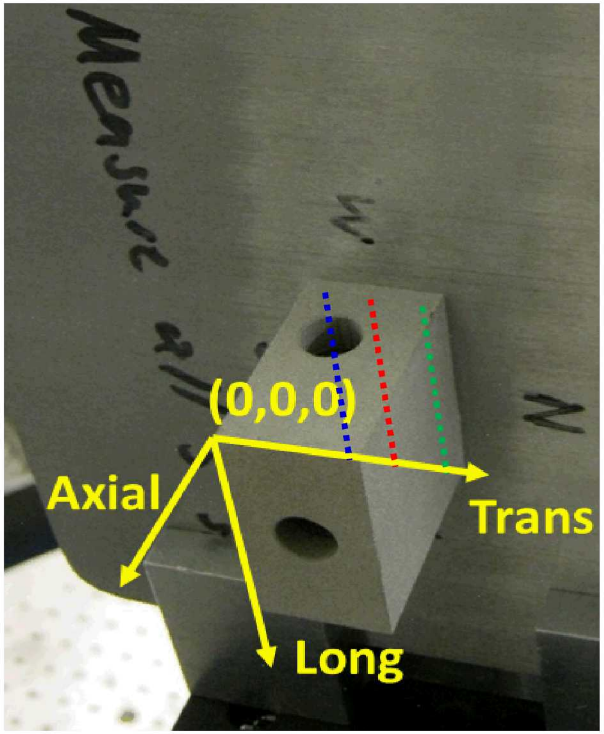


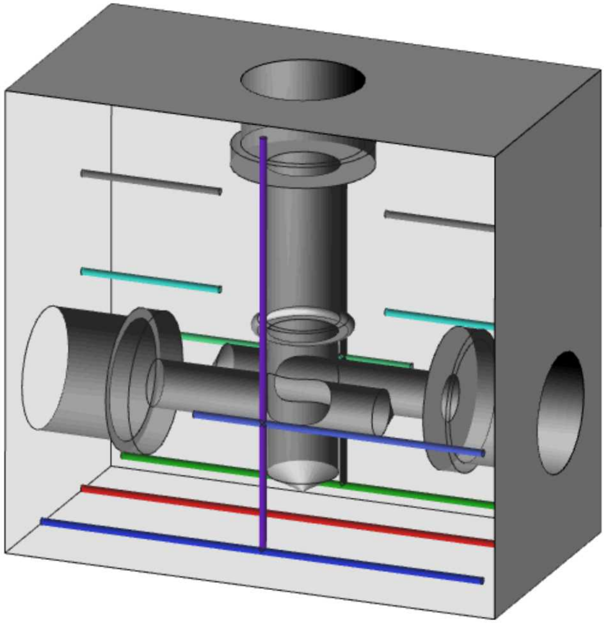
- Best spatial resolution of 0.5mm.
- Count times 5-60 minutes
- Sample table : horizontal travel ±30 cm, vertical ±60 cm, 370º rotation.
  - 1500 Kg capacity.
- Titanium and Vanadium difficult or impossible.

- λ=1-4Å.
- Beam cross section : 2mm x 2 mm
- Usually easy to get 3 orthogonal strain components.

Neutron Diffraction (ND) Measurements on AM Part

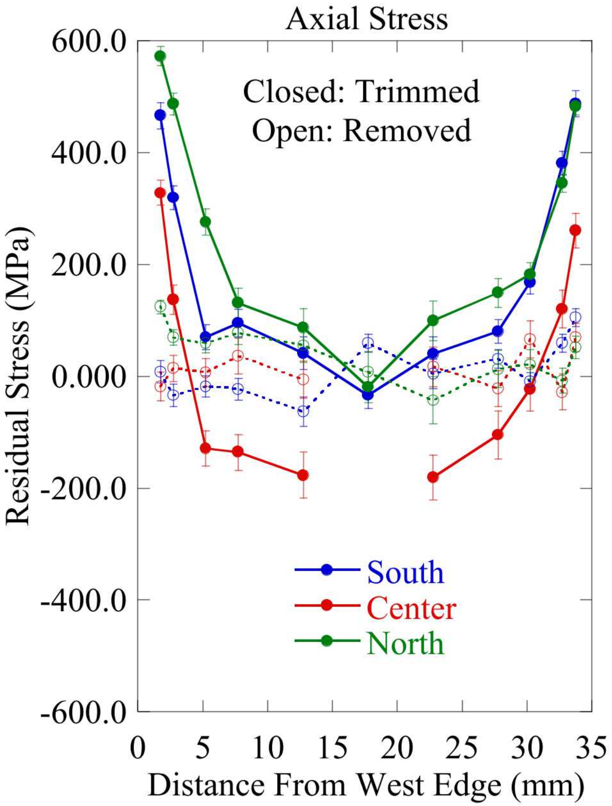


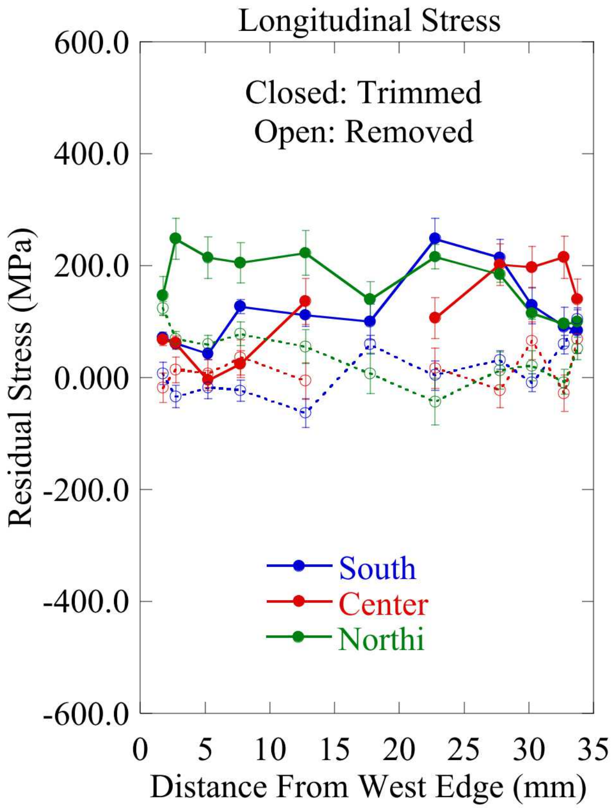


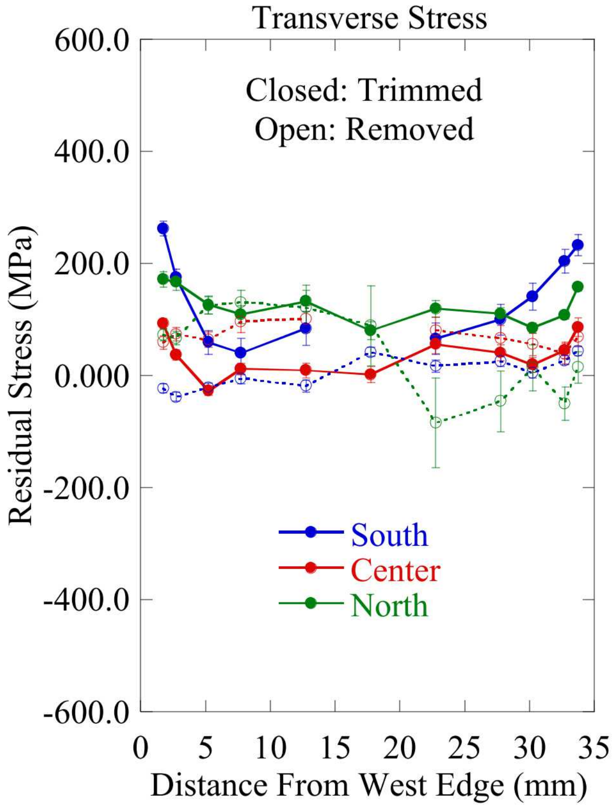


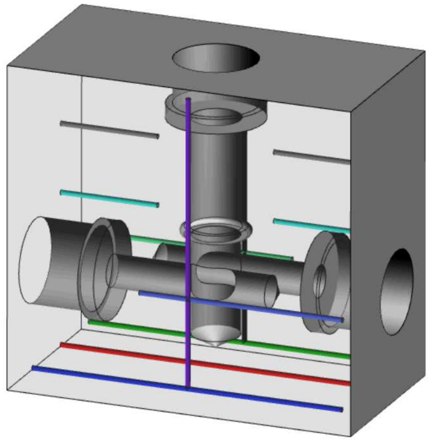
- 316L stainless steel part
- >1000 layers
- Internal channels
- Neutron Diffraction results from Don Brown, Bjørn Clausen, and Maria Strantza at LANSCE

Stress Results Before and After Base Plate is Cut





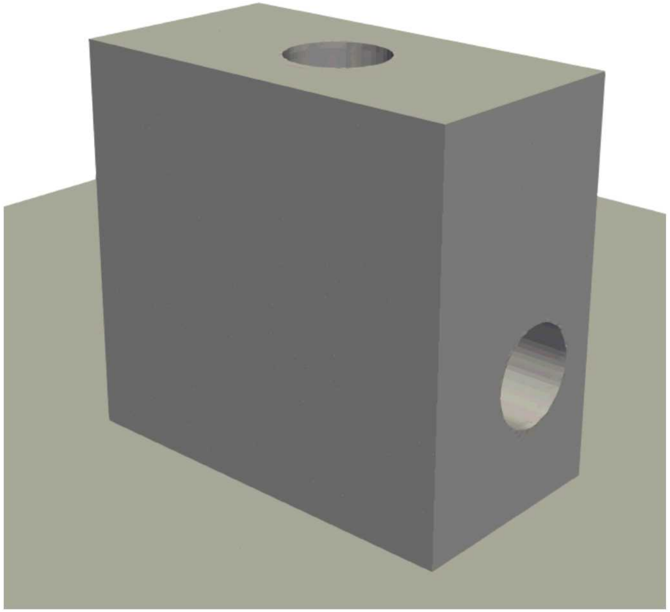




Slide: Don Brown

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)
- Strain tensor 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.

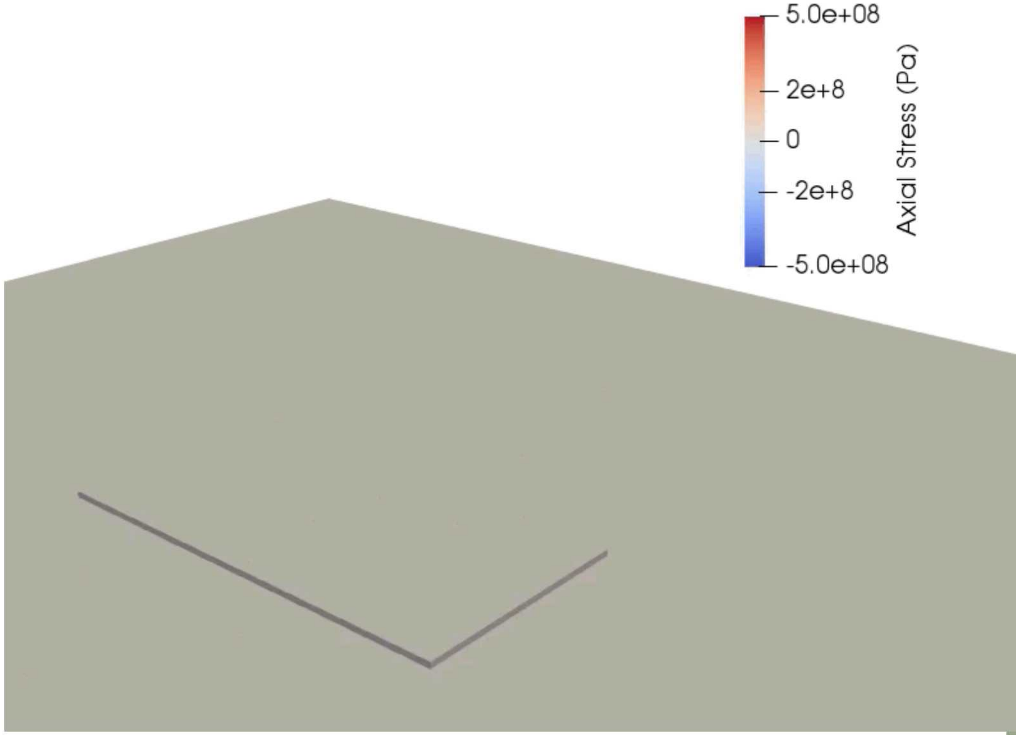
$$\dot{\kappa} = \kappa\frac{\dot{\mu}}{\mu} + (H(\theta) - R_d(\theta)\kappa)\dot{\epsilon}_p$$

Anisotropic Inherent Strain Model Using “Quiet” Element Approach

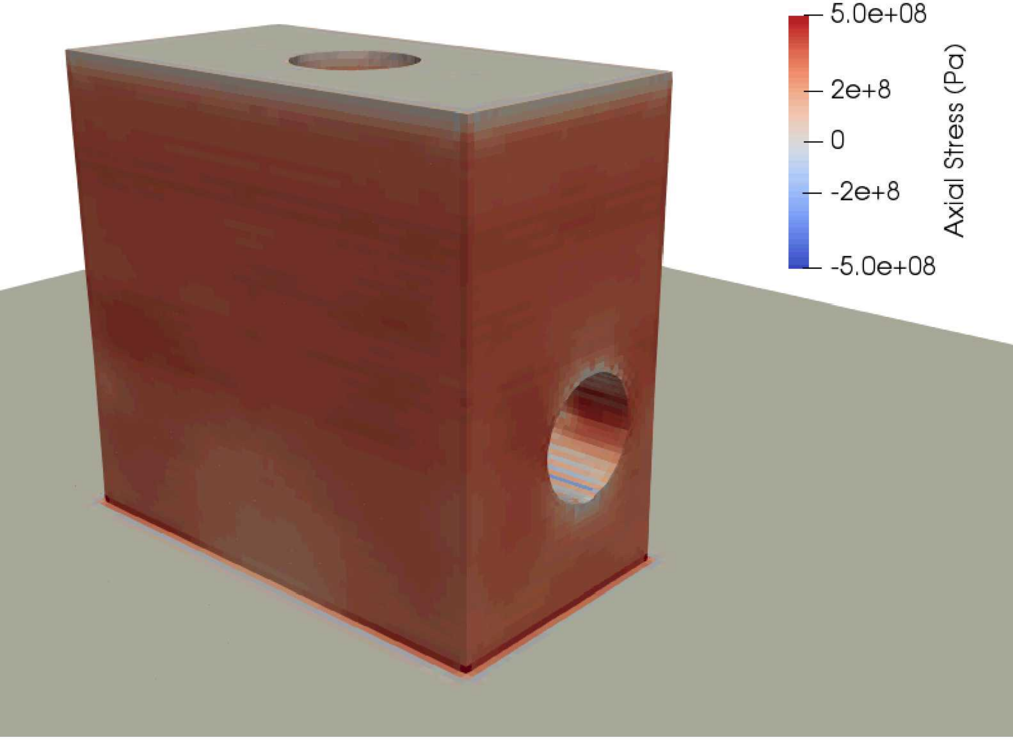
- Transverse (normal to build direction) strains are reduced
- Results are qualitatively reasonable
- Elements activated using “quiet element” approach (reduced stiffness)

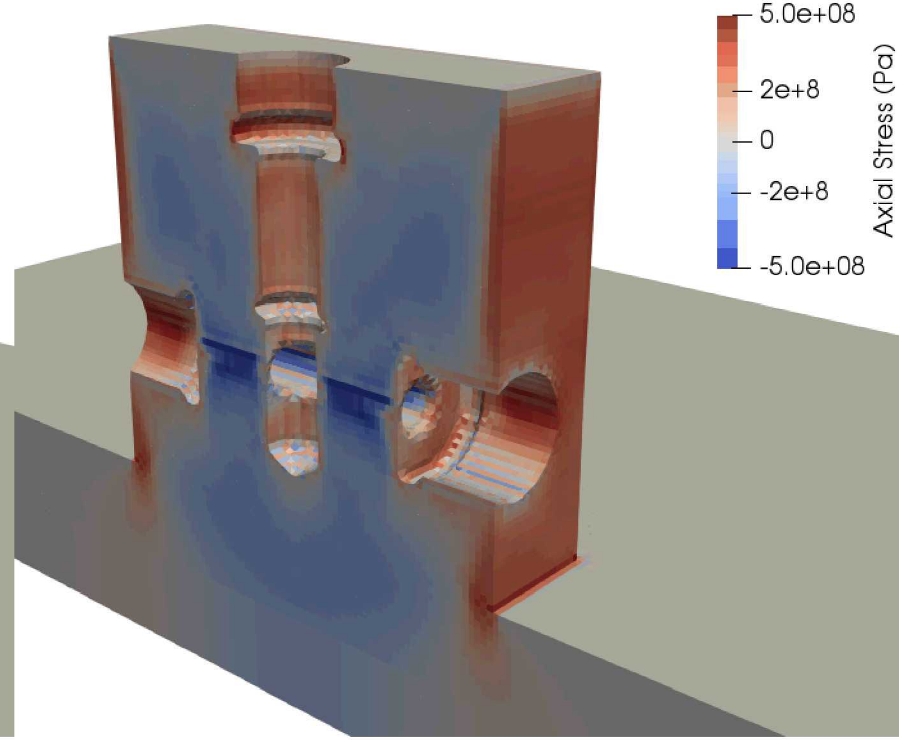
$$\varepsilon = \begin{bmatrix} -0.002 & 0 & 0 \\ 0 & \boxed{-0.02} & 0 \\ 0 & 0 & -0.002 \end{bmatrix}$$

Build Direction



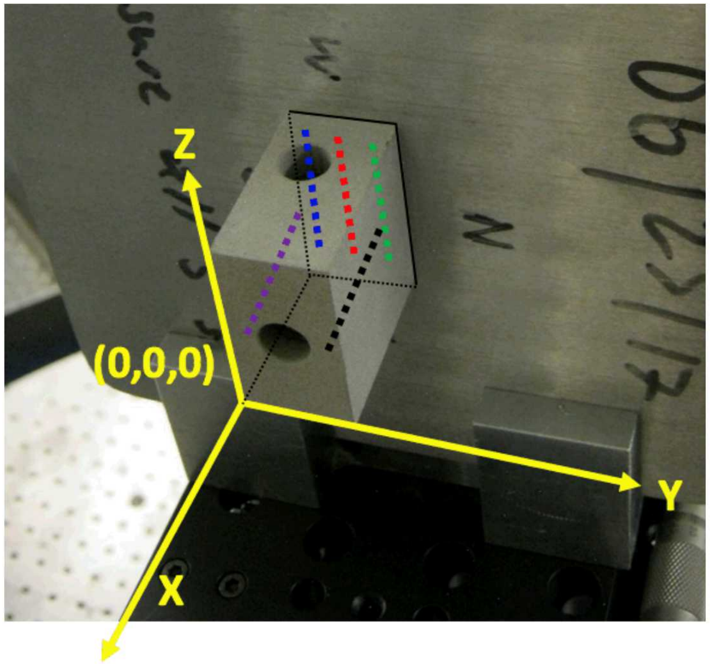
Inherent Strain Stress Contours

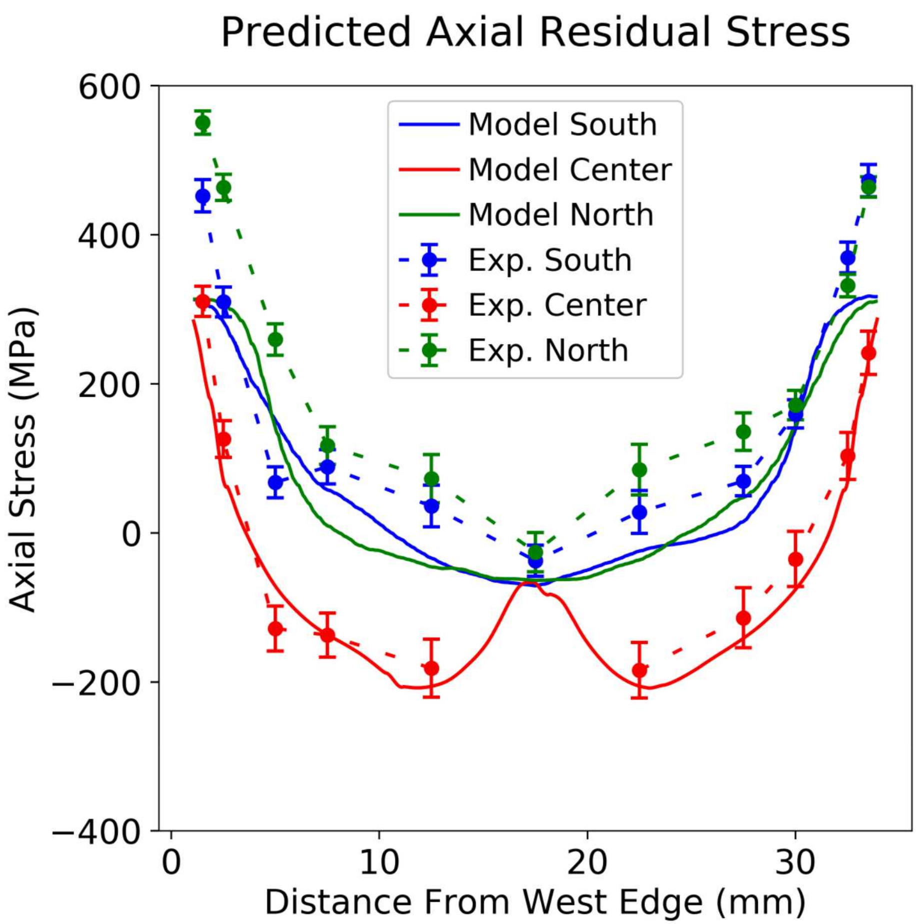




- Axial stress values appear similar to ND measurements
  - ~ 300 MPa exterior, ~ -200 MPa interior
- Wall time ~30 min on 60 cpus (~12X faster than real-time 6 hr build)

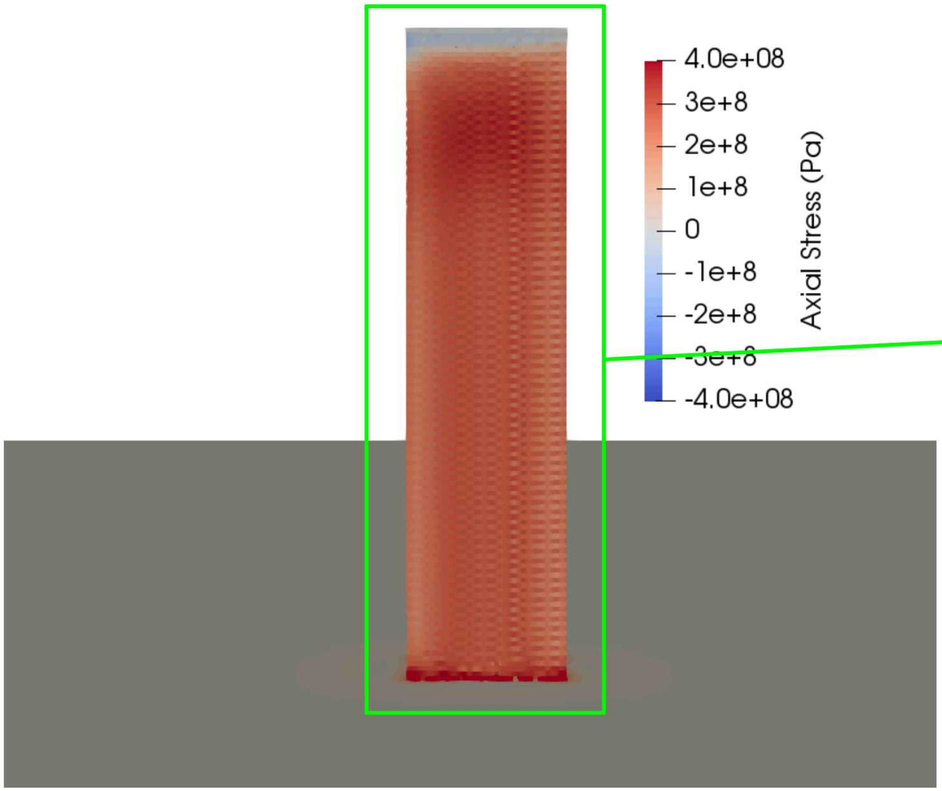
Residual Stress Predictions Compare Well with ND Results for Center Line





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

Second Attempt: Multiscale Inherent Strain Method With Fully Inactive Elements



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

- Run full fine-scale solution on manageable part with same process settings – tensile dogbone gage section
- Upscale strain information to inherent strain model
- Use fully inactive elements rather than quiet elements in inherent strain model
- Could capture process dependent information

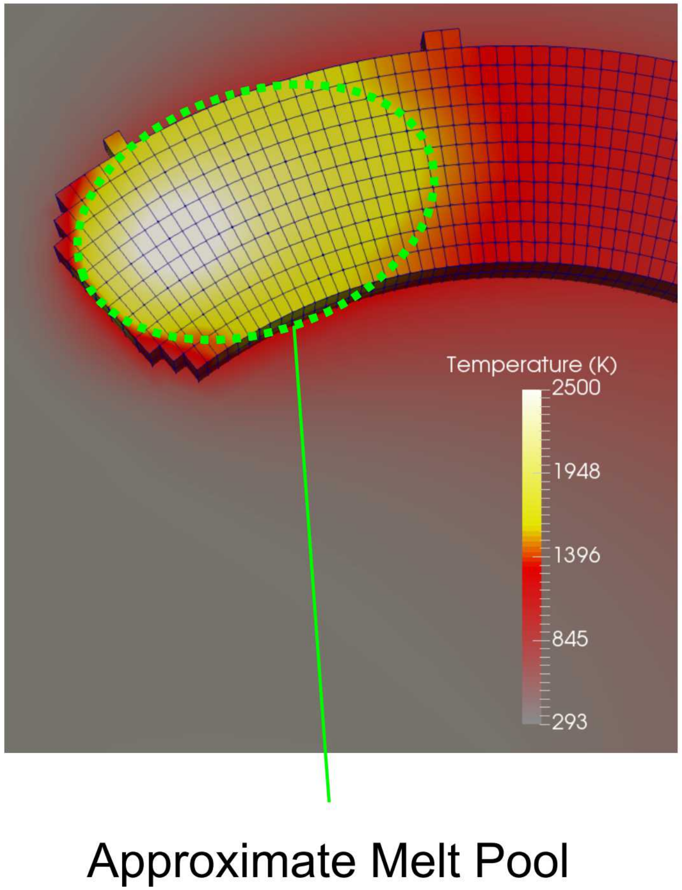
Full Simulation Thermal Approach

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.



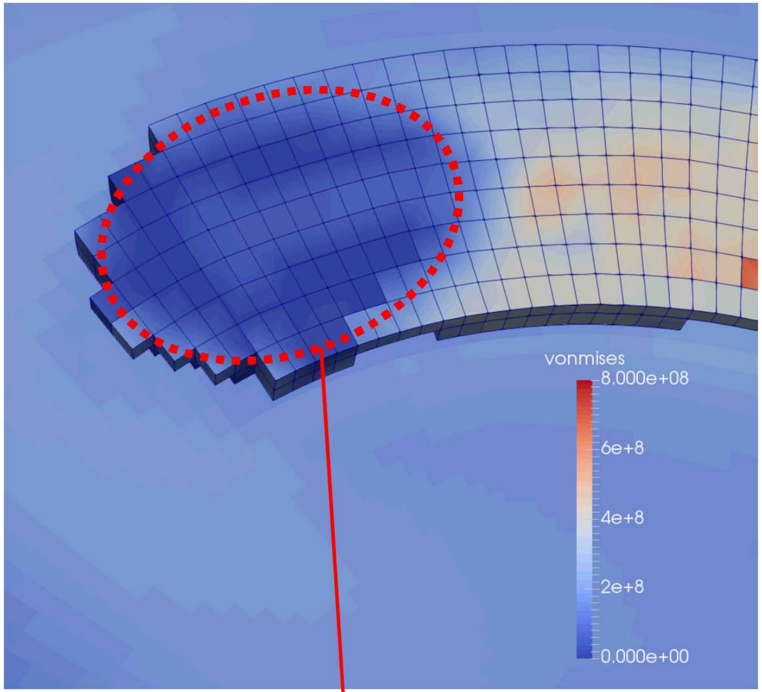
Full Simulation Solid Mechanics Approach

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

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

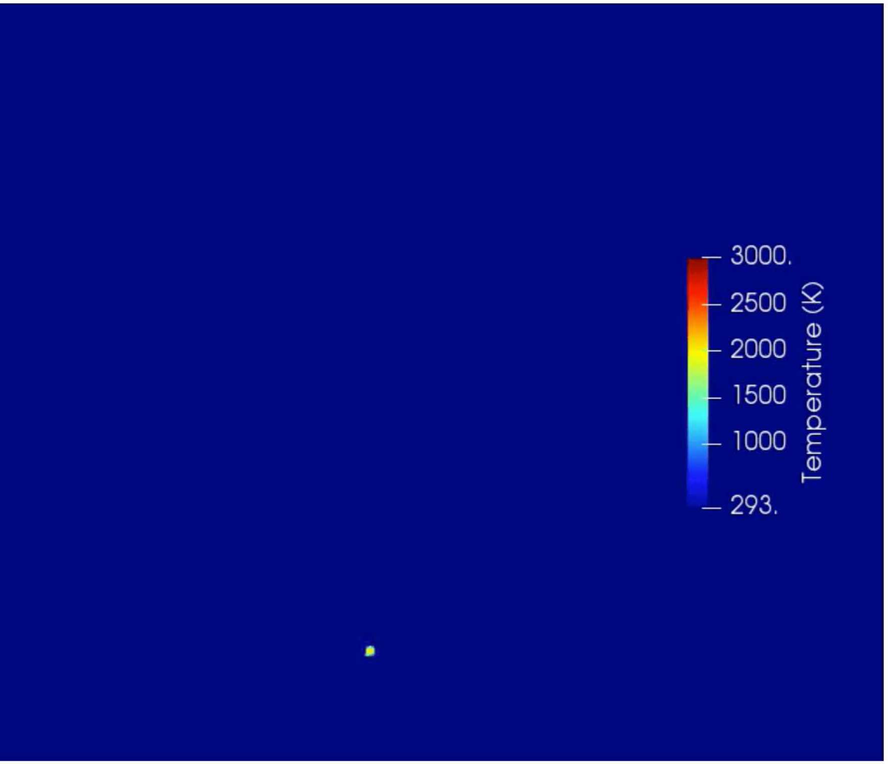
Elements are activated once they reach melt temperature

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

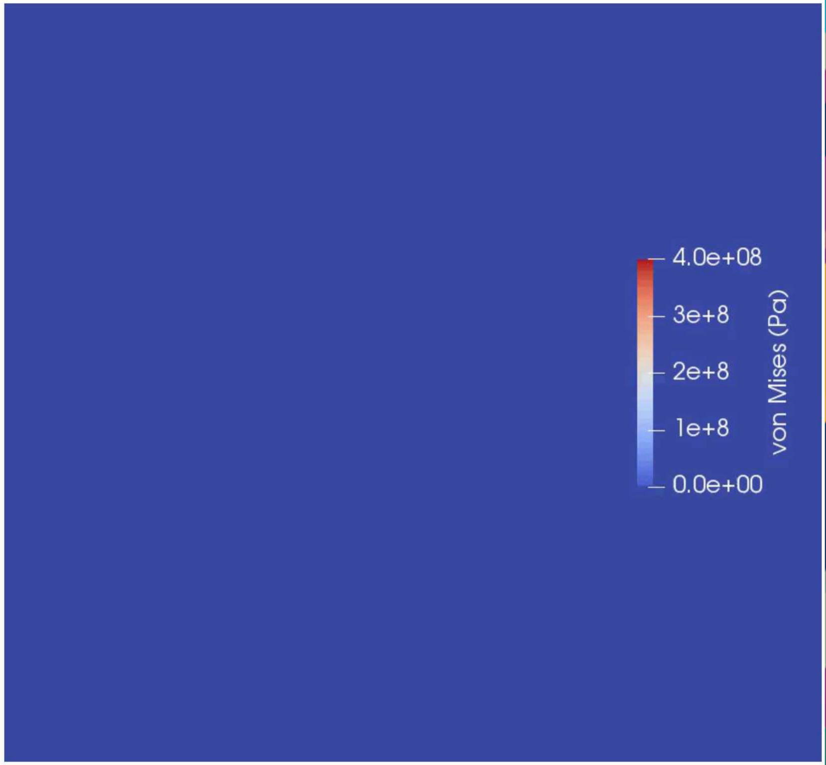


Approximate Melt Pool (~zero stress)

Full Simulation Thermal and Structural Results



Thermal



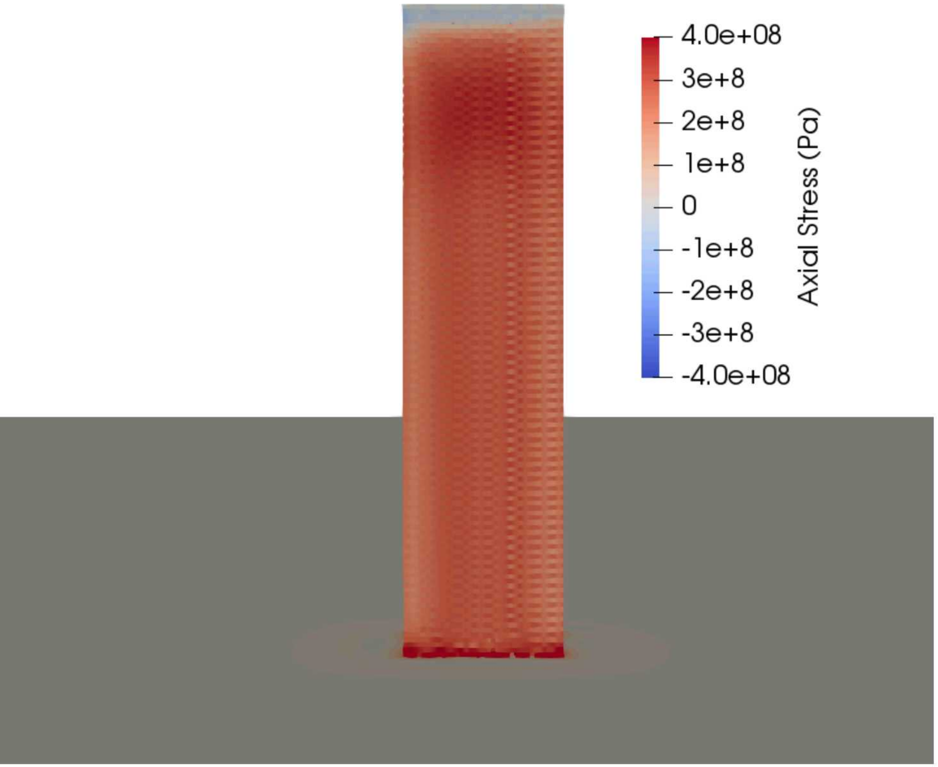
Structural

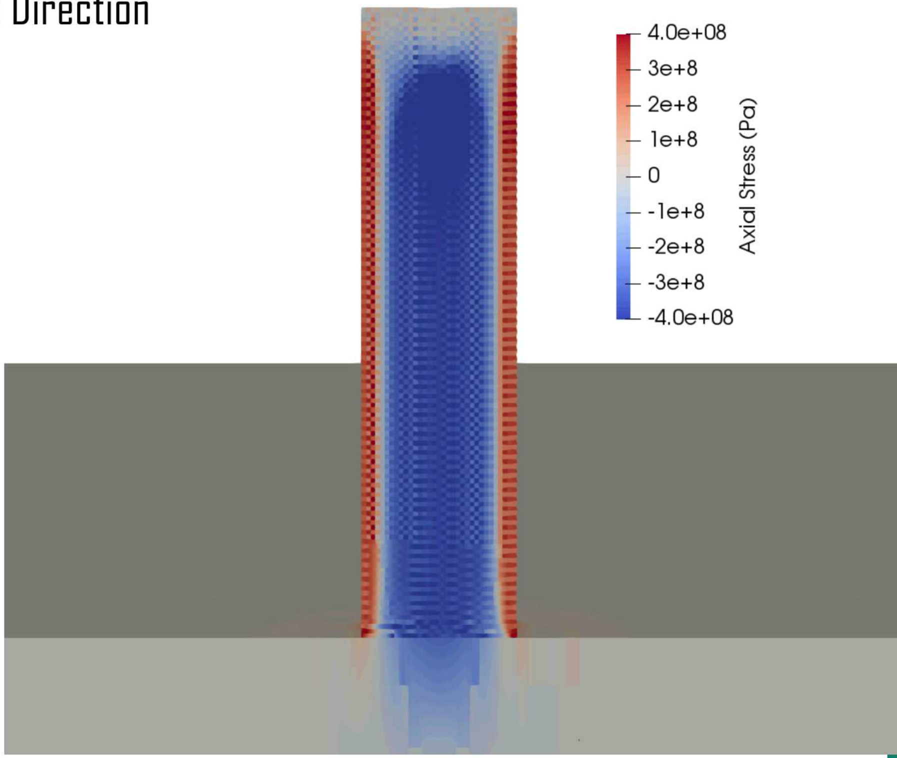
Significant Tensile and Compressive Residual Stresses Remain

$$\bar{\varepsilon} = \begin{bmatrix} -0.019 & 0 & 0 \\ 0 & -0.019 & 0 \\ 0 & 0 & 0.026 \end{bmatrix}$$

Build Direction

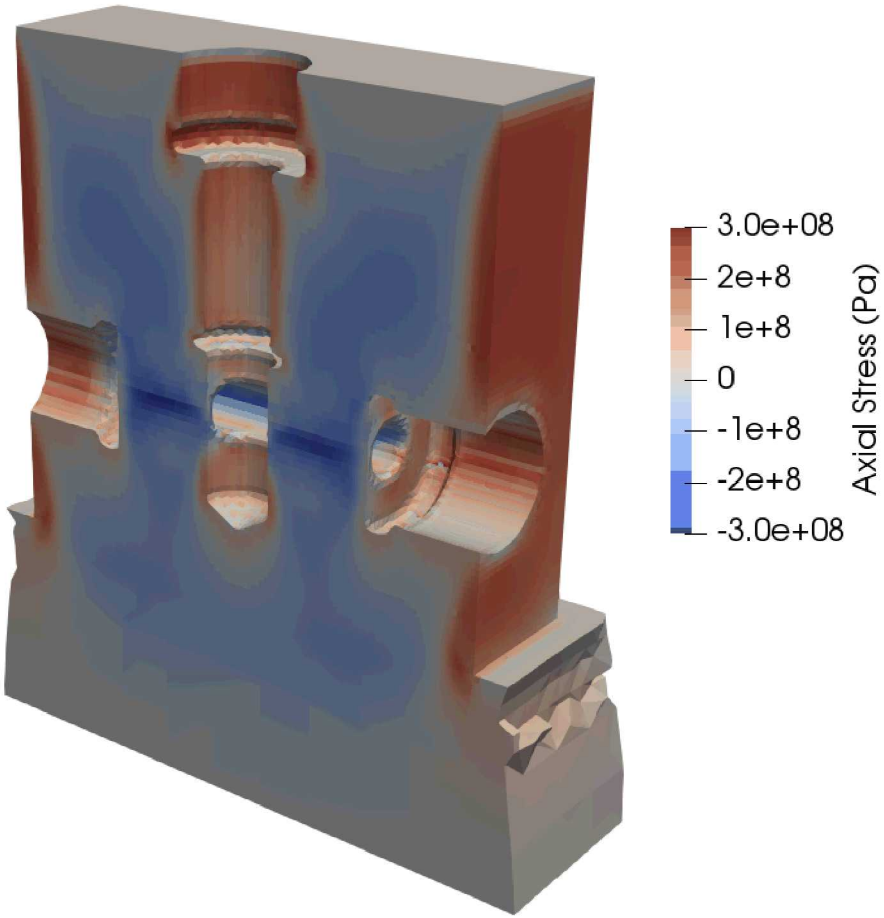
Mid-plane Cut View

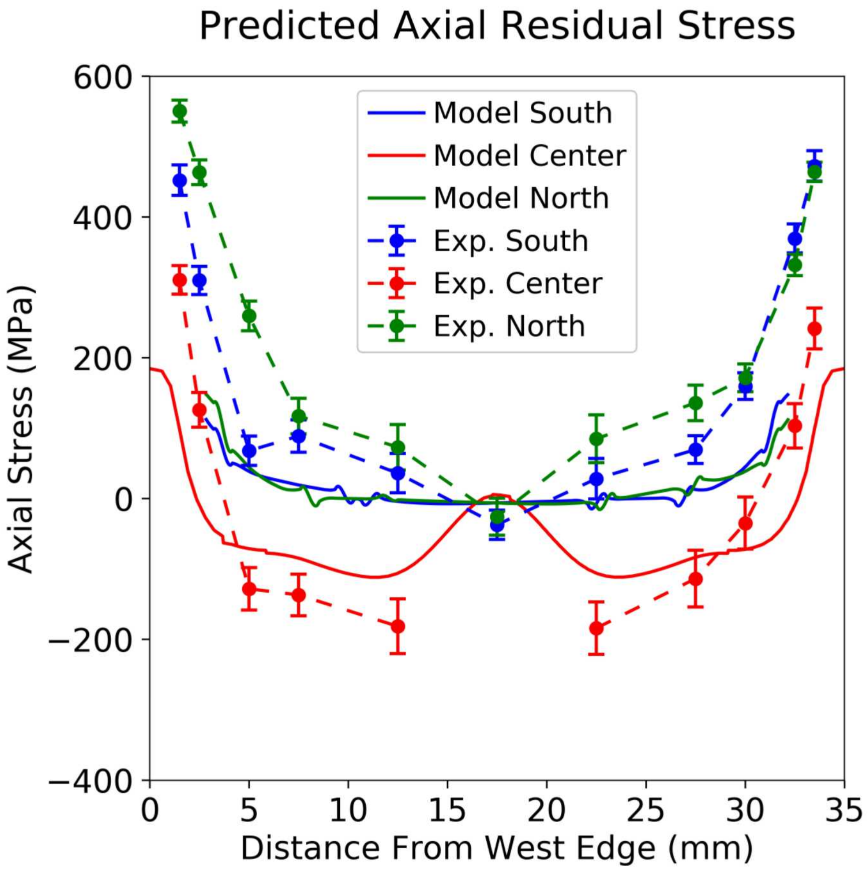




- Average strain values are upscaled to inherent strain model

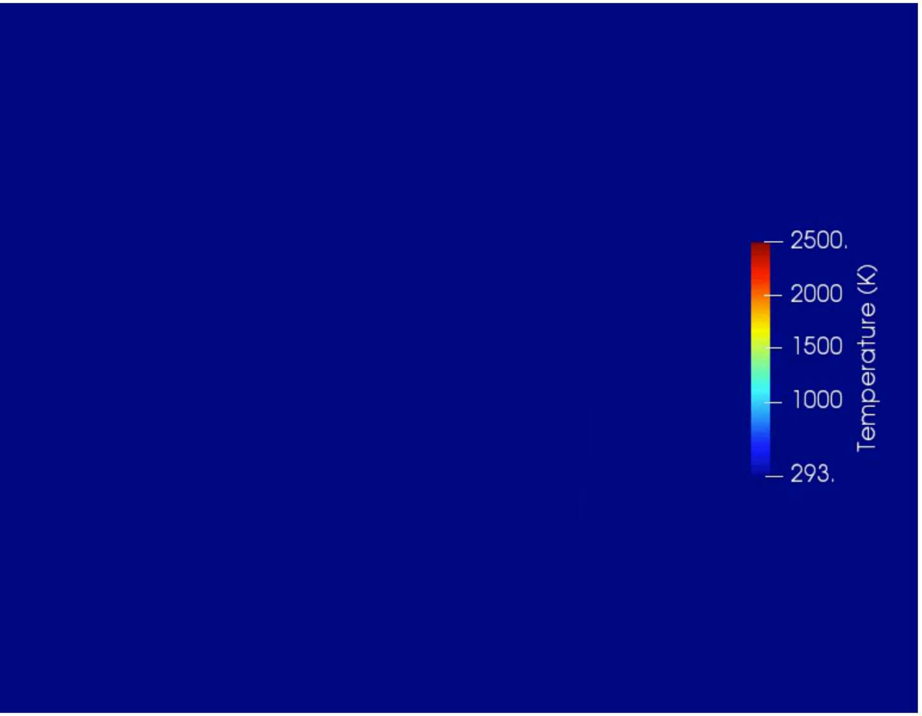
Results Show More Deviation Than Quiet Element Approach But Faster Solution Time

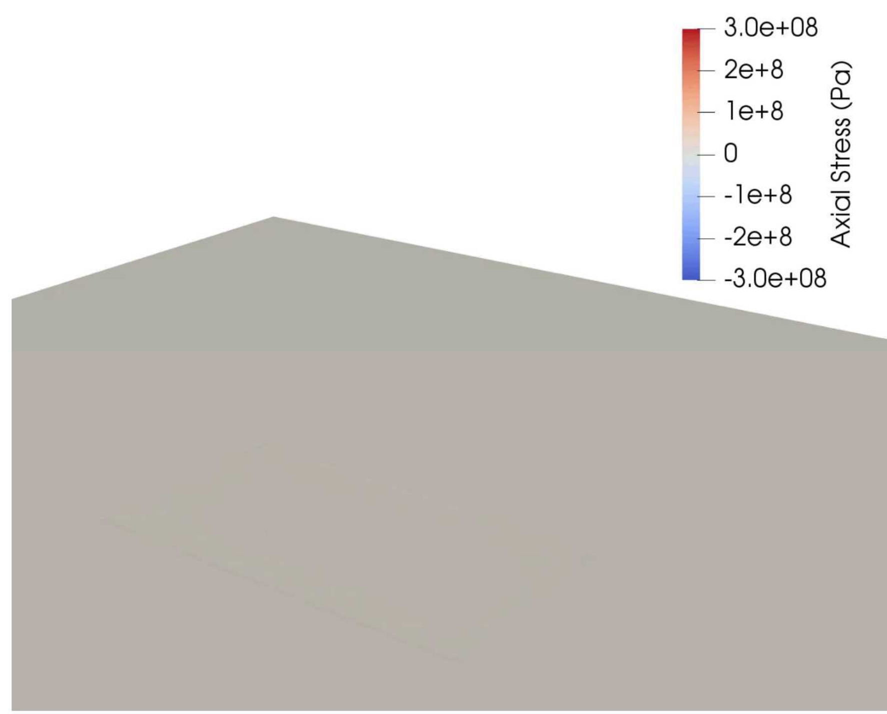




- Fully inactive element activation method reduces wall time to ~8 min on 60 cpus (45x faster than real-time 6 hr build)

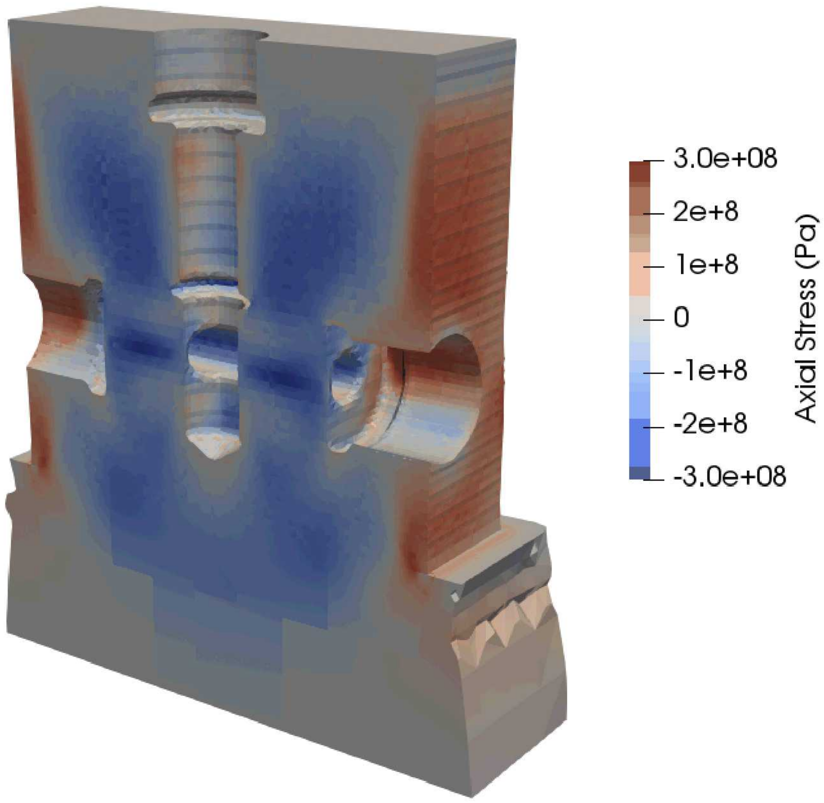
Lumped Laser Method

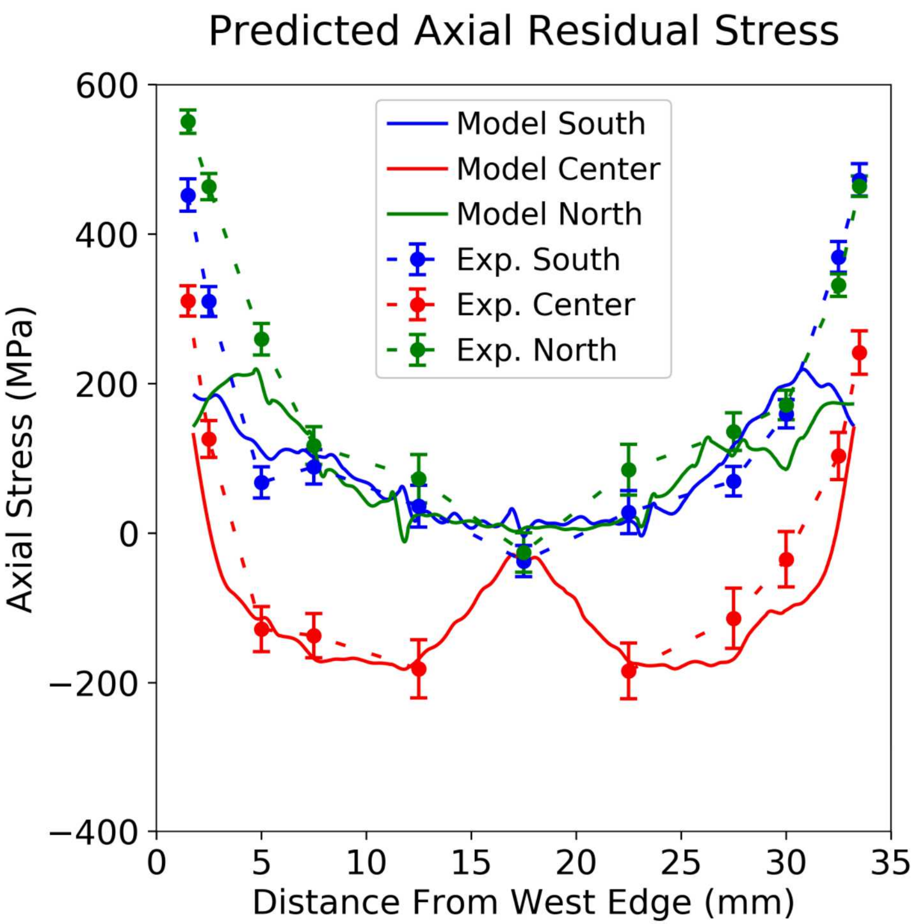




- Approach similar to Hodge *et al.* 2014 and 2016; Stender *et al.* 2018; Strantza , Ganeriwala *et al.* 2018
- ~3 mm laser diameter
- Laser radius to layer height ratio and total inter-layer cooling time held constant from actual conditions
- 0.84 mm layer height
- Laser speed unchanged – 1400 mm/s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

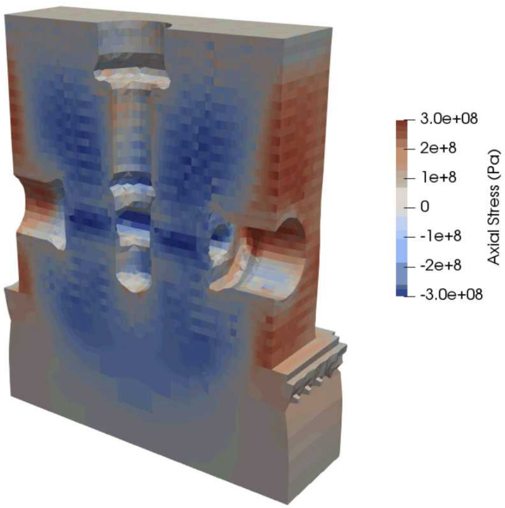
Results With 40 Layers and ~0.4mm Elements Compare Well With Experiments

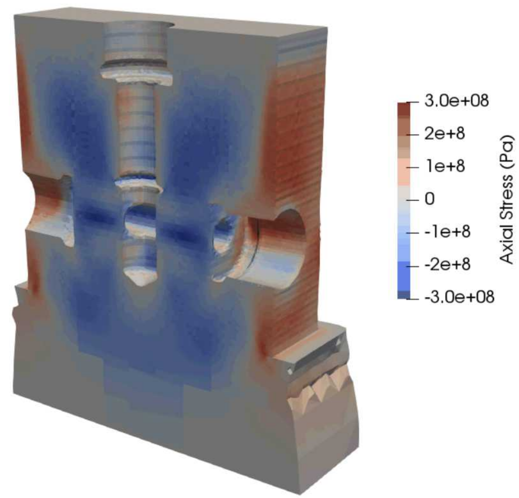




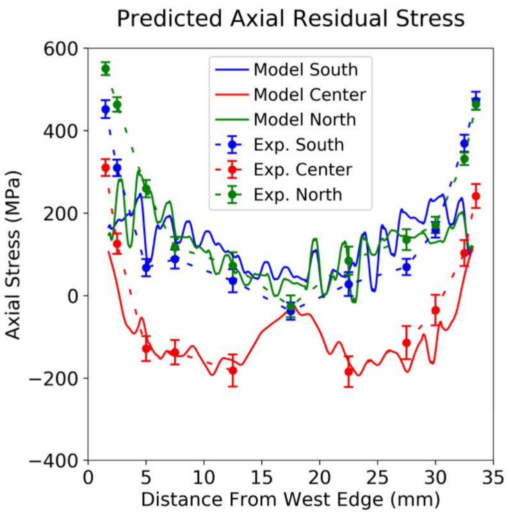
- Method begins to capture stress asymmetry in green and blue lines that inherent strain method misses

Effect of Layer Agglomeration and Mesh Size

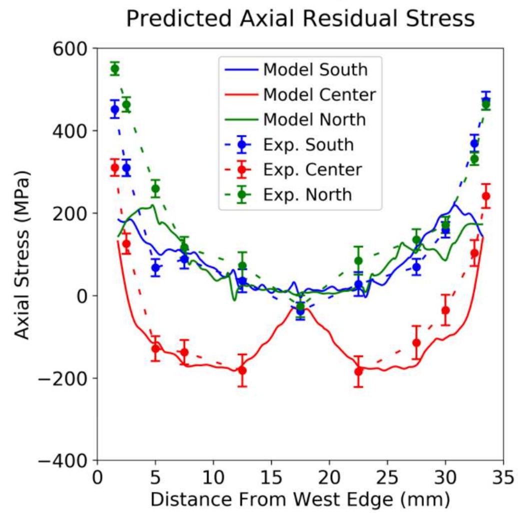




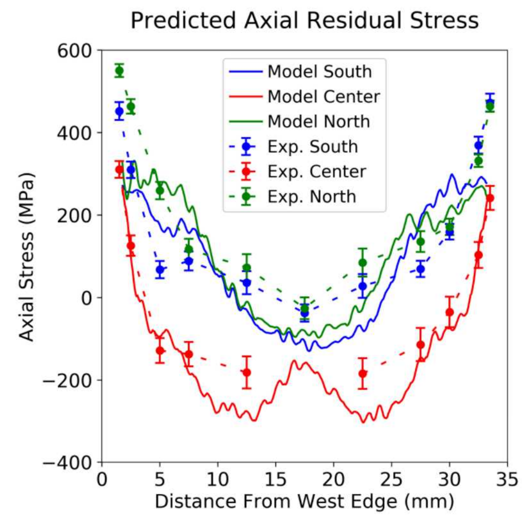
*Showed excessive heating



40 Layers
0.8mm Elements
3mm Laser

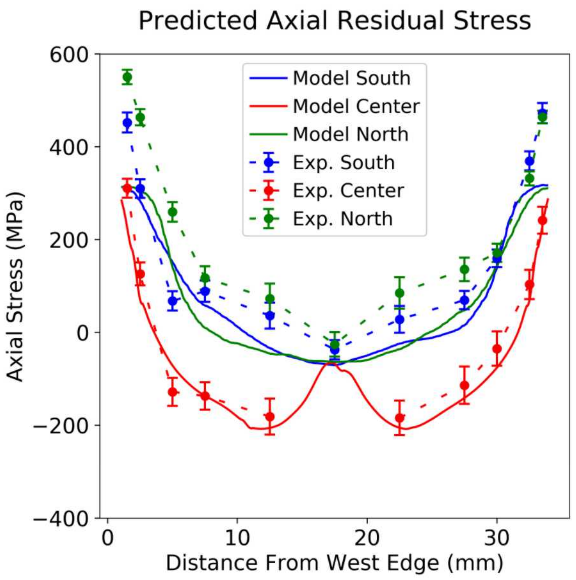


40 Layers
0.4mm Elements
~3mm Laser

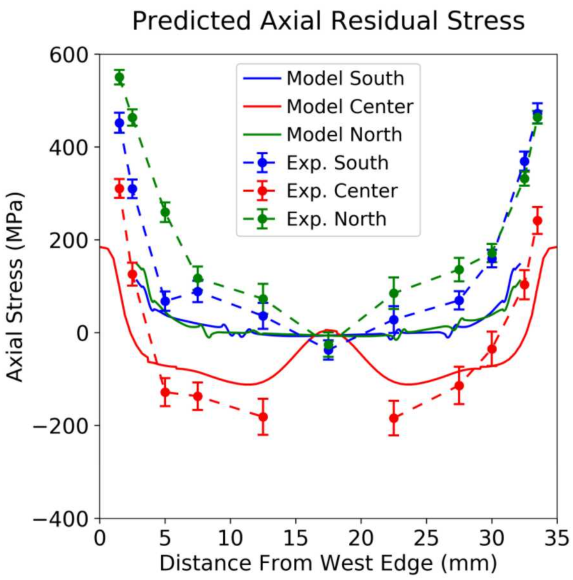


80 Layers
0.4mm Elements
~1.5mm Laser

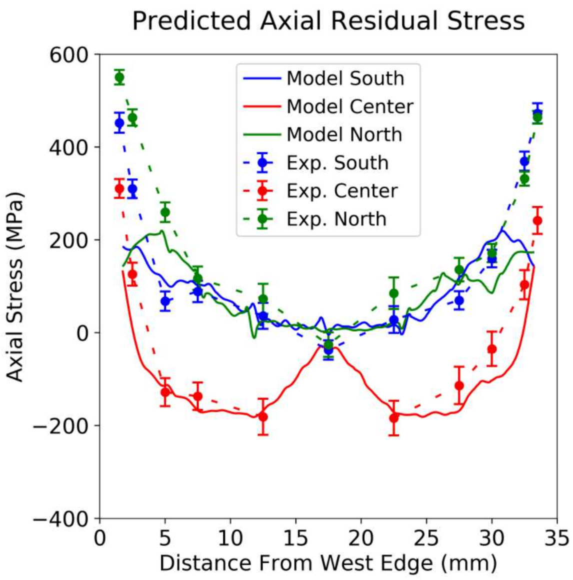
Comparison of Approximation Methods



Inherent Strain with Quiet Elements
30 mins on 60 cpus



Multiscale Inherent Strain with Inactive Elements
8 mins on 60 cpus



Lumped Laser with 40 Layers and ~0.4mm Elements
6 hours on 100 cpus

Conclusions

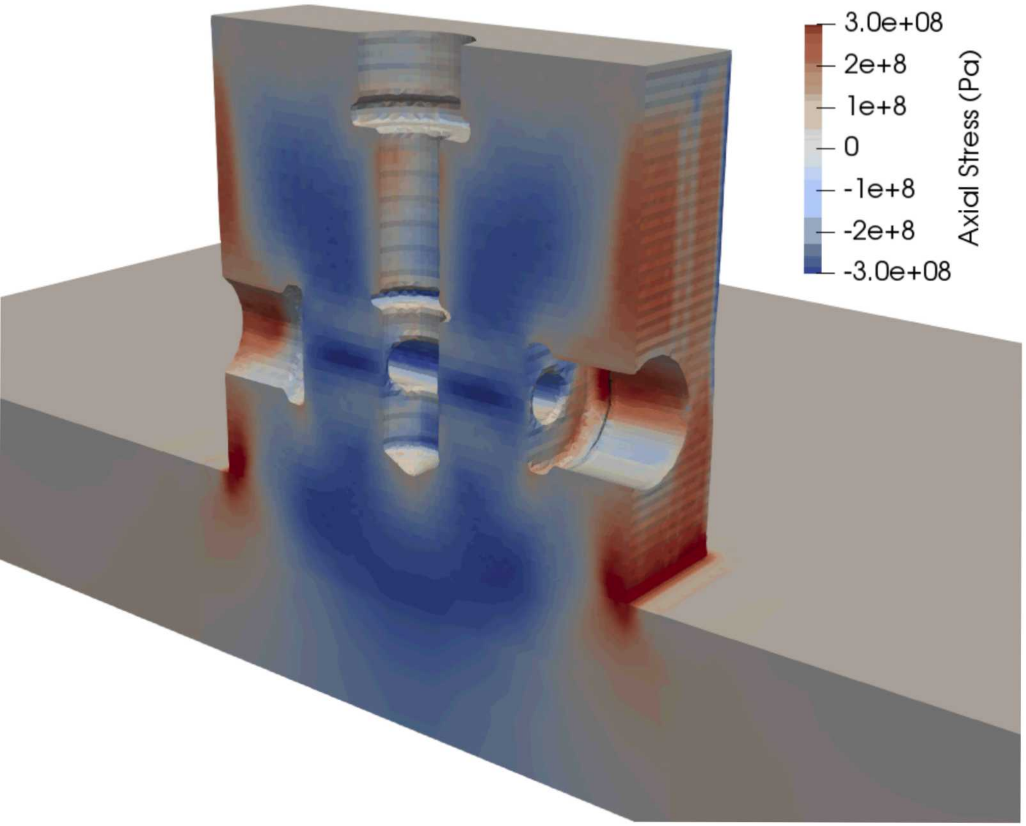
- Neutron diffraction can be used to determine residual stresses in AM parts
- Stresses can be near yield level.
- Stresses relax when removed from base plate, and components distort.
- Exemplar part contains very high residual stresses (at or above yield)
- Residual stress can be (approximately) predicted using efficient reduced order methods
- Residual stress predictions near edges of part need improvement in inherent strain method
- Coarse element size can lead to stress oscillations

Future Work

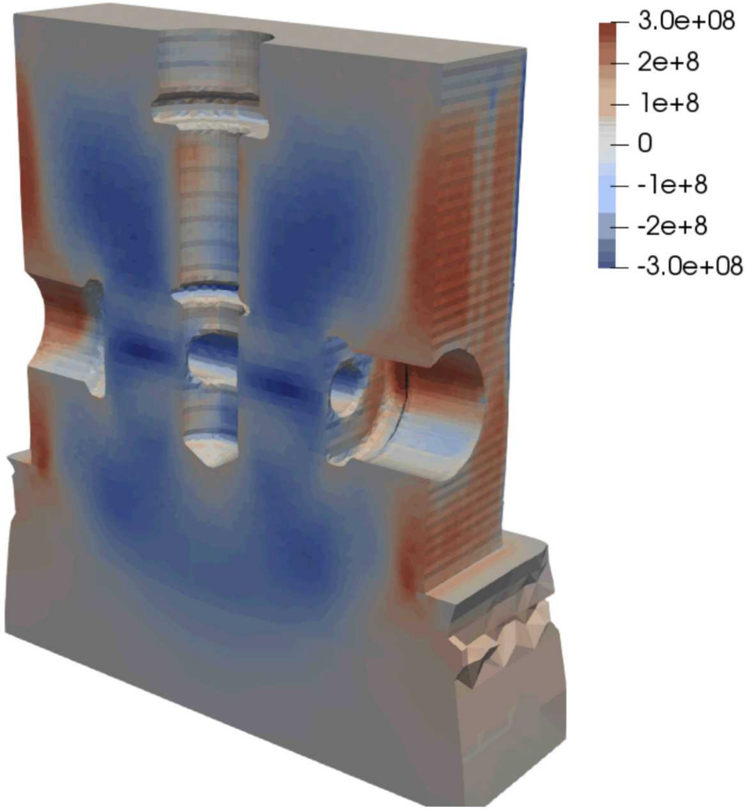
- Heat input in lumped laser model needs to be validated
- Average stresses over 2mm volume for direct comparison to ND results

Questions?

Importance of Baseplate Boundary Conditions



Full baseplate, fixed base

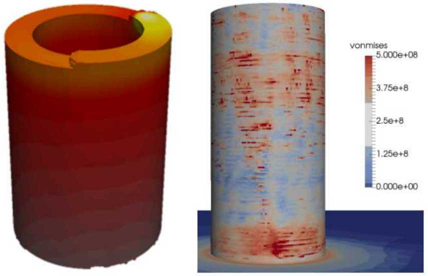


Trimmed baseplate, free base

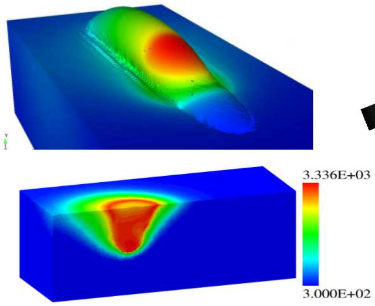
SNL Modeling Work

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

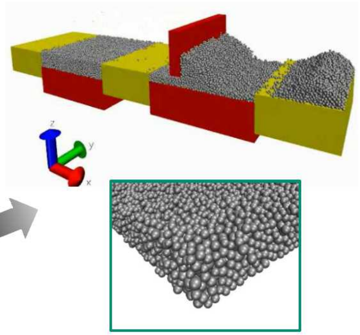
Part Scale Thermal & Solid Mechanics
Kyle Johnson, Kurtis Ford, Mike Stender, Lauren Beghini & Joe Bishop



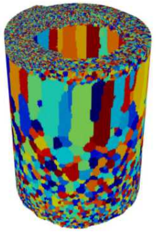
Mesoscale Thermal Behavior
Mario Martinez & Brad Trembacki



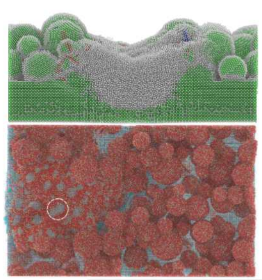
Powder Spreading
Dan Bolintineanu



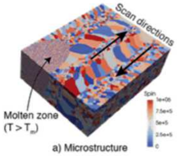
Part Scale Microstructure
Theron Rodgers



Powder Behavior
Mark Wilson



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



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

Length Scale (m)