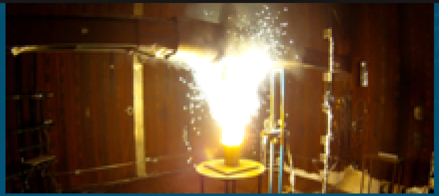
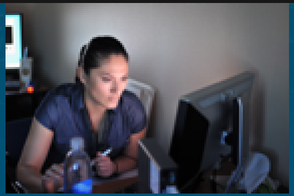
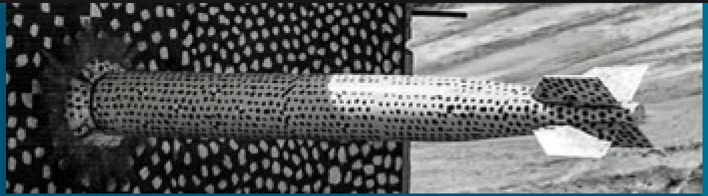
Sandia National Laboratories

SAND2021-6233C

Optimization-based Design for Additive Manufacturing

CONTRIBUTORS

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PRESENTED BY

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U.S. DEPARTMENT OF ENERGY NNSA

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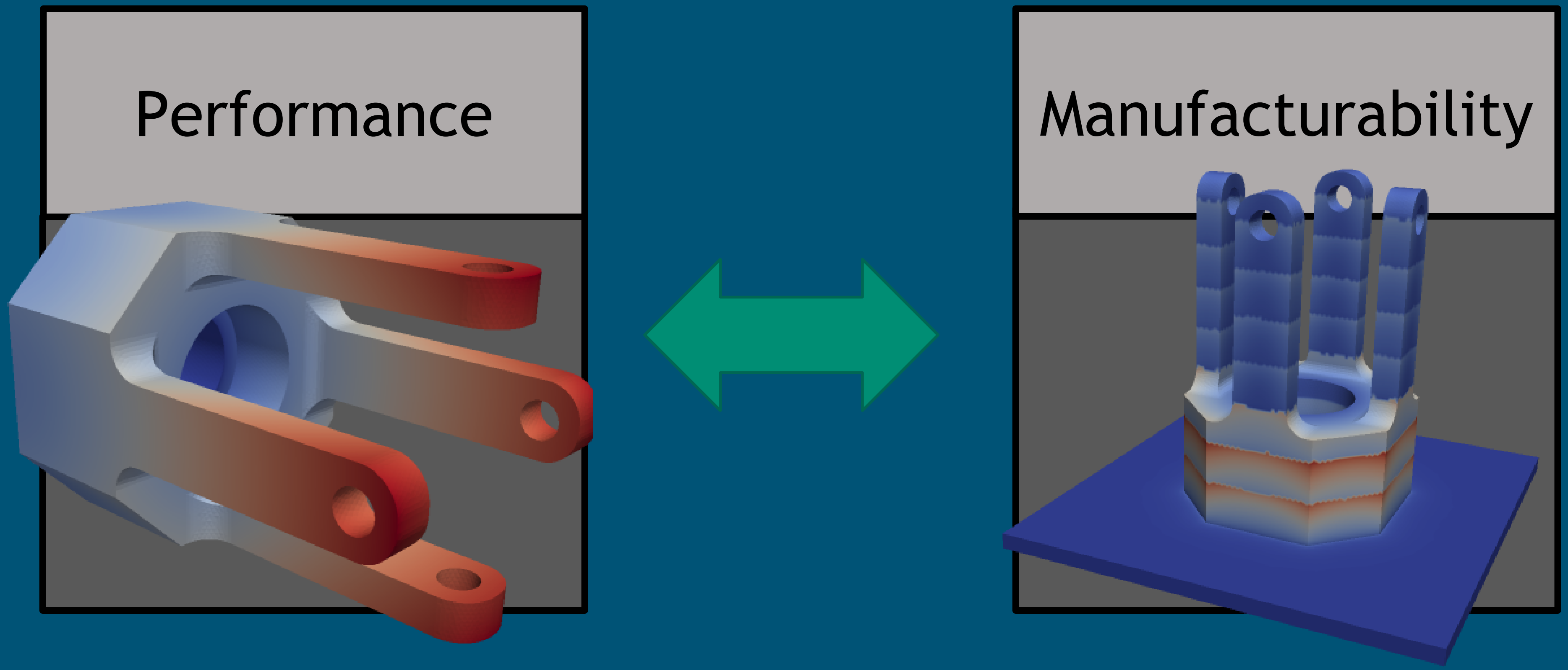
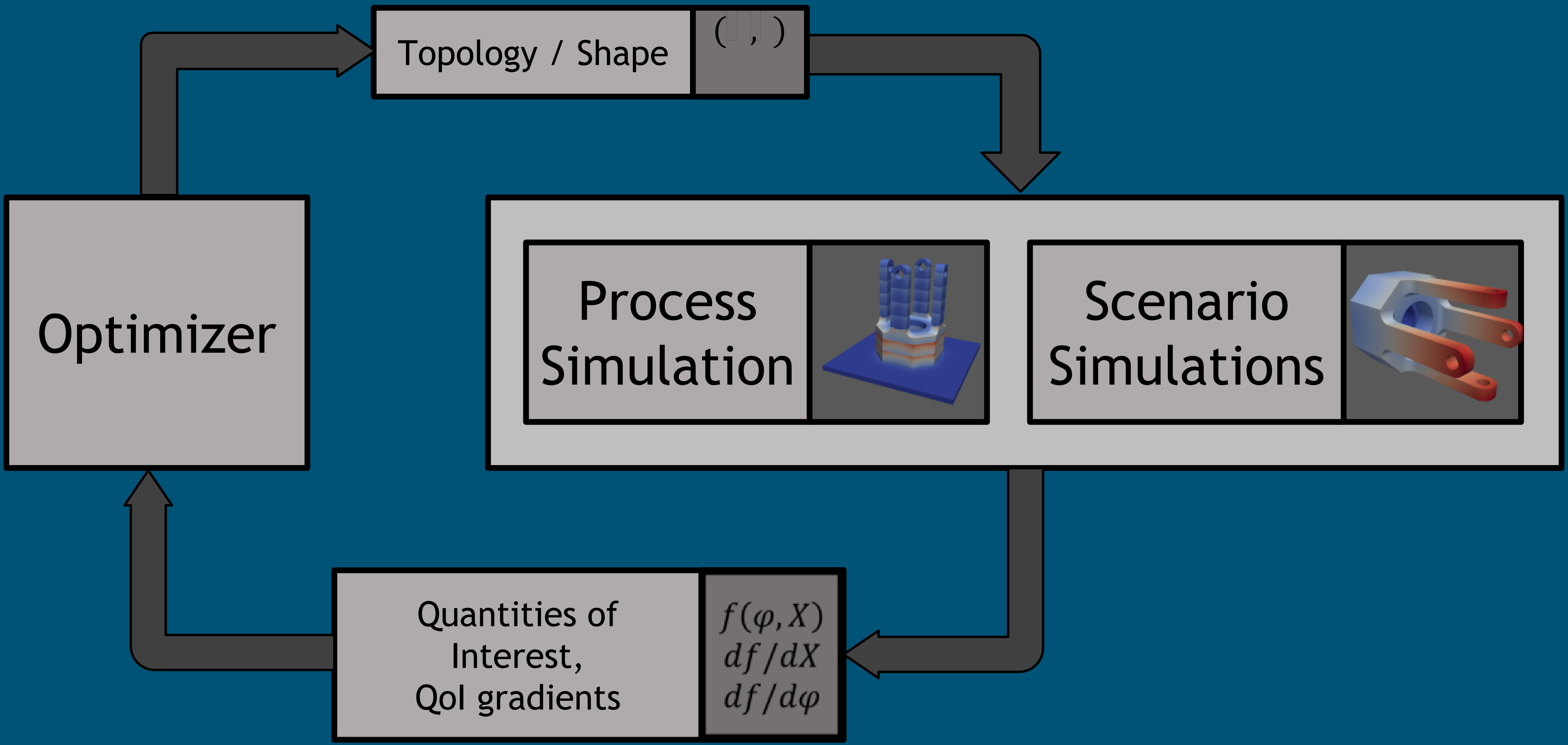
Design for AM



DfAM: Approach



Process-aware Shape/Topology Optimization

Problem: $\min_{\varphi, X} f\big(\varphi, X, U(\varphi, X), S(\varphi, X), \mathcal{U}(\varphi, X)\big)$

Process solutions: $U(\varphi, X) = \{u_I(\varphi, X) \mid I = 1 \ldots n_I\}$

$S(\varphi, X) = \{s_I(\varphi, X) \mid I = 1 \ldots n_I\}$

Load case solutions: $\mathcal{U}(\varphi, X) = \{\mathcal{u}_J(\varphi, X) \mid J = 1 \ldots n_c\}$

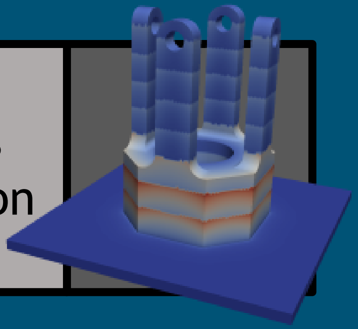
Process: $g_I(\varphi, X, u_I, s_{I-1}) = 0$ for $I = 1 \ldots$

Load cases: $c_J(\varphi, X, u_{n_I}, s_{n_I}, \mathcal{u}_J) = 0$ for $J = 1 \ldots$

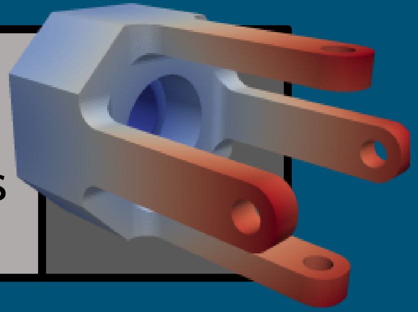
Linear constraint: $h(\varphi, X) \leq 0$

Objective: $f = \sum_{K=1}^{n_c} \alpha_K f_K\big(\varphi, X, \mathcal{u}_K(\varphi, X)\big) + \alpha_m f_m\big(\varphi, X, U(\varphi, X), S(\varphi, X)\big)$

Process Simulation



Load case Simulations



Performance Objective(s)

Manufacturability Objective(s)

Process-aware Shape/Topology Optimization

$$g_I(\varphi, X, u_I, s_{I-1}\,; C, \varepsilon^{IS}) = 0 \quad \text{for} \quad I = 1 \ldots$$

n_l: Number of sequence steps

Inherent strain method (elastic):

$$g_I = \begin{Bmatrix} R^I \\ H^I \end{Bmatrix}$$

Small strain Elastostatics: $R^I = F^I_{int}(\varphi, X, u_I, s_{I-1}\,; C, \varepsilon^{IS}) - F^I_{ext}$

State update: $H^I = s_I - s_{I-1} - B(u_I)$

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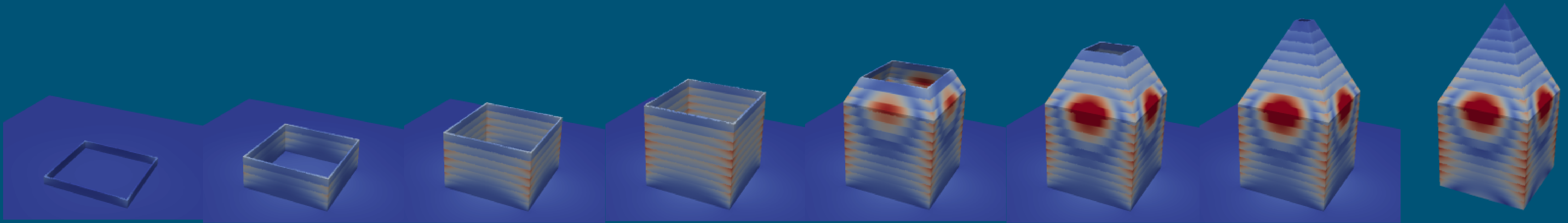
Forward Solution (What is the manufacturability of the current design?)

$f_m(\varphi, X, U(\varphi, X), S(\varphi, X))$



Process-aware Shape/Topology Optimization

$$\hat{f}_m = f_m + \sum_{k=1}^{n} \lambda^{k^T} R^k + \sum_{k=1}^{n} \mu^{k^T} H^k$$

$$\begin{aligned}
\frac{d\hat{f}_m}{d\varphi} &= \frac{\partial f_m}{\partial \varphi} \\
&+ \sum_{k=1}^{n} \left(\frac{\partial f_m}{\partial u^k}\frac{\partial u^k}{\partial \varphi} + \frac{\partial f_m}{\partial c^k}\frac{\partial c^k}{\partial \varphi} \right) \\
&+ \sum_{k=1}^{n} \lambda^{k^T} \left(\frac{\partial R^k}{\partial \varphi} + \frac{\partial R^k}{\partial u^k}\frac{\partial u^k}{\partial \varphi} + \frac{\partial R^k}{\partial c^{k-1}}\frac{\partial c^{k-1}}{\partial \varphi} \right) \\
&+ \sum_{k=1}^{n} \mu^{k^T} \left(\frac{\partial H^k}{\partial \varphi} + \frac{\partial H^k}{\partial u^k}\frac{\partial u^k}{\partial \varphi} + \frac{\partial H^k}{\partial c^k}\frac{\partial c^k}{\partial \varphi} + \frac{\partial H^k}{\partial c^{k-1}}\frac{\partial c^{k-1}}{\partial \varphi} \right)
\end{aligned}$$

Process-aware Shape/Topology Optimization

$$\frac{d\hat{f}_m}{d\varphi} = \frac{\partial f_m}{\partial \varphi} + \sum_{k=1}^{n} \left(\lambda^{k^T} \frac{\partial R^k}{\partial \varphi} + \mu^{k^T} \frac{\partial H^k}{\partial \varphi} \right)$$

$$+ \left(\frac{\partial f_m}{\partial c^n} + \mu^{n^T} \frac{\partial H^n}{\partial c^n} \right) \frac{\partial c^n}{\partial \varphi}$$

$$+ \sum_{k=1}^{n} \left(\frac{\partial f_m}{\partial u^k} + \lambda^{k^T} \frac{\partial R^k}{\partial u^k} + \mu^{k^T} \frac{\partial H^k}{\partial u^k} \right) \frac{\partial u^k}{\partial \varphi}$$

$$+ \sum_{k=1}^{n-1} \left(\frac{\partial f_m}{\partial c^k} + \mu^{k^T} \frac{\partial H^k}{\partial c^k} + \mu^{k+1^T} \frac{\partial H^{k+1}}{\partial c^k} + \lambda^{k+1^T} \frac{\partial R^{k+1}}{\partial c^k} \right) \frac{\partial c^k}{\partial \varphi}$$

Process-aware Shape/Topology Optimization

(last step)

$$\frac{\partial f_m}{\partial c^n} + {\mu^n}^T \frac{\partial H^n}{\partial c^n} = 0$$

$$\frac{\partial f_m}{\partial u^n} + {\lambda^n}^T \frac{\partial R^n}{\partial u^n} + {\mu^k}^T \frac{\partial H^n}{\partial u^n} = 0$$

(kth step), $\mathrm{k} = \mathrm{n} - 1, \ldots, 2, 1$

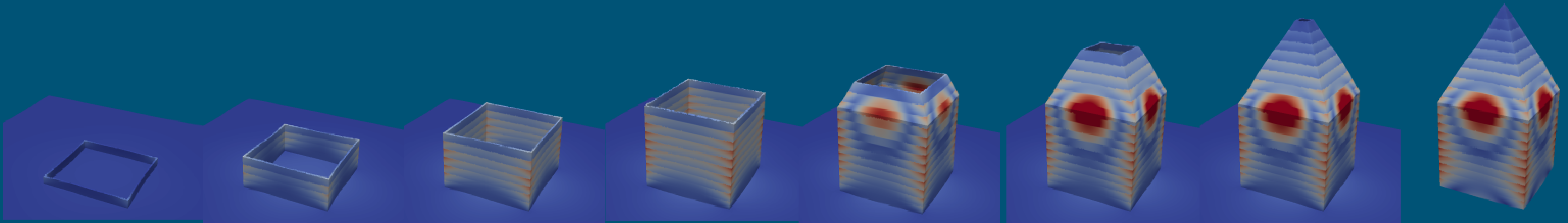
$$\frac{\partial f_m}{\partial c^k} + {\mu^k}^T \frac{\partial H^k}{\partial c^k} + {\mu^{k+1}}^T \frac{\partial H^{k+1}}{\partial c^k} + {\lambda^{k+1}}^T \frac{\partial R^{k+1}}{\partial c^k} = 0$$

$$\frac{\partial f_m}{\partial u^k} + {\lambda^k}^T \frac{\partial R^k}{\partial u^k} + {\mu^k}^T \frac{\partial H^k}{\partial u^k} = 0$$

/

Adjoint Solution (How does the manufacturability change with design changes?)

$f_m(\varphi, X, U(\varphi, X), S(\varphi, X))$



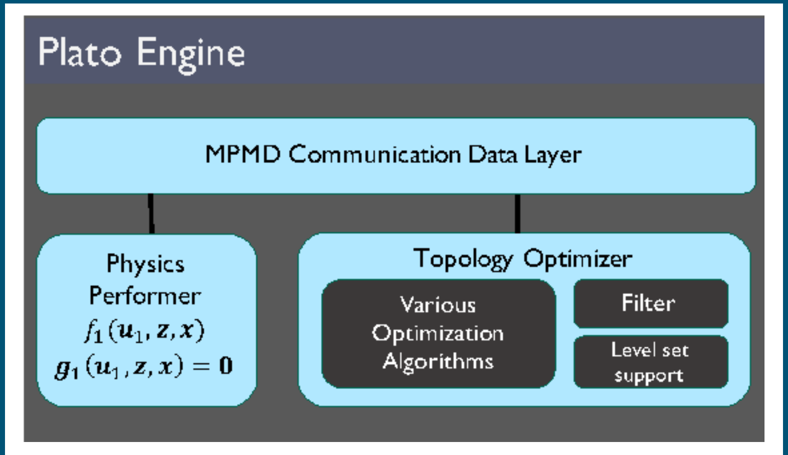
What is Plato?

Plato is a suite of tools for applying optimization to engineering problems with an emphasis on optimization-based design.

plato
OPTIMIZATION-BASED DESIGN

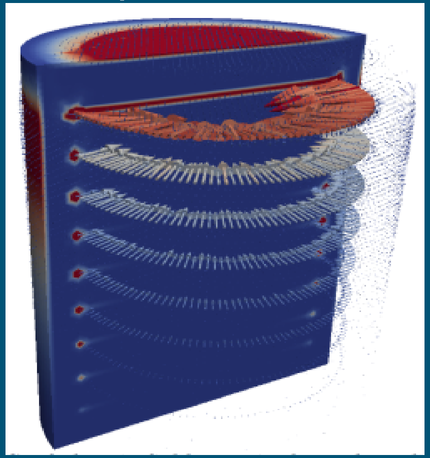
Plato Engine

Open-source architecture for orchestrating MPMD optimization problems



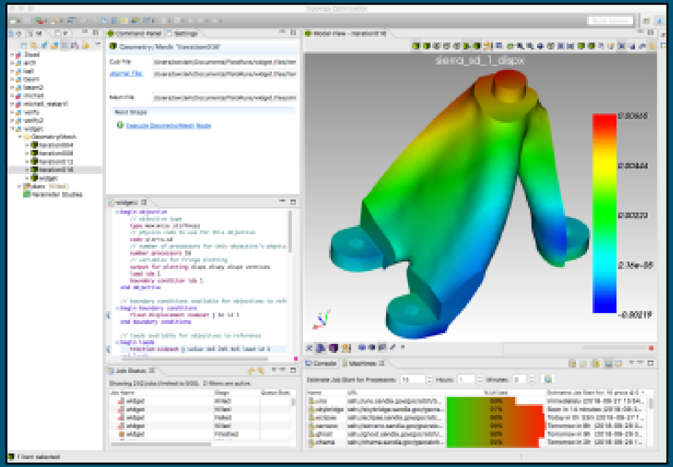
Plato Analyze

Open-source FEA code architected specifically for performance portability and use in gradient-based optimization

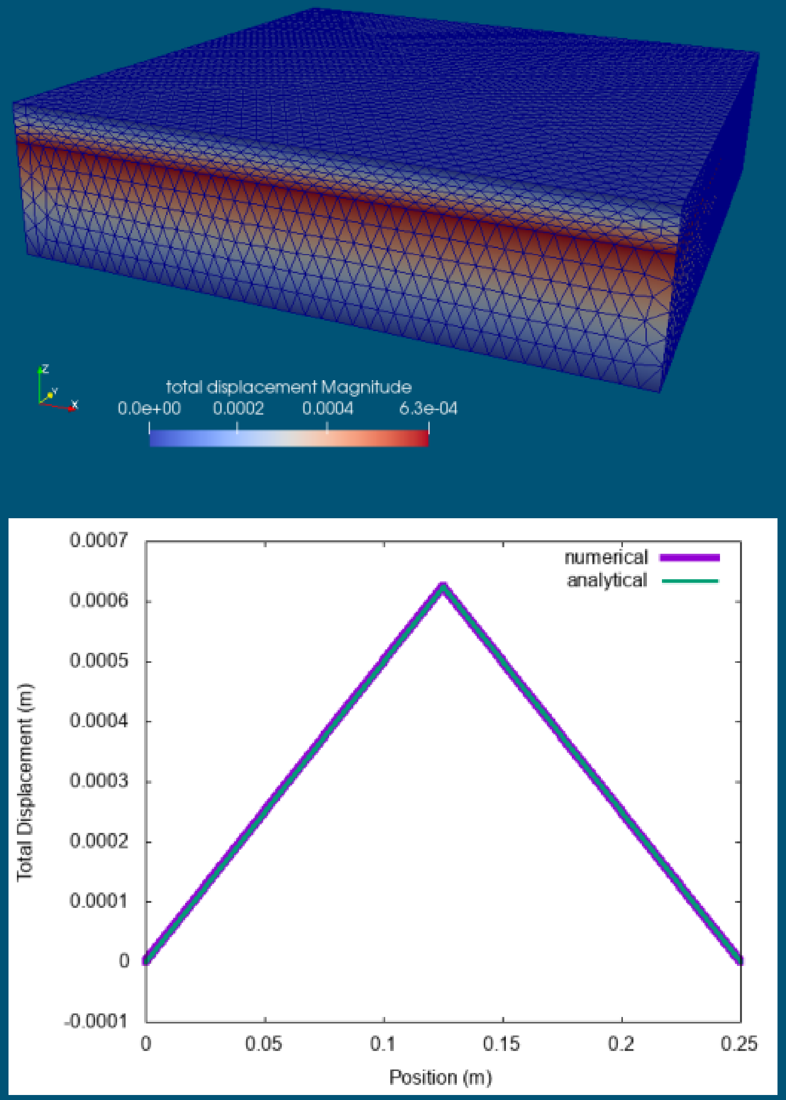


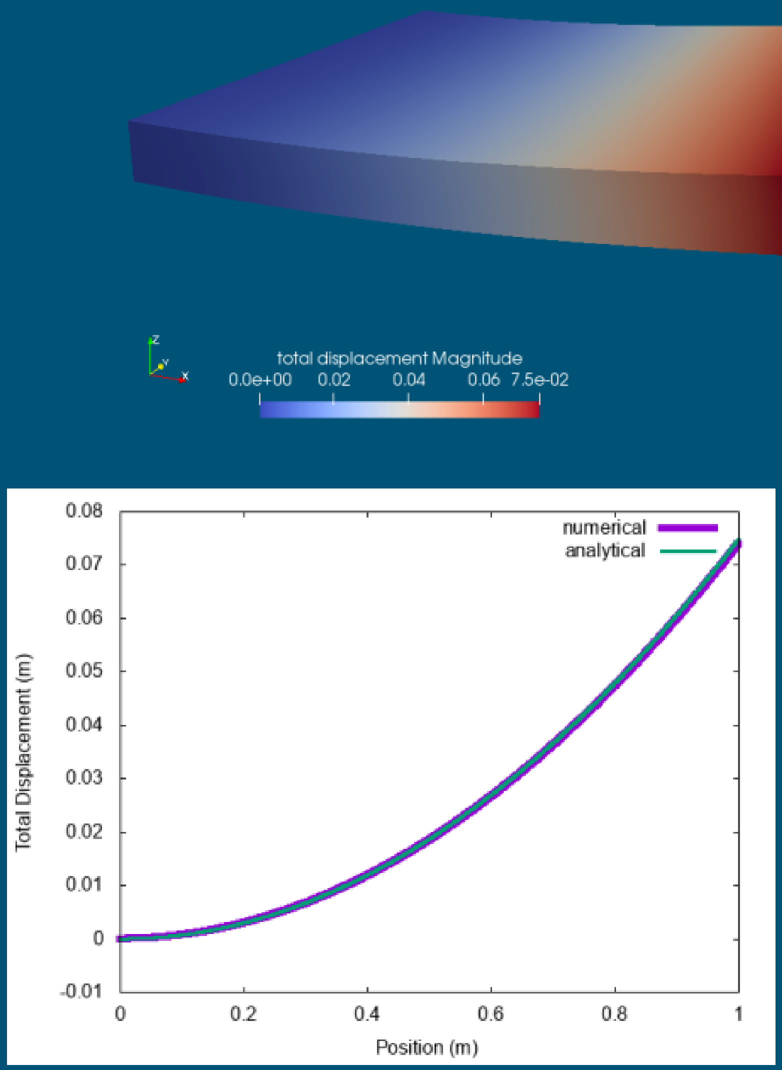
Plato v2.3

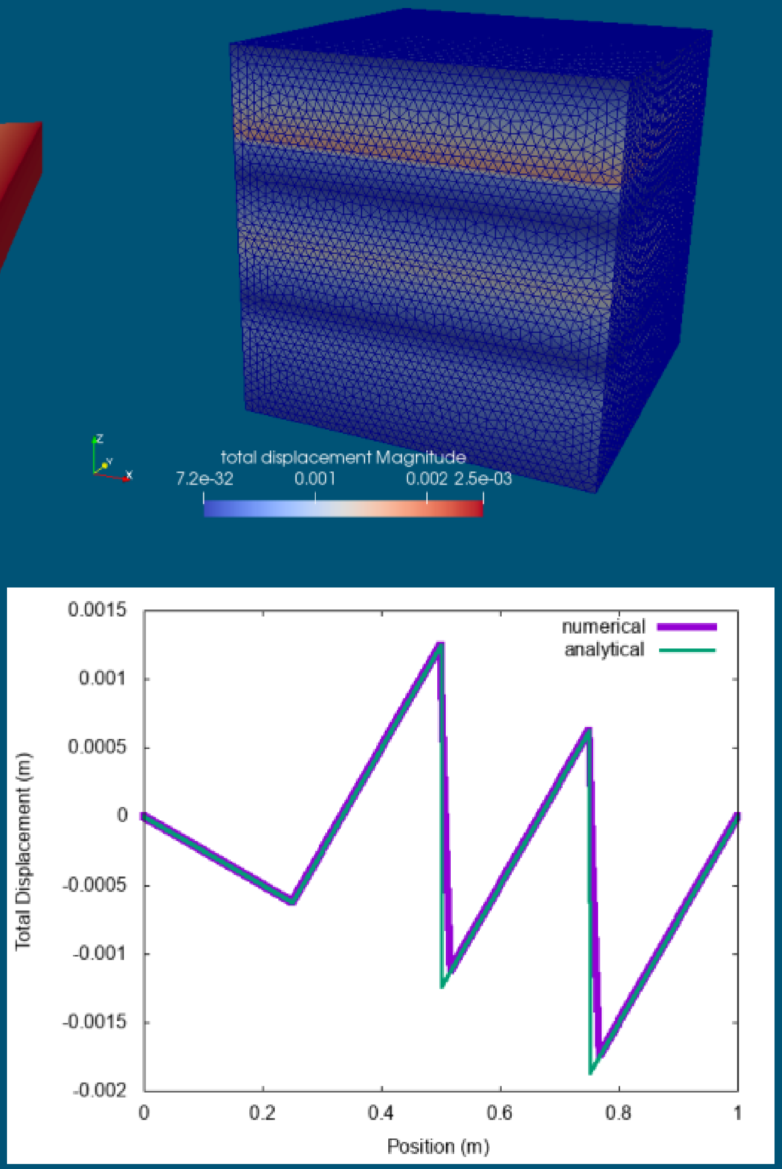
GUN-licensed Plato product including Plato-SAW GUI, Sierra/SD and some support for using Plato Analyze



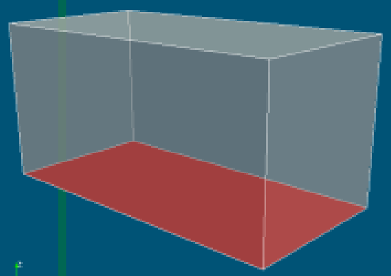
Testing, Verification, and Validation



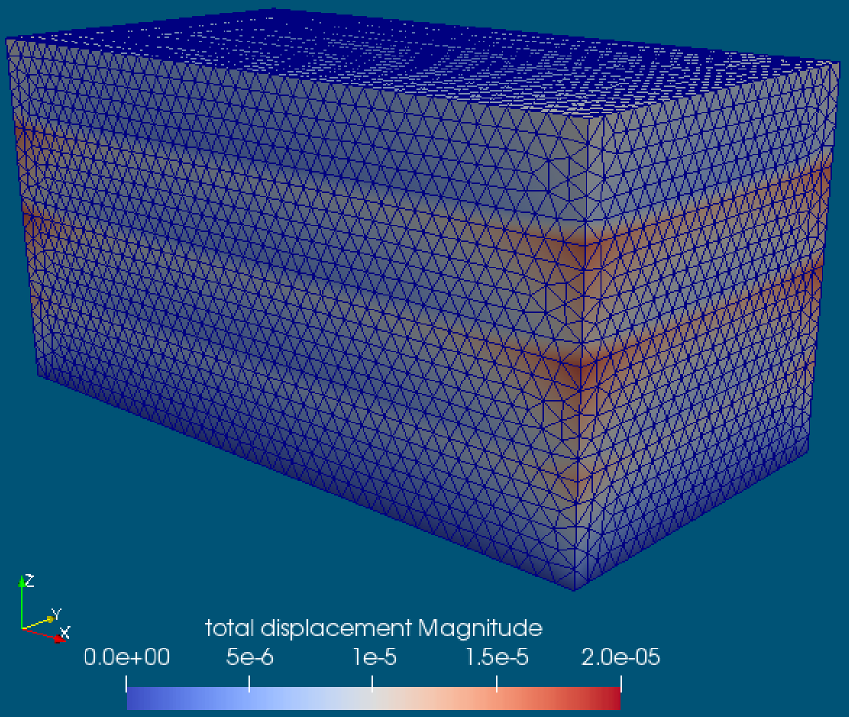




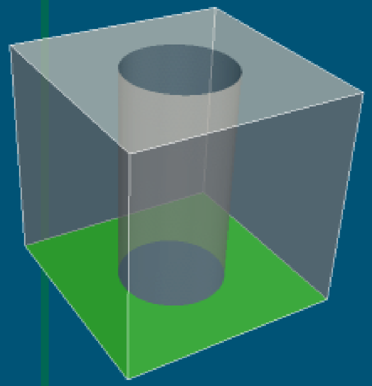
Testing, Verification, and Validation



Topology sensitivities: Randomly perturb the nodal densities and compare the predicted vs compute gradients vs step size.

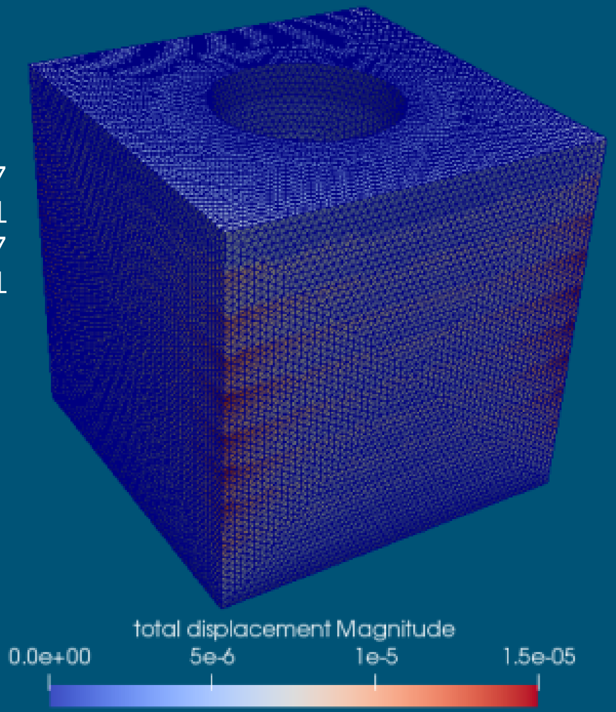


Step Size	Grad'*Step	FD Approx	abs(Error)
1.00000000e-01	1.03614525e-03	1.03614525e-03	2.38499368e-12
1.00000000e-02	1.03614525e-03	1.03614530e-03	4.42565318e-11
1.00000000e-03	1.03614525e-03	1.03614497e-03	2.85467809e-10
1.00000000e-04	1.03614525e-03	1.03614326e-03	1.98971396e-09

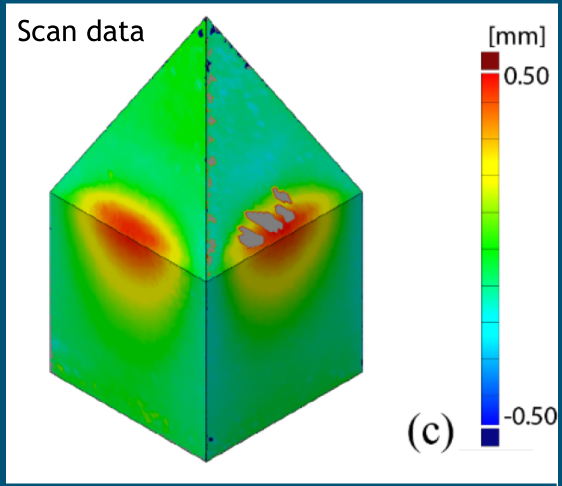


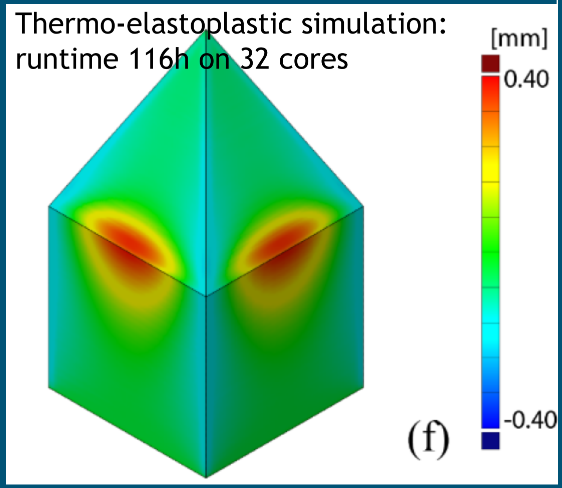
Shape sensitivities: Compute the sensitivities, increment shape parameters, and compute new objective.

```
Objective value:
1.29526388939

Shape sensitivities:
X width: 1.180865479582657
Y width: 2.153667356794931
Z width: 2.154590003921607
Radius: -4.397825196763741

Step size: 0.01

Predicted new value:
1.3475894287252181

Computed new value:
1.3500506130617436

Relative error:
0.001900141242789151
```

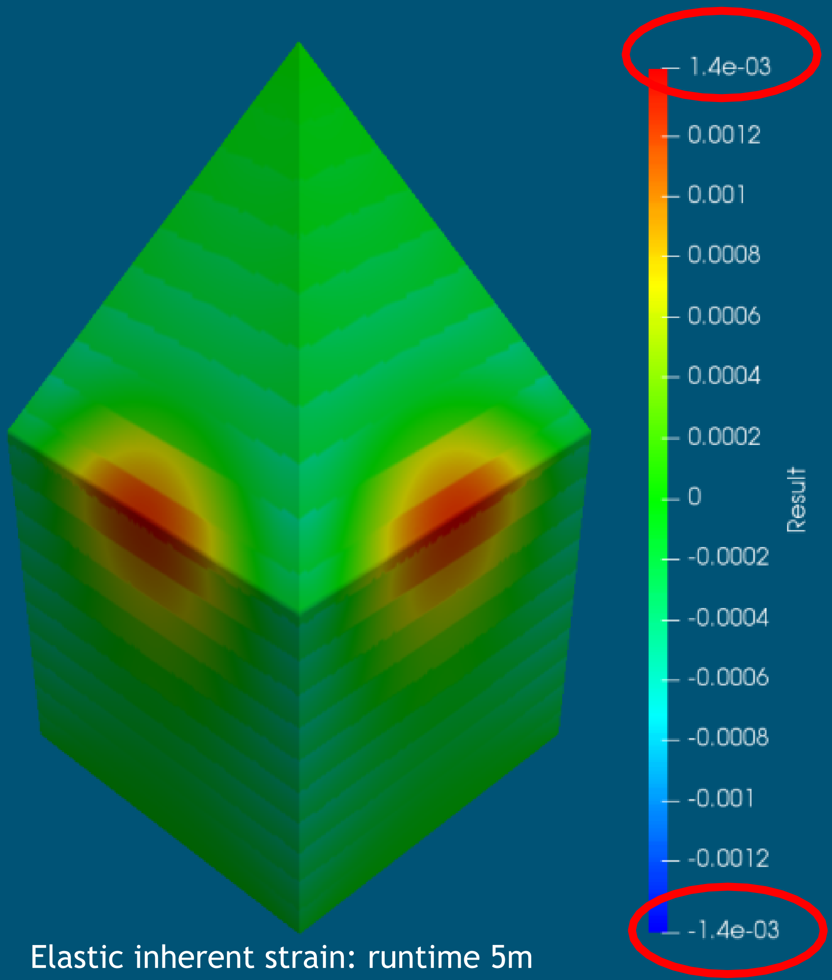


Testing, Verification, and Validation

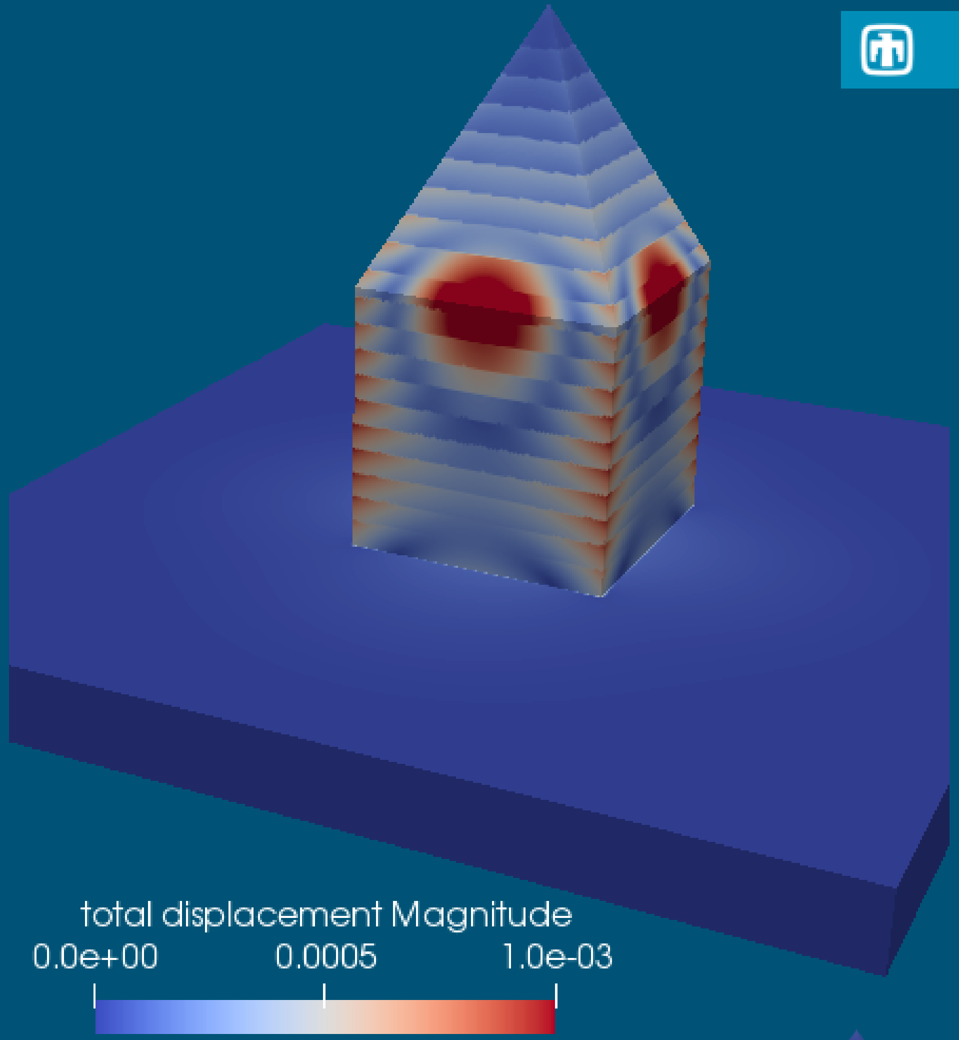


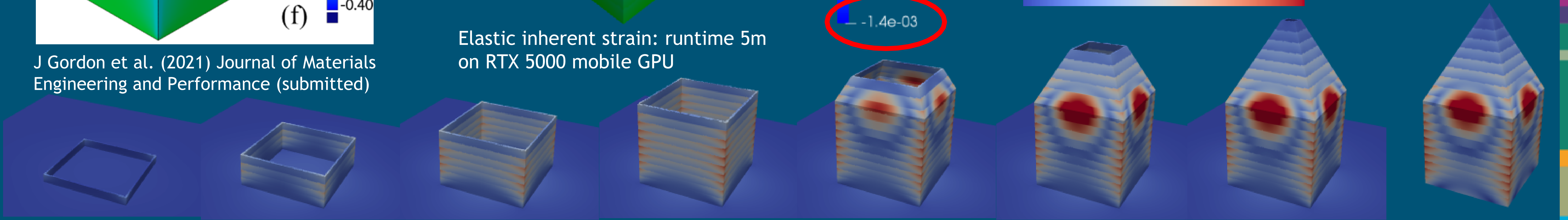


J Gordon et al. (2021) Journal of Materials Engineering and Performance (submitted)

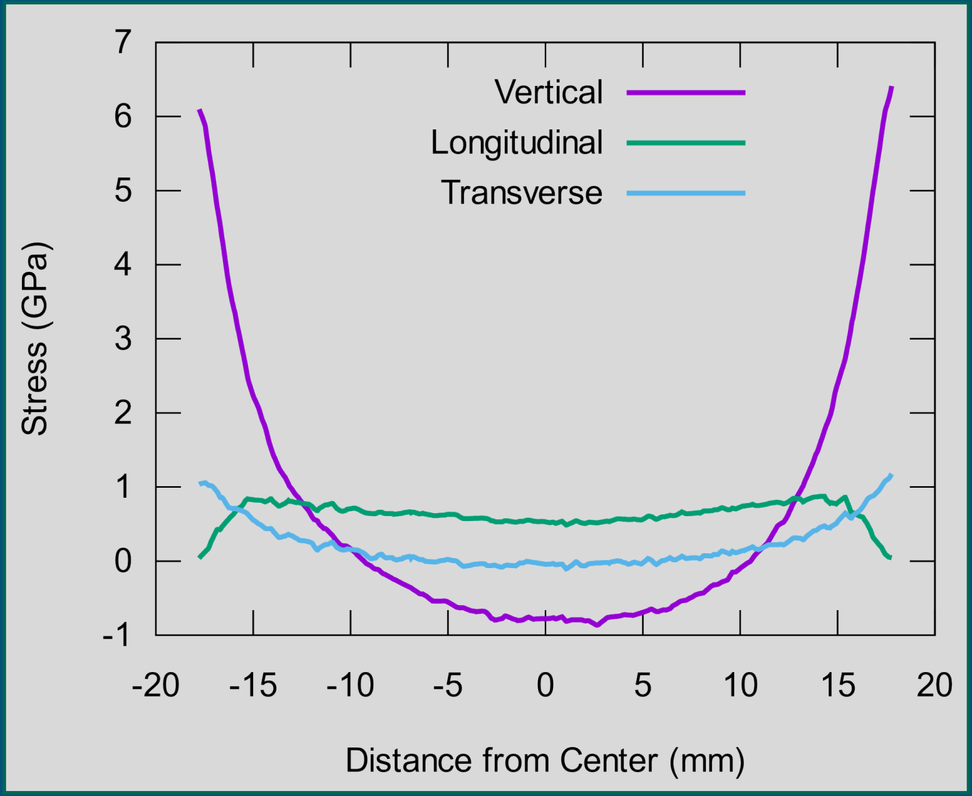


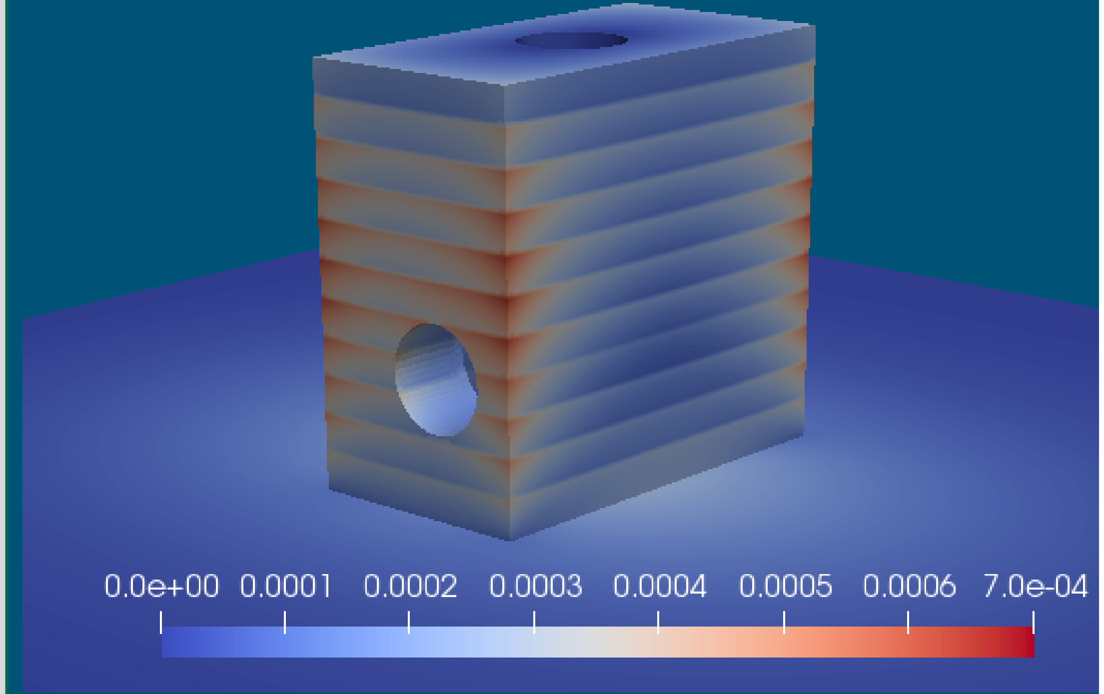
Elastic inherent strain: runtime 5m on RTX 5000 mobile GPU



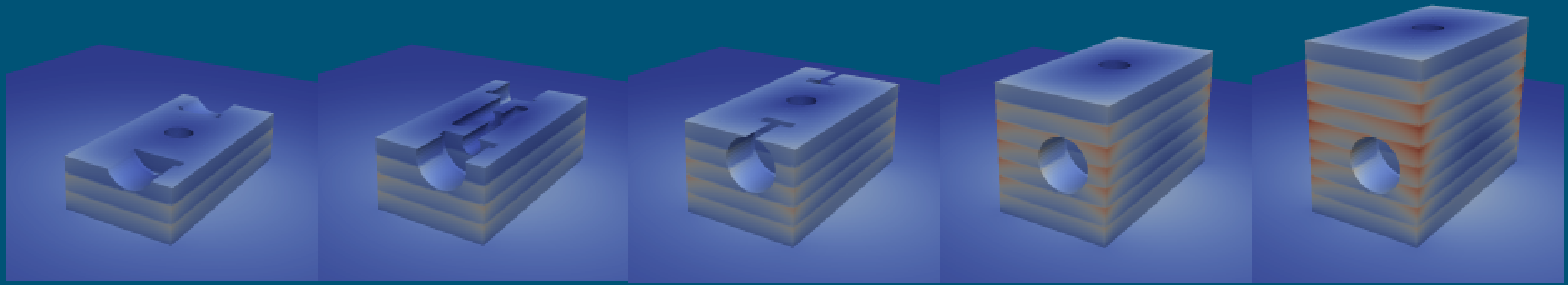


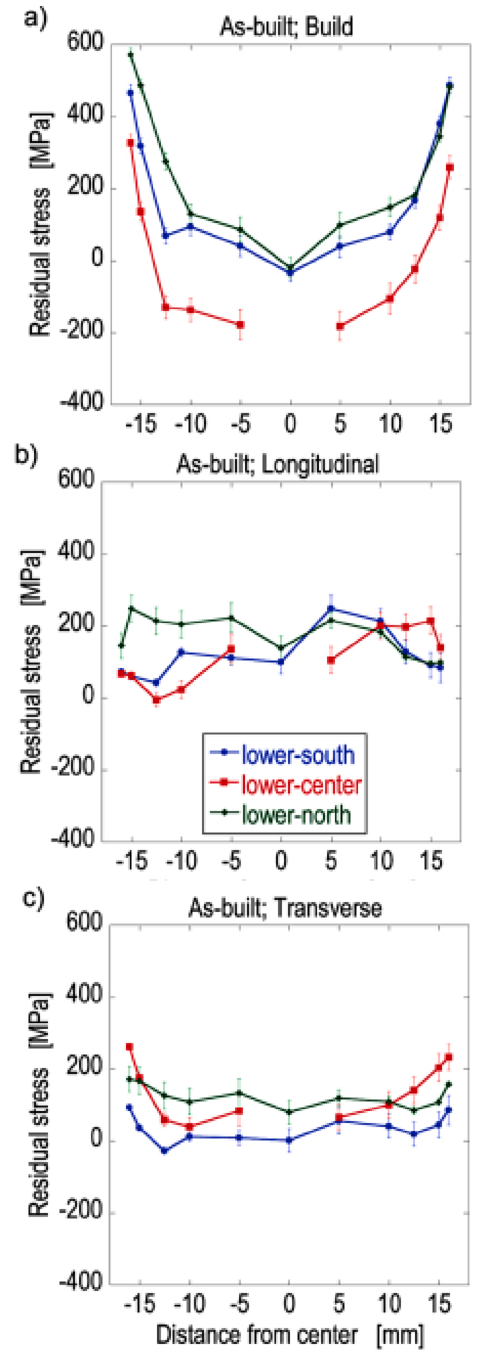
Testing, Verification, and Validation



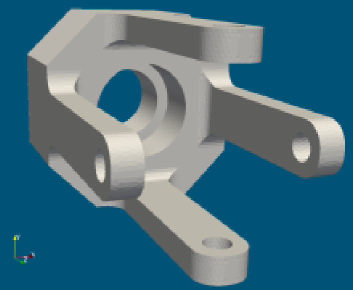


Elastic inherent strain: runtime 2m on RTX 5000 mobile GPU

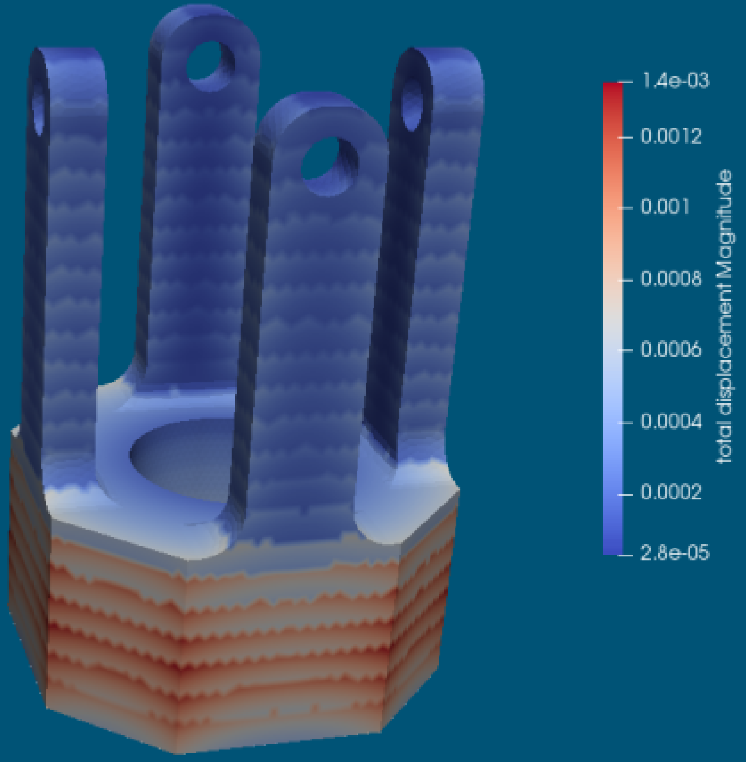




B. Clausen (2020) Additive Manufacturing Vol 36

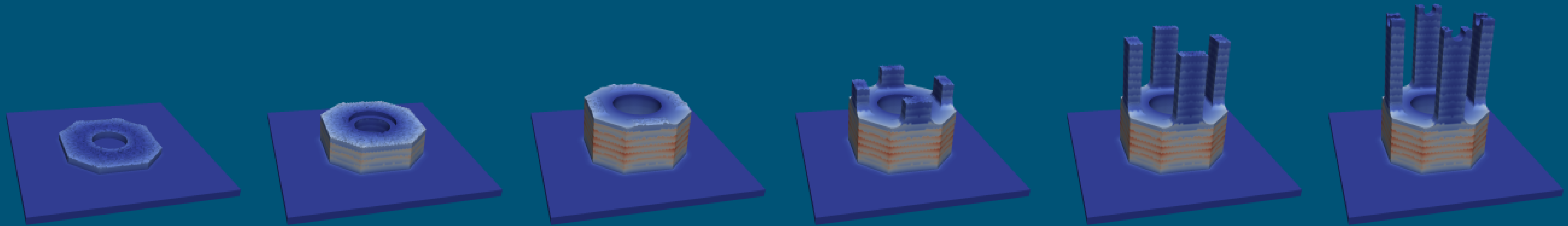


Process Aware Example



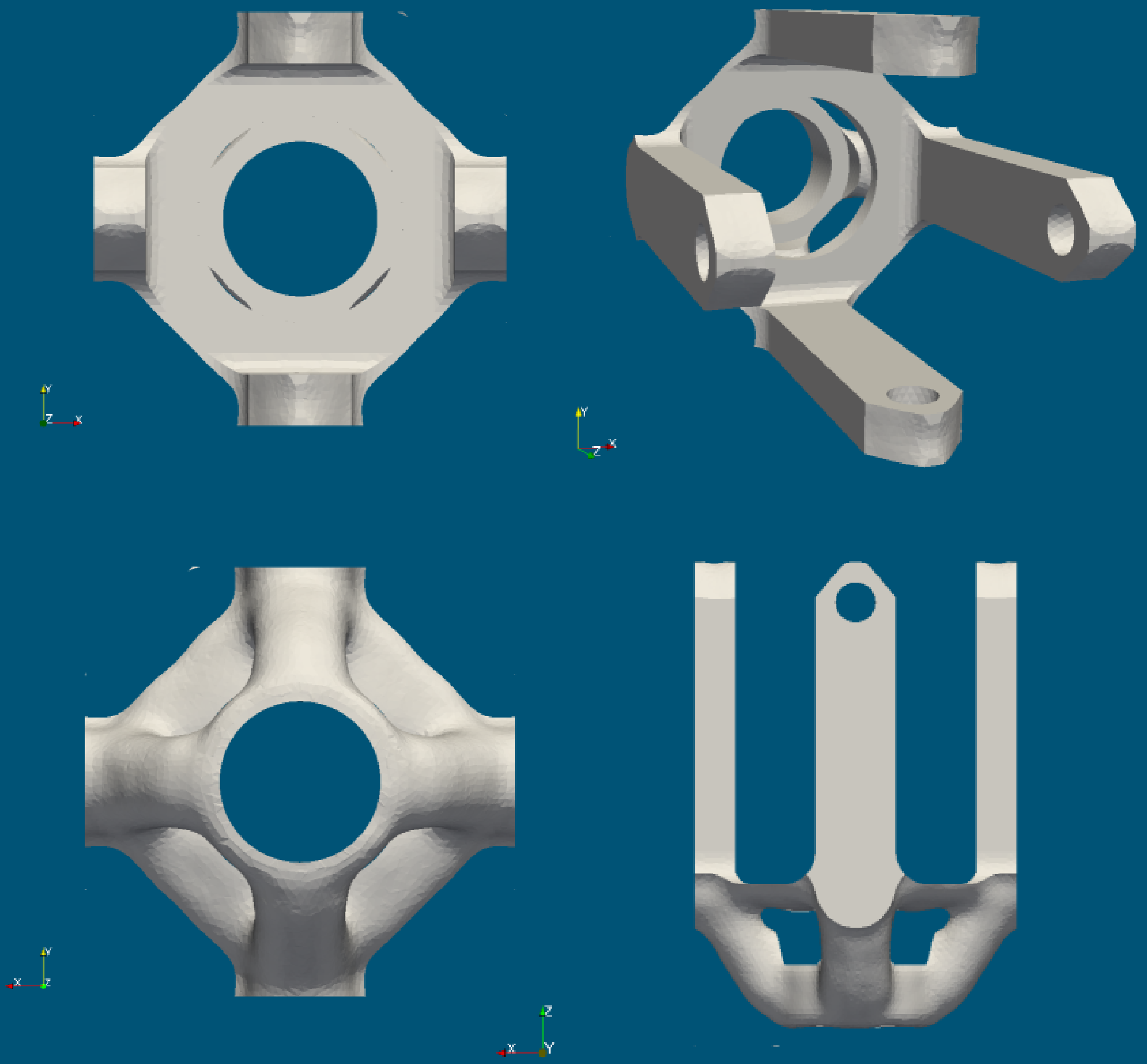
Performance: Compliance

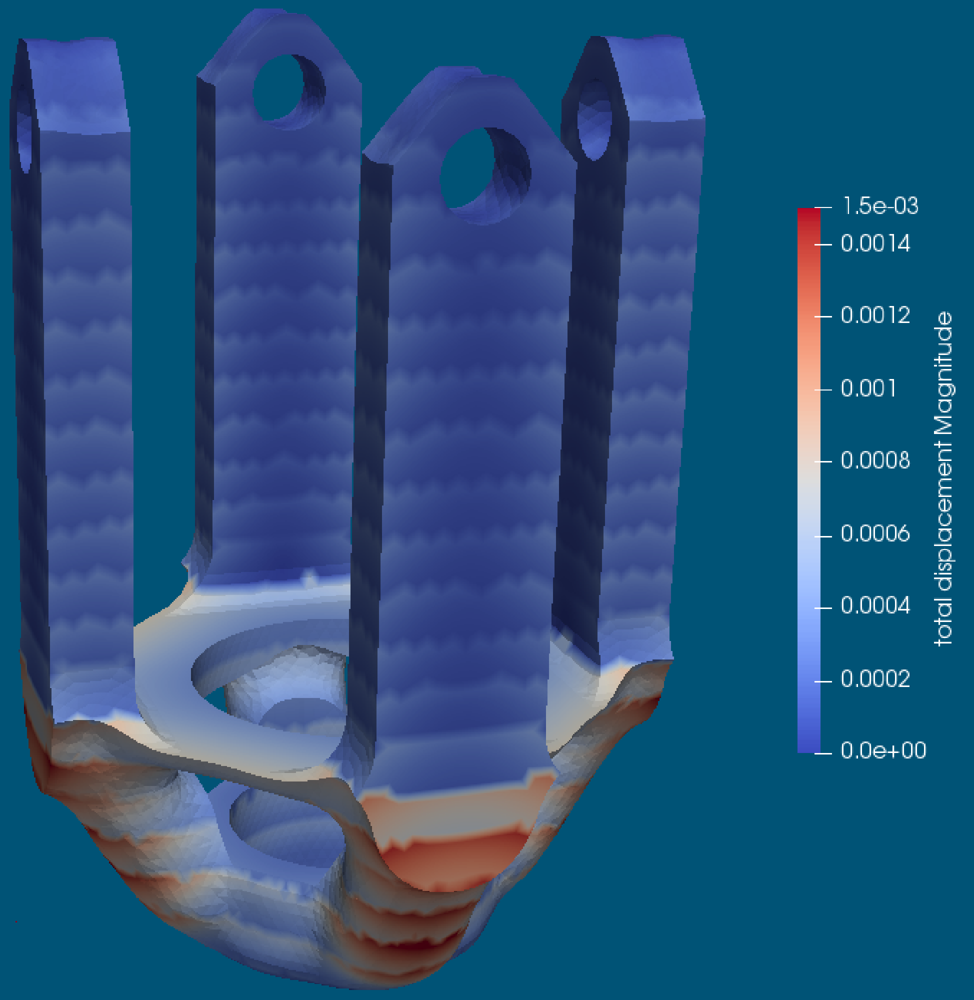
Manufacturability: Residual energy



Process Aware Example

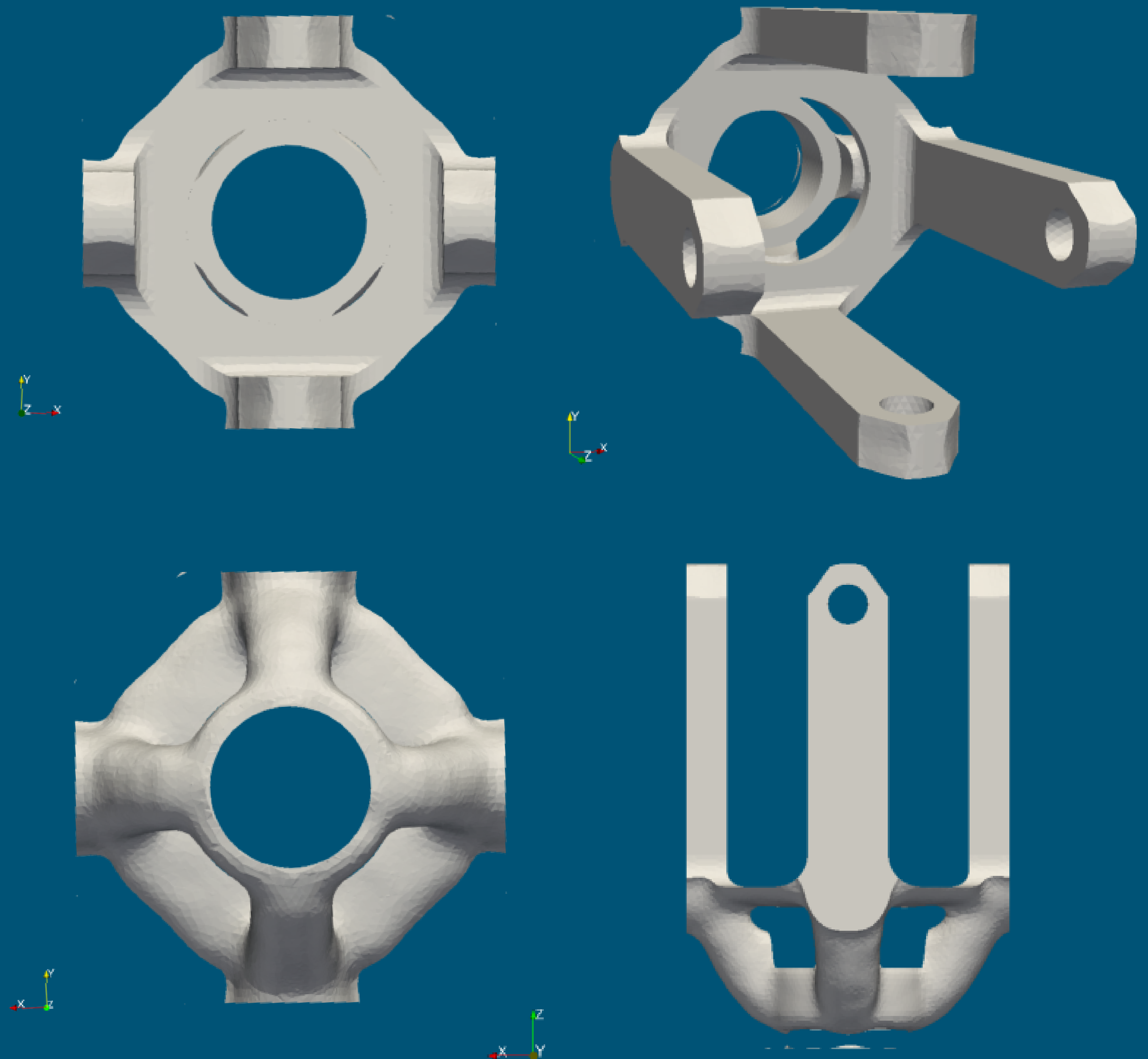
Manufacturability priority: 0.01
Displacement: 5.236 mm
Residual Energy: 4124 KJ
Deflection: -0.0405 mm

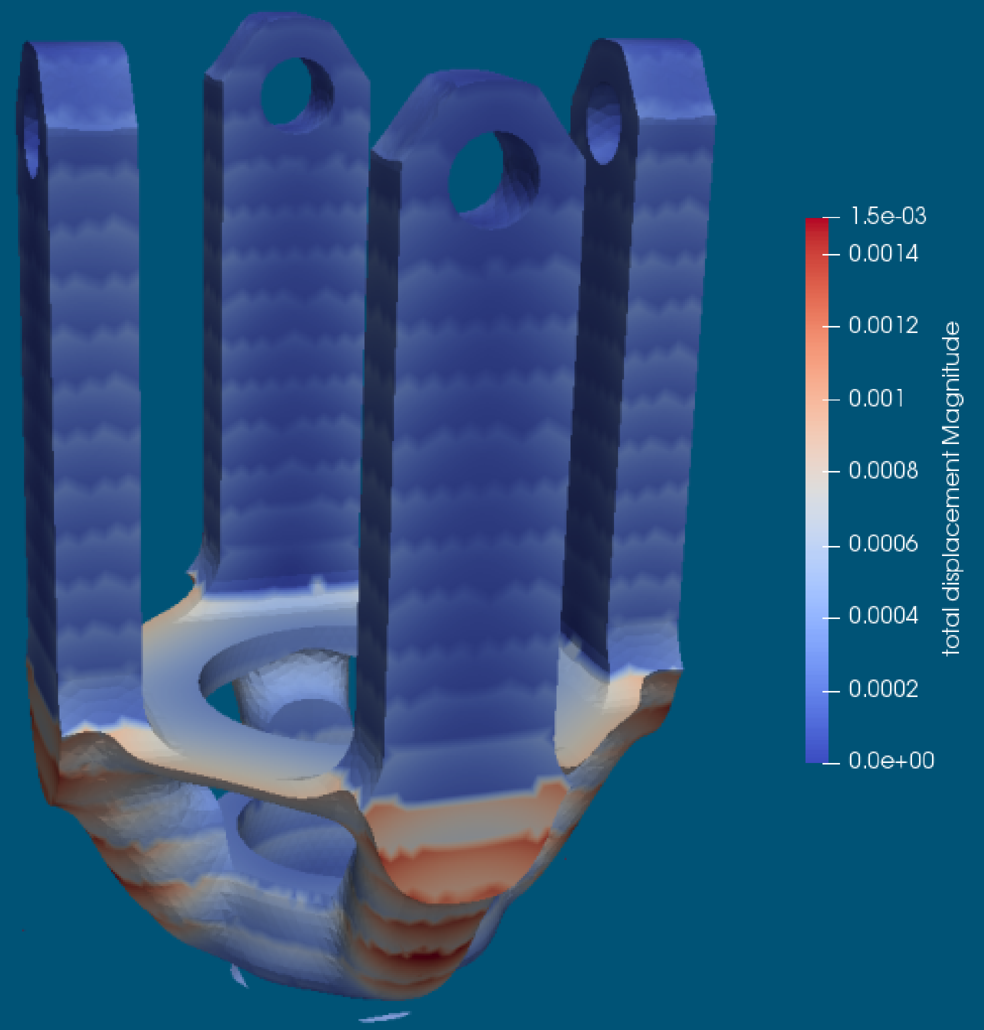




Process Aware Example

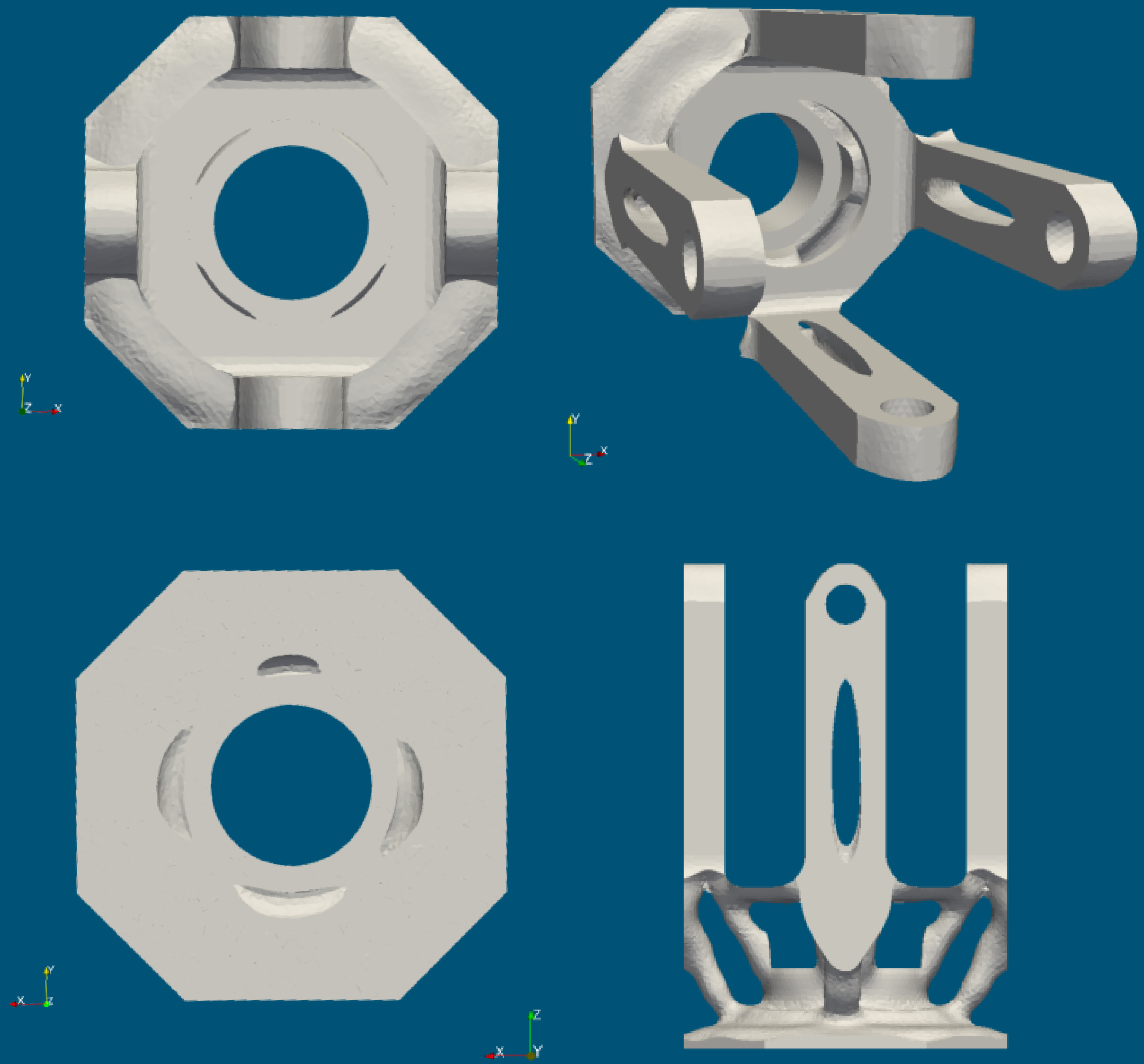
Manufacturability priority: 0.3
Displacement: 5.551 mm (+6.0%)
Residual Energy: 3720 KJ (-9.8%)
Deflection: -0.029 mm (-28.4%)

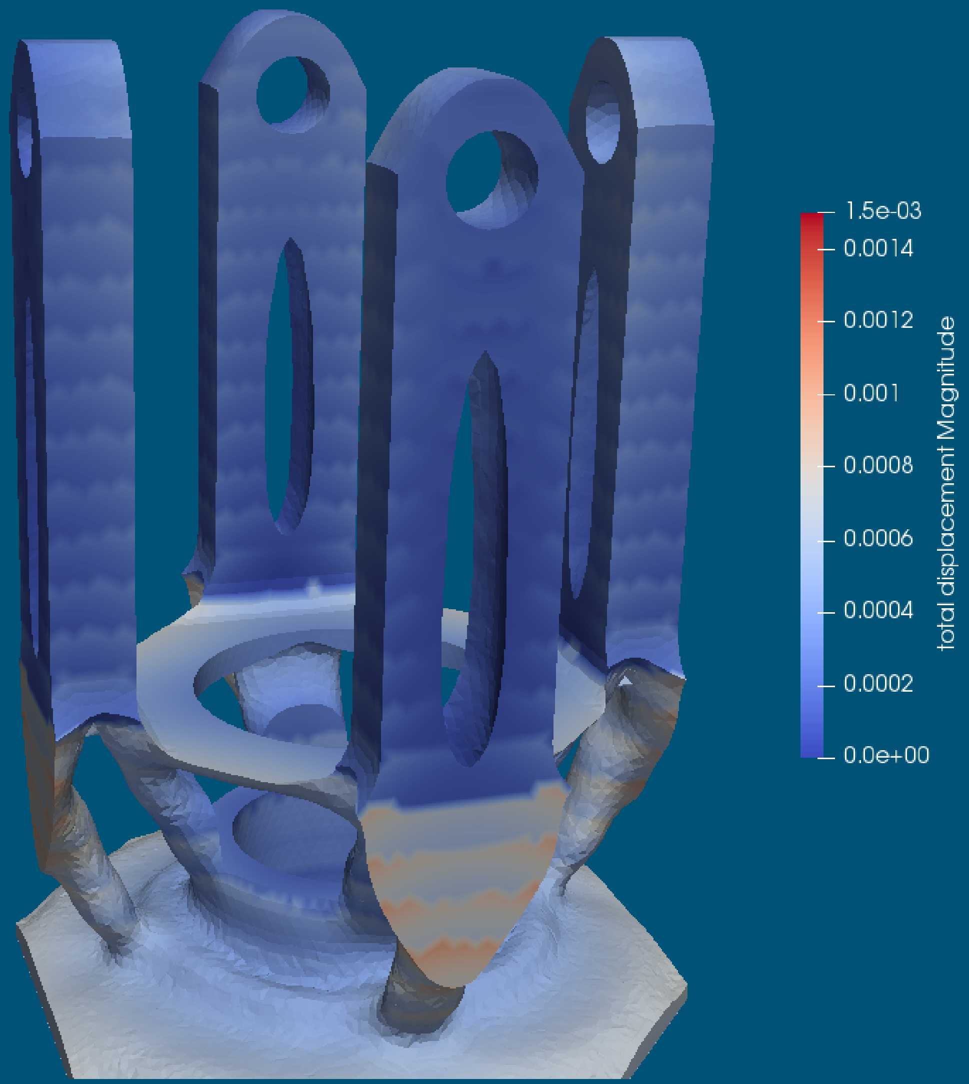


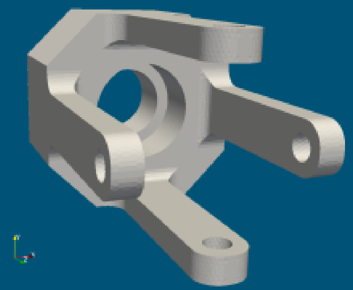


Process Aware Example

Manufacturability priority: 0.5
Displacement: 10.8 mm (+106.3%)
Residual Energy: 1645 KJ (-60.0%)
Deflection: 0.155 mm (-484.0%)







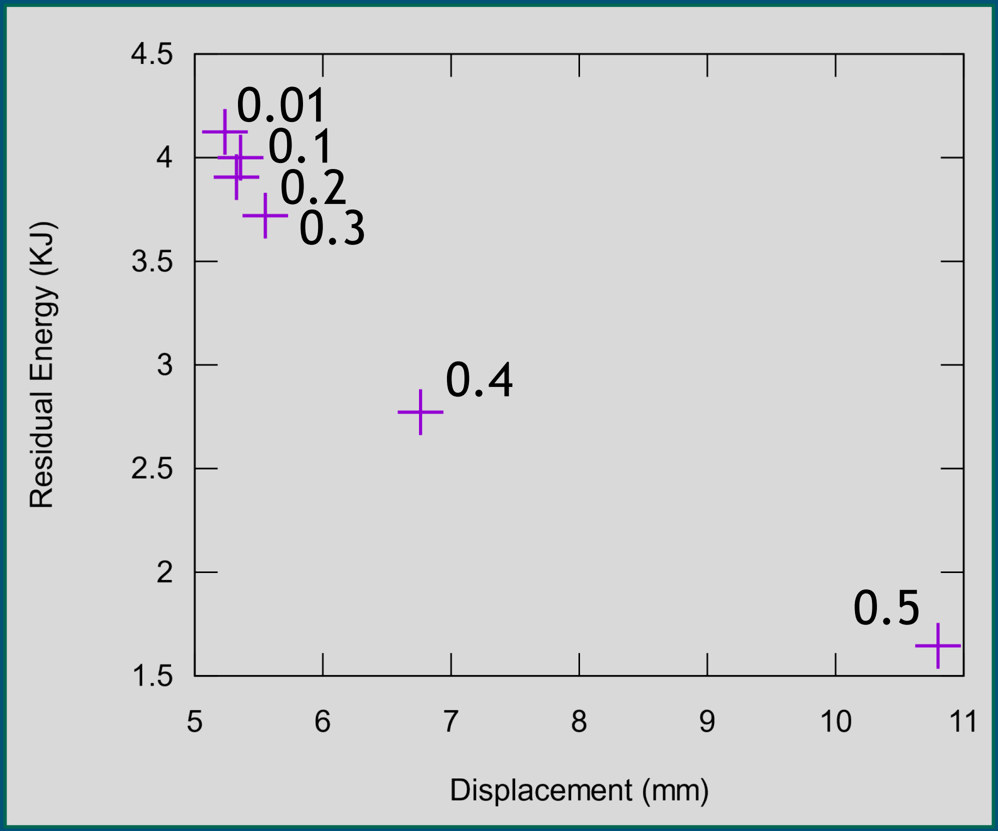
Process Aware Example

Observations:

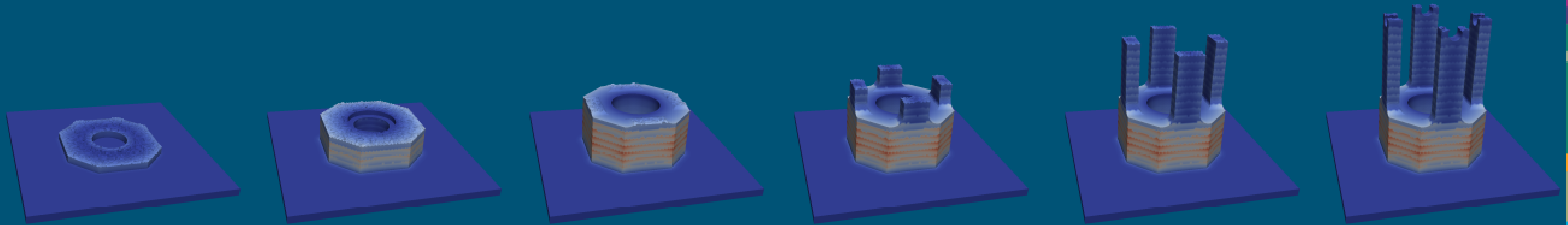
1. The run-time for process-aware TO with elastic inherent strain is practical. Roughly 90 minutes on a mobile GPU (RTX 5000, 0.5 Tflops).
2. Significant decreases in residual energy are associated with sparser structure.

Next Steps:

1. More criteria (displacement, stress p-norm)
2. Plasticity (needs hatching)
3. Differentiable support structure
4. Thermo-plasticity



Trade-off between compliance and residual energy. Point labels are the priority assigned to residual energy.



Thank you!