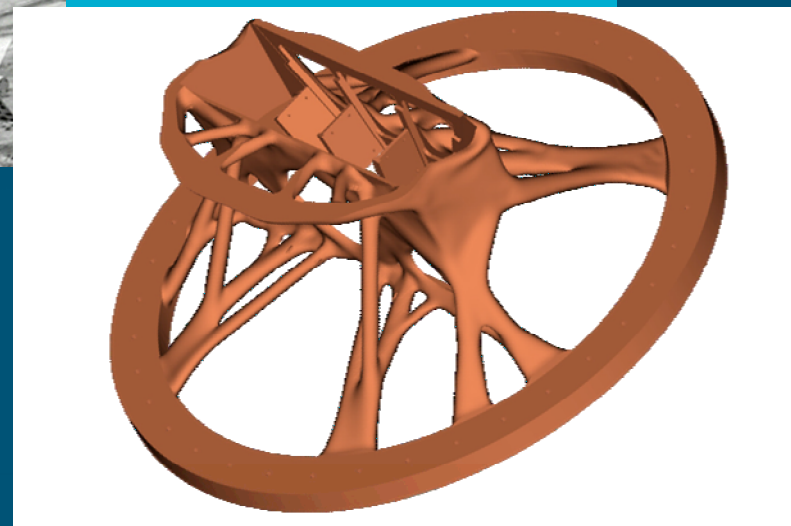
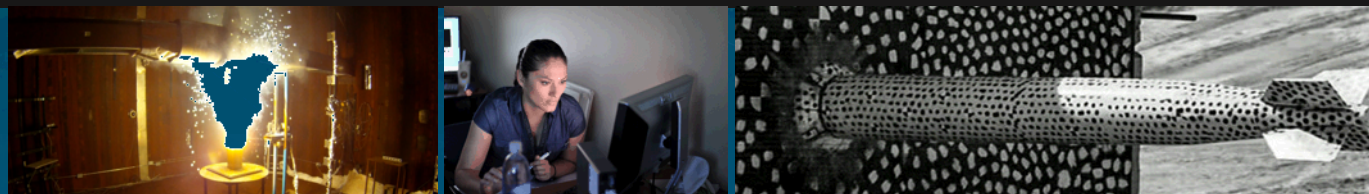


Material-aware Topology Optimization



CONTRIBUTORS

Miguel Aguilo, Brett Clark, Peter Coffin,
Joshua Robbins, Brett Sneed

PRESENTED BY

Joshua Robbins

Design freedom of AM: Additive Manufacturing (AM) expands the engineering design space by enabling creation of freeform geometries that can be driven by performance requirements rather than manufacturing constraints.

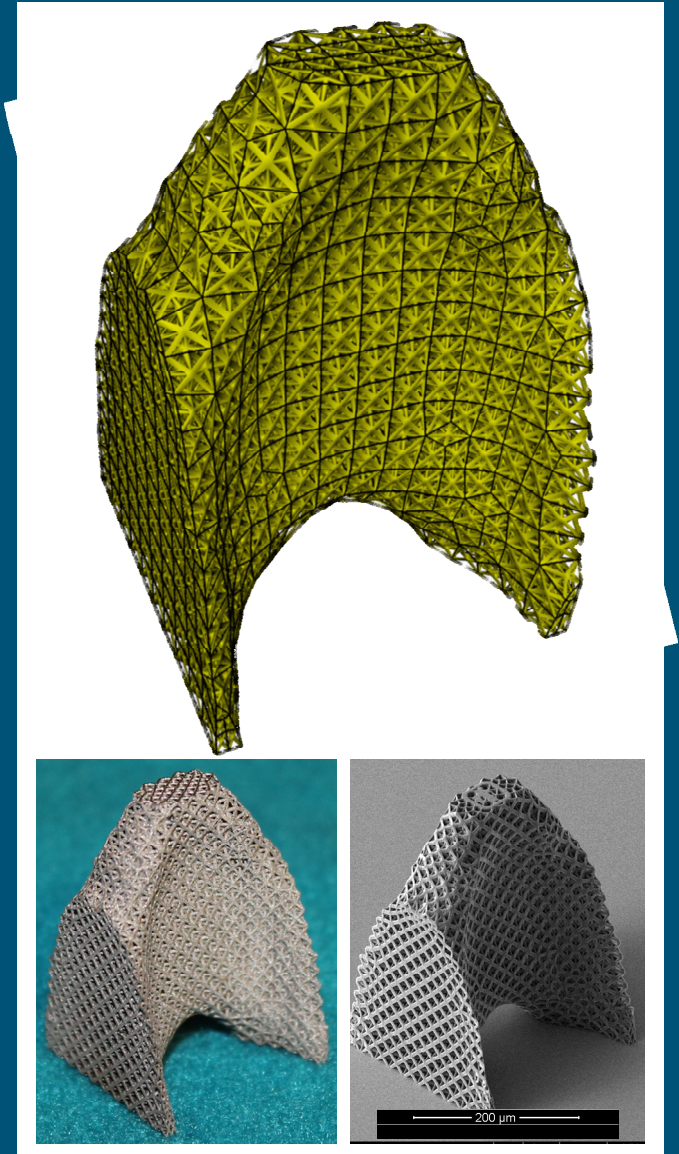
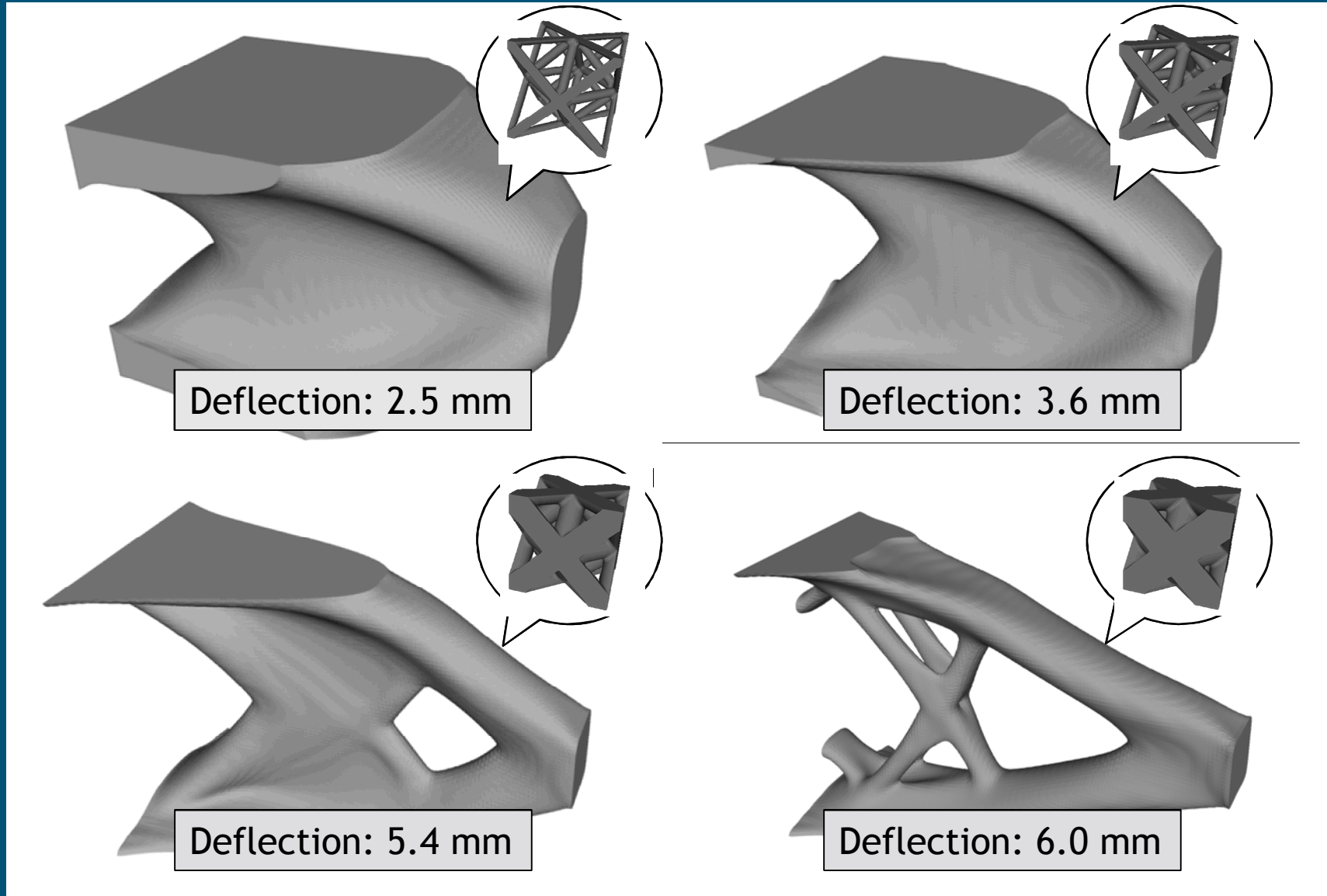
Qualification Challenge: Widespread adoption of this technology has been slow due to limitations in printed material quality and accompanying difficulties in part qualification.

- **Process Improvement:** The most common approach in overcoming this qualification challenge is to pursue improvements in AM processes and resulting material quality.
- **Design for AM:** Alternatively, material imperfections can be incorporated into the design optimization problem so that designs are robust to deviations from the ideal material, thereby enabling the use of AM technology “as-is”.

Overview of Plato: This presentation will cover the development of optimization based design tools that facilitate component qualification by accounting for AM material quality in the optimization process.

Material-aware Topology Optimization: By composing objectives that reflect details of the as-printed material, designs can be computed that i) use existing, well characterized AM processes, and ii) meet essential performance requirements.

Design Freedom of Additive Manufacturing



What about stress, fatigue, buckling, as well as uncertainty in material response?

Accounting for real material response is imperative if architected materials are going to be deployed:

- Design for ideal response (stress, fatigue, buckling).
- Design for real response (uncertainty in realized material and geometry).

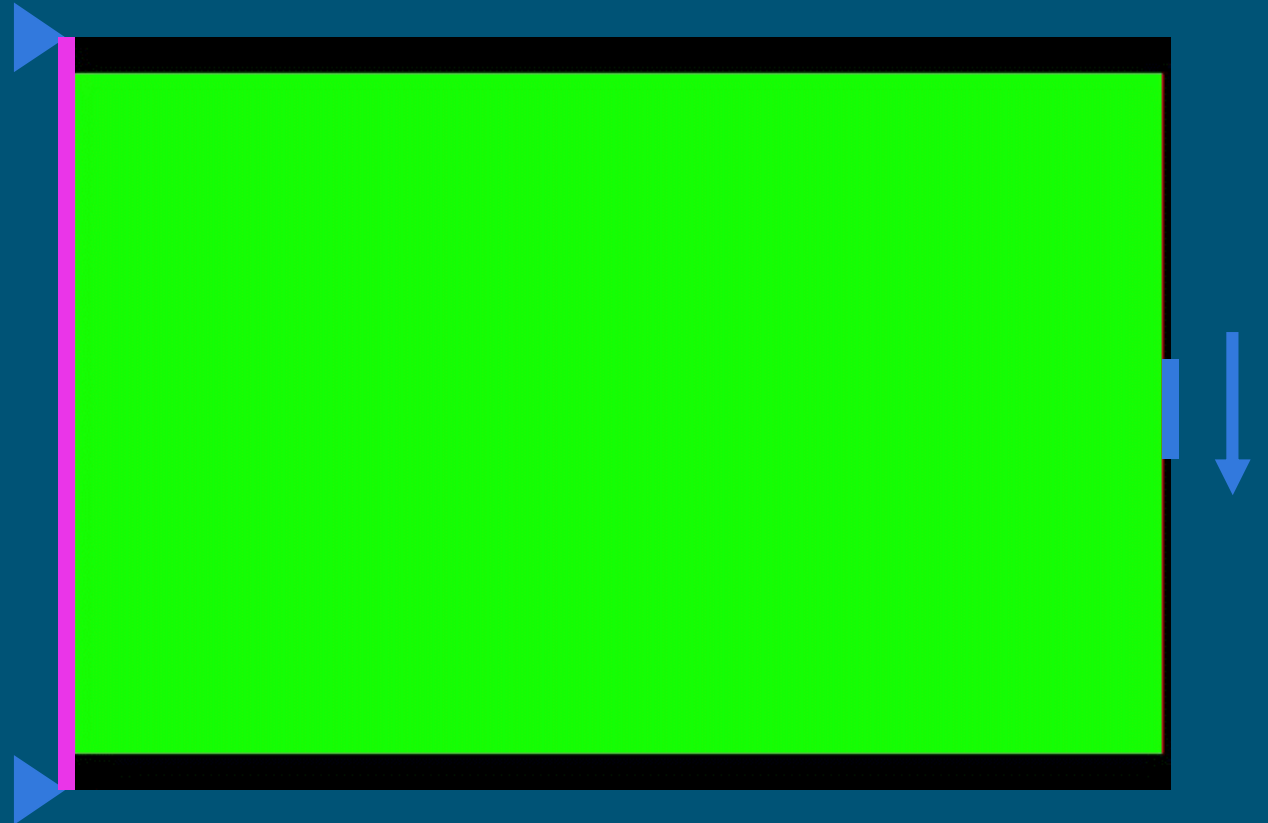
Overview of Plato

Objective: Provide a design environment that can leverage existing simulation tools and emerging HPC architectures.

Forward Problem:



Inverse Problem:



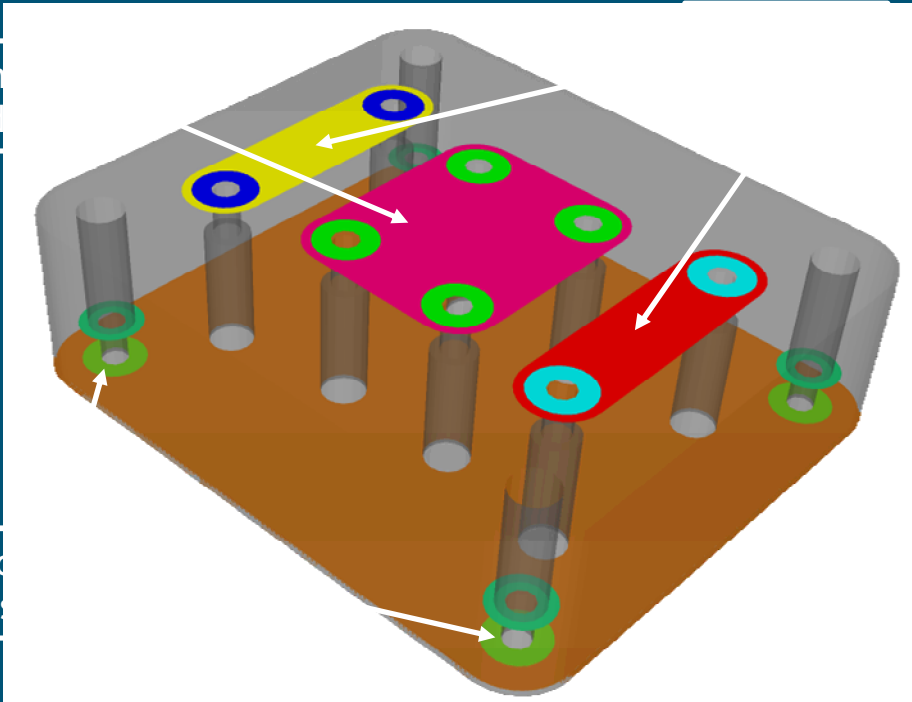
Approach: Use topology optimization to let performance objectives dictate the design

Overview of Plato

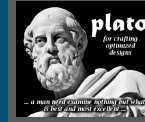


Mechan
Load

Mechan
Con



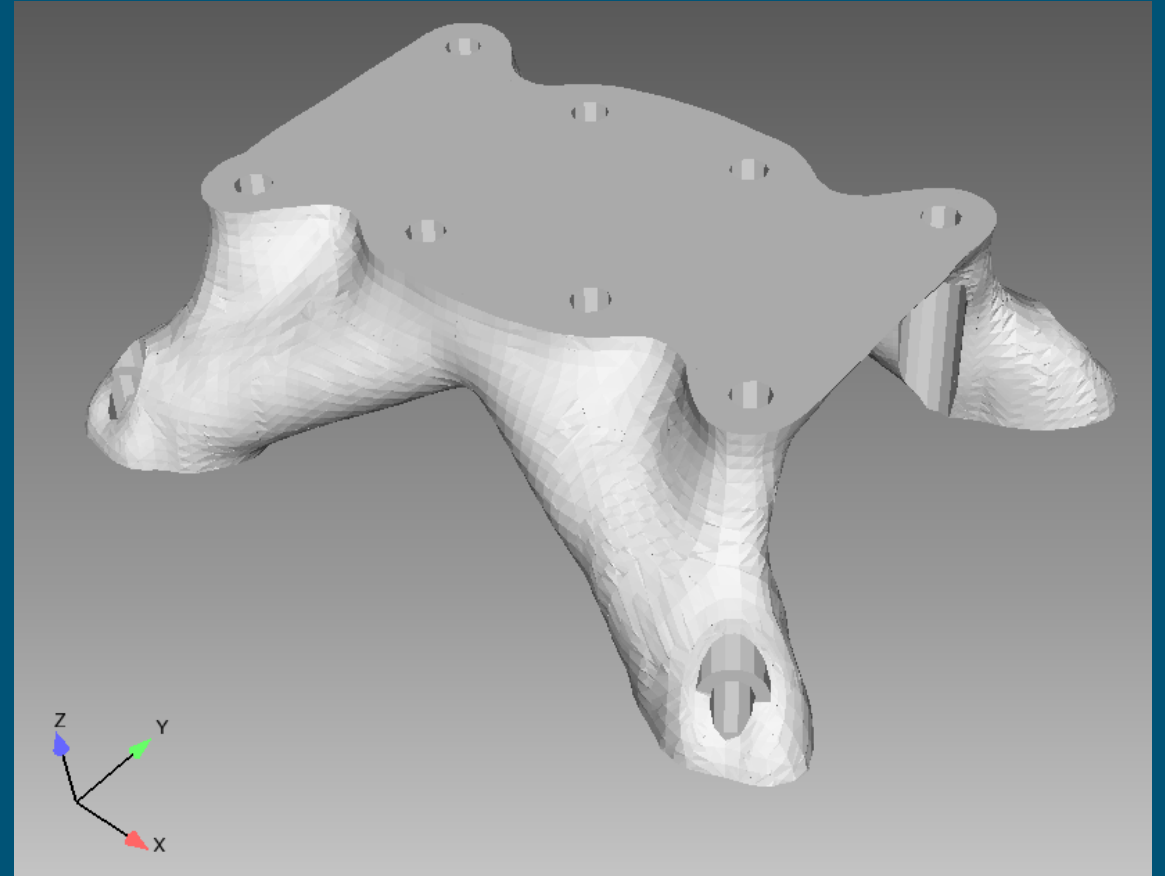
Sierra
(40 procs)



Plato
(10 procs)



Albany
(30, 35 procs)



Material-aware Topology Optimization

Incorporate ideal response:

- Asymptotic homogenization (Albany)
- Anisotropic linearity envelope (Albany, Plato Analyze)

Sampling-based and PDF-based methods to incorporate uncertainty of material response and loads

- MPMD configuration permits concurrent parallel runs
- Plato Analyze (GPU-based, lower cost/flops)

Asymptotic Homogenization

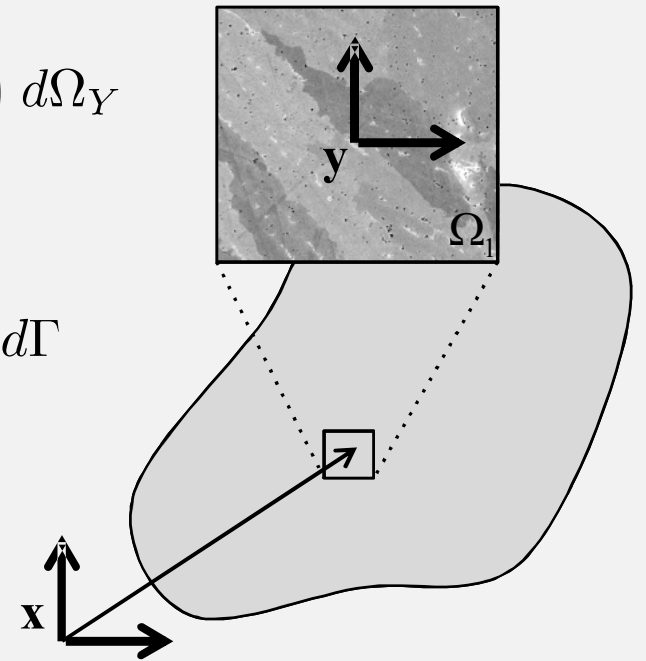
Displacement: $\tilde{\mathbf{u}}(\mathbf{x}, \mathbf{y}) = \mathbf{u}(\mathbf{x}, \mathbf{y}) + \epsilon \mathbf{u}(\mathbf{x}, \mathbf{y}) + \epsilon^2 \mathbf{u}(\mathbf{x}, \mathbf{y}) + \dots \quad \mathbf{y} = \mathbf{x}/\epsilon$

Cell Problems: $\int_{\Omega_Y} C_{ijkl}(\mathbf{y}) \frac{\partial \chi_k^{qr}}{\partial y_l} \frac{\partial v_i}{\partial y_j} d\Omega_Y = \int_{\Omega_Y} C_{ijqr}(\mathbf{y}) \frac{\partial v_i}{\partial y_j} d\Omega_Y \quad \text{for } q, r = 1, 2, 3$

Homogenized Constants: $C_{ijkl}^e = \frac{1}{|\Omega_Y|} \int_{\Omega_Y} \left(C_{ijkl}(\mathbf{y}) - C_{ijkl}(\mathbf{y}) \frac{\partial \chi_i^{kl}}{\partial y_j} \right) d\Omega_Y$

Macroscale Problem: $\int_{\Omega_X} C_{ijkl}^e \frac{\partial u_k^0(\mathbf{x})}{\partial x_l} \frac{\partial v_i(\mathbf{x})}{\partial x_j} d\Omega_X = \int_{\Gamma_t} t_i(\mathbf{x}) v_i(\mathbf{x}) d\Gamma$

Total Solution: $u_i(\mathbf{x}, \mathbf{y}) = u_i^0(\mathbf{x}) - \chi_i^{kl}(\mathbf{y}) \frac{\partial u_k^0(\mathbf{x})}{\partial x_l}$

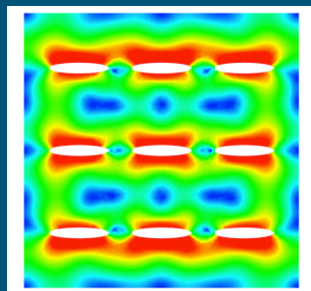
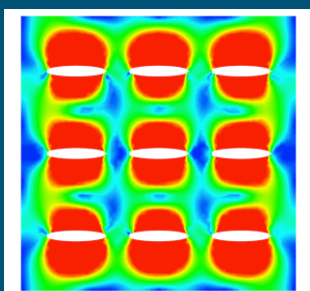
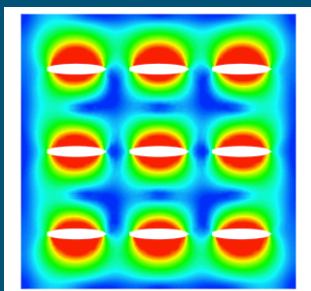


Homogenization: Structural Bracket

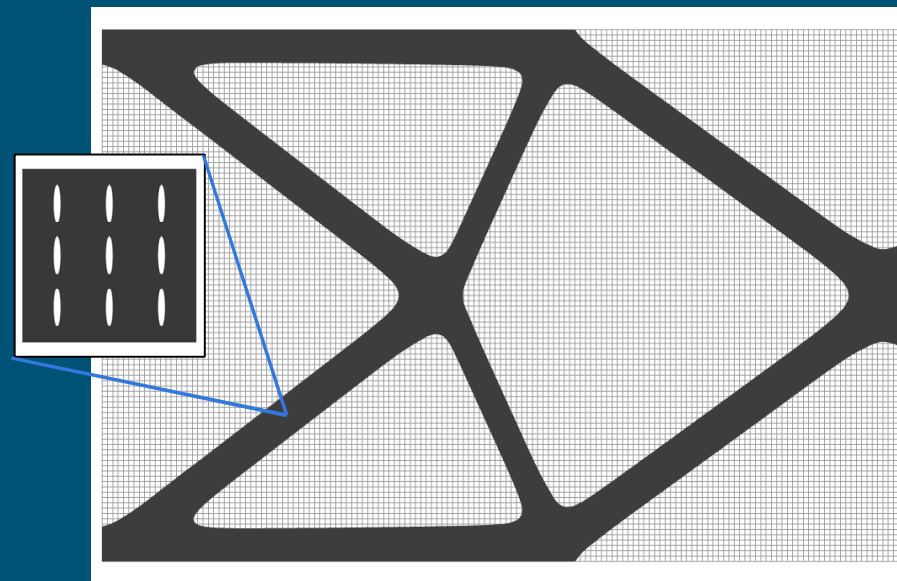
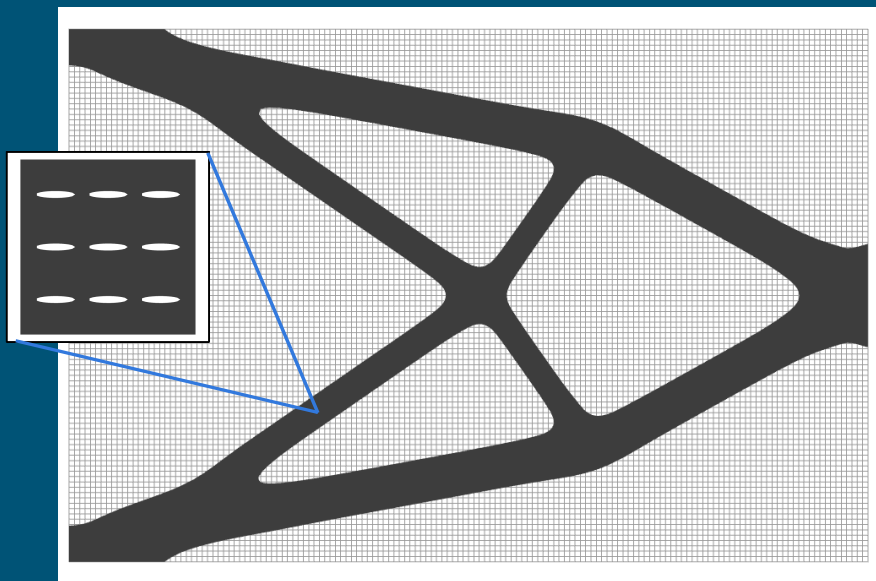


Cell Problems: $\nu = 0.3$ $E = 1.0 \times 10^9$

Homogenized Constants:

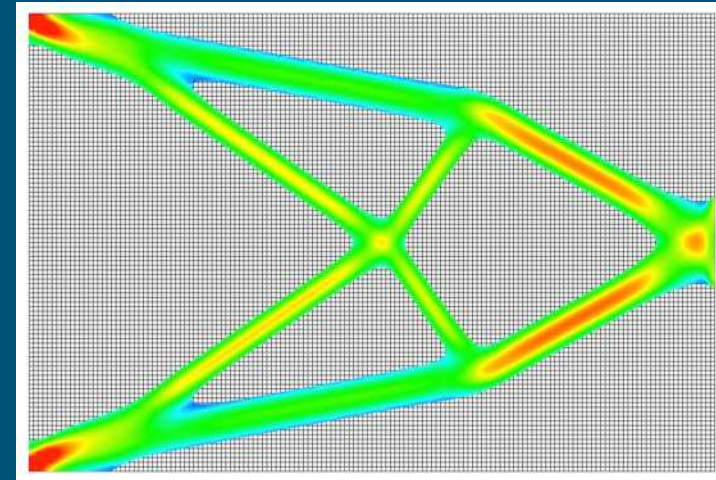
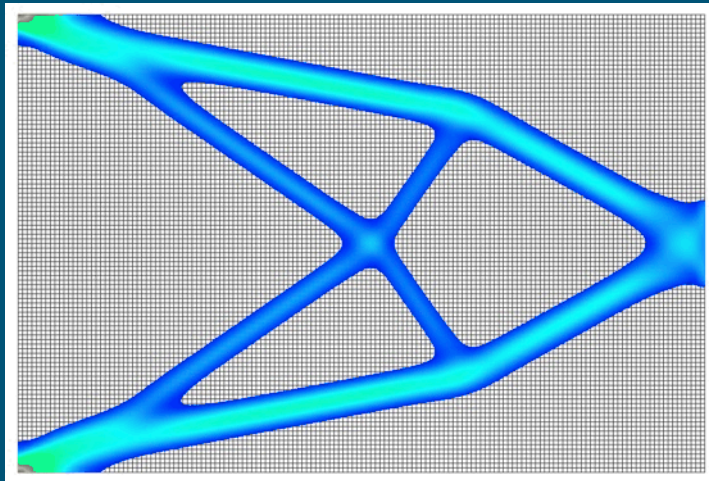
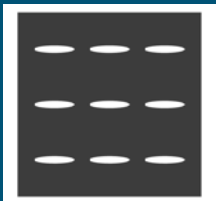
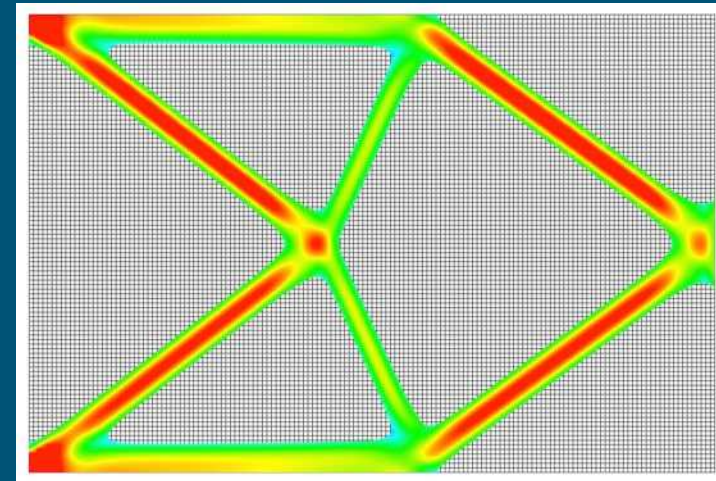
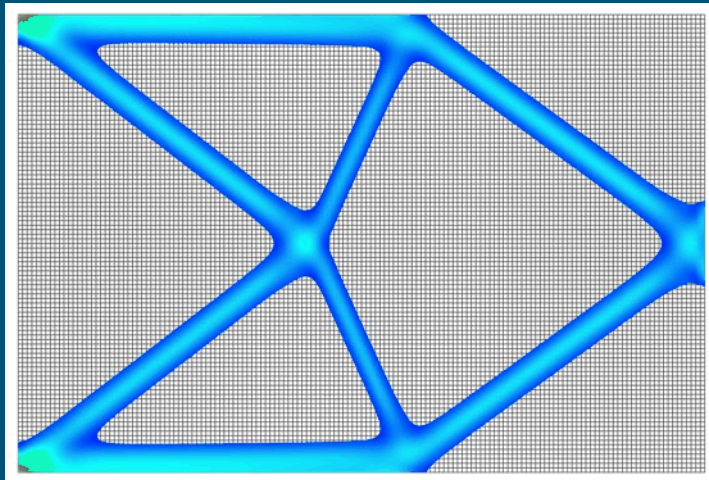


$$\begin{bmatrix} 1.3 \times 10^9 & 3.9 \times 10^8 & 0 \\ 3.9 \times 10^8 & 7.8 \times 10^8 & 0 \\ 0 & 0 & 5.7 \times 10^8 \end{bmatrix}$$



Homogenization: Structural Bracket

$$u_i(\mathbf{x}, \mathbf{y}) = u_i^0(\mathbf{x}) - \chi_i^{kl}(\mathbf{y}) \frac{\partial u_k^0(\mathbf{x})}{\partial x_l}$$



Average total stress

Maximum total stress

Material-aware stress minimization

$$\text{Objective: } \min_{\mathbf{z}, \mathbf{x}} f(\mathbf{u}, \mathbf{z}, \mathbf{x})$$

$$\text{PDE Constraint: } \mathbf{g}(\mathbf{u}, \mathbf{z}, \mathbf{x}) = \mathbf{0}$$

$$\text{Inequality Constraint: } h(\mathbf{u}, \mathbf{z}, \mathbf{x}) \leq 0$$

$$f = \left[\int_{\Omega} \left(\frac{\bar{\sigma}}{\sigma_y} \right)^p dV \right]^{1/p}$$

$$\bar{\sigma} = \left(\frac{\phi(\mathbf{S}', \mathbf{S}'')}{4} \right)^{1/a}$$

$$\mathbf{s}' = \mathbf{C}' \mathbf{s}$$

$$\mathbf{s}'' = \mathbf{C}'' \mathbf{s}$$

$$\phi = \sum_{i=1}^3 \sum_{j=1}^3 |S'_i - S''_j|^a$$

Material constants: \mathbf{C}' , \mathbf{C}'' , a , σ_y

Material-aware stress minimization

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Thermal and mechanical compliance minimization

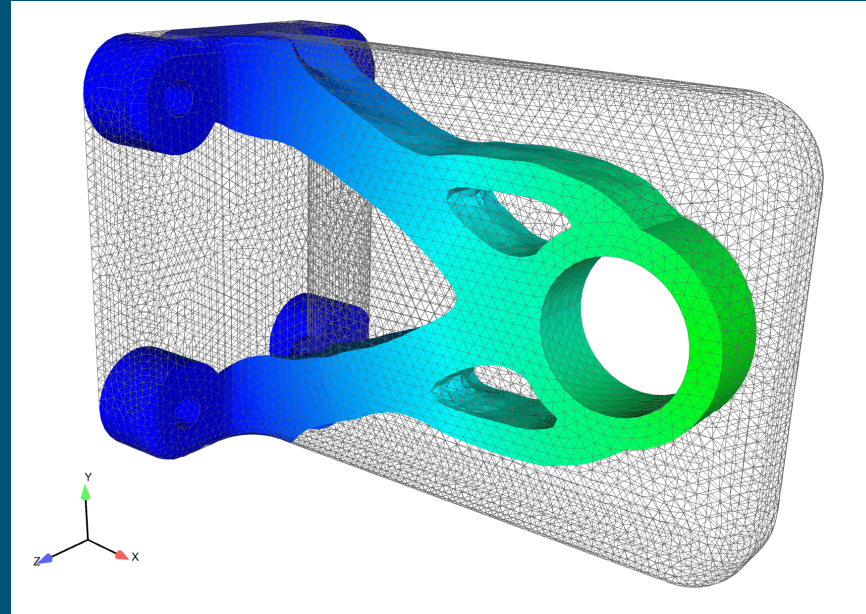
Mechanical and thermal load cases. 2 GPUs.

elements: 187k

dofs: 110k

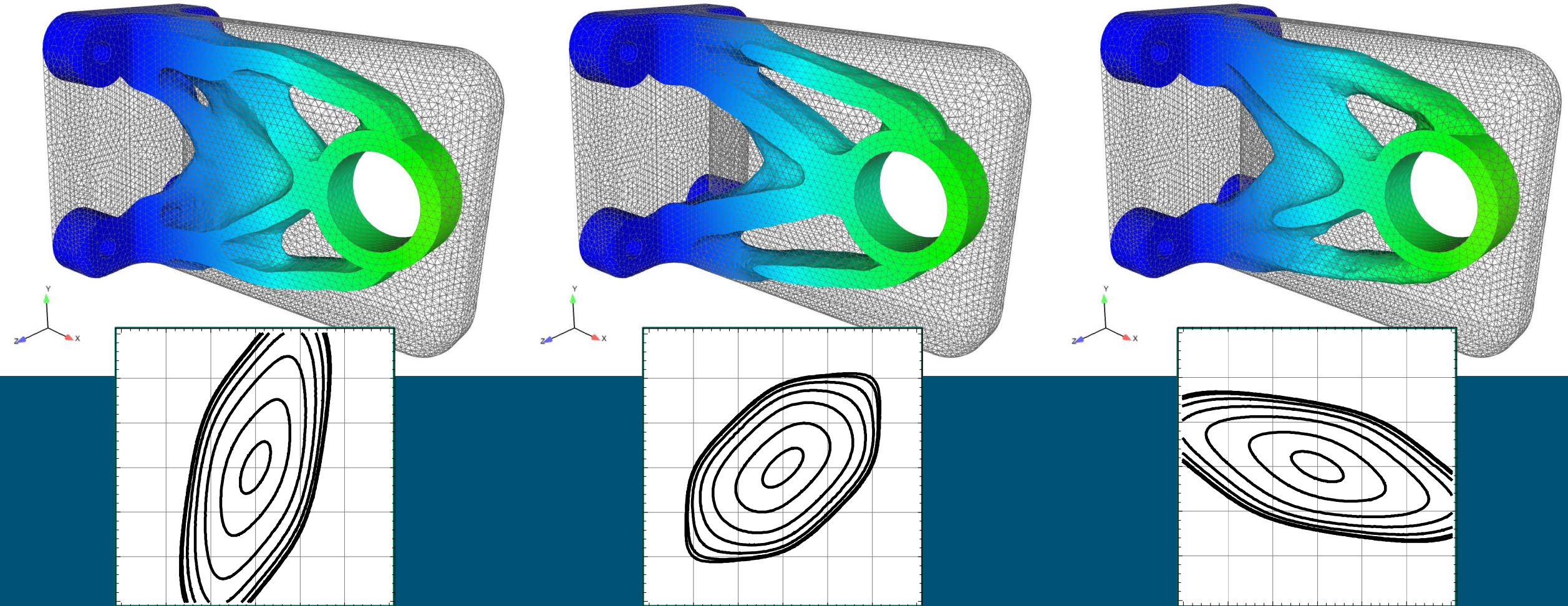
iterations: 26

Run time: 28s



Material-aware stress minimization

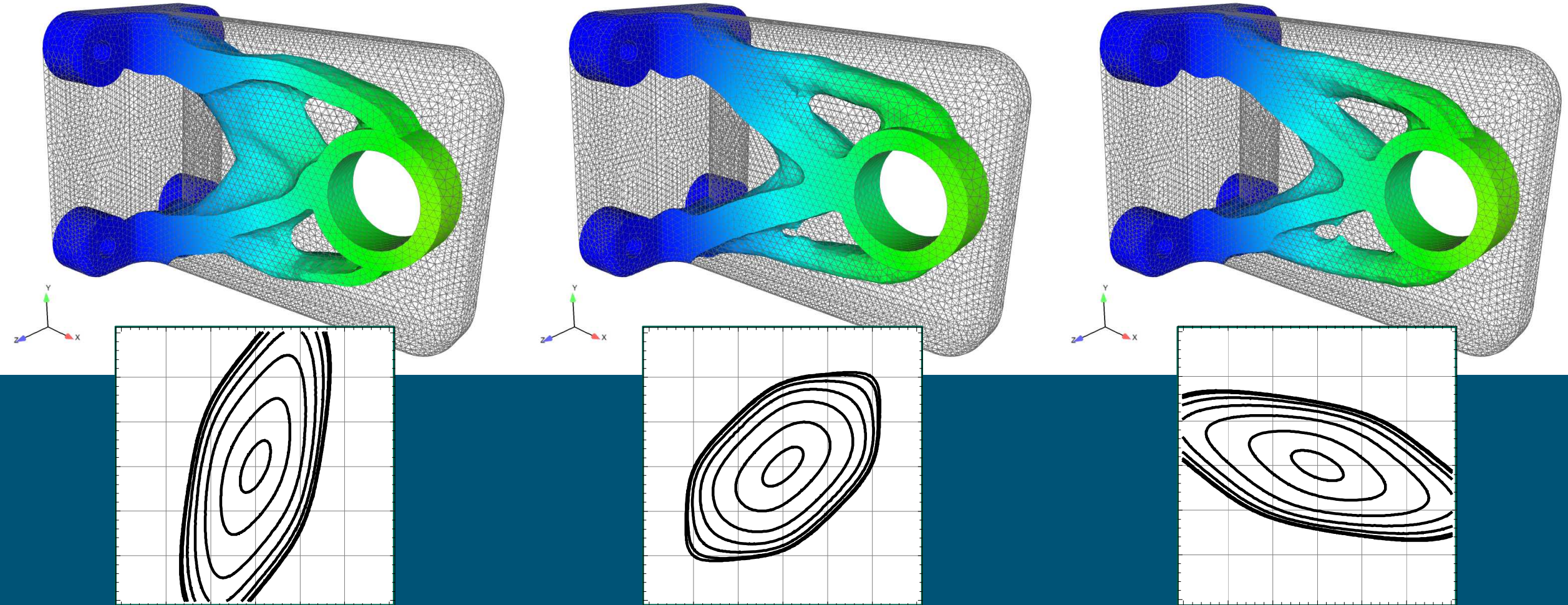
Vf: 0.25



Material-aware stress minimization

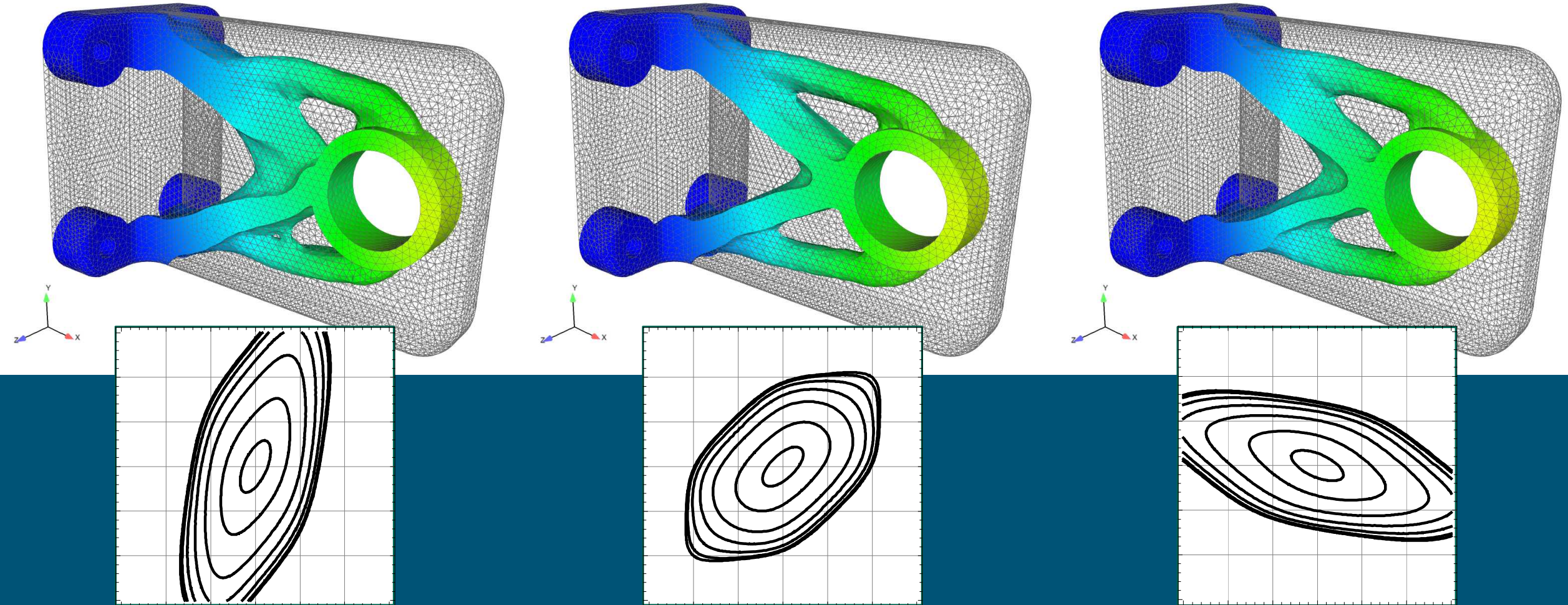


Vf: 0.20



Material-aware stress minimization

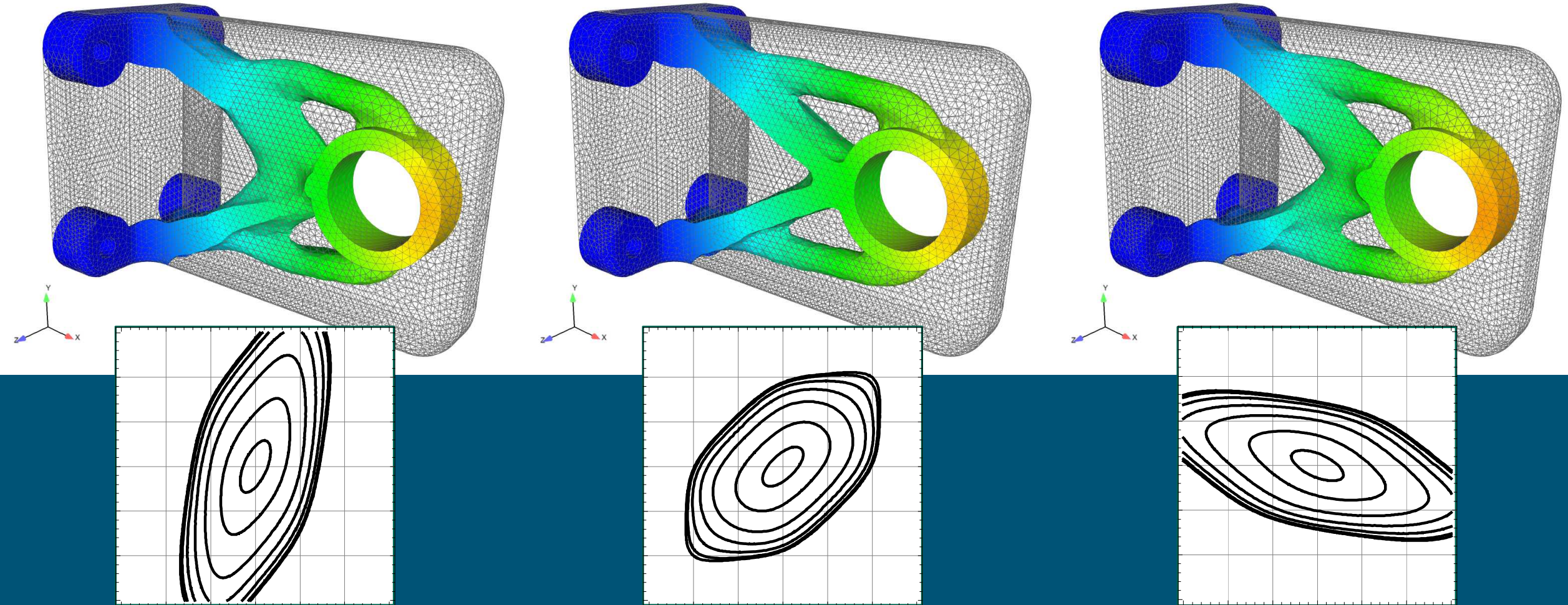
Vf: 0.15

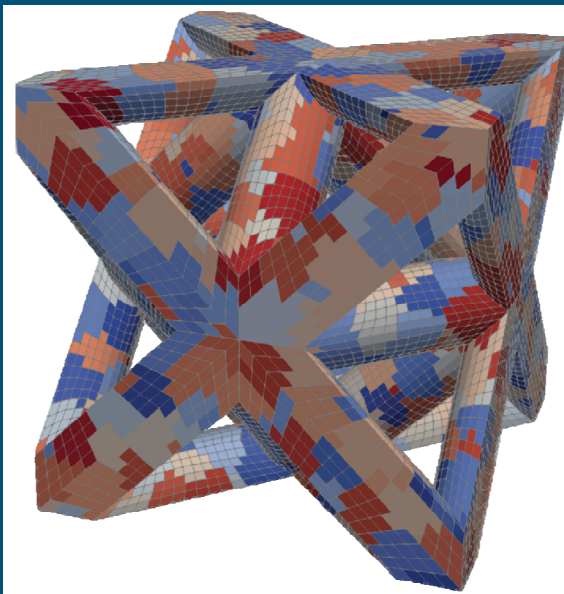
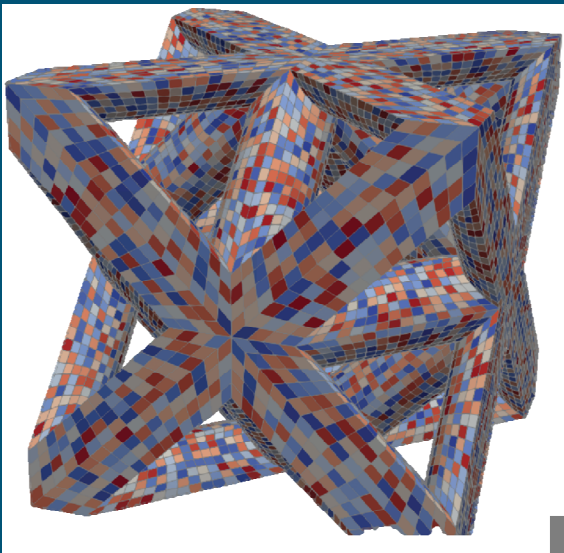


Material-aware stress minimization



Vf: 0.10

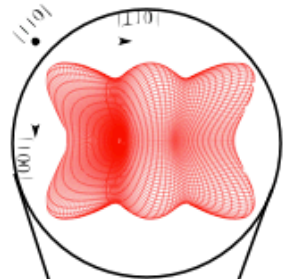




Elastic stiffness tensor

$$\sigma^{PK2} = \mathbf{C}^e : \mathbf{E}^e$$

$$\mathbf{E}^e = \frac{1}{2} (\mathbf{F}^{eT} \mathbf{F}^e - \mathbf{I})$$



Kinematics of plastic flow

$$\mathbf{F} = \mathbf{F}^e \times \mathbf{F}^p$$

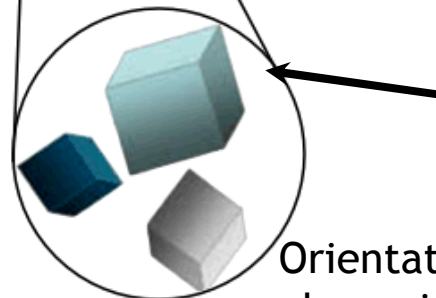
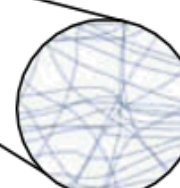
$$\mathbf{L}^p = \dot{\mathbf{F}}^p \mathbf{F}^{p-1} = \sum_{\alpha=1}^{N_{\text{sys}}} \dot{\gamma}^{\alpha} (\bar{\mathbf{s}}^{\alpha} \otimes \bar{\mathbf{m}}^{\alpha})$$

Deformation Mechanisms

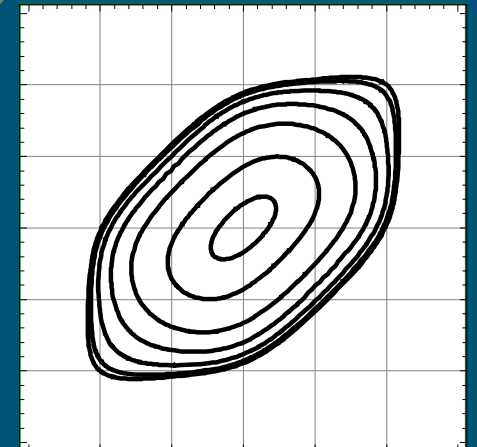
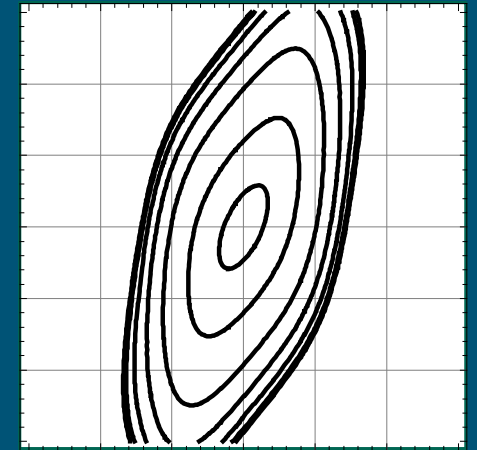
$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0 \left| \frac{\tau^{\alpha}}{\tau_{CRSS}^{\alpha}} \right|^{1/m} \text{sgn}(\tau^{\alpha})$$

$$\tau_{CRSS}^{\alpha} = \lambda G_{[110]} b \sqrt{\rho^{\alpha}}$$

$$\frac{d\rho^{\alpha}}{d\gamma^{\alpha}} = H_1^{KM} \sqrt{\rho^{\alpha}} - H_2^{KM} \rho^{\alpha}$$



Orientation phase, interfaces



Summary

Approach: compose objectives that reflect details of the as-printed material so designs can be computed that i) use existing, well characterized AM processes, and ii) meet essential performance requirements.

Progress:

- Developed Plato Engine to enable sampling-based and PDF-based methods for incorporation of uncertainty.
- Using normalized stress objective to account for material yield behavior.

Current effort:

- Computing/measuring material data for Barlat model.
- *Stress constraint* with volume objective.