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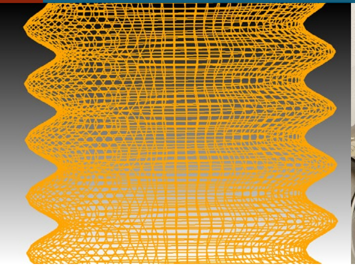
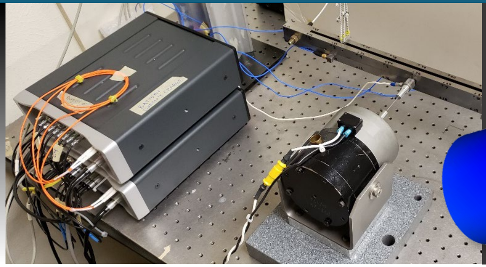
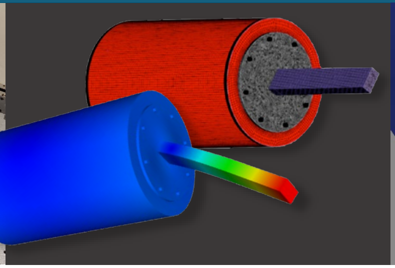
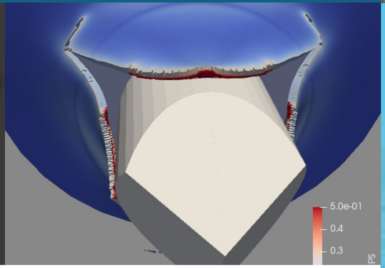
Distortion Compensation for Metal Additive Manufacturing









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August 2, 2022

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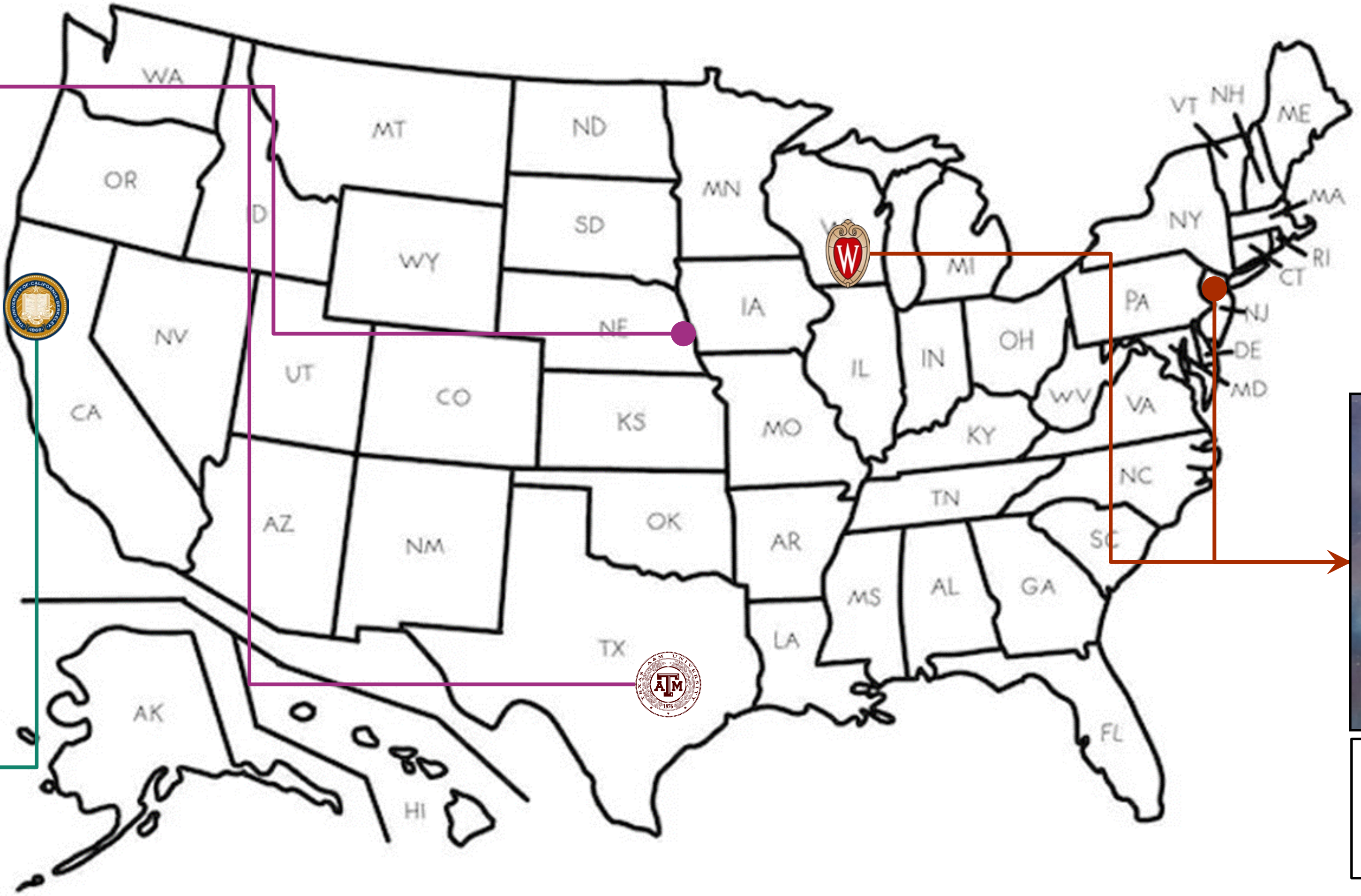
Collette Gillaspie

Theresa Honein



Mehmet Sirtalan

Contents

- Background information: Distortion in metal additive manufacturing
  - Why distortion happens?
  - How do we quantify it?
- Distortion compensation optimization algorithm
- Results validation: It works!

BACKGROUND & MOTIVATION

Metal Additive Manufacturing: Selective Laser Sintering (SLS)

Fig. 1 Video on metal additive manufacturing. https://www.youtube.com/watch?v=yiUUZxp7bLQ

Metal Additive Manufacturing: Selective Laser Sintering (SLS)

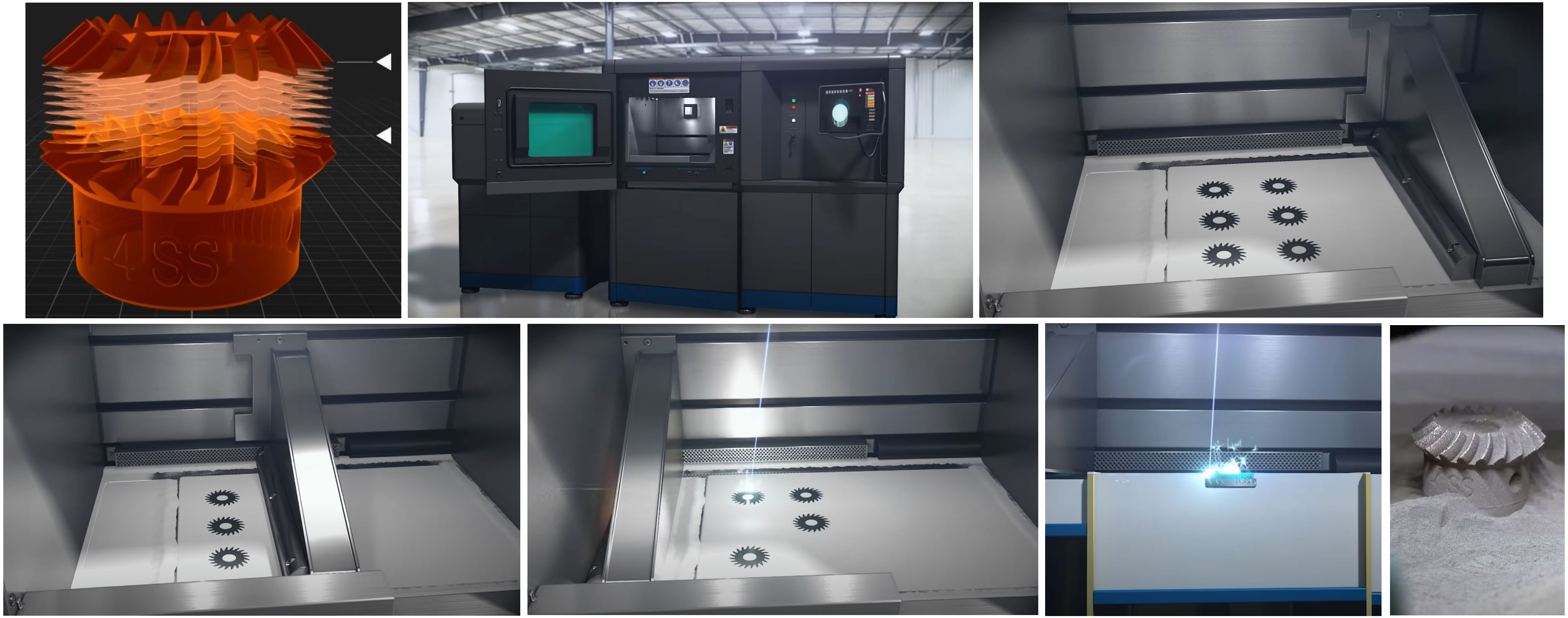


Fig. 2 Images of metal additive manufacturing.

Metal Additive Manufacturing → Problem Formulation → Deformation Prediction

Problem: Distortion

High temperature gradients → Residual stress → Stress causes distortion

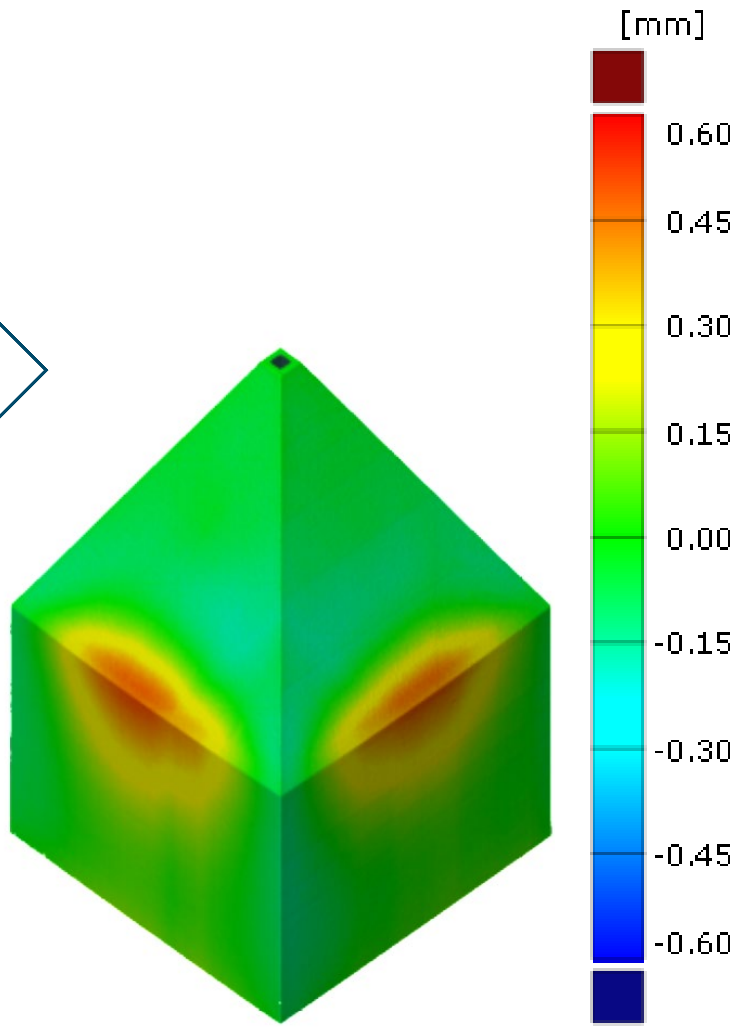


Fig. 3 Distortion of uncompensated printed part relative to CAD geometry.

Problem: Distortion

High temperature gradients → Residual stress → Stress causes distortion

Solution: Distortion Compensation

Get deformations → Back apply them to initial geometry → Print modified geometry

Goal: Printed Geometry Distorts Into Desired Geometry

Deformation Prediction

- Modeling Approaches
  - Thermomechanical simulations
  - Inherent strain method: mechanical simulations
  - Modified inherent strain methods
- Optical approaches

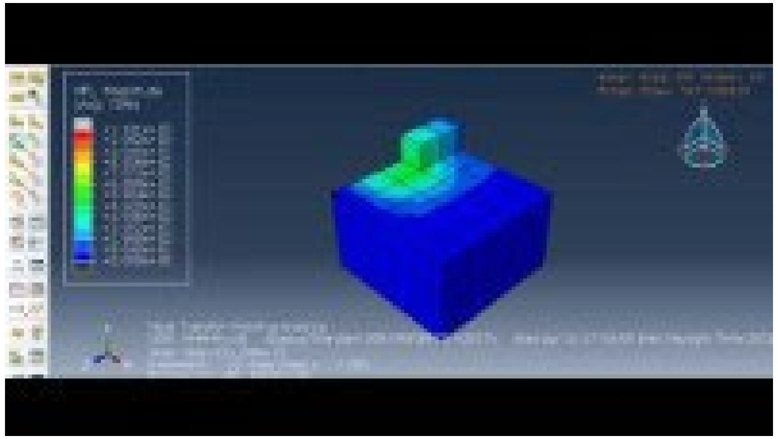


Fig. 4 Element birth simulation using Abaqus.
https://www.youtube.com/watch?v=FqE3kj9ESVc

Fig. 5 ATOS Compact Scan: Blue Light 3D Scanner.
https://www.youtube.com/watch?v=T-RkQioXHYg

Deformation Prediction

- Modeling Approaches
  - Thermomechanical simulations
  - Inherent strain method: mechanical simulations
  - Modified inherent strain methods

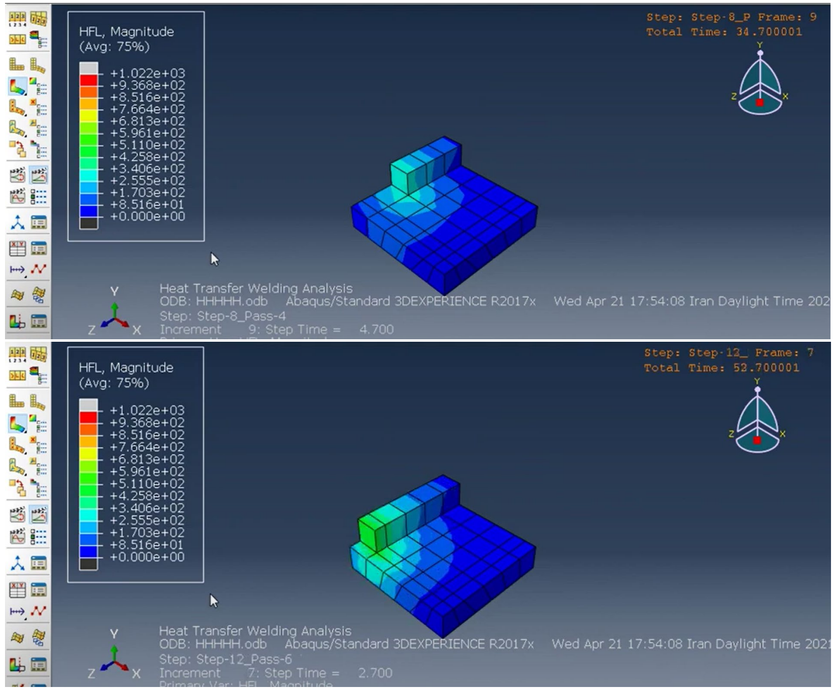


Fig. 6 Element birth simulation using Abaqus. https://www.youtube.com/watch?v=FqE3kj9ESVc

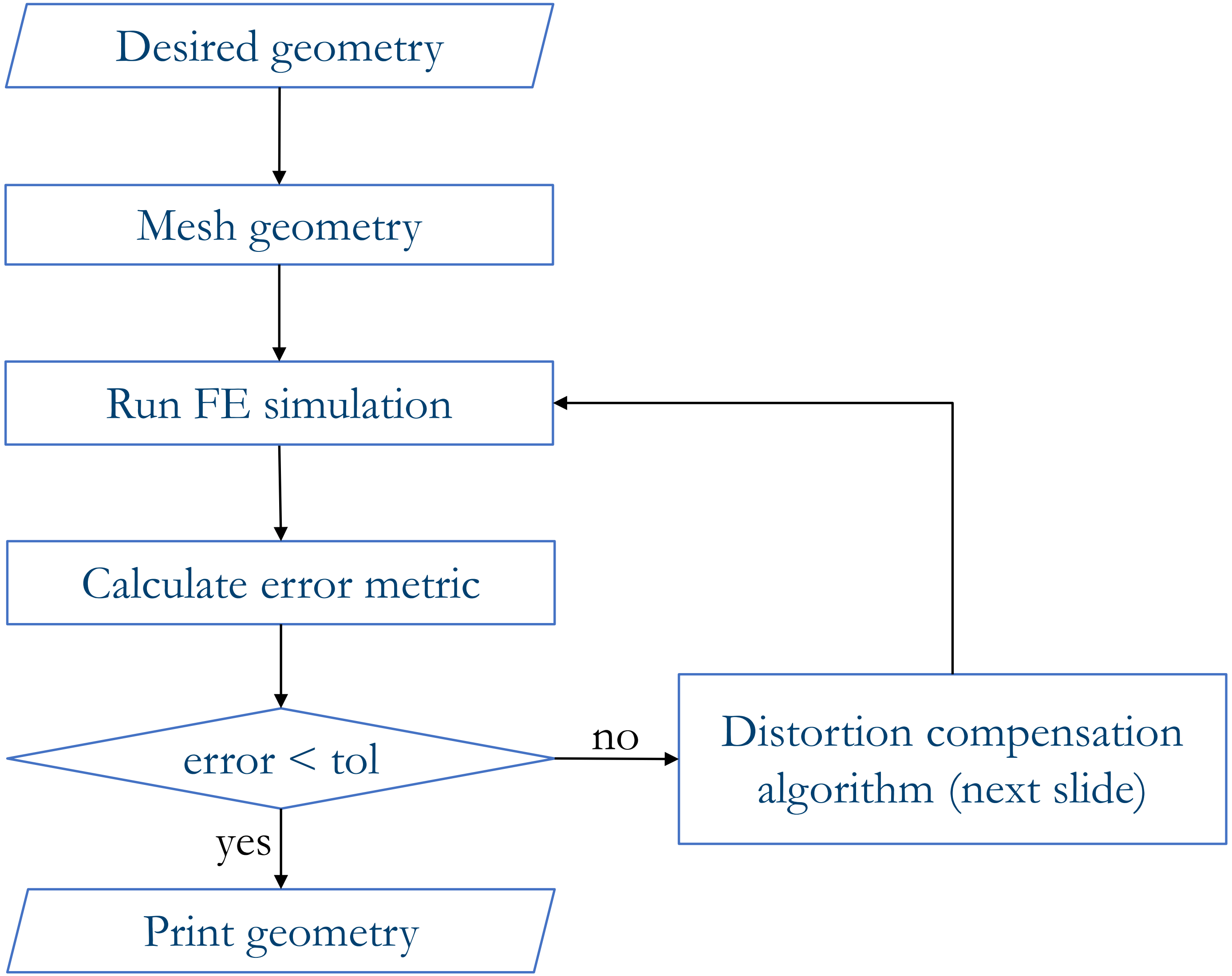
- Optical approaches

Fig. 7 ATOS Compact Scan – Blue Light 3D Scanner. https://www.youtube.com/watch?v=T-RkQioXHYg

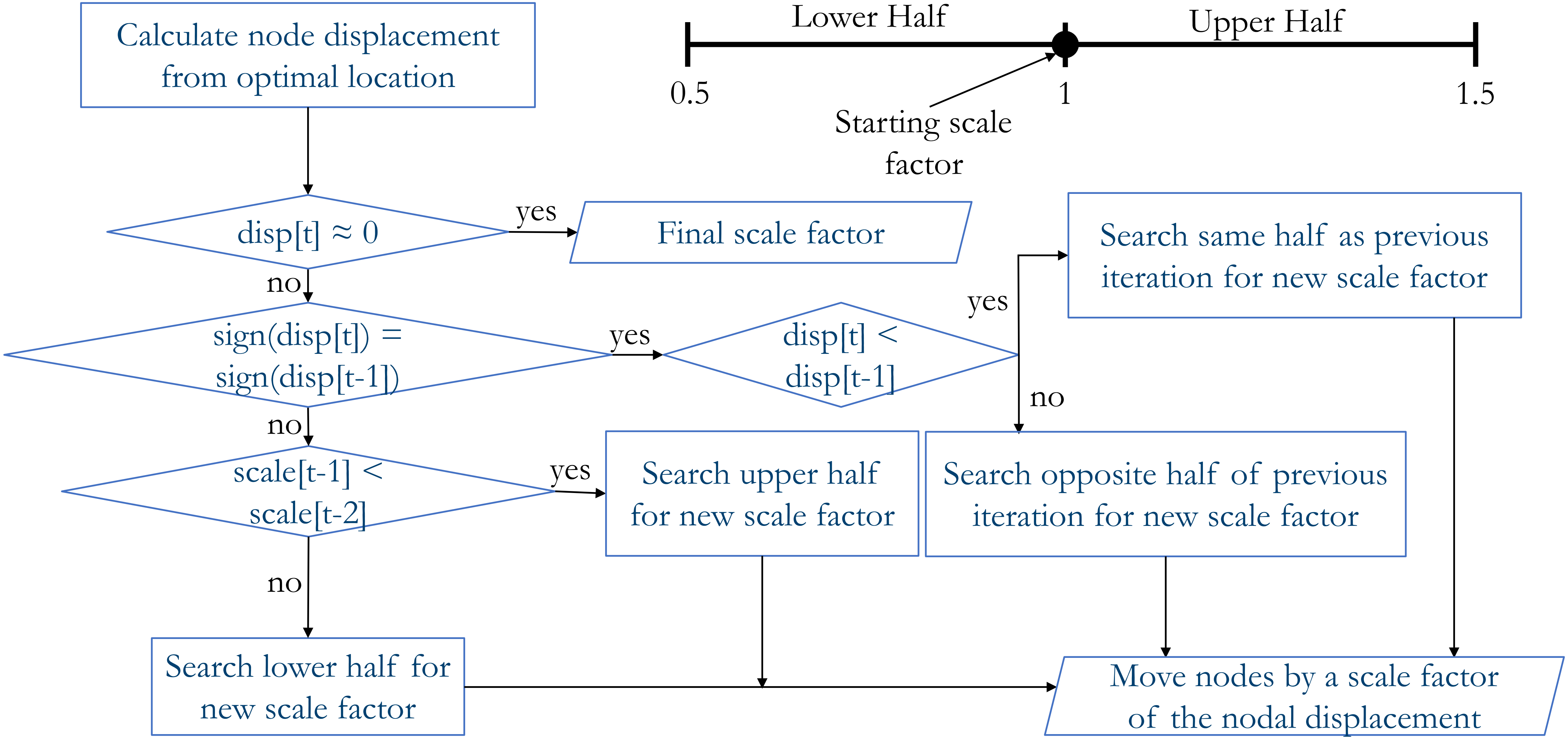
Metal Additive Manufacturing → Problem Formulation → Deformation Prediction

PROJECT WORKFLOW

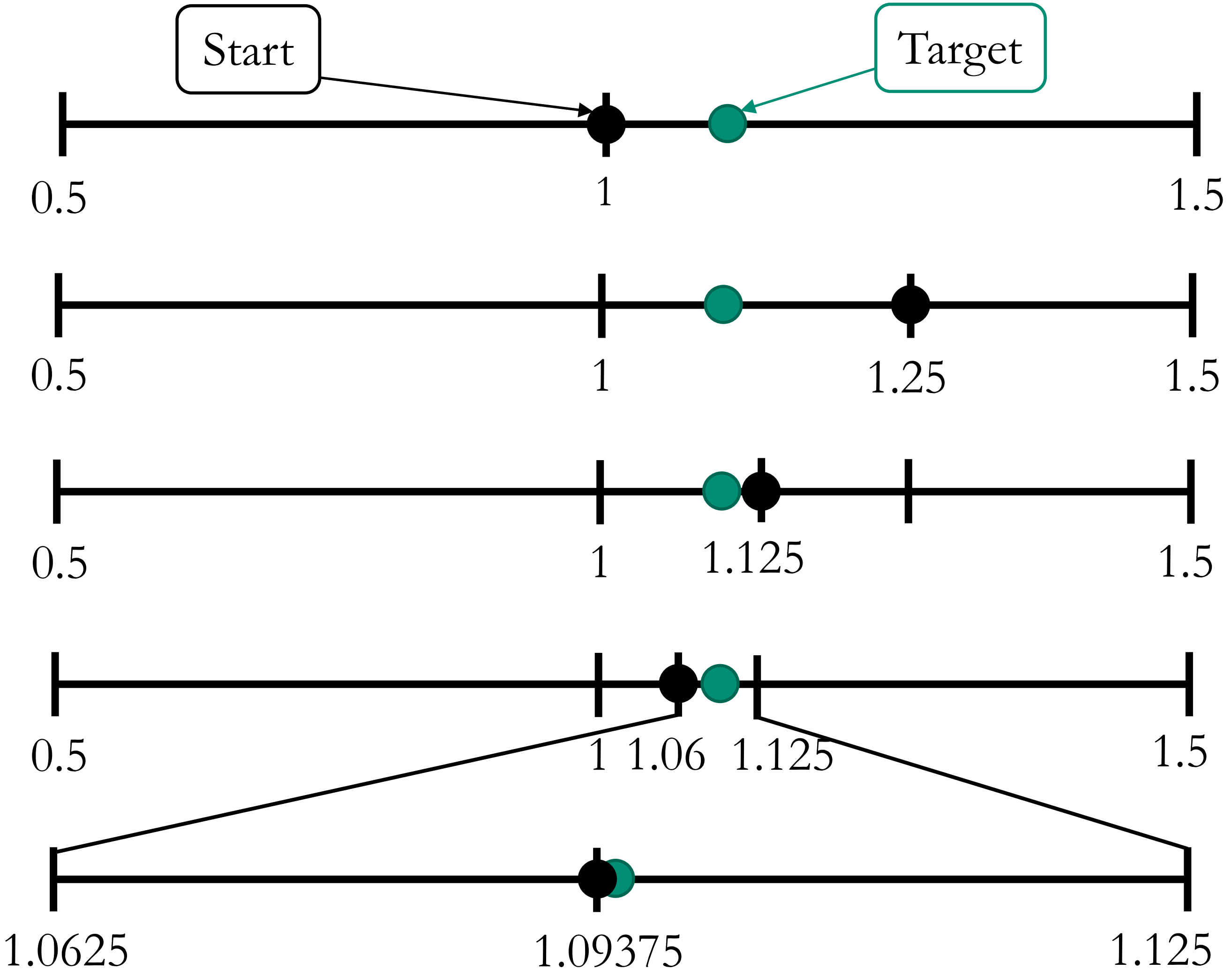
Distortion Compensation Optimization Workflow



Distortion Compensation Algorithm Workflow



Distortion Compensation Algorithm Example



Apply initial distortion compensation (100%)

Distortion too high; same sign as initial distortion → increase scale to 125% for second iteration

Distortion changed sign → overcompensated! Invert previous operation: reduce scale to 112.5%

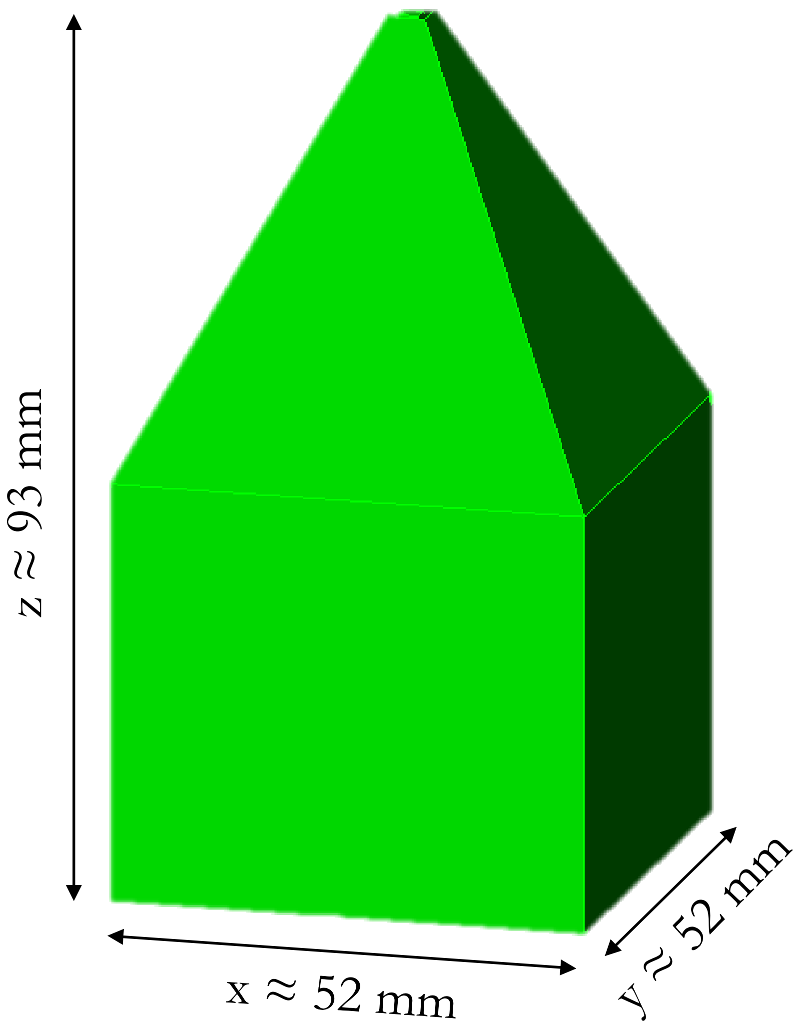
Distortion has same sign, decreased in magnitude → repeat previous operation: reduce scale to 106.25%

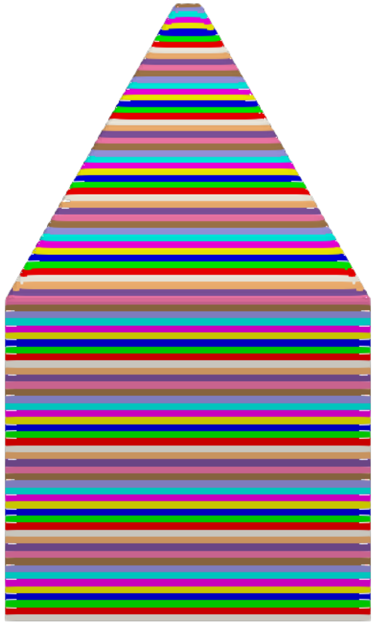
Distortion changed sign → overcompensated! Invert previous operation: increase scale to 109.375%

Distortion within tolerance after final iteration, print corresponding geometry.

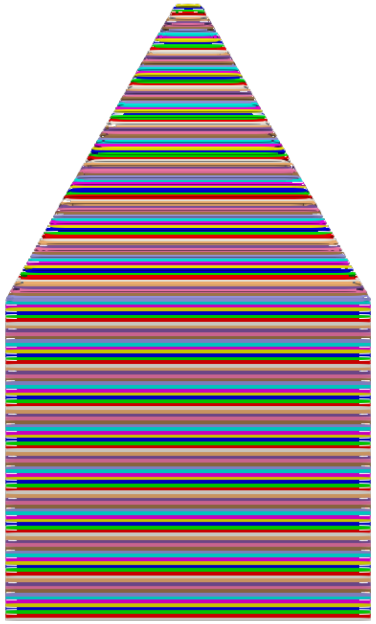
PROJECT RESULTS

Model & Mesh Overview





- Number of Layers: 93
- Element Type: HEX8
- Element Size: 0.50 mm
- Number of Elements: 257108



- Number of Layers: 185
- Element Type: HEX8
- Element Size: 0.25 mm
- Number of Elements: 1531176

Material Models

- 300 series austenitic stainless steel (304L and 316L)
- Elastic model fit to widely established 304L data
  - Young's modulus: 200e9 Pa
  - Poisson's ratio: 0.25
- Elastic-Plastic model fit to 316L tensile data
  - Young's modulus: 200e9 Pa
  - Poisson's ratio: 0.3
  - Yield stress: 500e6 Pa
  - Hardening modulus: 500e6 Pa
  - Hardening exponent: 0.55

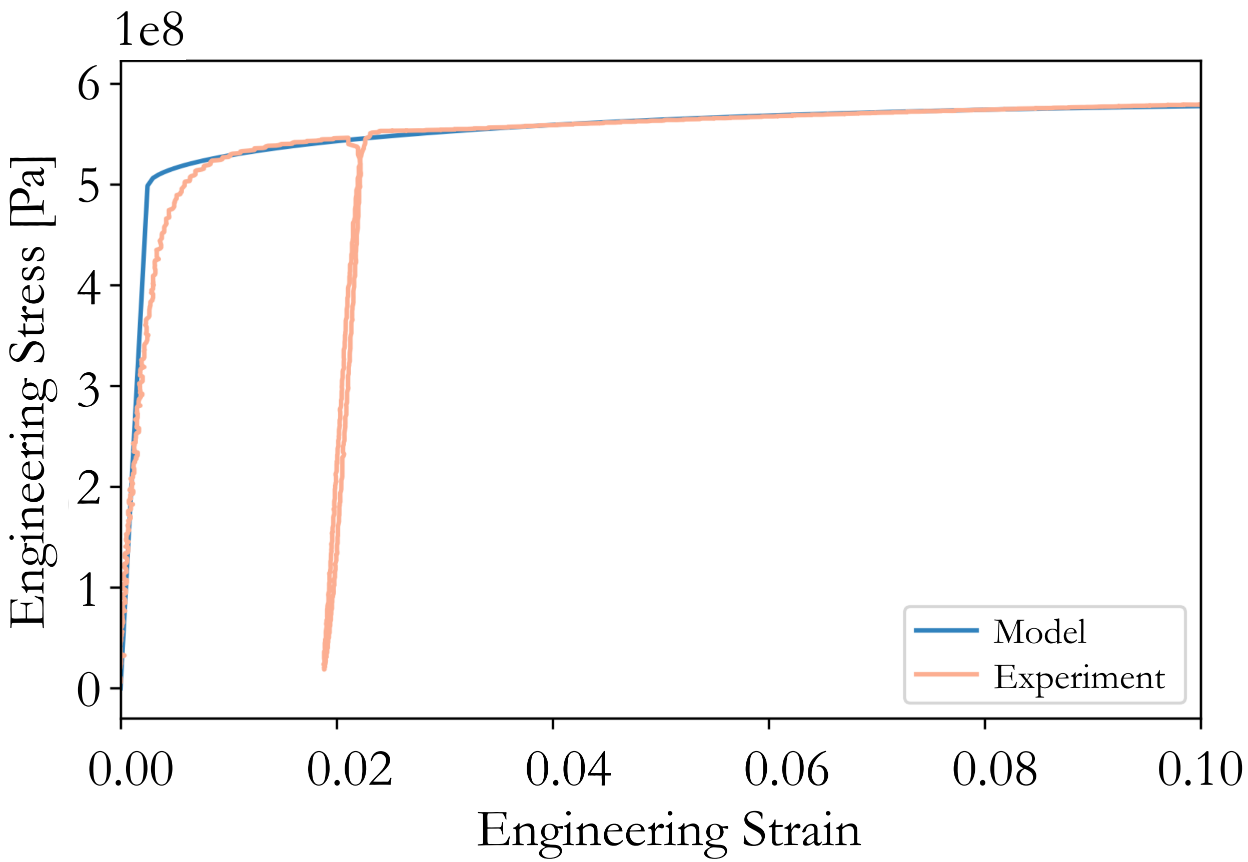
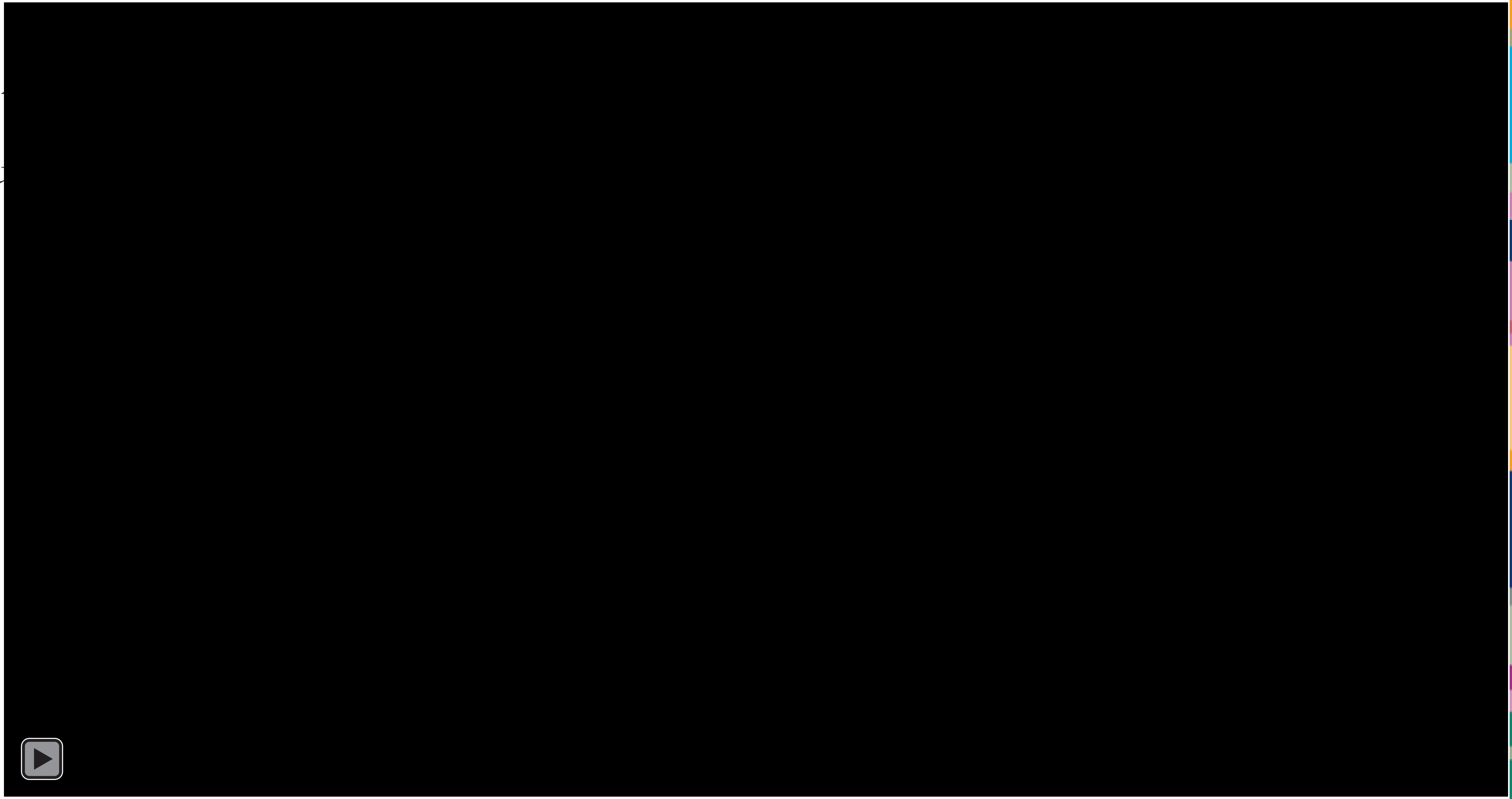


Fig. 8 Stress-strain curve for 316L stainless steel.

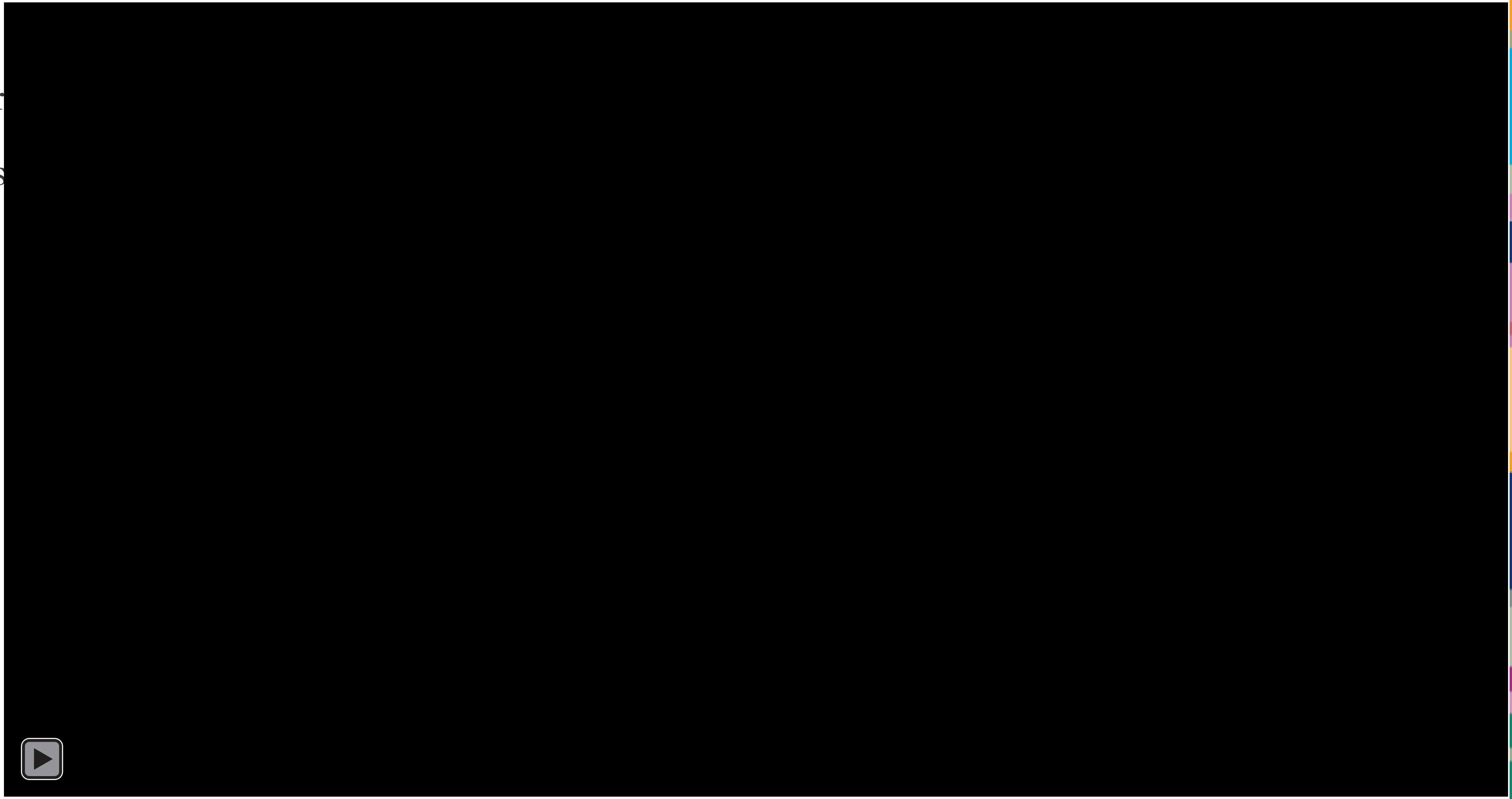
Element Birth Scheme

- Layer-by-layer elemen
- Inactive elements accu



Distortion Results: Elastic-Plastic Model

- Number of Processor
- Inherent Strain Values
  - Strain in x ≈ -2%
  - Strain in y ≈ -2%
  - Strain in z ≈ 2%



Distortion Results: As-Built Distortion Significantly Reduced

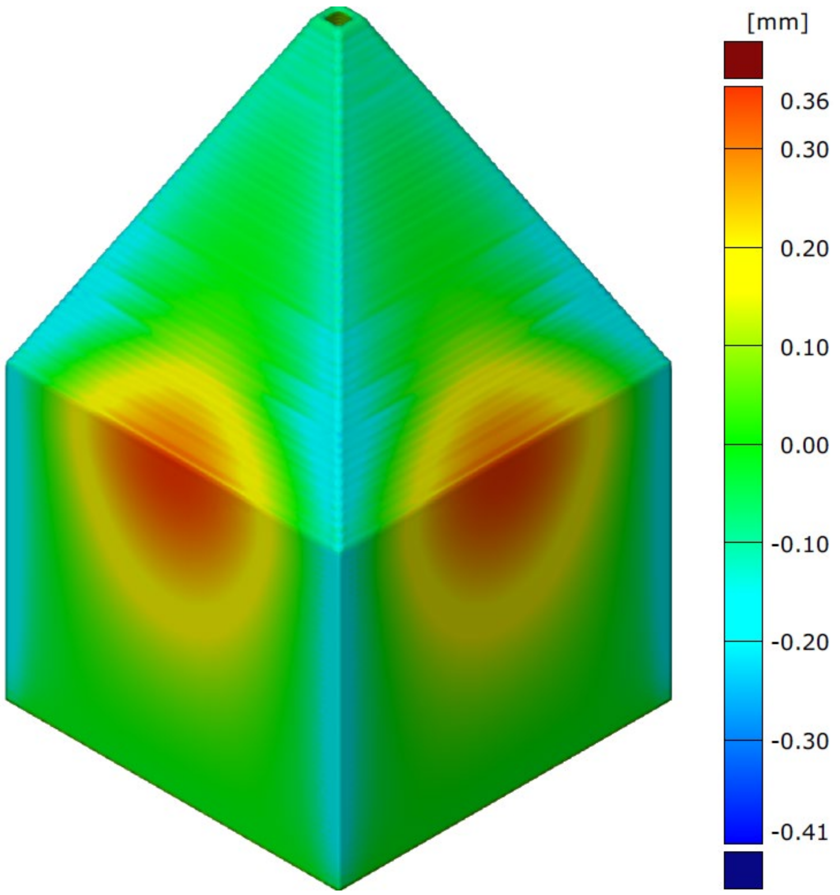


Fig. 9 Simulated deformation of elastic-plastic model without distortion compensation.

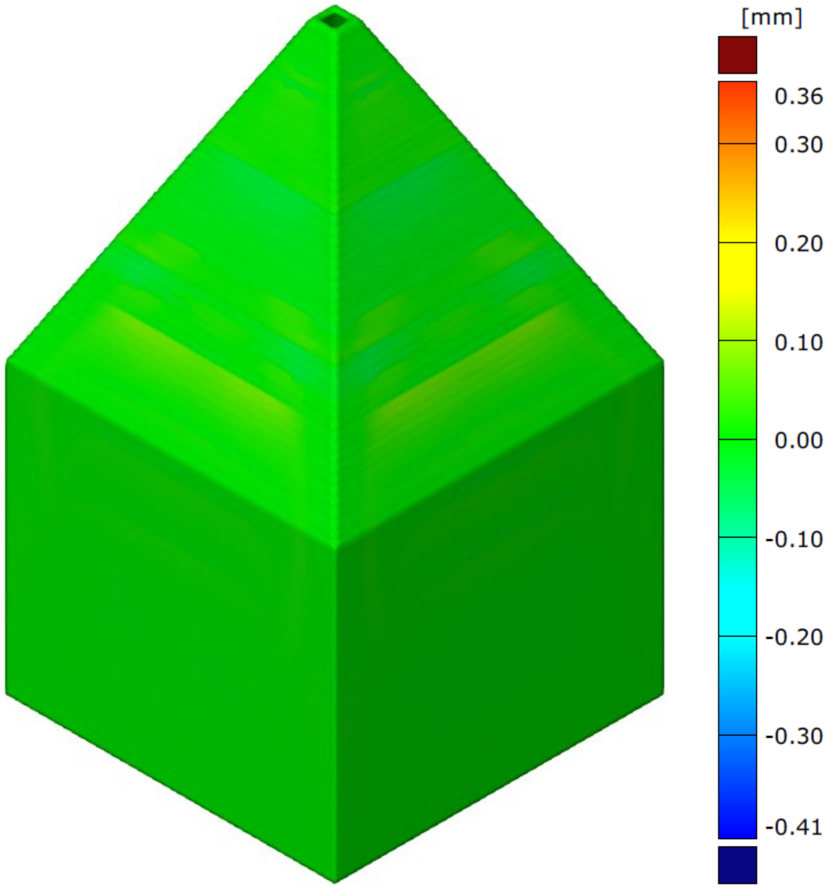
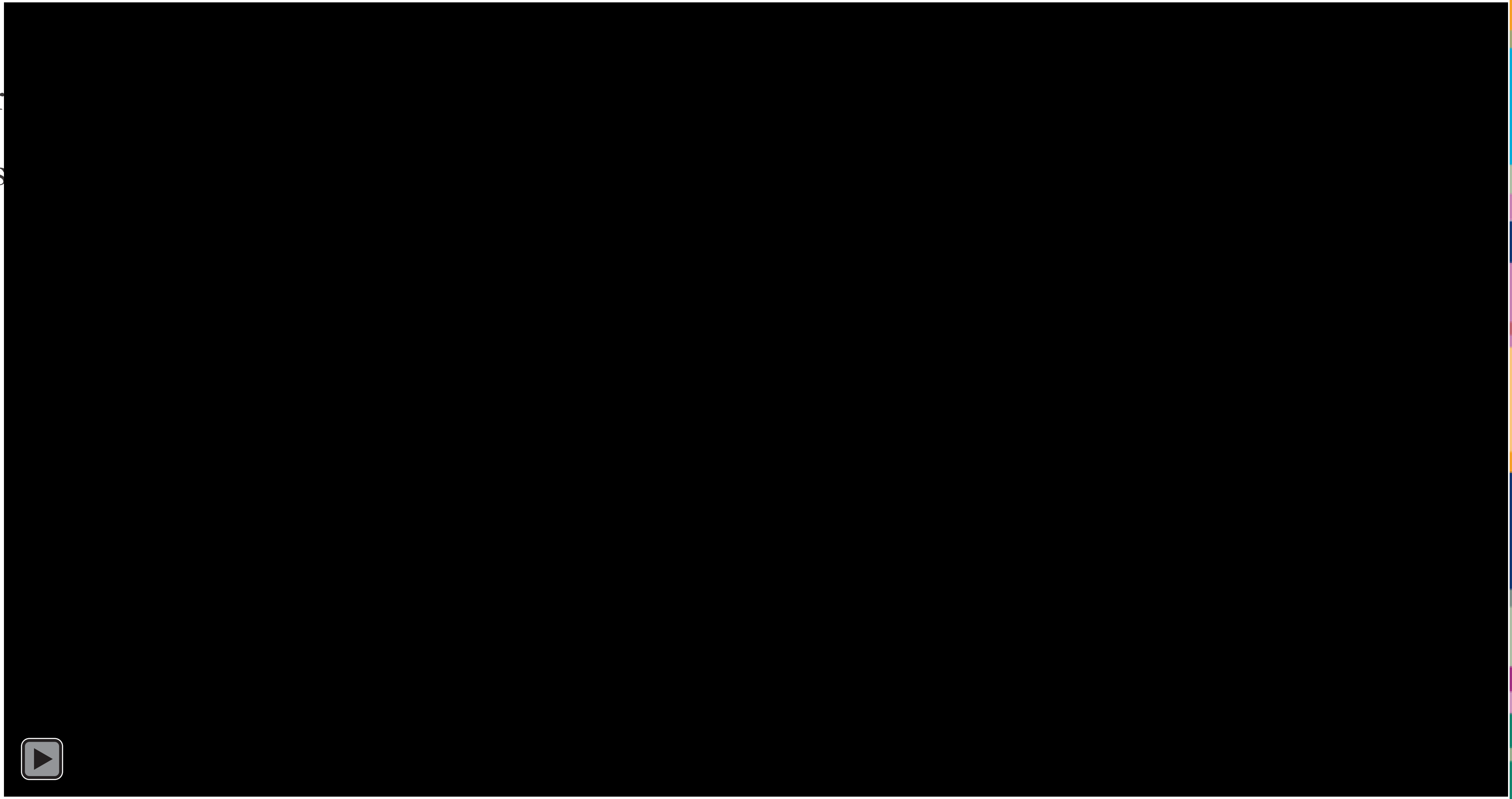


Fig. 10 Simulation deformation of elastic-plastic model with optimized distortion compensation.

Distortion Results: Elastic Model

- Number of Processor
- Inherent Strain Values
  - Strain in x = -0.2%
  - Strain in y = -0.2%
  - Strain in z = 0.2%



Distortion Results: As-Built Distortion Significantly Reduced

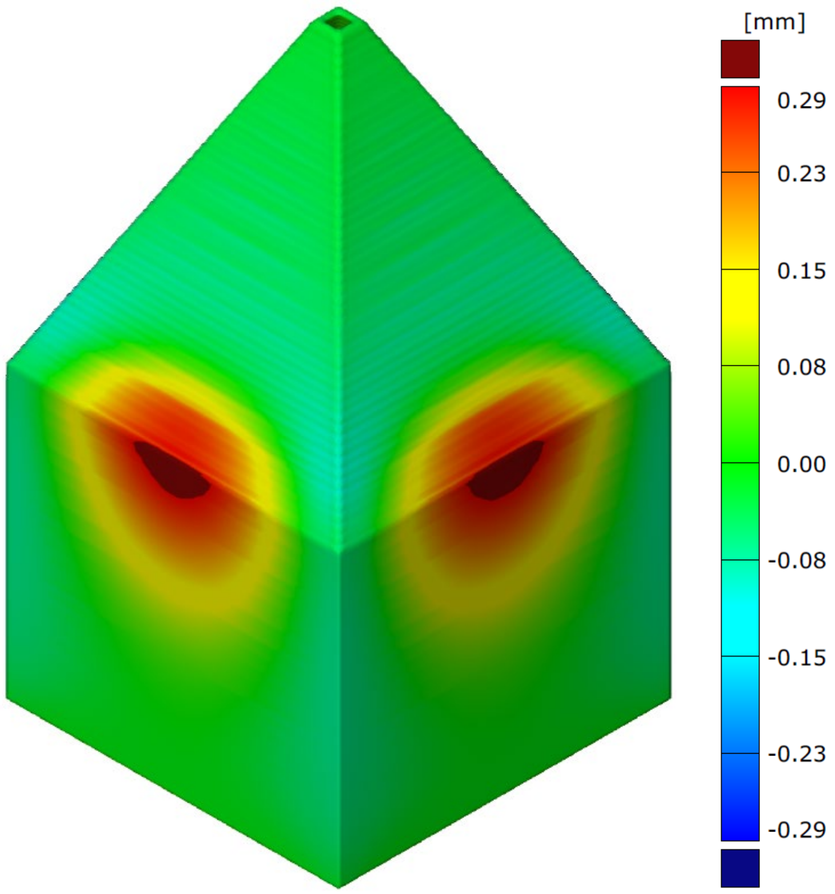


Fig. 11 Simulated deformation of elastic model without distortion compensation.

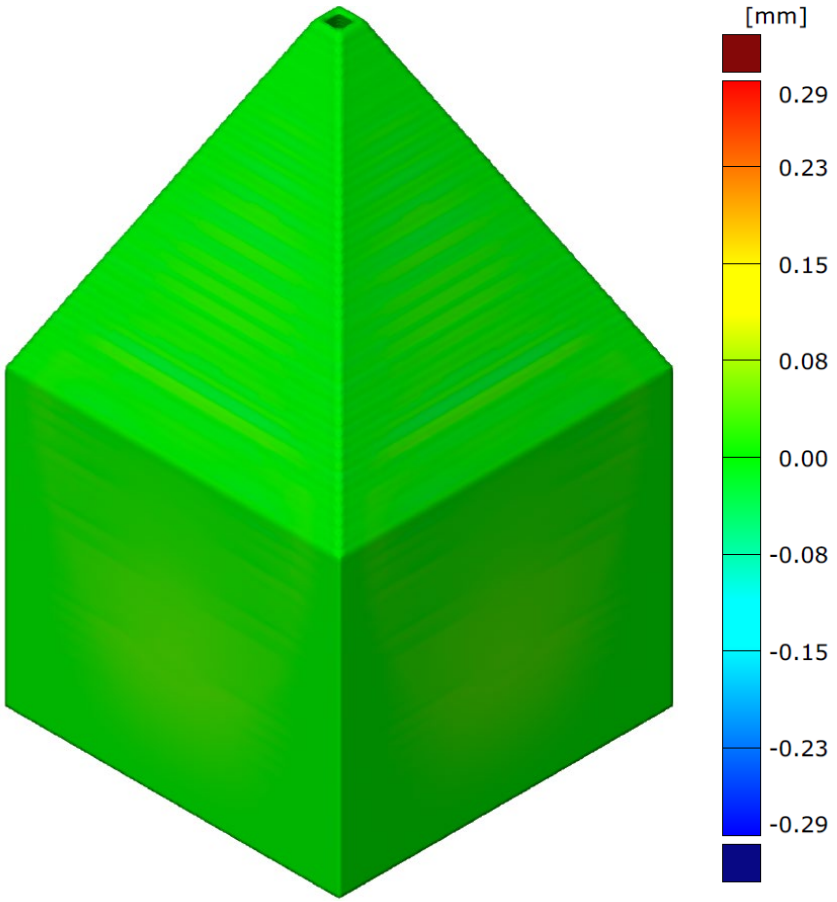


Fig. 12 Simulation deformation of elastic model with optimized distortion compensation.

Algorithm Statistics: Errors

Model	Iteration	Iteration Avg 2-Norm Error	Minimized Avg 2-Norm Error
Elastic-Plastic	1	2.45E-7	2.45E-7
	2	4.30E-8	4.17E-8
	3	3.32E-8	2.58E-8
	4	**2.45E-8**	2.58E-8
Elastic	1	1.70E-7	1.70E-7
	2	3.49E-8	3.39E-8
	3	2.46E-8	2.06E-8
	4	1.96E-8	**1.65E-8**

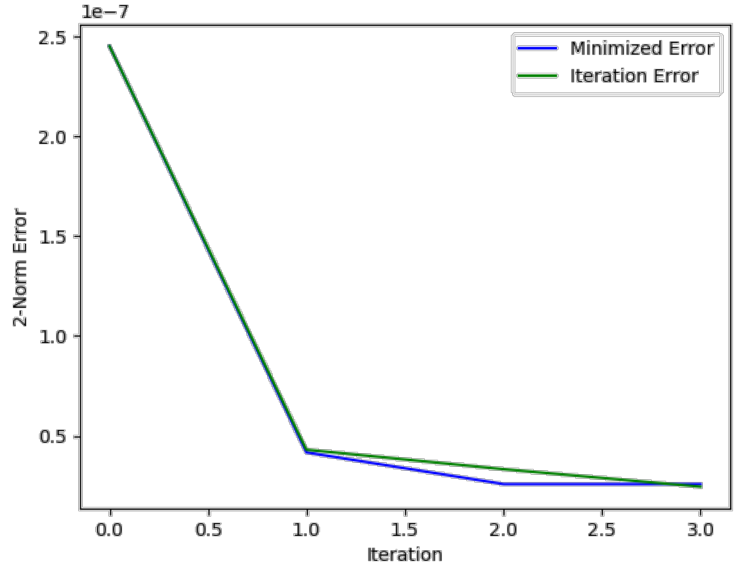


Fig. 13 Elastic-plastic model error per iteration.

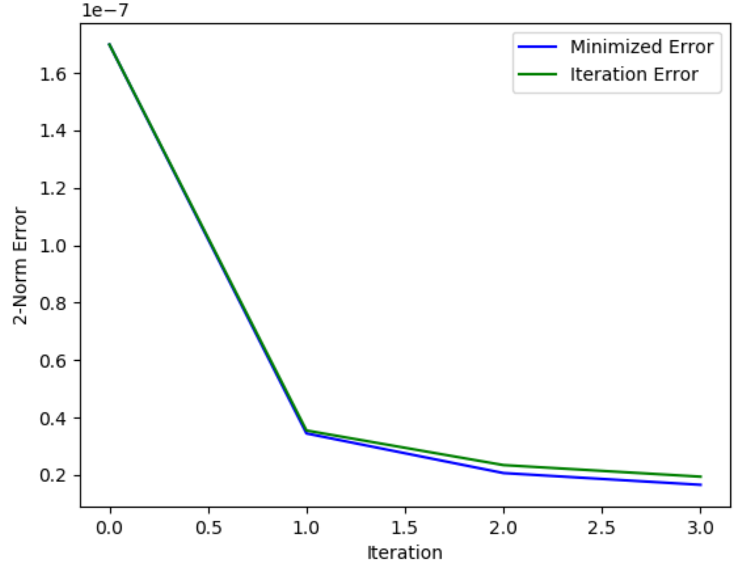


Fig. 14 Elastic model error per iteration.

Algorithm Statistics: Runtimes

Model	Average SIERRA Time per Iteration	Average EPU Time per Iteration	Average Algorithm Time per Iteration	Average Total Time per Iteration	Number of Iterations	Total Time for all Iterations
Elastic-Plastic	21.5 min	4.3 min	7.1 sec	25.9 min	4	1.73 hrs
Elastic	20.4 min	5.8 min	9.8 sec	26.9 min	4	1.76 hrs

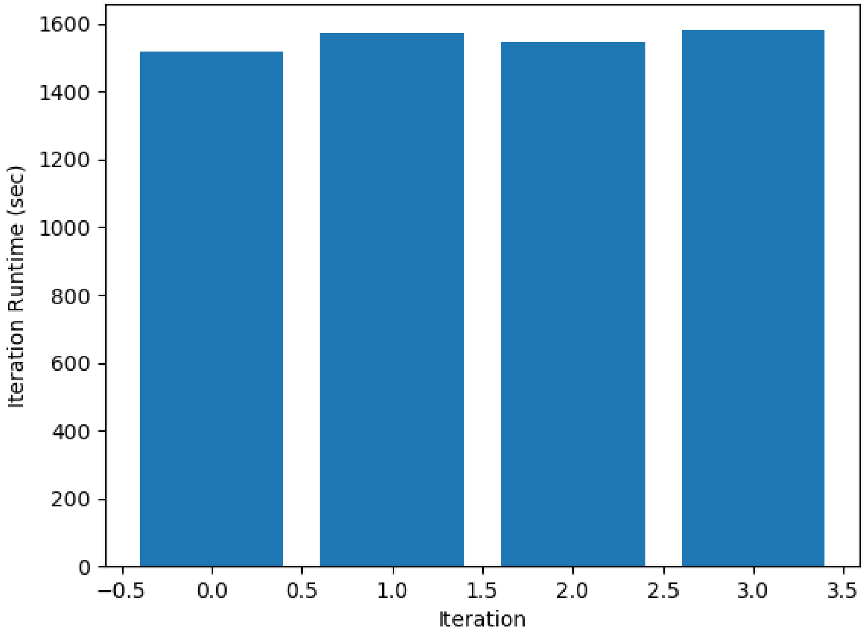


Fig. 15 Elastic-plastic model runtime per iteration.

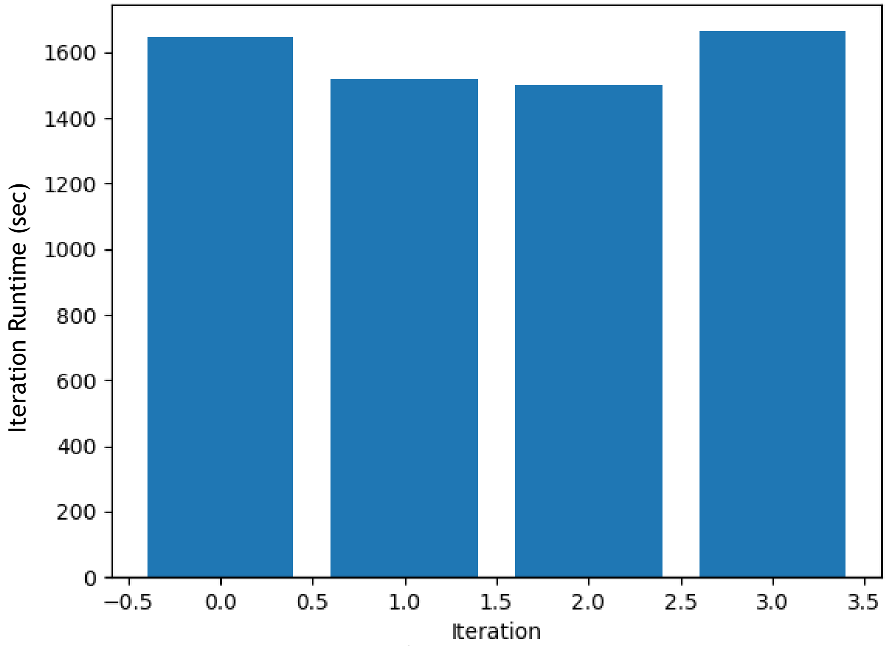


Fig. 16 Elastic model runtime per iteration.

Conclusions & Future Work

- Conclusions:
  - The distortion of metal builds with SLS is an impediment to the reliability and widespread adoption of additive manufacturing.
  - We developed an efficient numerical distortion compensation optimization workflow which outputs a CAD file that will distort into the desired geometry when printed.
  - We developed a comprehensive tool to obtain a geometrically compensated stereolithography file from a mesh input
  - We tested this algorithm on a thin house geometry, and it works!
- Future work:
  - Integrate coupled thermomechanical modeling techniques into the workflow
  - Validate the algorithm with a printed proof-of-concept

Acknowledgements

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- Further appreciation is extended to the NOMAD team—Deborah Fowler, Robert Kuether, Joseph Bishop, Jill Blecke, and Brooke Allensworth—for their organization and guidance.
- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

THANK YOU!

We will take your questions at this time.

References

X. Liang, Q. Chen, L. Cheng, Q. Yang, A. To, A modified inherent strain method for fast prediction of residual deformation in additive manufacturing of metal parts, in: 2017 International Solid Freeform Fabrication Symposium, University of Texas at Austin, 2017. doi: http://dx.doi.org/10.26153/tsw/16972.

BACKUP SLIDES

IS vs MIS methods

$$\epsilon_{to} = \epsilon_e + \epsilon_p + \epsilon_{th} + \epsilon_{pt} + \epsilon_{cr}$$
$$\epsilon^* = \epsilon_{to} - \epsilon_e = \epsilon_p + \epsilon_{th} + \epsilon_{pt} + \epsilon_{cr}$$

Original inherent strain method

$$\epsilon^* = \epsilon_p$$

Contribution of the plastic deformation to the IS of the AM process

$$\epsilon_p^* = \epsilon_p^I$$

Contribution to the IS in the AM process

$$\epsilon_{th} = \epsilon_e^I - \epsilon_e^S$$

Modified inherent strain model

$$\epsilon^* = \epsilon_p^* + \epsilon_{th}^*$$

ϵ_{to} total strain

ϵ_e elastic strain

ϵ_p plastic strain

ϵ_{th} thermal strain

ϵ_{pt} phase transformation

ϵ_{cr} creep strain

ϵ^* inherent strain

ϵ_p^I largest compressive plastic strain at intermediate state

ϵ_e^I elastic strain at the intermediate state

ϵ_e^S elastic strain at the steady state

Compensated Geometry: Elastic-Plastic Model

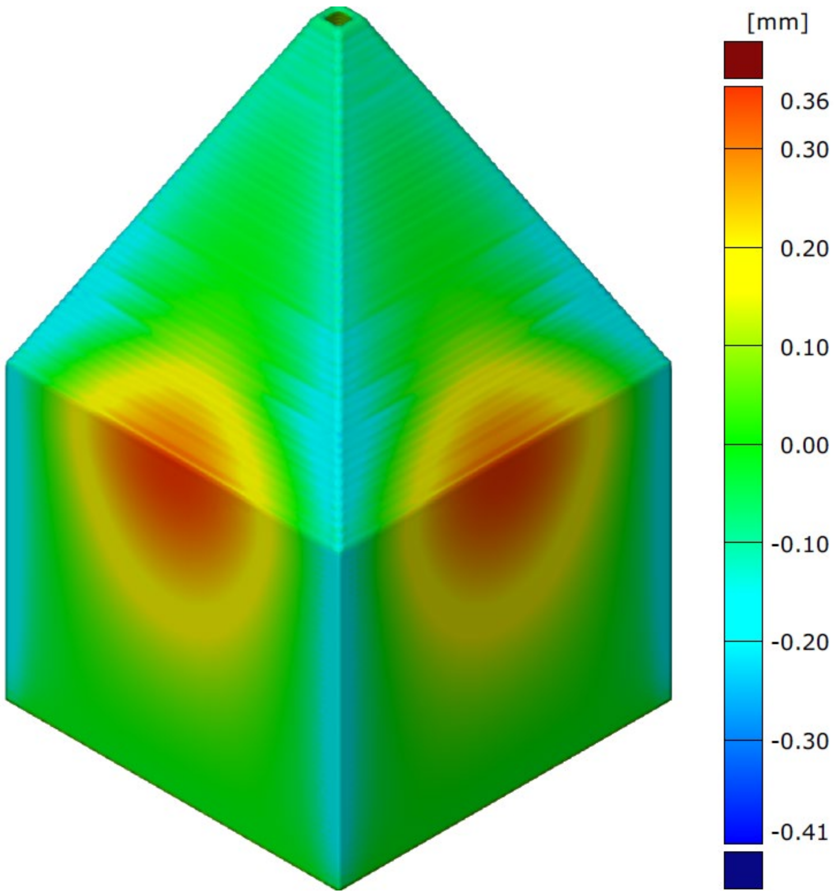

Fig. 17 Simulated deformation without distortion compensation.

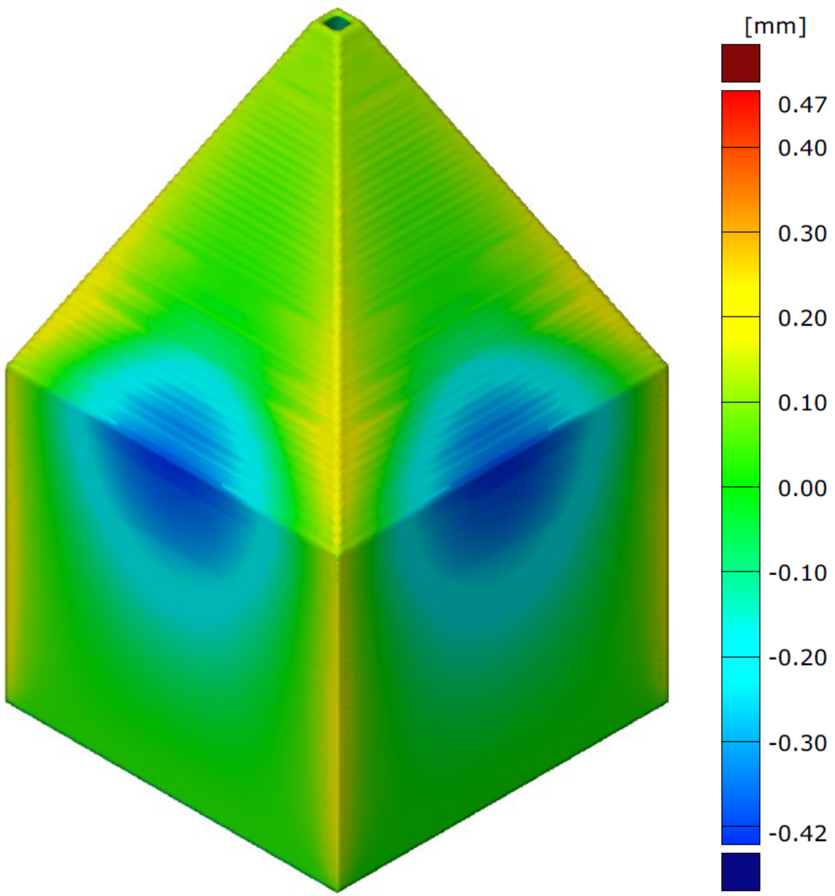

Fig. 18 Distortion compensated file (final geometry to be printed).

Compensated Geometry: Elastic Model

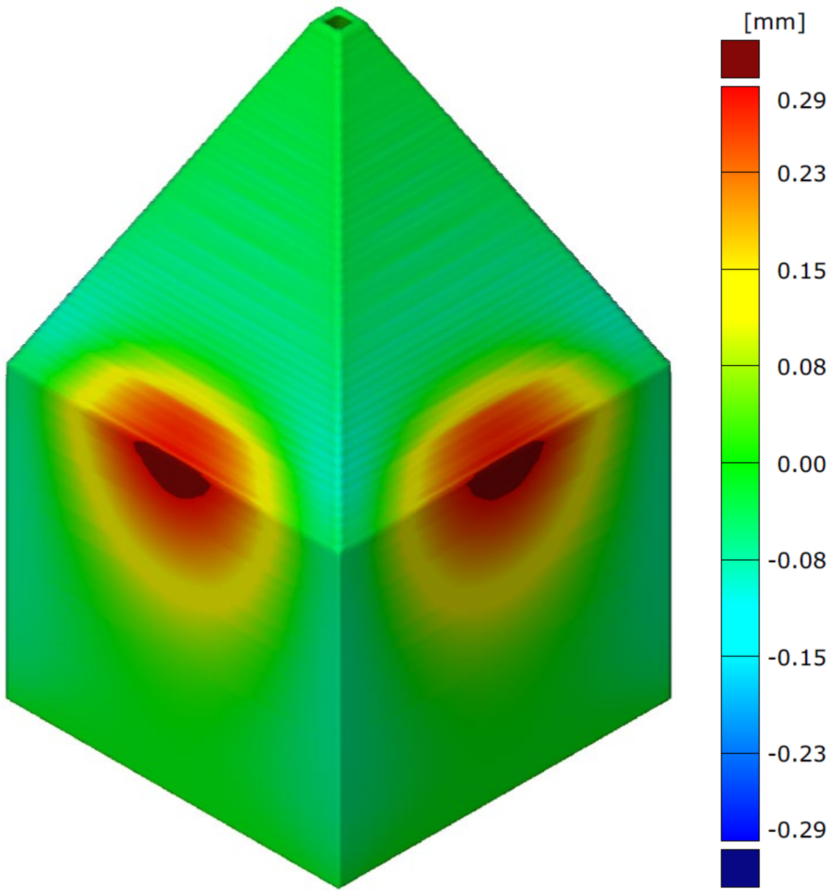

Fig. 19 Simulated deformation without distortion compensation.

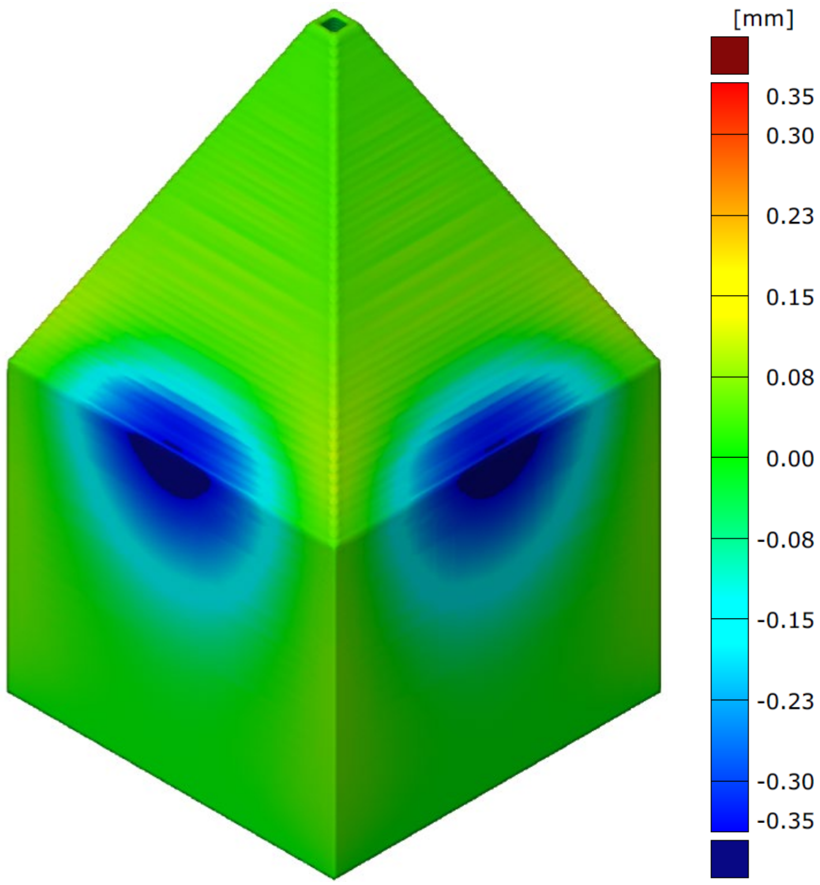

Fig. 20 Distortion compensated file (final geometry to be printed).

Comparing Experimental Data vs Simulated Data for Uncompensated Build

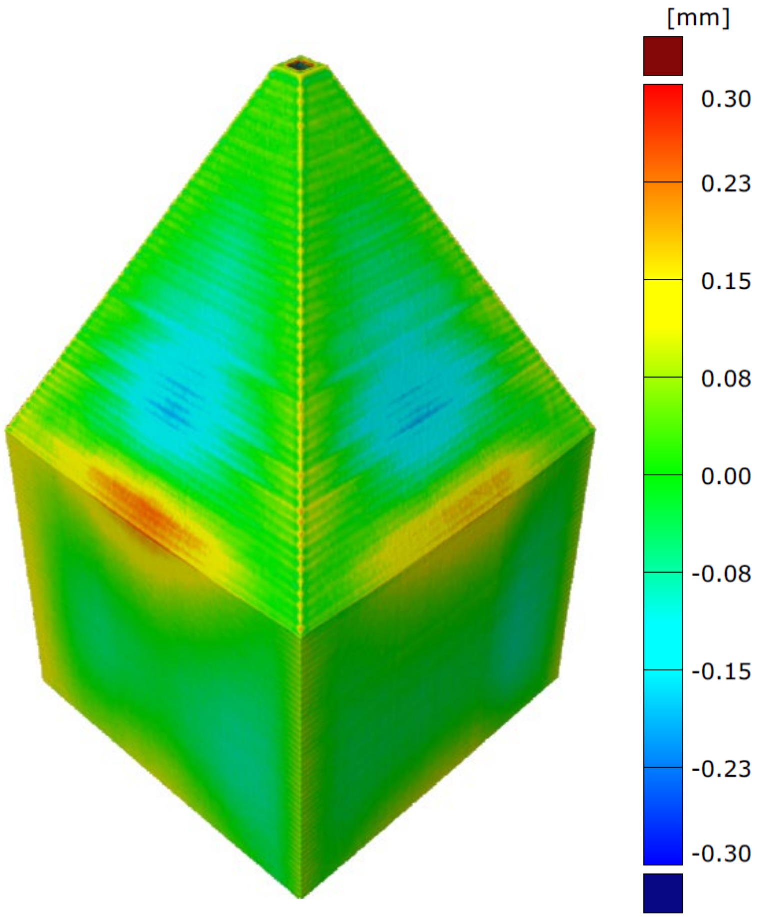

Fig. 21 Elastic-plastic model.

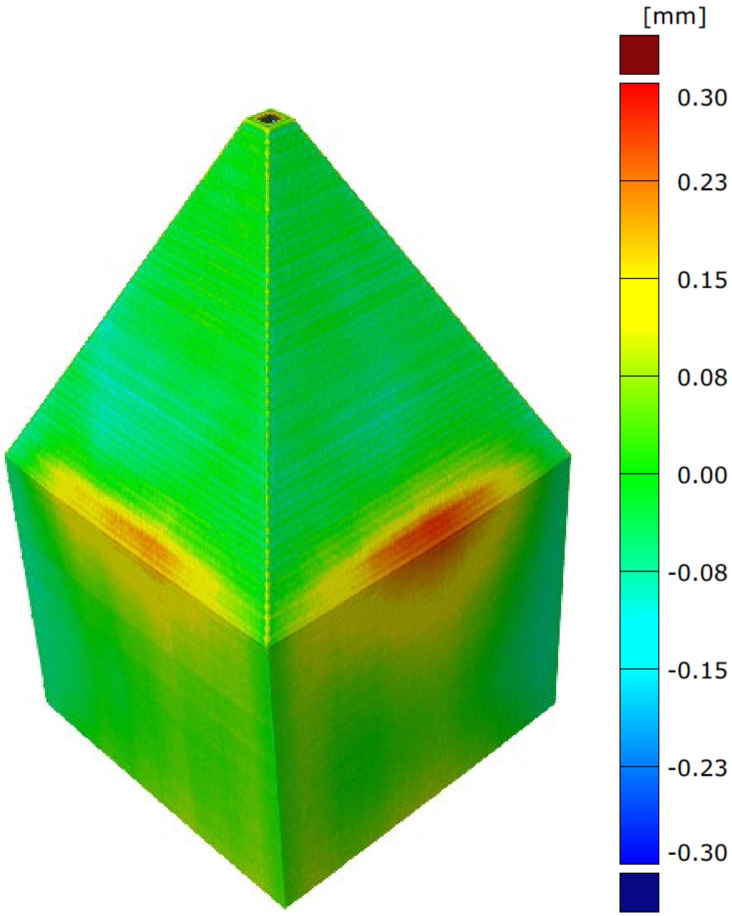

Fig. 22 Elastic model.