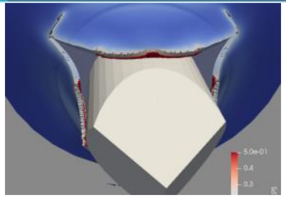
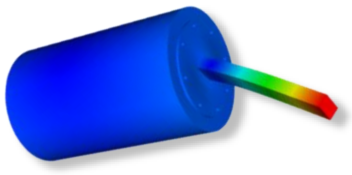
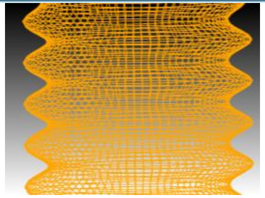
Distortion Compensation for Additive Manufacturing

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Agenda

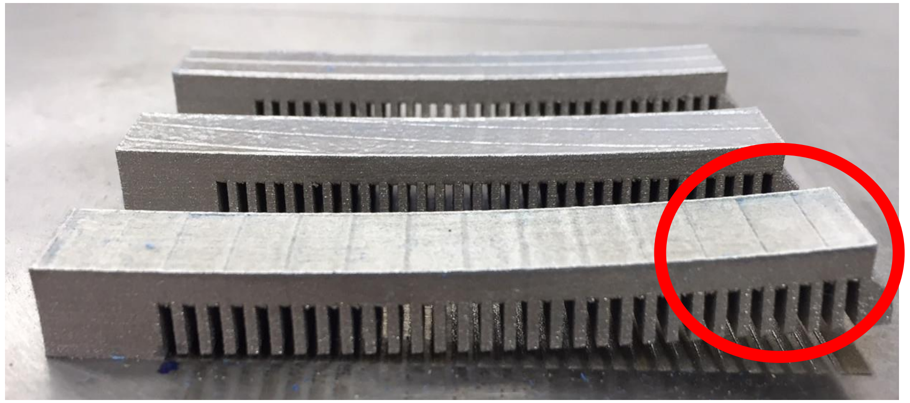
1. **Project Background:** Manufacturing Process
2. **Project Workflow:** Numerical Analysis and Code
3. **Results:** Validation and Parametric Study

Background & Motivation

Problem Definition: Distortion in Metal Additive Manufacturing

- Modern-day industry demands for high quality and exact metal AM components
- High temperature gradients and heat transfer rates generate significant residual stresses and ultimately cause distortion in the part

High temperature gradients → Residual stress → Distortion



Metal AM: Laser Powder Bed Fusion (LPBF)

LPBF Basic Process:
1. Layer of material is spread over build platform
2. Laser fuses first layer of the model
3. New powder layer is spread across previous layer
4. Further layers are fused and added
5. Process repeats until the entire model is finished

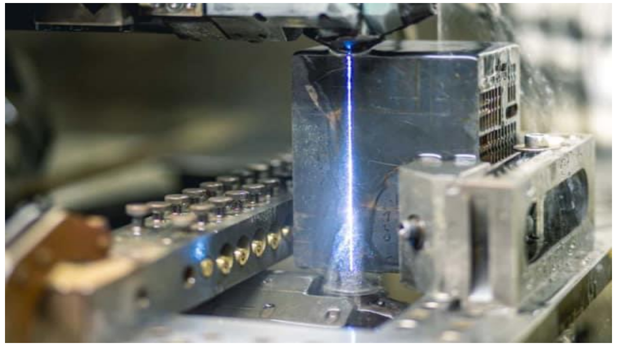
https://www.youtube.com/watch?v=v7Zy5juMJ-M

Post-Processing for Metal AM

1. Heat Treatment:
   - Relieves internal stress and improves physical and structural properties
   - Annealing
   - Quenching


Heat → Hold → Cool

2. Electrical Discharge Machining (EDM)
   - High-precision
   - Flexible and safe detachment of component from 3D printing platform (build plate)



Baseplate Removal

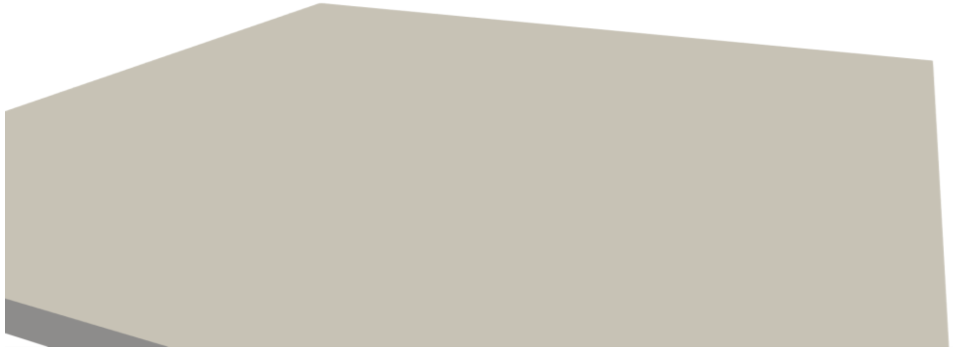
Proposed Investigation

- Validate the digital model with experimental testing.
- Investigate the ability of computational analysis to reduce distortion effects in metal AM by:
  1. Predicting the deformation of parts by simulating the printing process, heat treatment, and baseplate removal procedures of a part in Sierra.
  2. Compensating for the predicted distortion of a part by modifying the 3d geometry.
  3. Conducting a parametric study to gain insights into the behavior and performance of the process under different boundary conditions.

Project Workflow

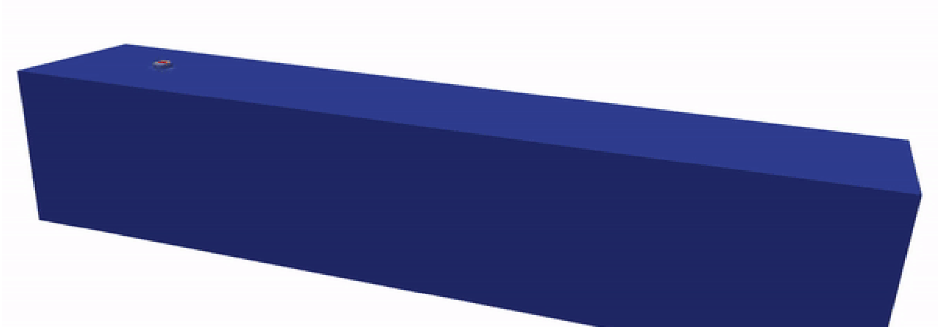
Finite Element Simulation (SIERRA)

✓ Layer Activation + Inherent Strains



VS

× High Fidelity Multiphysics Simulation *



Printing Process:

- Layers are activated one at a time
- Artificial strains are applied to each layer
  - **Inherent Strain** values are calibrated using experiments
  - Representative of total "left-over" strain after melting and solidification
- Total mechanical response is calculated
- Acceptable accuracy and greater computational efficiency vs high-fidelity simulation

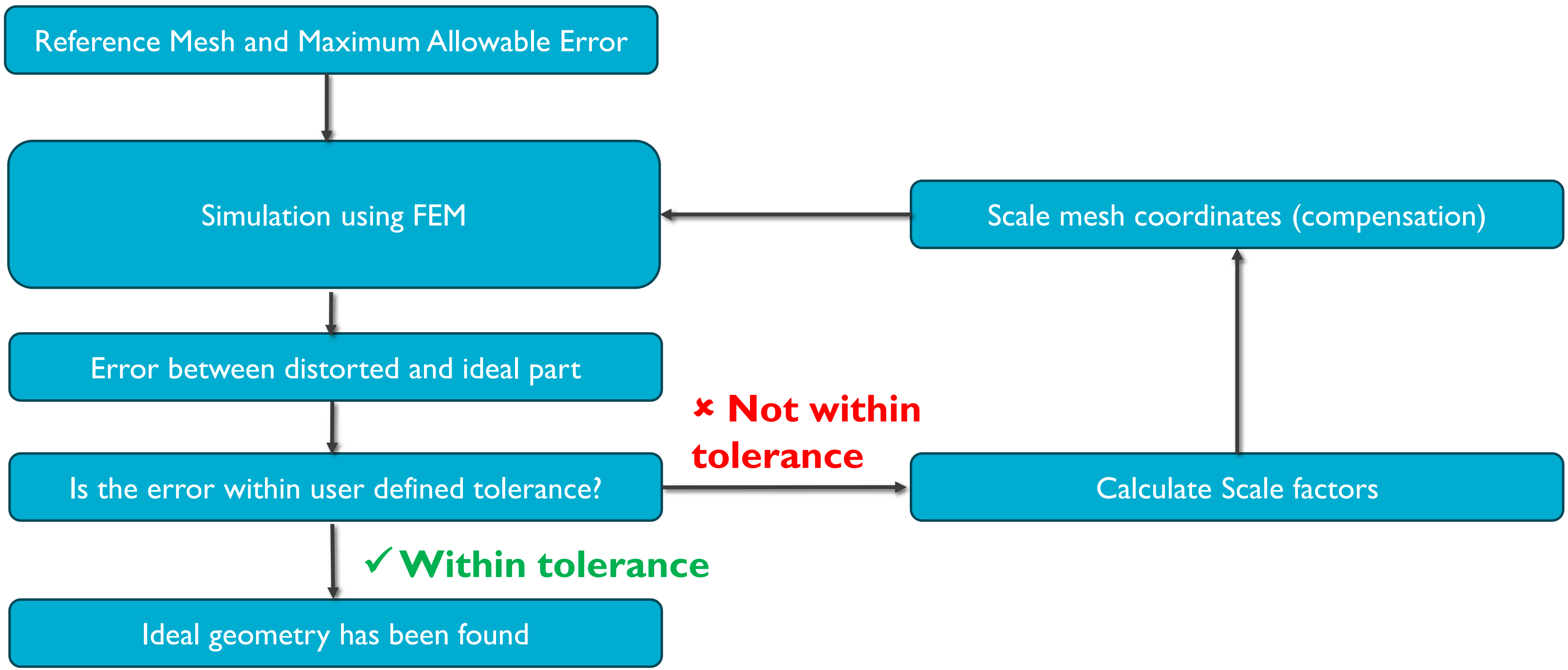
Heat Treatment:

- Material properties are temperature dependent
- Surface temperatures and heat flux are applied, and mechanical response is calculated

EDM Baseplate Removal:

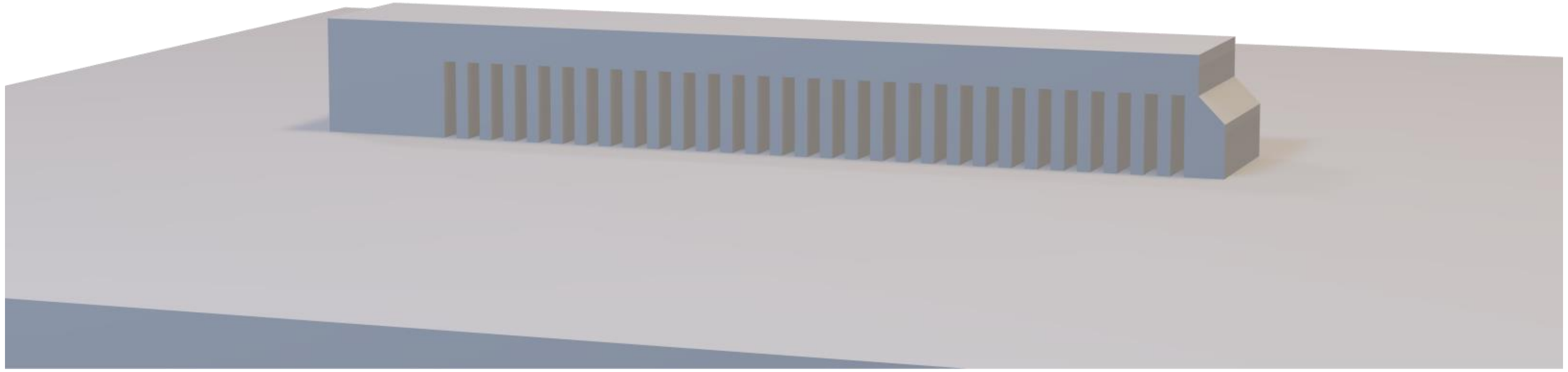
- Layer of elements is deactivated allowing internal stresses to cause displacements

Distortion Compensation (Python)



Validation

Reference Geometry: Harmonica



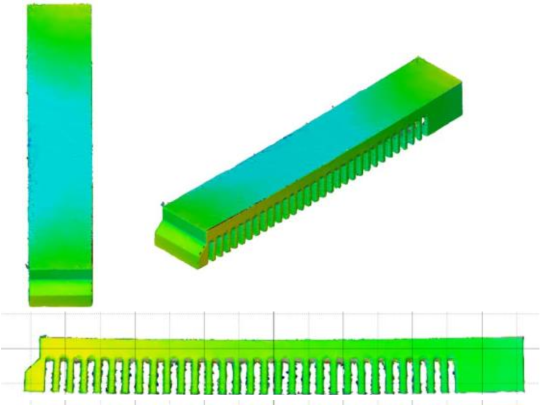
5 mm thick baseplate

Material	304L Stainless Steel
Constitutive Law	Linear Elastic
Mass Density	8030 kg/m^3
Thermal Conductivity	14.22 W/mK
Specific Heat Capacity	478.9 J/(kg C)
Inherent Strains	**-2 % along x** **-2 % along y** **+2 % along z**
Young's Modulus (at 22 C)	200 GPa
Poisson Ratio (at 22 C)	0.25
Yield Stress	0.21 GPa

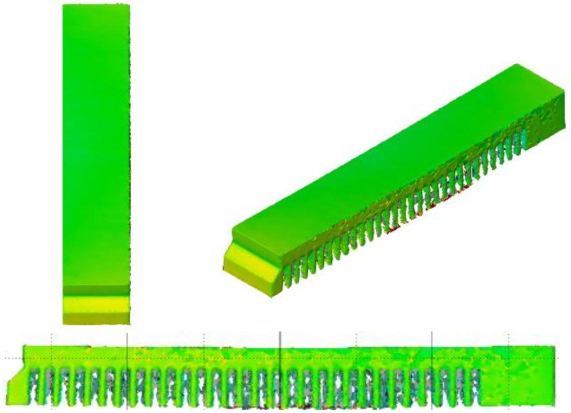
Real Part Scans vs Simulated Results: **Difference in Displacements**

- Simulated displacements are largely within ± 0.3 mm of actual displacements

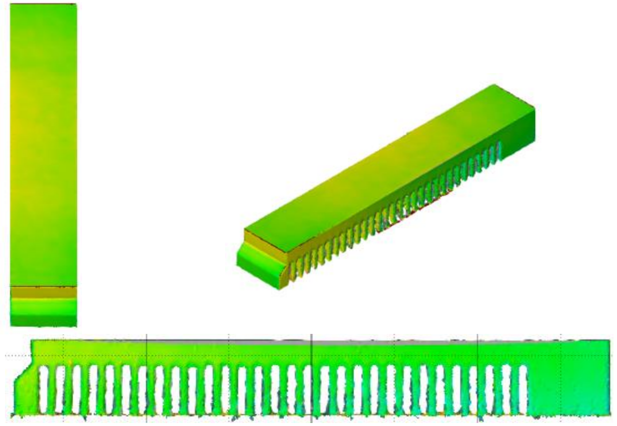
Δ displacement (scan – simulation)



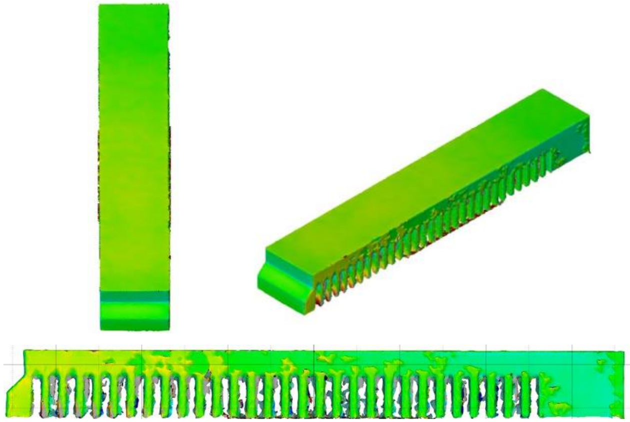
Case 1: Heat Treatment at 600˚C



Case 2: Heat Treatment at 700˚C



Case 3 Heat Treatment at 1000˚C



Case 4: Heat Treatment at 1120˚C

Results and Discussion

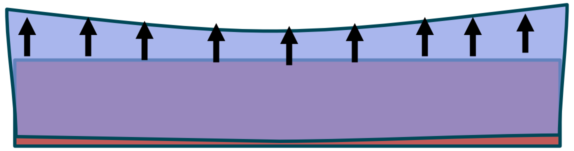
Performance Enhancements and Code Quality Improvements

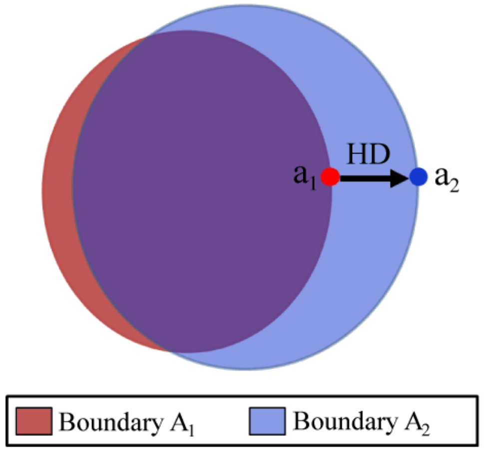
DISCO (Distortion Compensator): Python wrapper around SIERRA (C++)

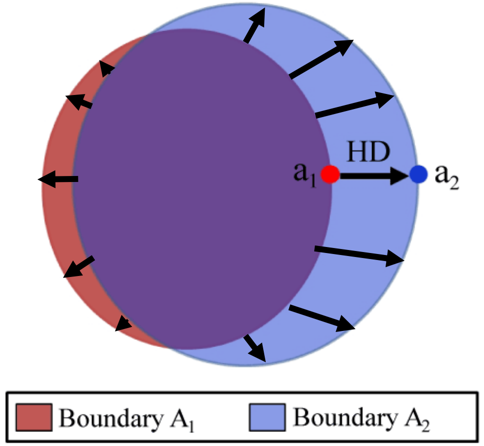
Edits	Impact on Code
Added parallelization to preprocessing algorithm.	Reduced 0.5-1-hour preprocessing step to 3 minutes (x10 – x20 faster)
Added parallelization to compensation algorithm.	Similar improvement for compensation algorithm
Object Oriented Programming	Enhanced useability

How do we quantify distortion?

Root Mean Square Error (RMSE)	Hausdorff Distance (HD)	Chamfer Distance (CD)
• Comparison of two different surfaces • RMS of displacements of top surface with respect to CAD file • Indicative of local distortion of a 2D surface • For similar surfaces, RMSE → 0	• Comparison of two different point clouds • Maximum distance between any pair of nearest neighbors (mm) • Indicative of local distortion • For similar point clouds, HD → 0	▪ Comparison two different point clouds ▪ Average distance between pairs of nearest neighbors (mm) ▪ Indicative of average distortion ▪ For similar point clouds, CD → 0

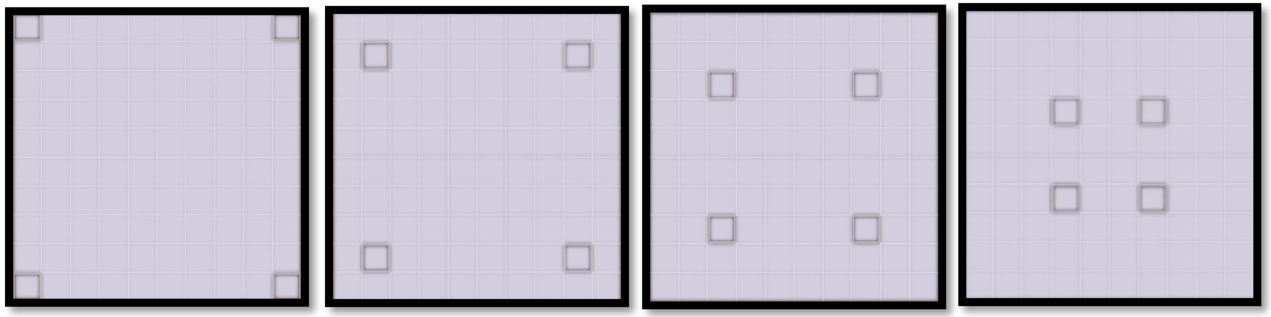




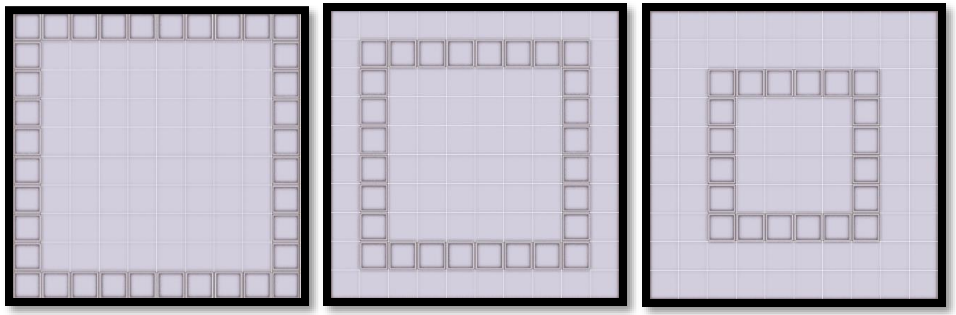


Parametric Study of Boundary Conditions: Location and Type

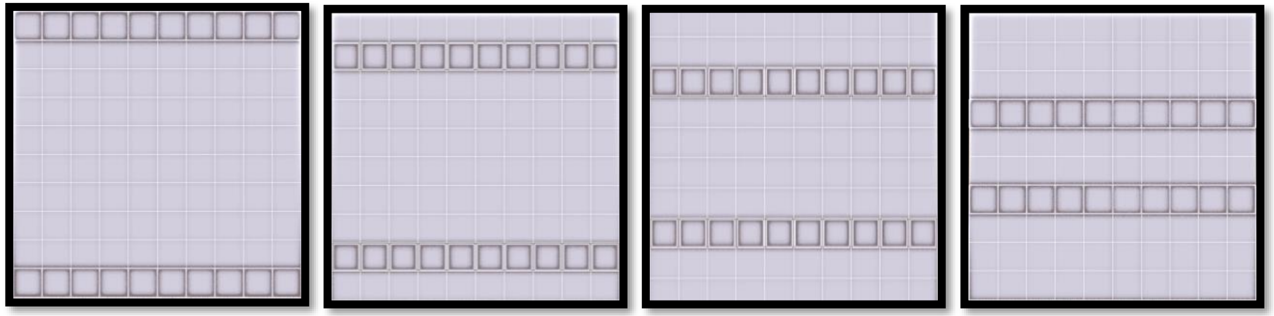
Case 1: Corner Clamps
- Pinned
- Fixed



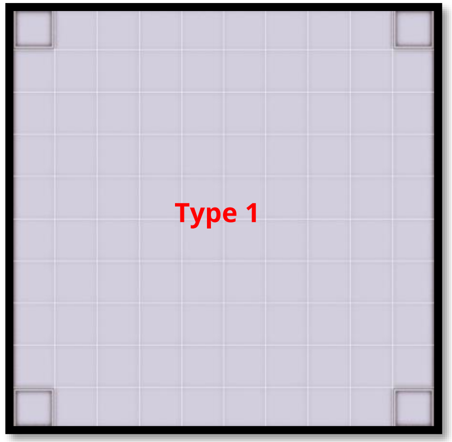
Case 2: Square Clamps
- Pinned
- Fixed

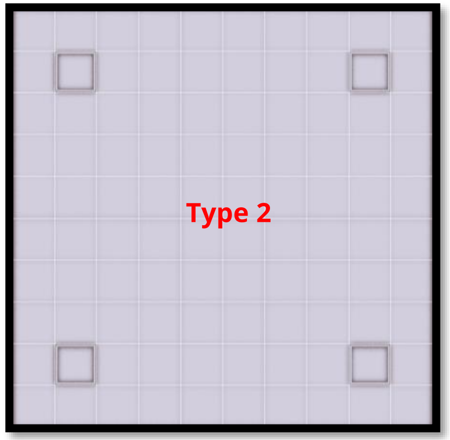


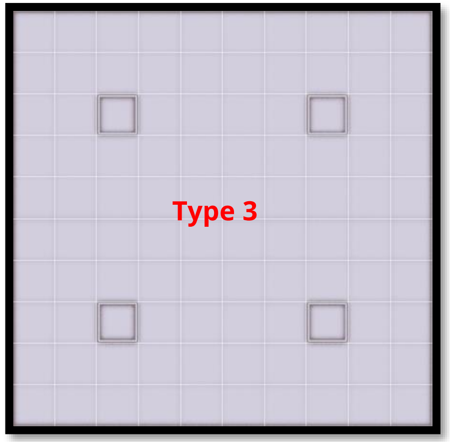
Case 3: Parallel Clamps
- Pinned
- Fixed

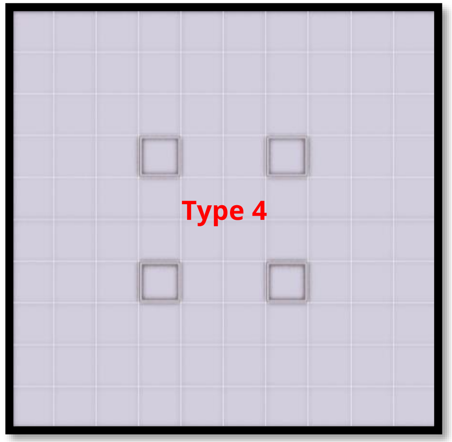


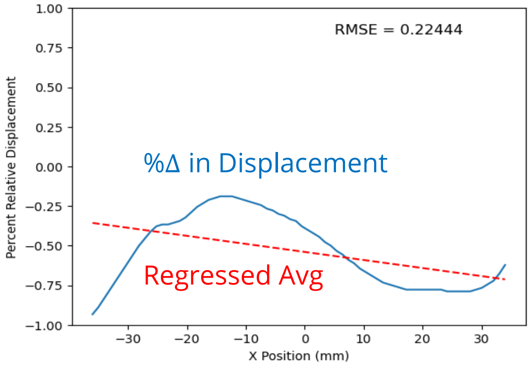
Case 1a: **Fixed Corner Clamps** (Heat Treatment at 600 °C)

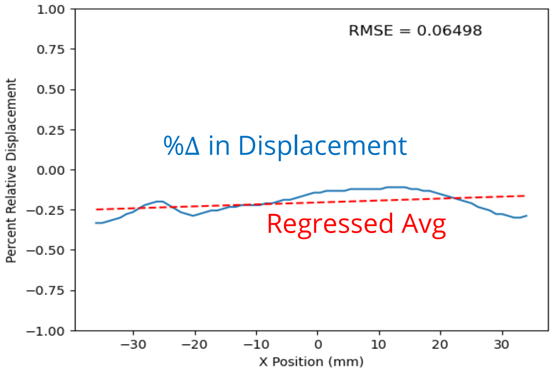


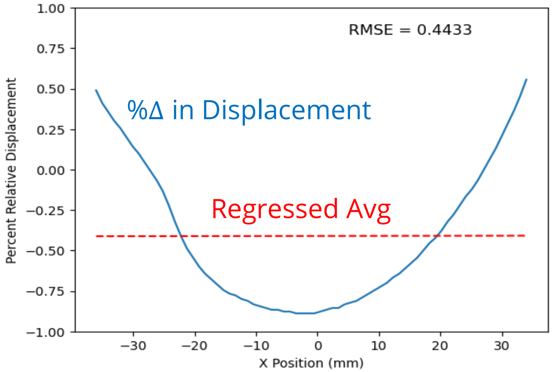


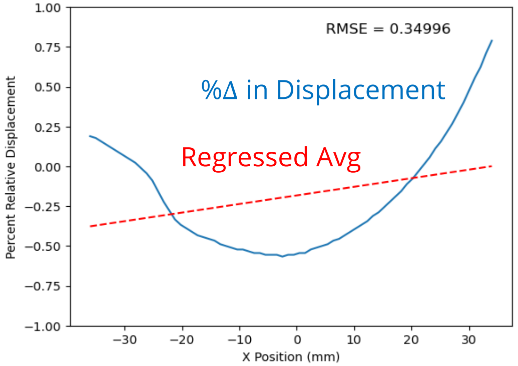








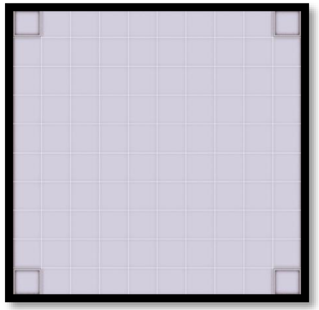


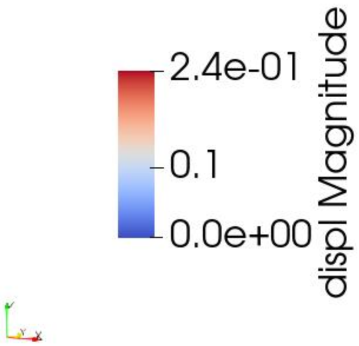


Hausdorff Distance:	**0.225 mm**	**0.345 mm**	**0.327 mm**	**0.406 mm**
Chamfer Distance:	**0.201 mm**	**0.282 mm**	**0.324 mm**	**0.380 mm**

Lower RMSE does not mean lower overall distortion

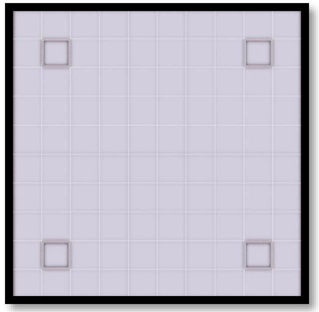
Displacement (mm) x10

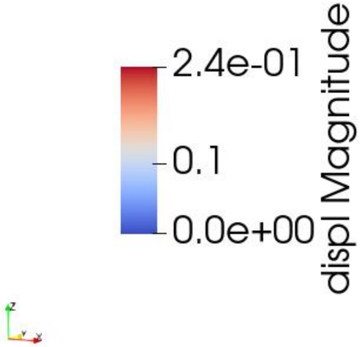




RMSE = 0.22444

Higher RMSE for the top face



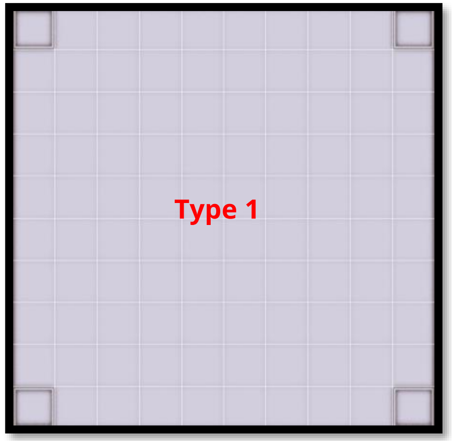


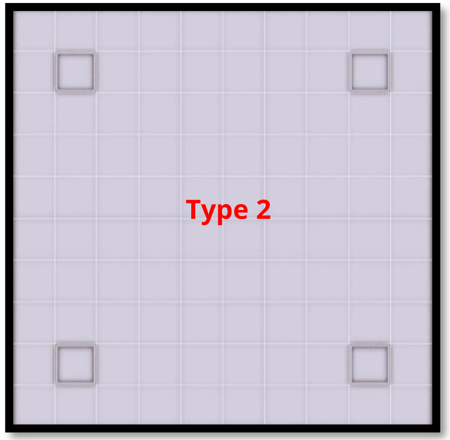
RMSE = 0.06498

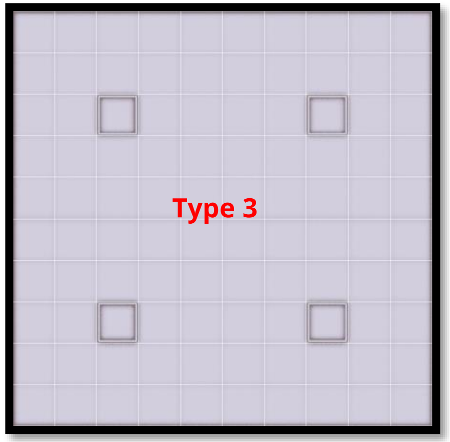
Lower RMSE for the top face

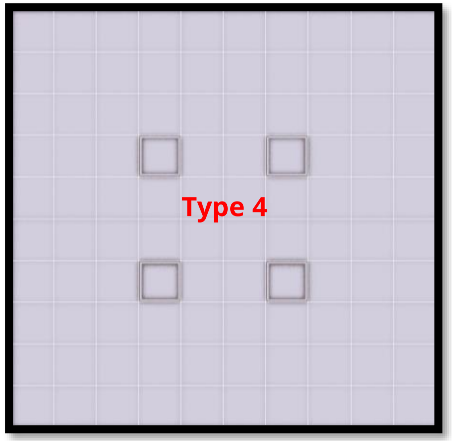
Large localized distortion

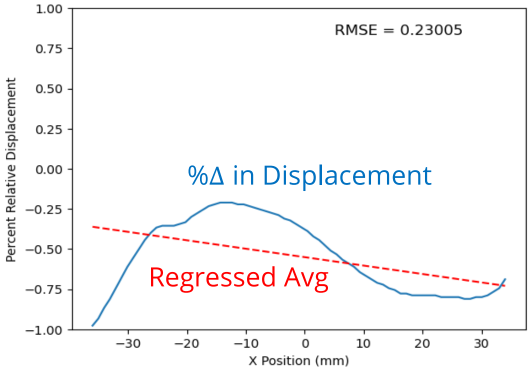
Case 1b: **Pinned Corner Clamps** (Heat Treatment at 600 °C)

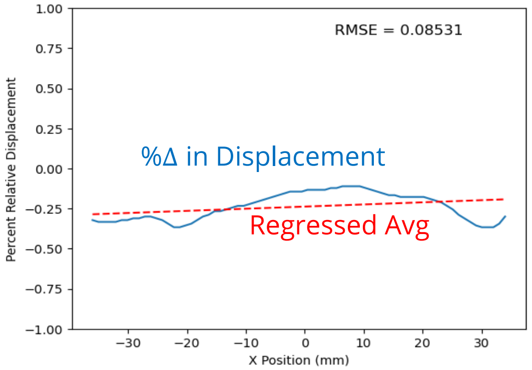


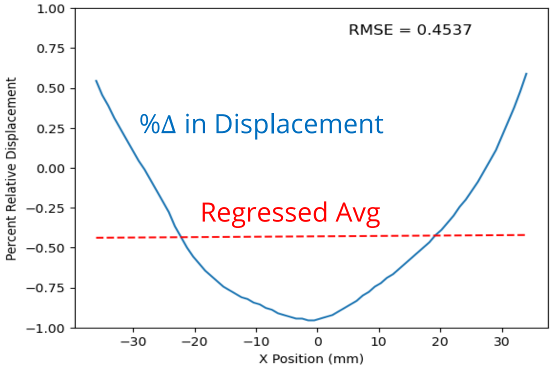


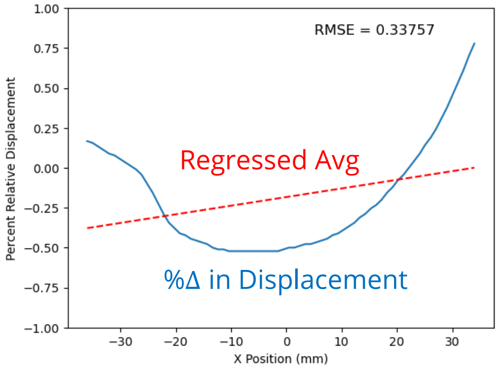






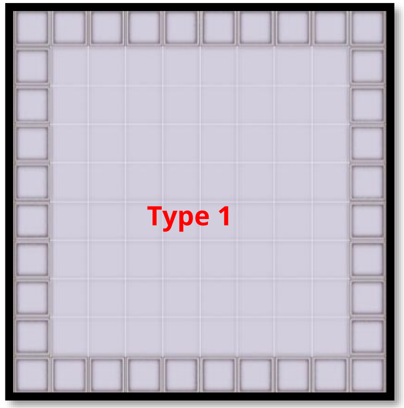


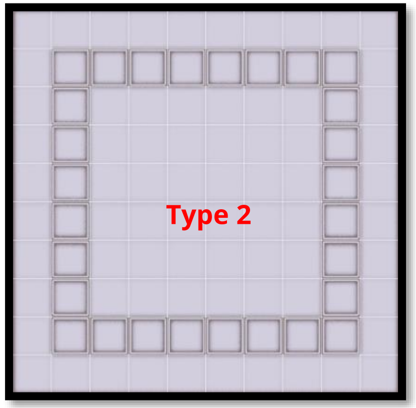


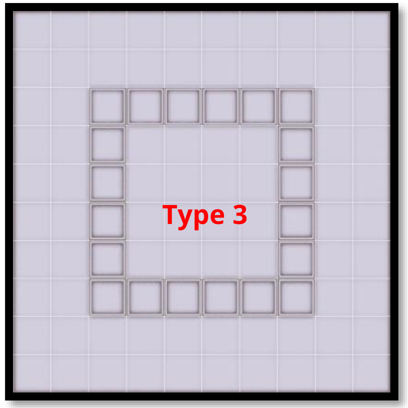


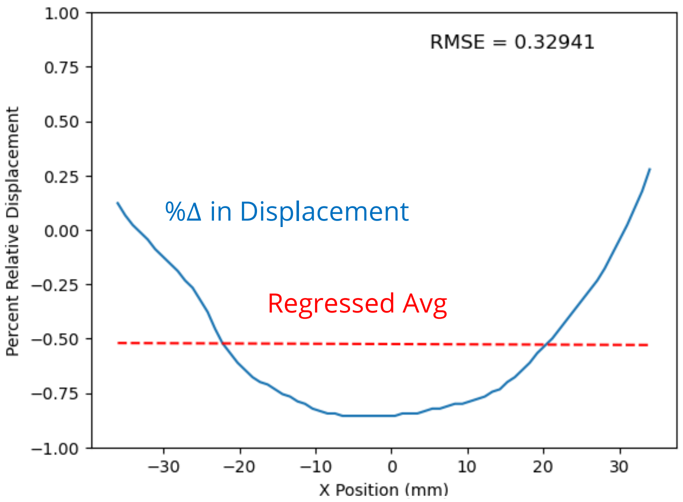
Hausdorff Distance:	**0.229 mm**	**0.351 mm**	**0.256 mm**	**0.386 mm**
Chamfer Distance:	**0.202 mm**	**0.298 mm**	**0.227 mm**	**0.359 mm**

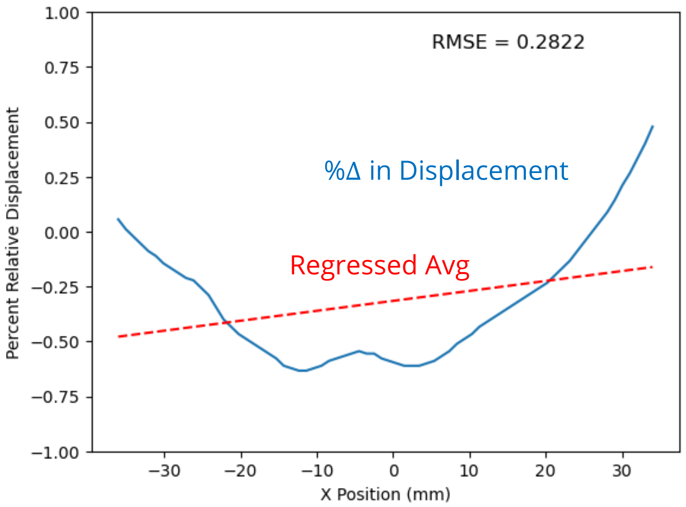
Case 2a: **Fixed Square Clamps** (Heat Treatment at 600 °C)

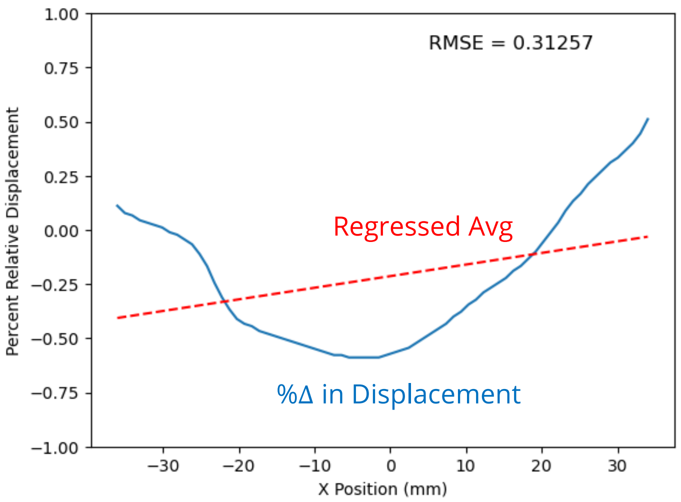






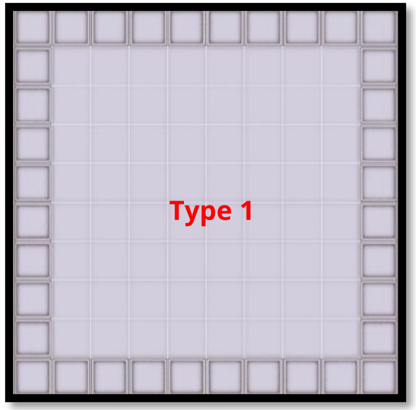


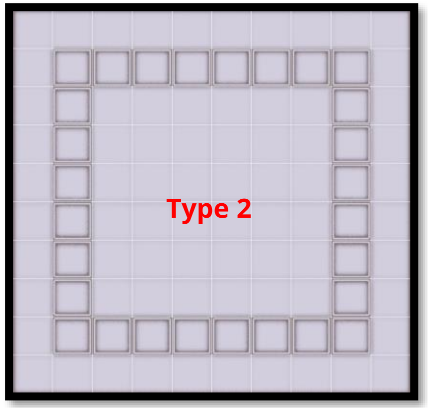


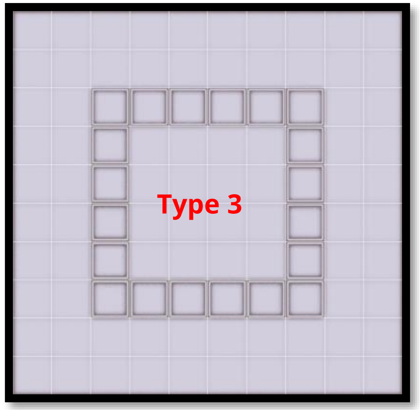


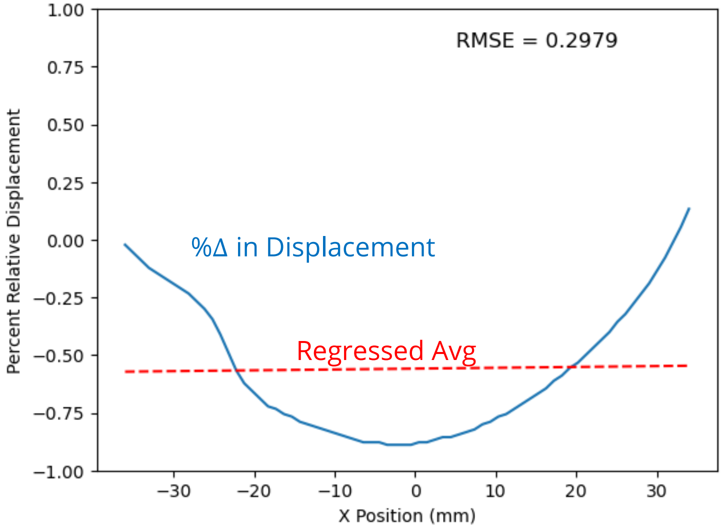
	Type 1	Type 2	Type 3
Hausdorff Distance:	**0.238 mm**	**0.383 mm**	**0.401 mm**
Chamfer Distance:	**0.259 mm**	**0.383 mm**	**0.413 mm**

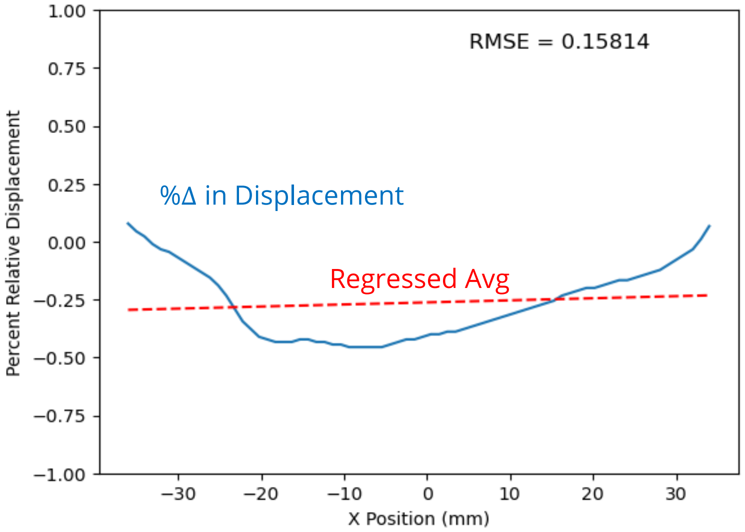
Case 2a: **Pinned Square Clamps** (Heat Treatment at 600 °C)

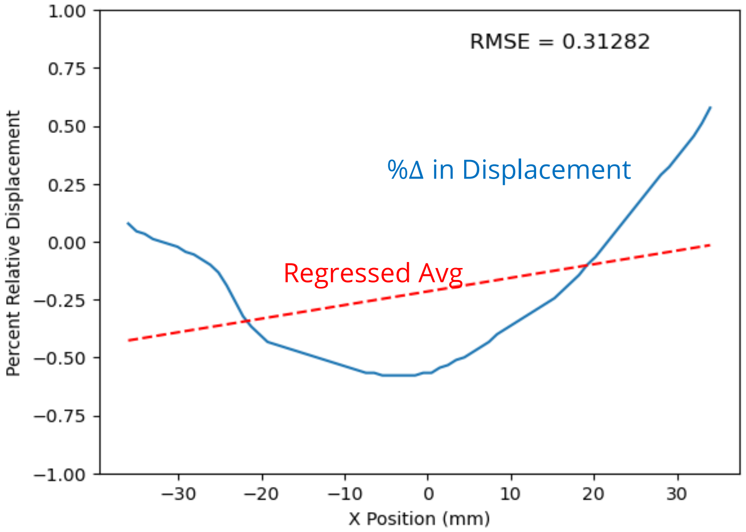






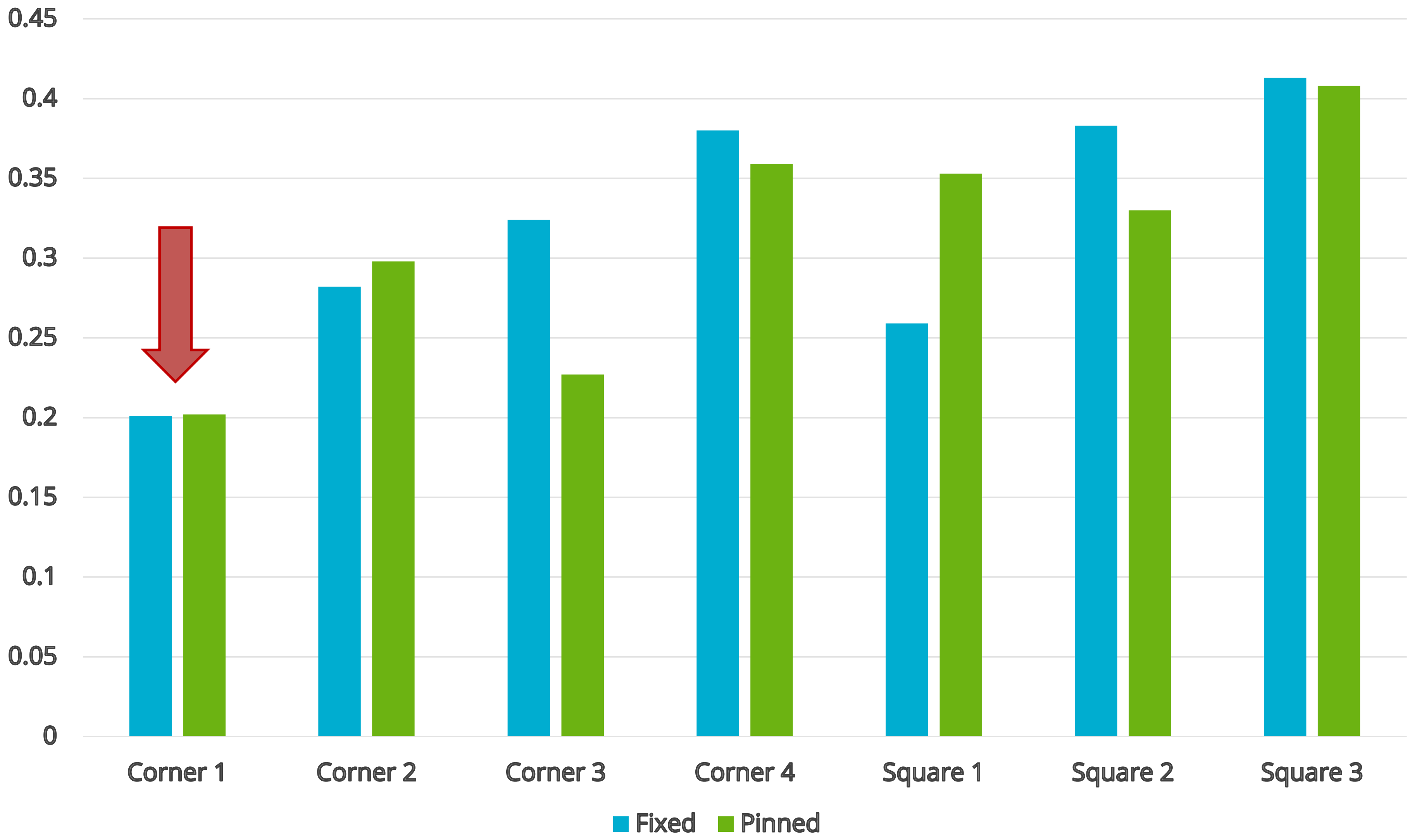




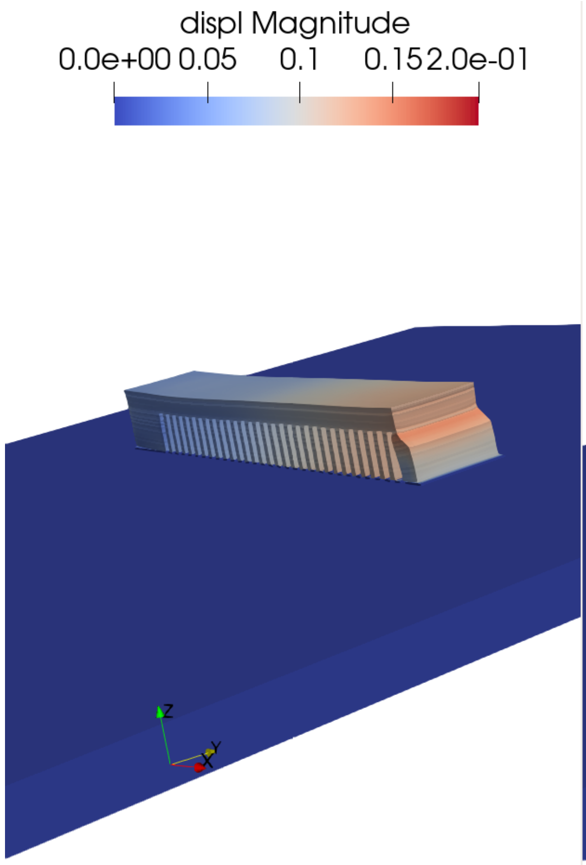


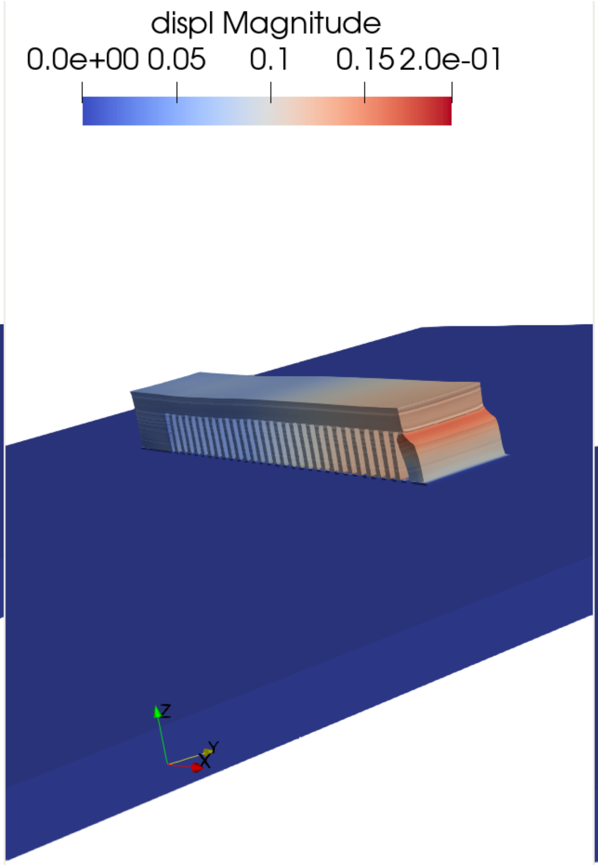
Hausdorff Distance:	**0.342 mm**	**0.329 mm**	**0.402 mm**
Chamfer Distance:	**0.353 mm**	**0.330 mm**	**0.408 mm**

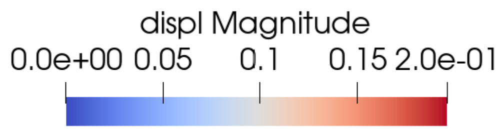
Minimum Chamfer Distance



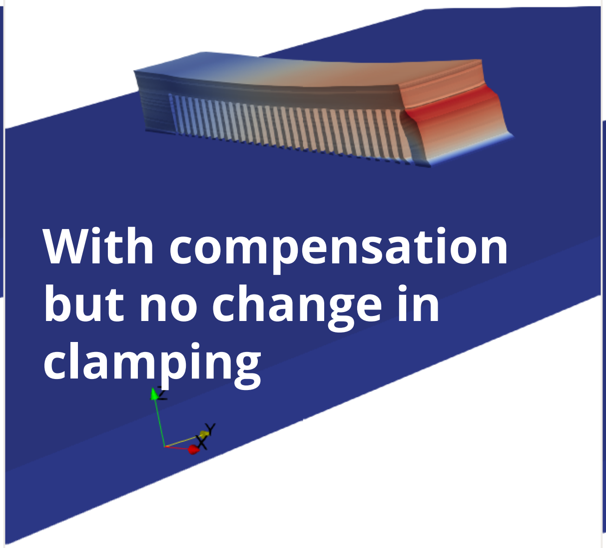
Clamping location affects distortion compensation: displacement





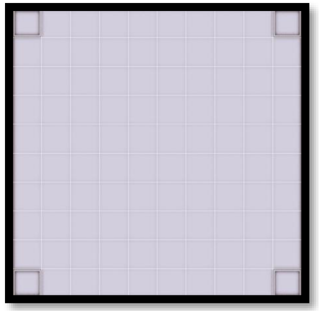


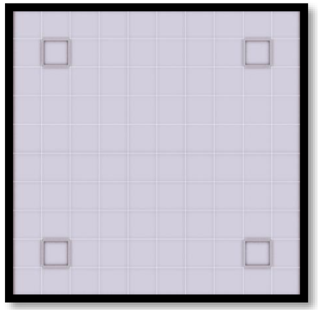
Results correspond to 6 iterations of the compensation loop

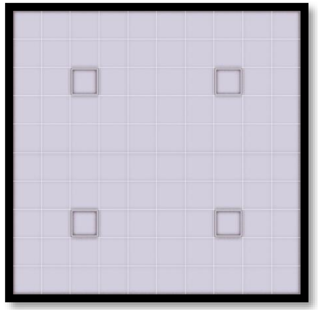


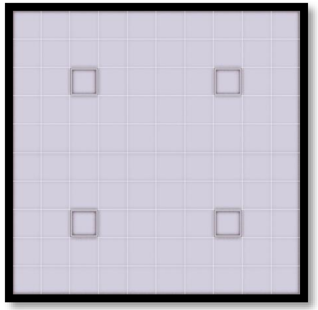
With compensation but no change in clamping

Baseline (without compensation)



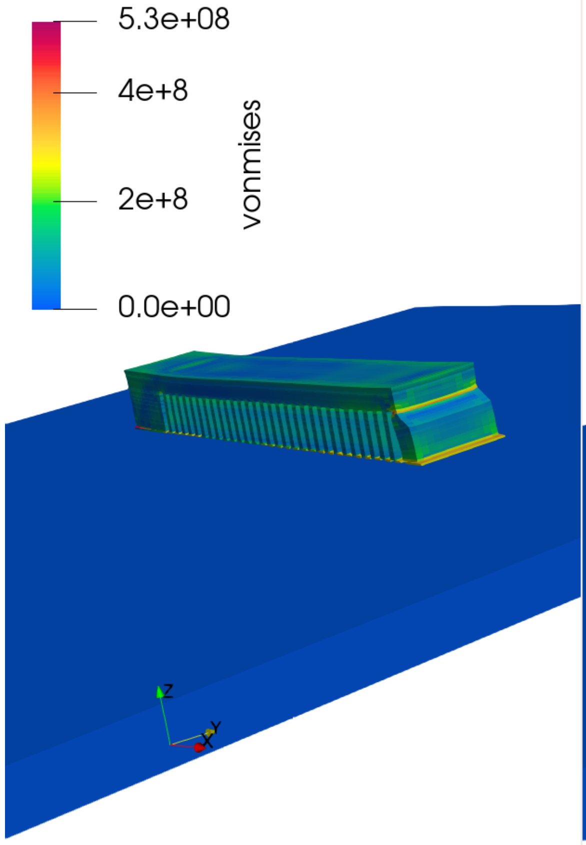


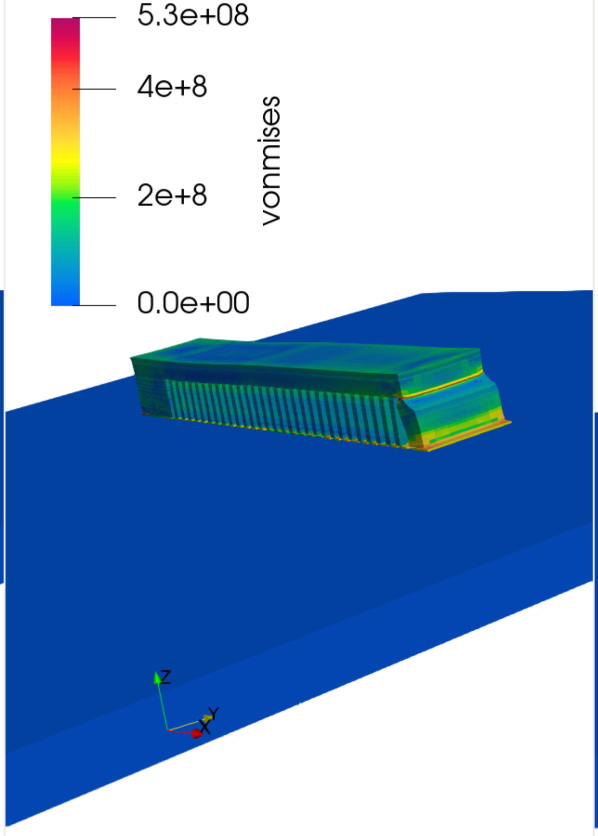


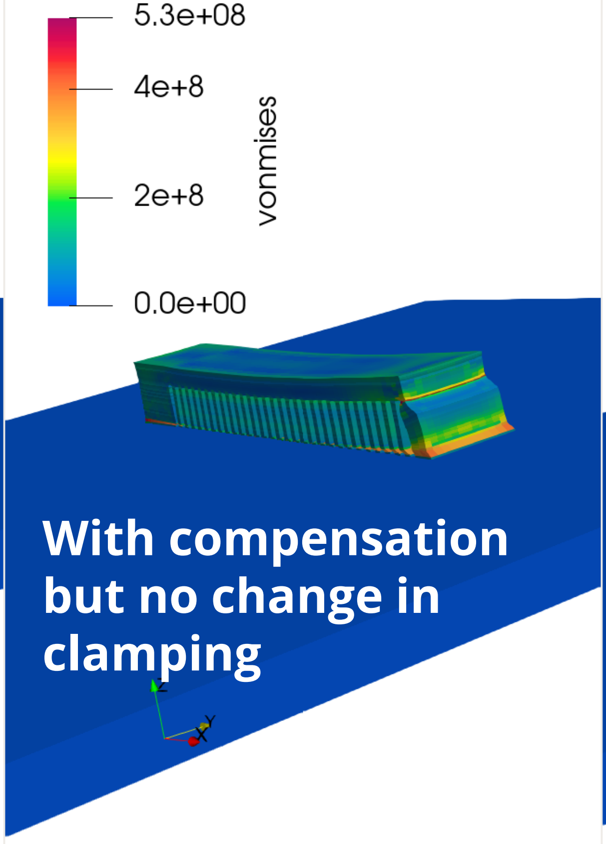


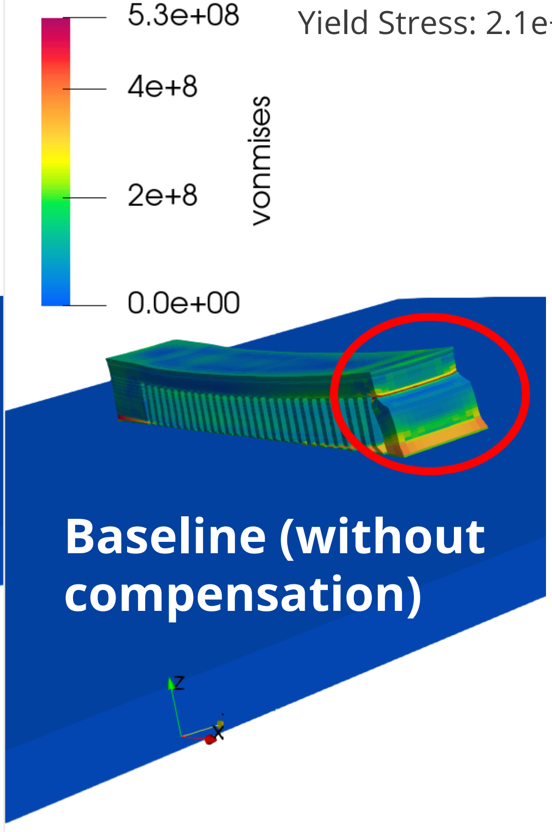
Clamping location affects distortion compensation: Von Mises Stress

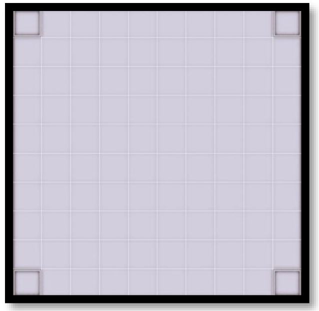
Yield Stress: 2.1e+08 Pa

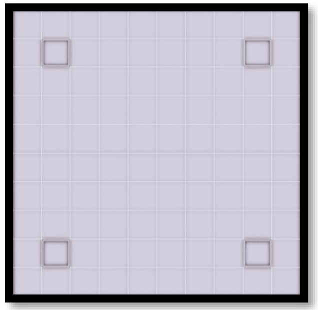


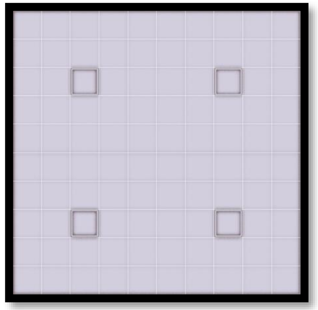


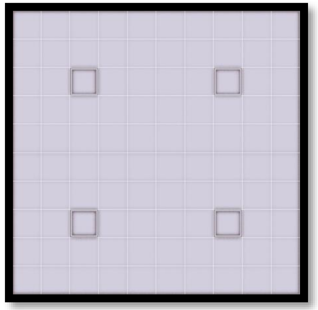




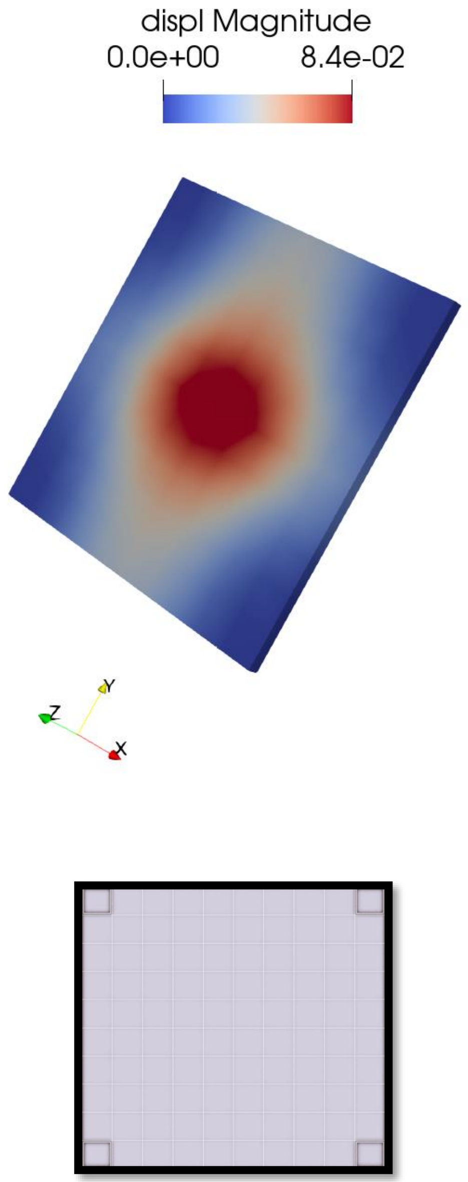


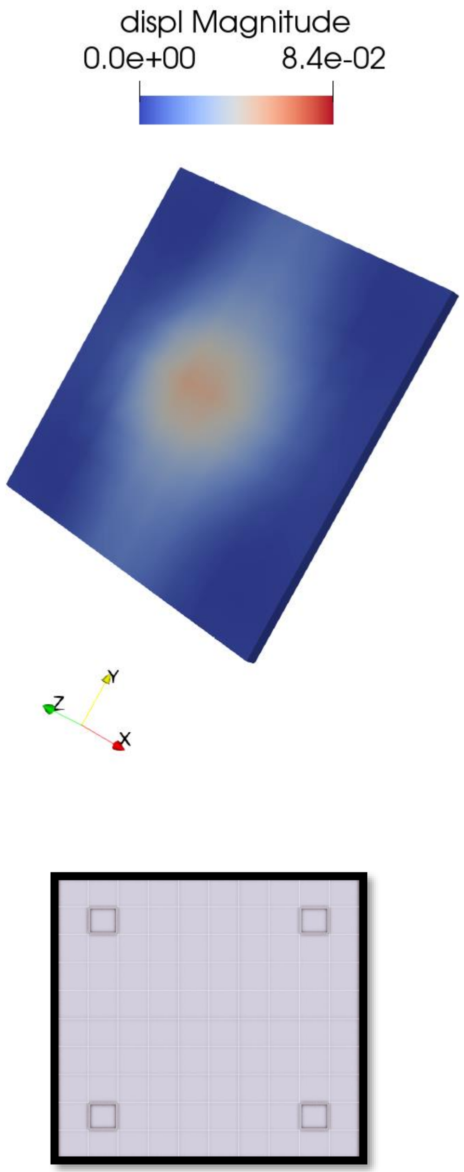


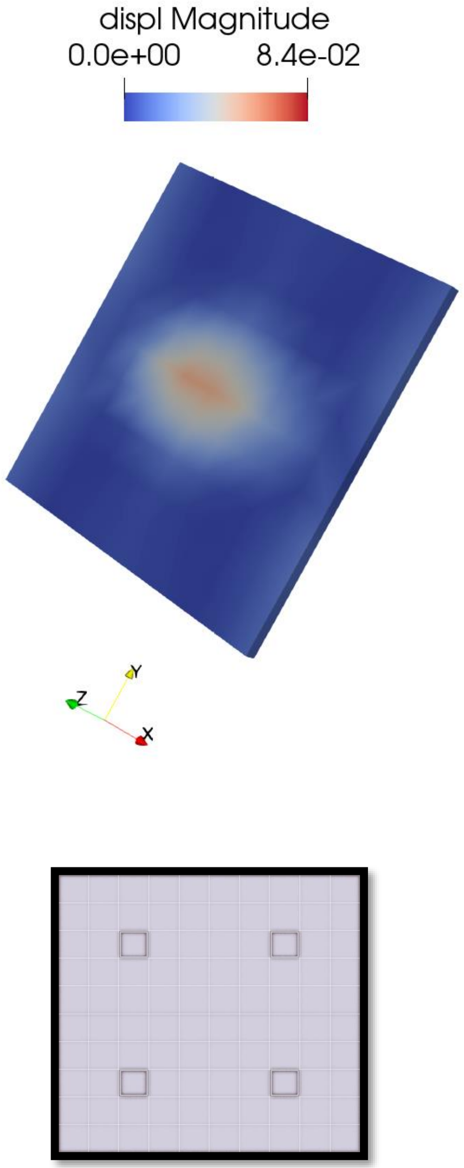


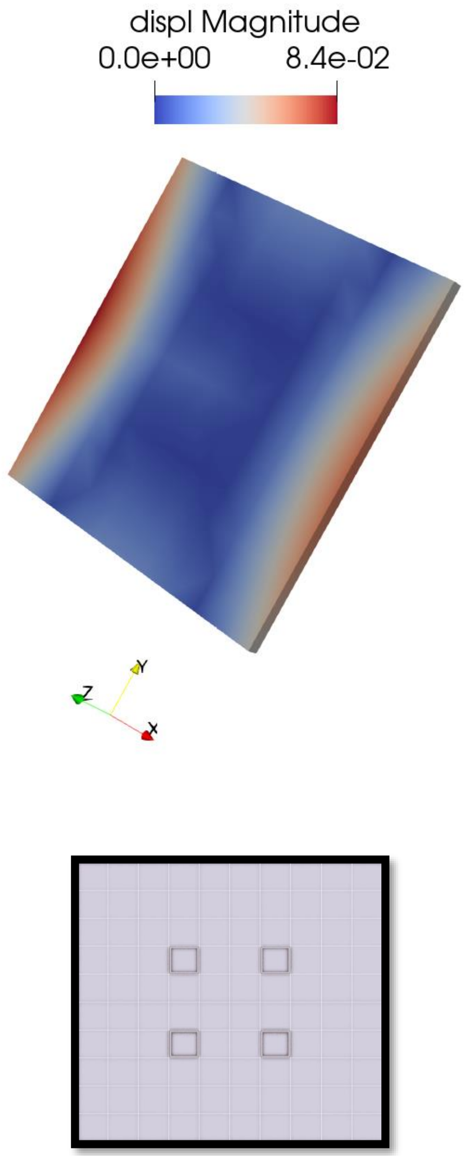


Baseplate distortion after heat treatment (before EDM)









Key Takeaways

- Location of clamps can significantly impact distortion.
  - Clamps that are closer to the part cause concave (upward) bending
  - Clamps that are further away from the part cause convex (downward) bending
  - Possibly caused by thermal buckling of baseplate during heat treatment
- Clamps located towards the outer edges of the baseplate can relieve residual stress
- Pinned clamps cause less distortion than fixed clamps
- **Distortion compensation is improved by moving clamps towards the outer edges of the baseplate**

Conclusion and Scope for Future Work

- Improved the performance of a finite element workflow to predict and compensate for distortion of additively manufactured metal parts.
- Validated the accuracy finite element code with respect to experimental results.
- Investigated the effect of clamping boundary conditions on residual stresses and distortion.
- In the future:
  - Run additional parametric studies
  - Investigate the effect of different thermal boundary conditions
  - Calculate optimal clamping locations for specific geometries to reduce distortions

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