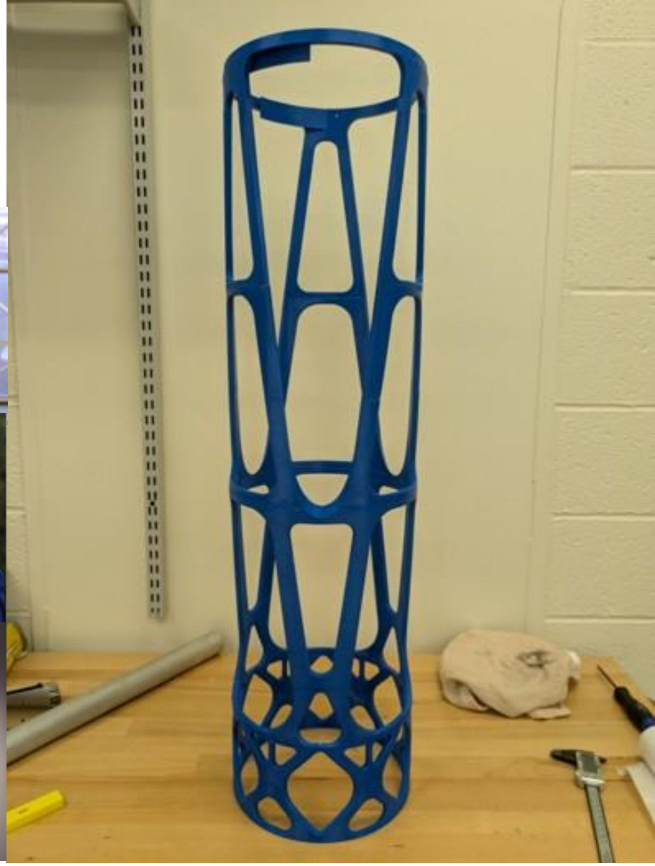
Additive Manufacturing of a Forward Metering Structure for Space Imaging Applications







Team Members:

Marvin Calderon
Arden Gao
Ethan Sanna
Jake Snyder

Customer:

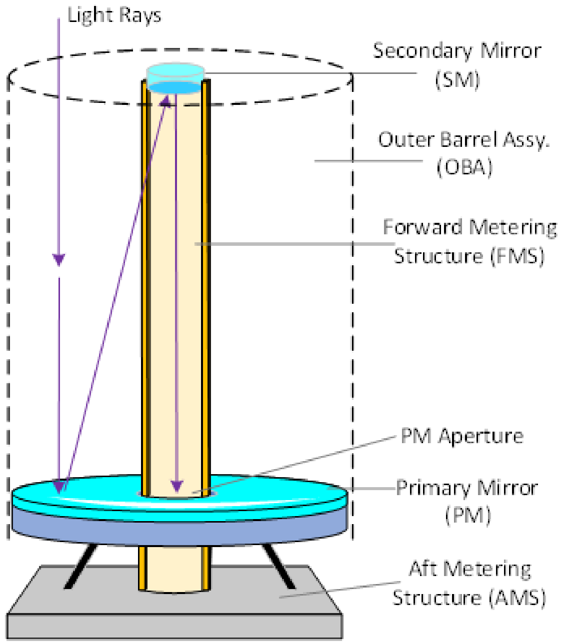
L3Harris

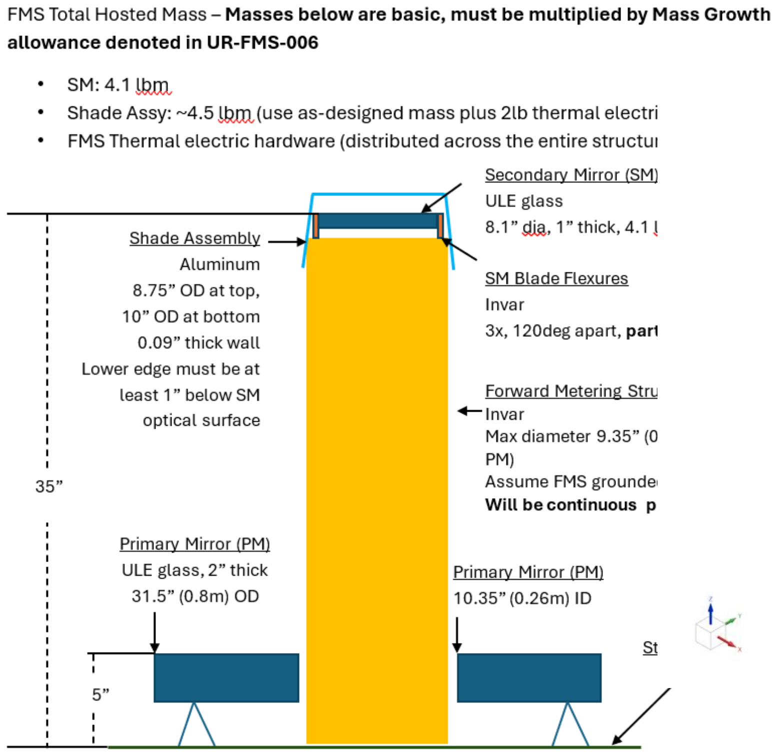
Project Overview:

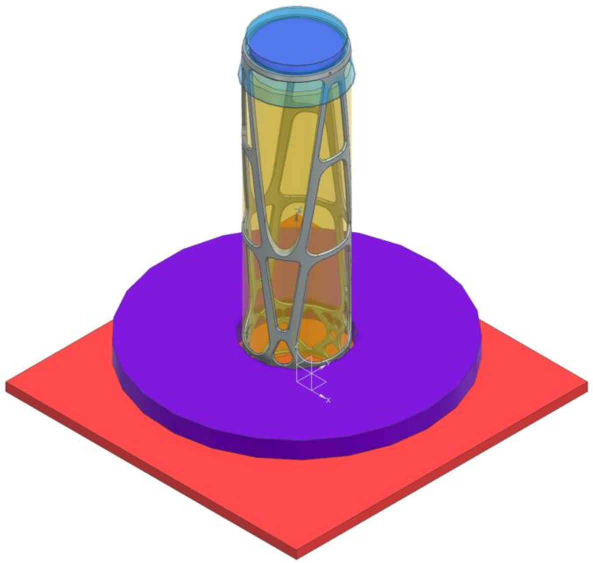
This project focuses on the design and manufacturing of a 3D metal-printed Forward Metering Structure (FMS) for an L3Harris space-based telescope. Metal 3D printing is a rapidly growing manufacturing paradigm because it enables fast production of complex, lightweight geometries that would be impractical for traditional manufacturing. The final deliverable will be a full-scale ABS prototype that will be validated through iterative material testing and model correlation.

Problem Statement

- The purpose of this project is focused on the design and fabrication of a 3D metal-printed forward metering structure (FMS) to connect and align the primary and secondary mirrors for a space-based telescope system.
- L3Harris have requested an additive process to reduce build time while maintaining critical structural performance.
  - This process allows the FMS to be fabricated as a monolithic part in a single build cycle as opposed to a multi-component assembly.
  - This approach also encourages the team to incorporate advanced geometries that would not be practical for manual assembly but could be easily achieved with 3D printing technology.
  - It's important to recognize that modest performance trade-offs will take place; however, the purpose of this project is to demonstrate a fast, repeatable, and cost-effective solution for the future of space-based technologies.
- The team's final deliverable will consist of a tested prototype and correlated model that meets industry requirements.







Deliverables, Requirements and Specifications

Deliverables:

- CAD Model
- Finite Element Model
- 3D Printed Prototype and Test Data
- Final Design Review/Paper

Requirements:

- Must connect AMS to the SM in one print
- Must be modelled with Invar (material)
- Must be producible by additive manufacturing

Specifications:

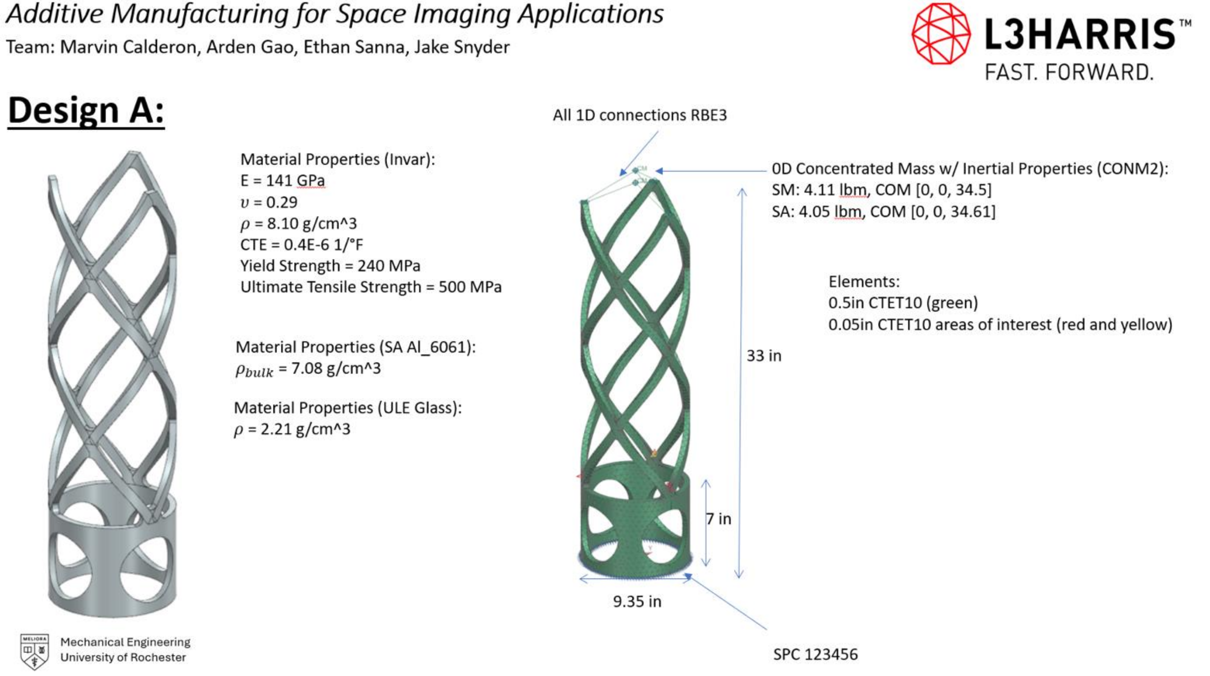
- Must maintain positive margins of safety against yield and ultimate failure when subjected to quasi-static launch loads of 30 g spherical sweep, swept at 15-degree increments
  - Yield FOS ≥ 2.0
  - Ultimate FOS ≥ 2.5
  - Ultimate Glass FOS ≥ 5
  - Buckling FOS ≥ 4.0

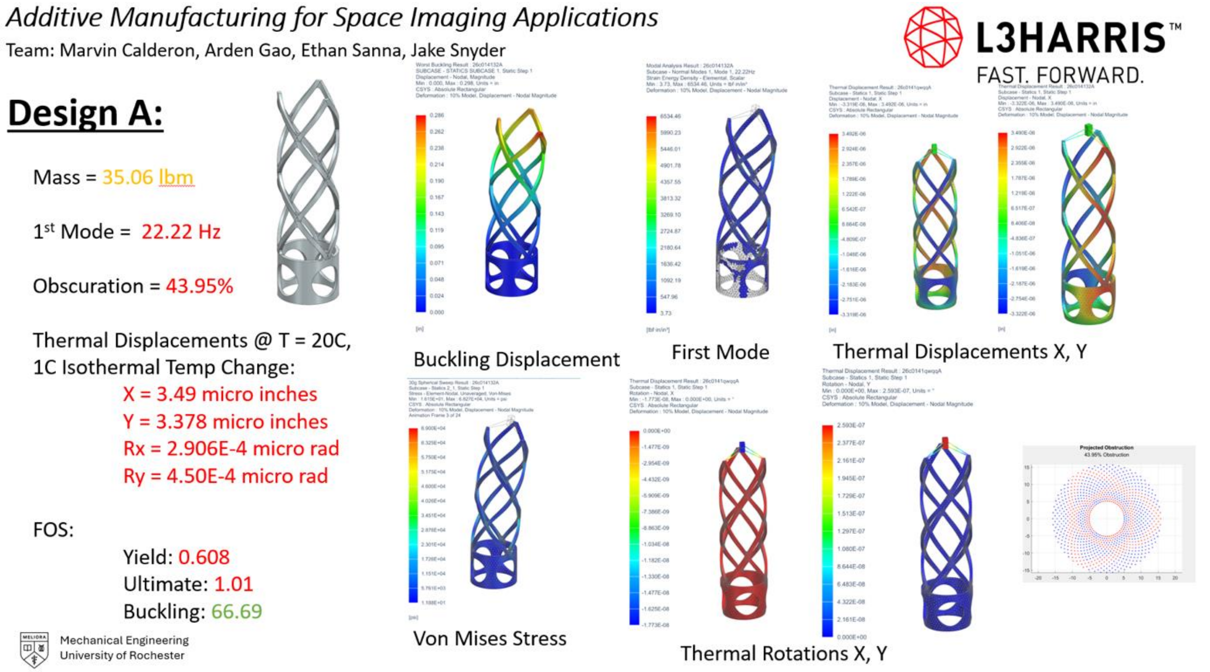
- Under a 1°C isothermal temperature change, the SM must only move:
  - 0.2 µm (7.87 micro inches) translation (RSS of X and Y)
  - 0.9 µrad rotation (RSS of Rx and Ry)
- FMS must not exceed a mass of 25 lbm
- Must obscure less than 22% of light coming from the PM
- 1^{st} vibrational mode must be greater than 60 Hz

Design Concepts

Design A:

- Iterating upon pre-existing diamond lattice structures
- Base left solid to increase stiffness
- Eliminates the top stiffening ring to reduce mass substantially

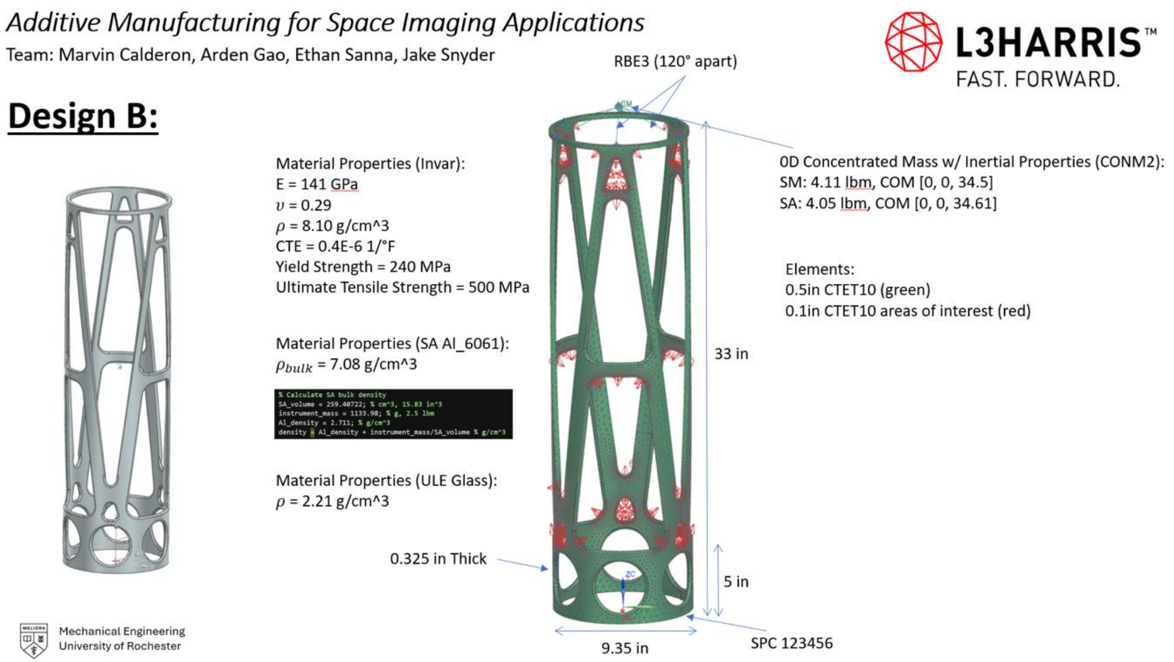


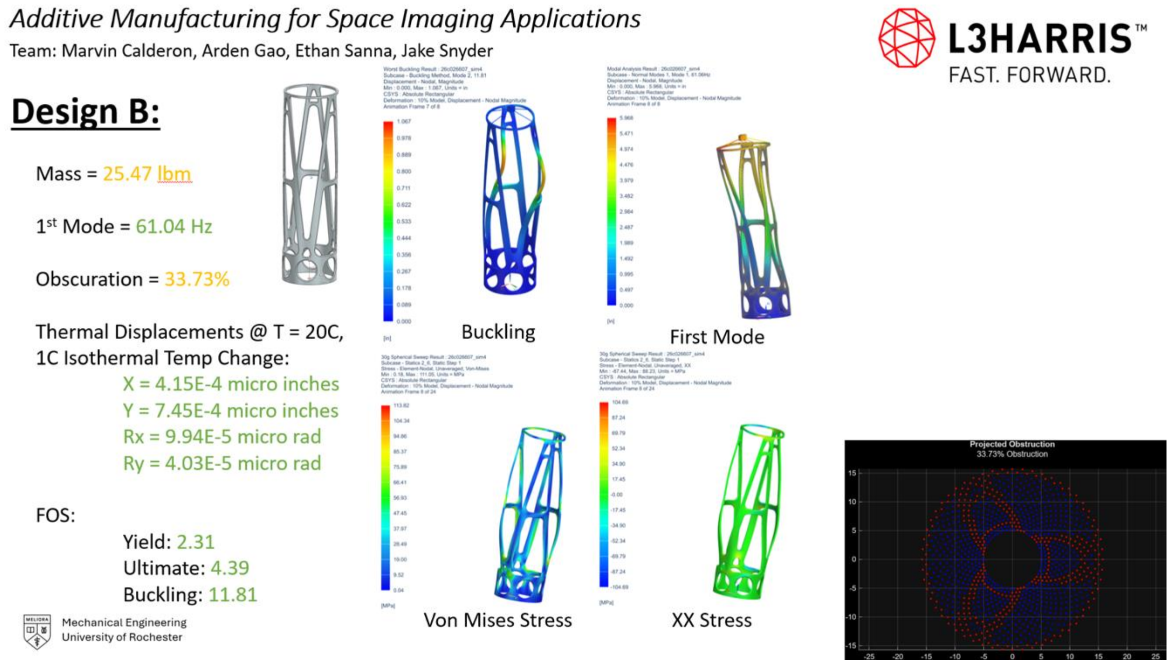


Design Concepts

Design B:

- Adapting existing triple bipod aerospace structures
- Base left solid to increase stiffness
- Top stiffening ring to increase modal results

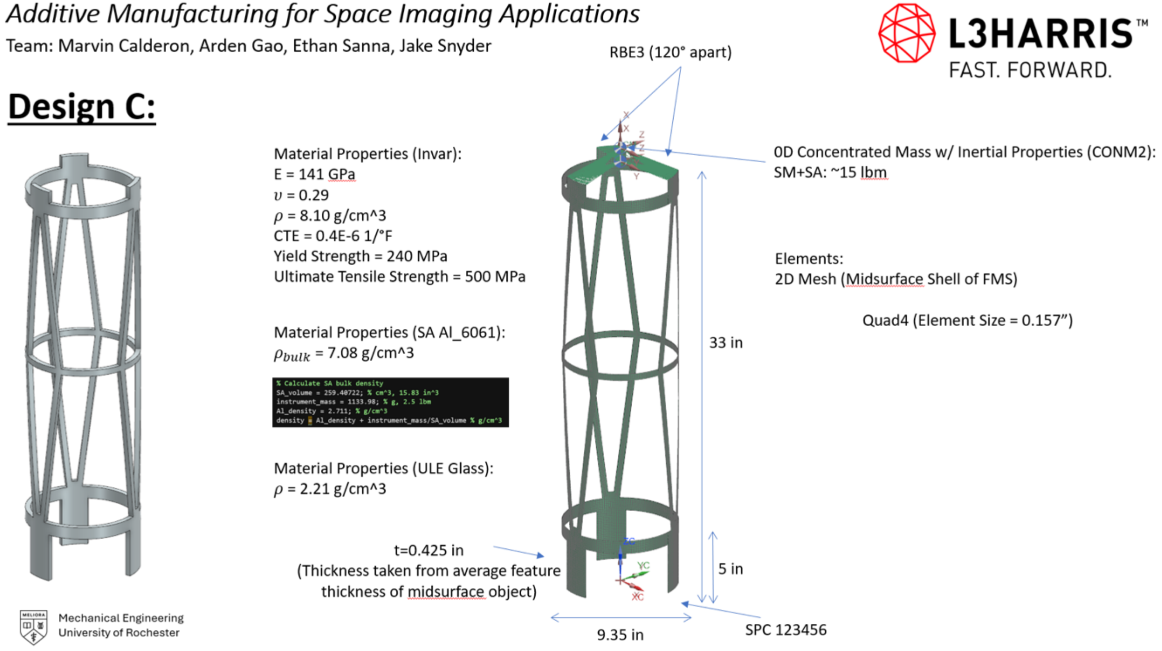


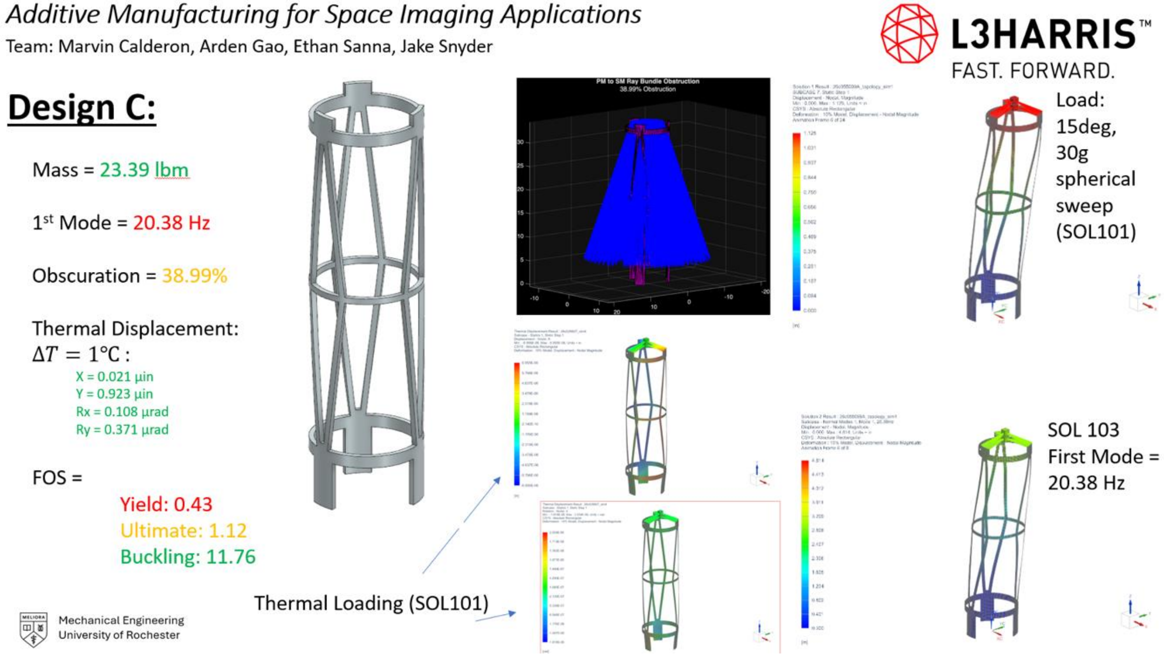


Design Concepts

Design C:

- Combining two triple bipod structures with truss-like elements
- Material subtracted from base to reduce mass leveraging fully fixed bottom
- Top ring to distribute loads from SM and SA

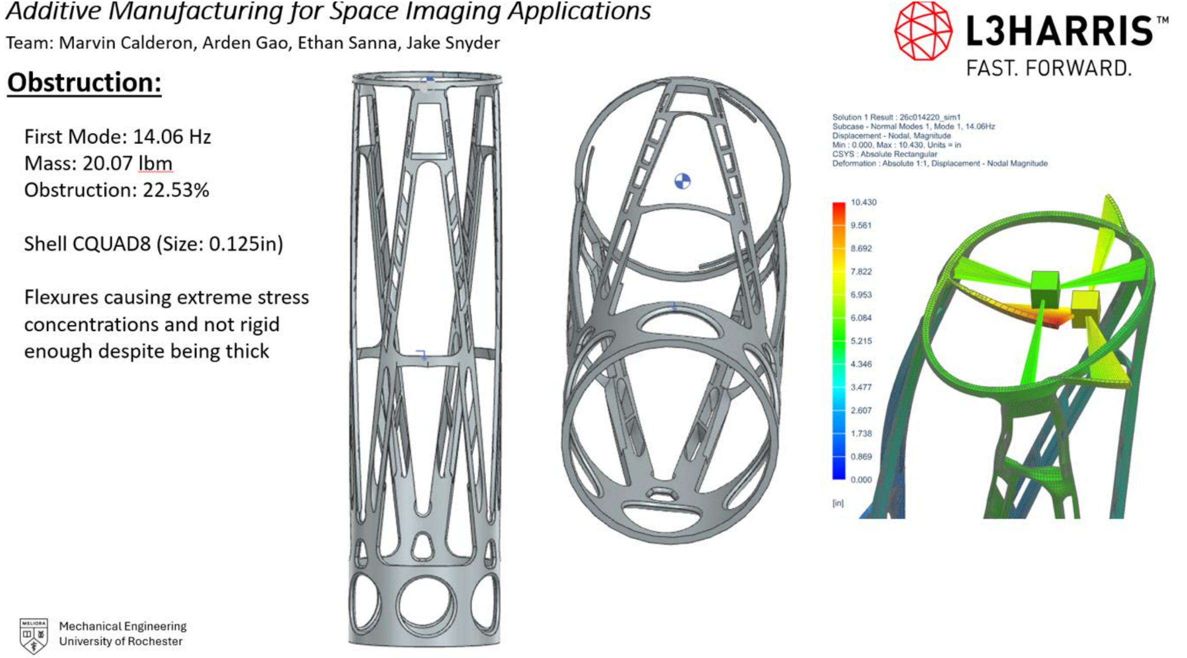




Design Concepts

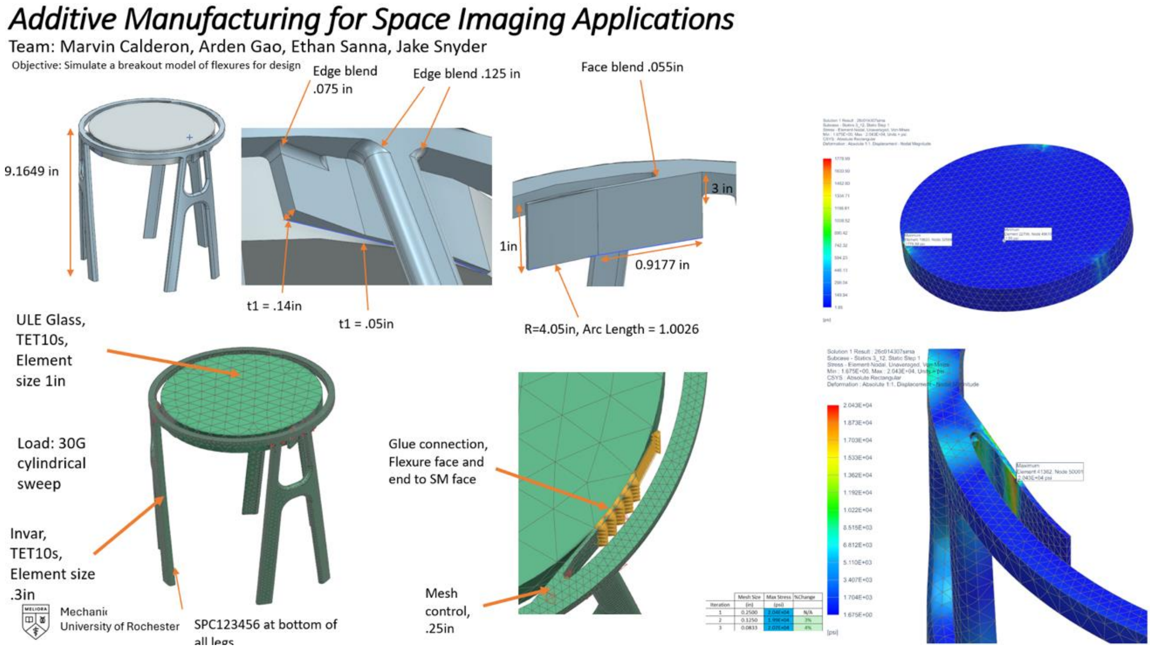
Design D:

- Optimized case study for obscuration requirement
- MATLAB obscuration code used to efficiently remove mass in the direction of the light vector

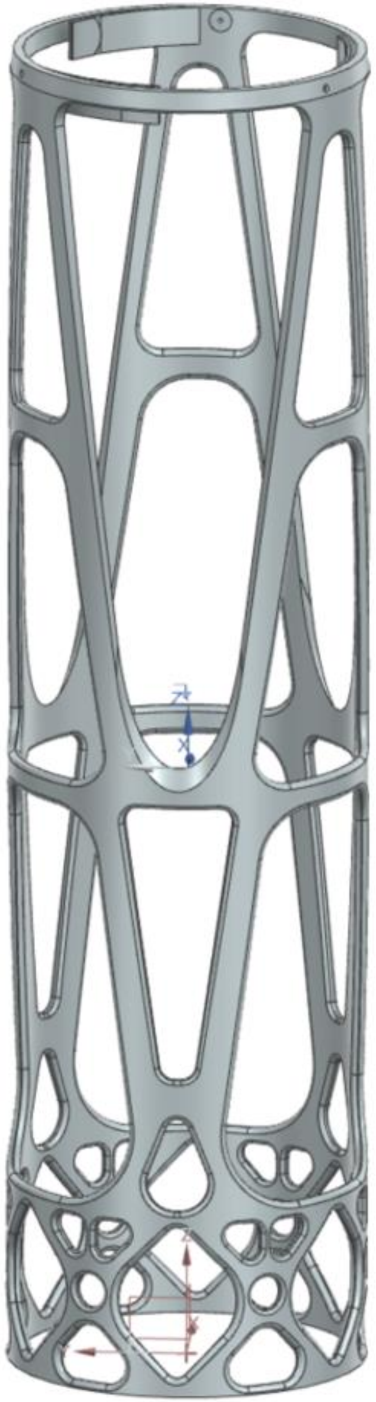


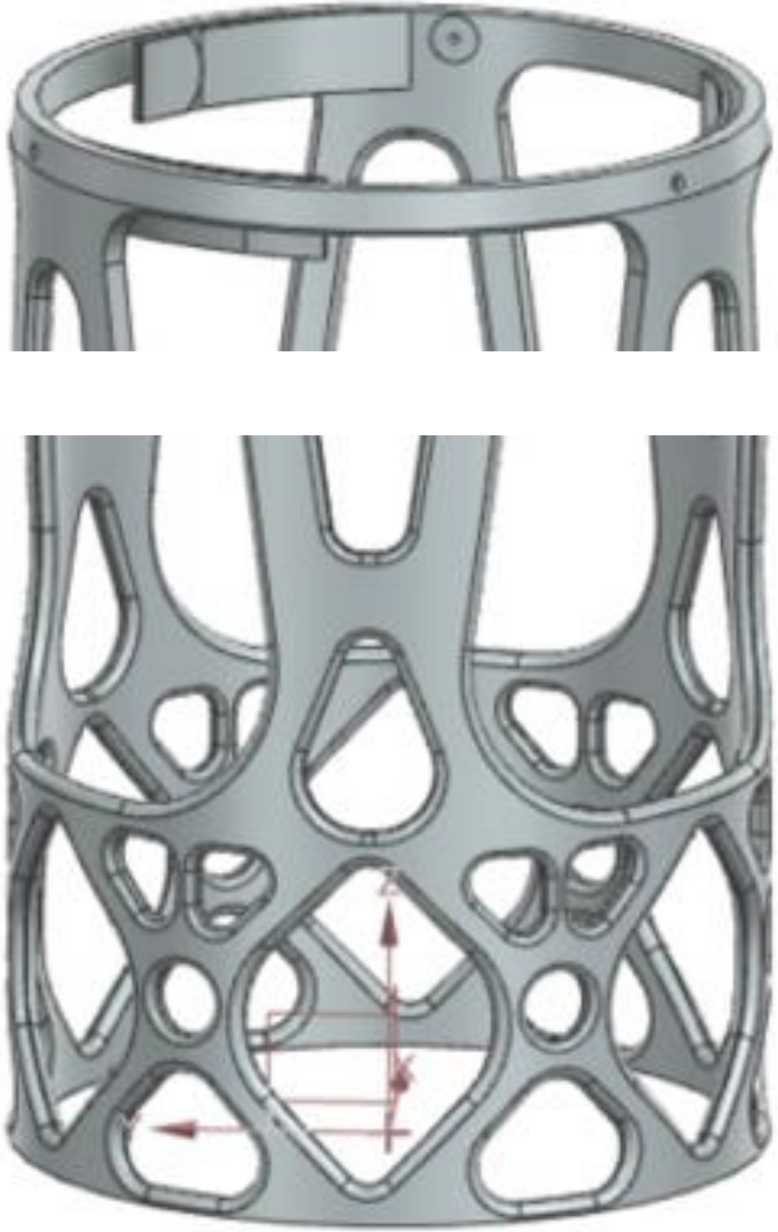
Design E:

- Initial design of flexures
- Extreme stress concentrations required aggressive edge blending



Final Design





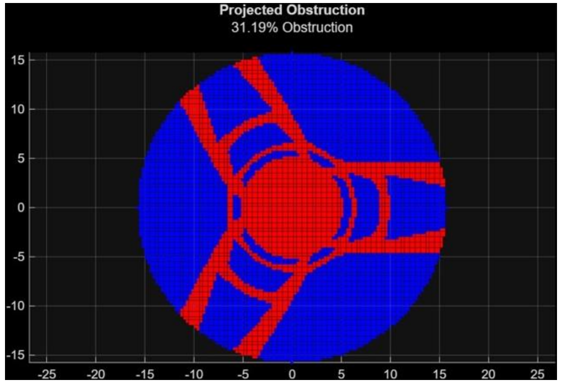
Current Project Status

Requirement ID	Description
[UR-FMS-001]	Quasi-static launch loads of 30 g spherical sweep, swept at 15-degree increments, while supporting all hosted hardware.
[UR-FMS-002]	Factors of Safety (FOS) • Yield ≥ 2.0 • Ultimate ≥ 2.5; • Ultimate Glass ≥ 5 • Buckling ≥ 2.5
[UR-FMS-003]	Under a 1°C isothermal temperature change, the average motion of the SM interface shall be limited to: • 0.2 µm (7.87 micro inches) translation (RSS of X and Y), and • 0.9 µrad rotation (RSS of Rx and Ry)
[UR-FMS-006]	Mass < 25 lbm
[UR-FMS-007]	First Mode > 60 Hz
[UR-FMS-020]	Obscuration < 22 %

	Final Design: Specifications
CRITERIA	Design: 26c026607A
UR-FMS-001	Compliant
UR-FMS-002	Yield: 0.0127 > 0 Ultimate: 0.526 > 0 SM Ultimate: 0.390 > 0 Buckling: 7.23
UR-FMS-003	RSS: 7.10 µin RSS: 0.0108 µrad
UR-FMS-006	24.63 lbm
UR-FMS-007	61.82 Hz
UR-FMS-020	31.19%

Legend

(green)	Expected Compliance
(red)	Not Compliant



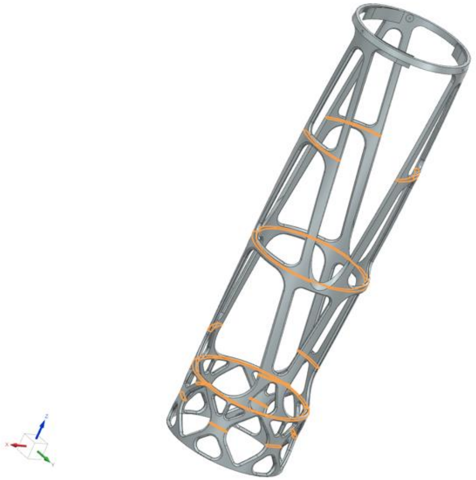
Current Project Status

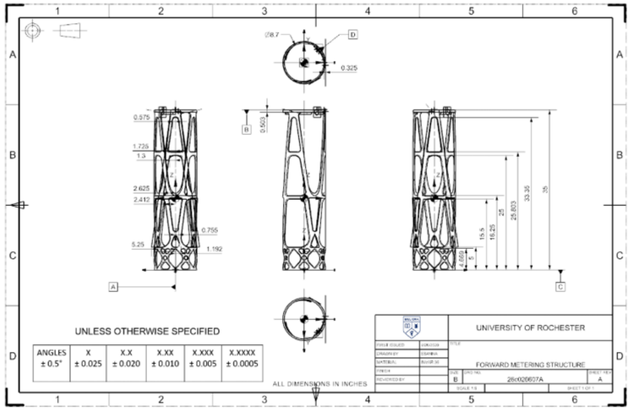
Deliverable ID	Description	Check
[CRDL-UR-001]	CAD file prototypes using NX (step file format) and 2D drawings	
[CRDL-UR-002]	Finite Element Model (FEM) in Nastran	
[CRDL-UR-003]	Final Design Report (FDR)	
[CRDL-UR-004]	Host design review meetings and provide supporting slides and drops of the CAD and FEM	
[CRDL-UR-005]	Concept Design Review (CDR)	
[CRDL-UR-006]	Preliminary Design Review (PDR)	
[CRDL-UR-007]	Final Design Review (FDR)	
[CRDL-UR-008]	3D printed prototype	
[CRDL-UR-009]	Model testing and validation	

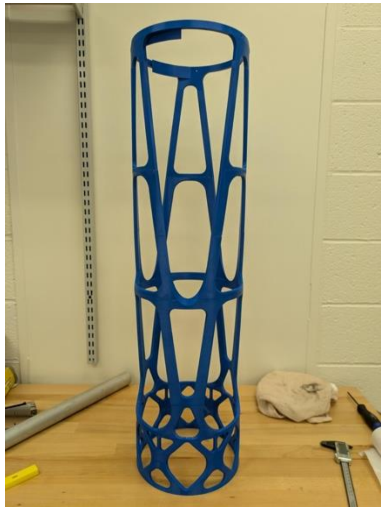
Legend

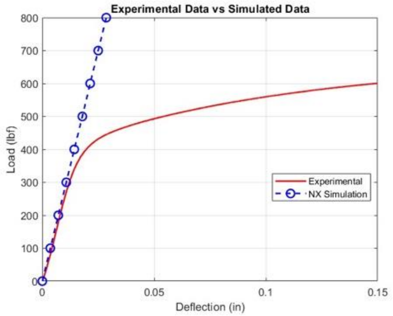
Complete

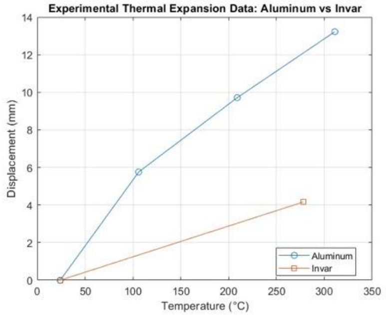
Incomplete

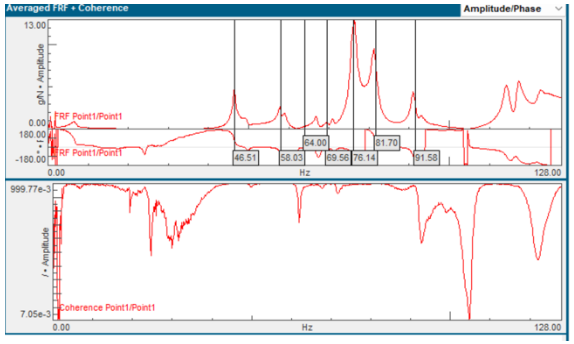




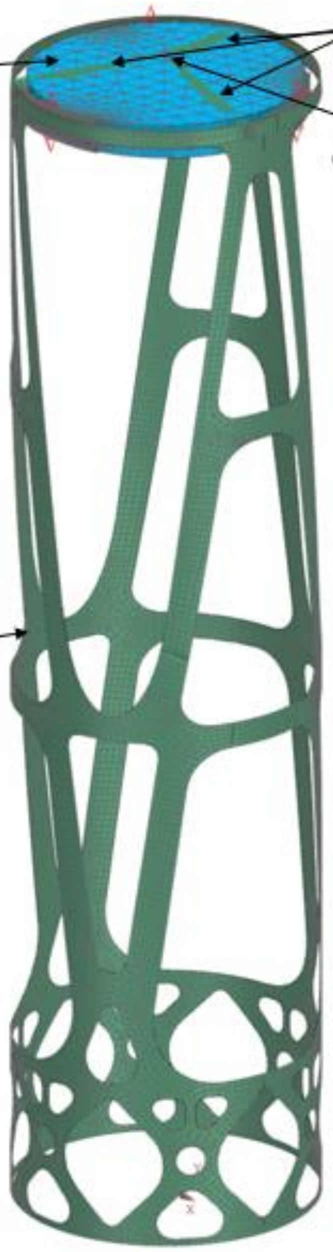


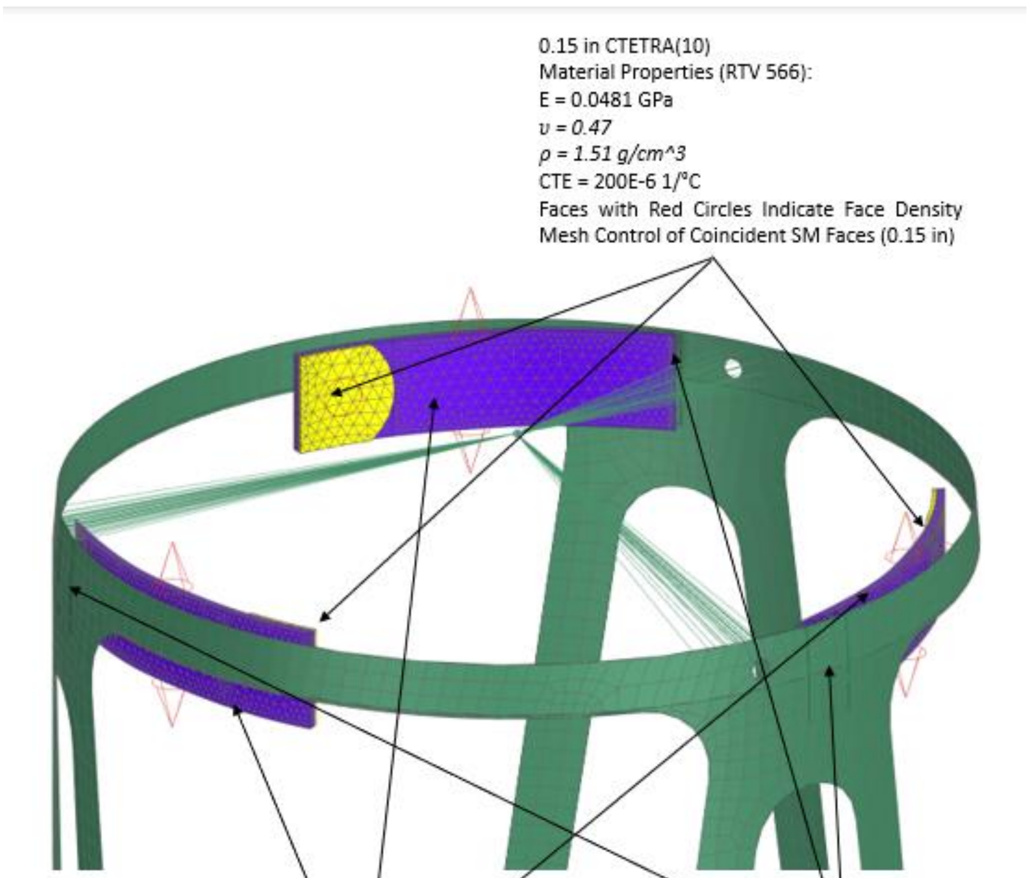






Analysis

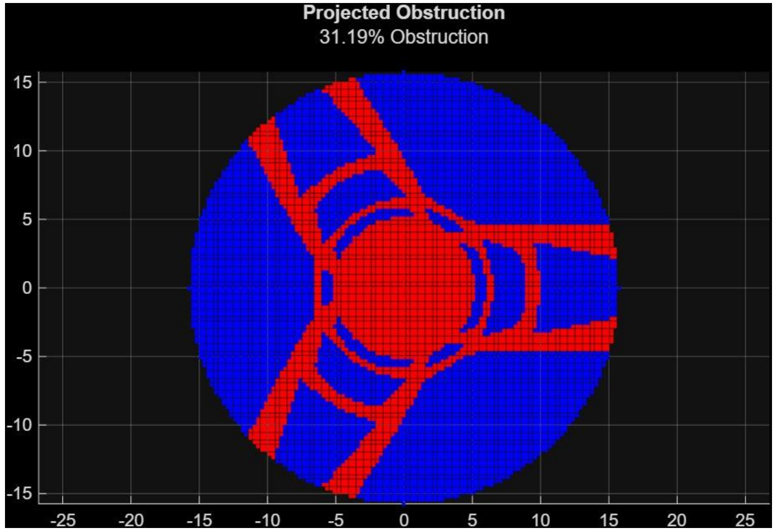

RBE3 (120° Apart)
1 in CTETRA(10)
Material Properties (ULE 7972 Glass):
E = 67.6 GPa
$\upsilon = 0.17$
$\rho = 2.21\ g/cm^3$
CTE = 30E-9 1/°C
Ultimate Tensile Strength = 49.8 MPa
CONM2 4.04 lbm, COM [0, 0, 35.61]
Material Properties (SA Al_6061):
$\rho_{bulk} = 7.08\ g/cm^3$
0.2 in CQUAD4 Shell Midsurface
Thickness: 0.325 in
Material Properties (Invar):
E = 141 GPa
$\upsilon = 0.29$
$\rho = 8.10\ g/cm^3$
CTE = 0.4E-6 1/°F
Yield Strength = 240 MPa
Ultimate Tensile Strength = 500 MPa

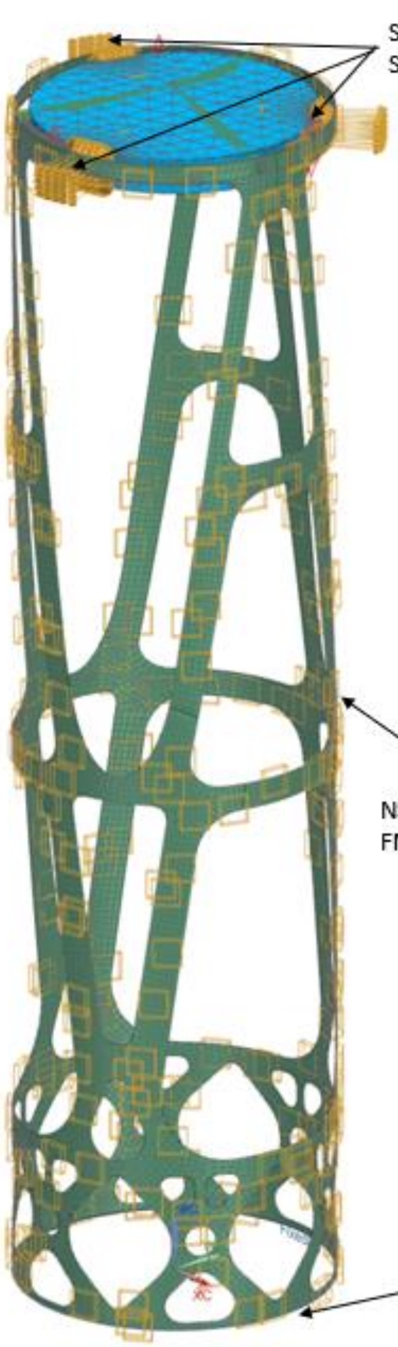

0.15 in CTETRA(10)
Material Properties (RTV 566):
E = 0.0481 GPa
$\upsilon = 0.47$
$\rho = 1.51\ g/cm^3$
CTE = 200E-6 1/°C
Faces with Red Circles Indicate Face Density Mesh Control of Coincident SM Faces (0.15 in)
0.15 in CTETRA(10)
Material Properties (Invar):
E = 141 GPa
$\upsilon = 0.29$
$\rho = 8.10\ g/cm^3$
CTE = 0.4E-6 1/°F
Yield Strength = 240 MPa
Ultimate Tensile Strength = 500 MPa
Faces with Red Cones Indicate Face Density Mesh Control (0.05 in)
RBE2 (Face to Face)

Analysis

Simulations:

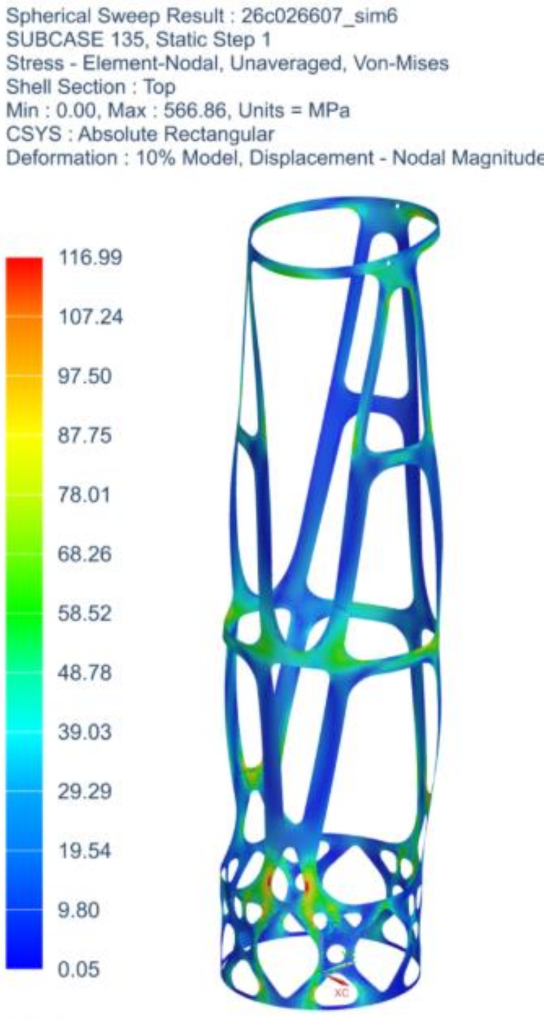
- SOL 101: Linear Statics
  - MOS, FOS of Yield and Ultimate Stresses
- SOL 103: Real Eigenvalues
  - First Mode
- SOL 105: Linear Buckling
  - Buckling FOS
- SOL 101: Linear Statics
  - Isothermal Displacements
- MATLAB
  - Obscuration

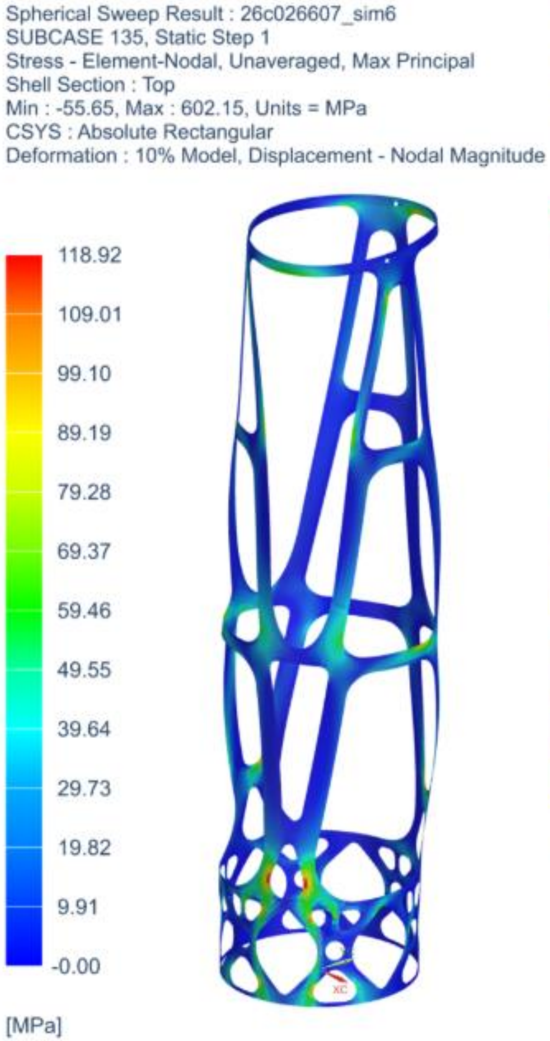


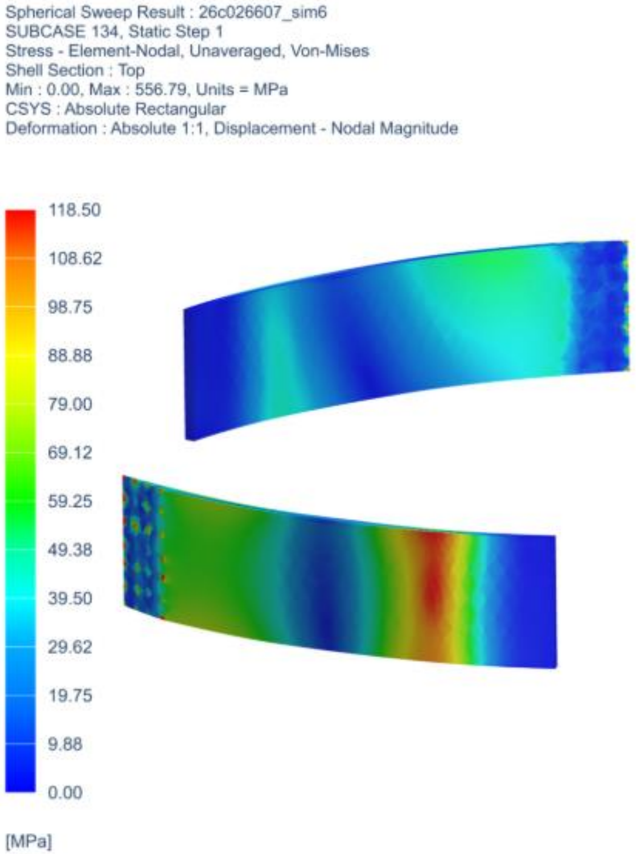


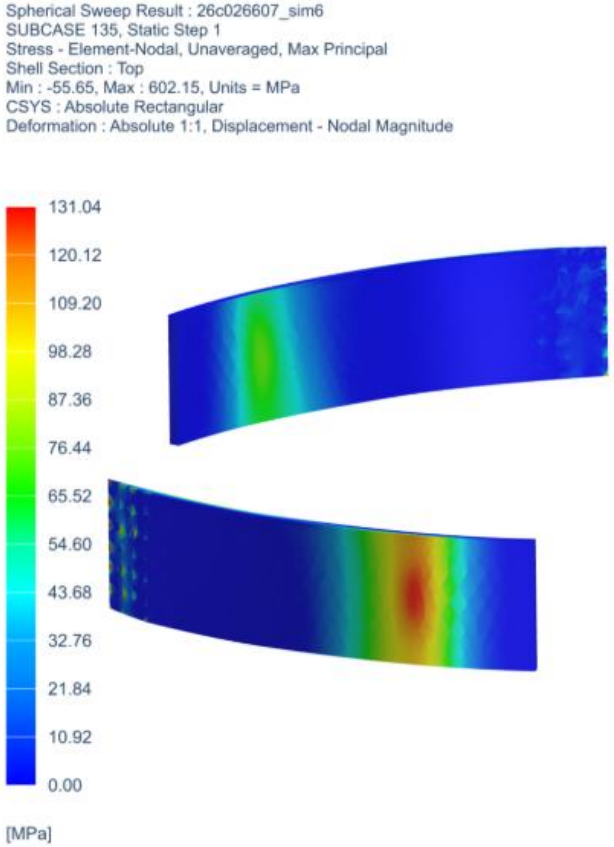
Analysis

Spherical Sweep: Yield Stress < 120 MPa and Ultimate Stress < 200 MPa



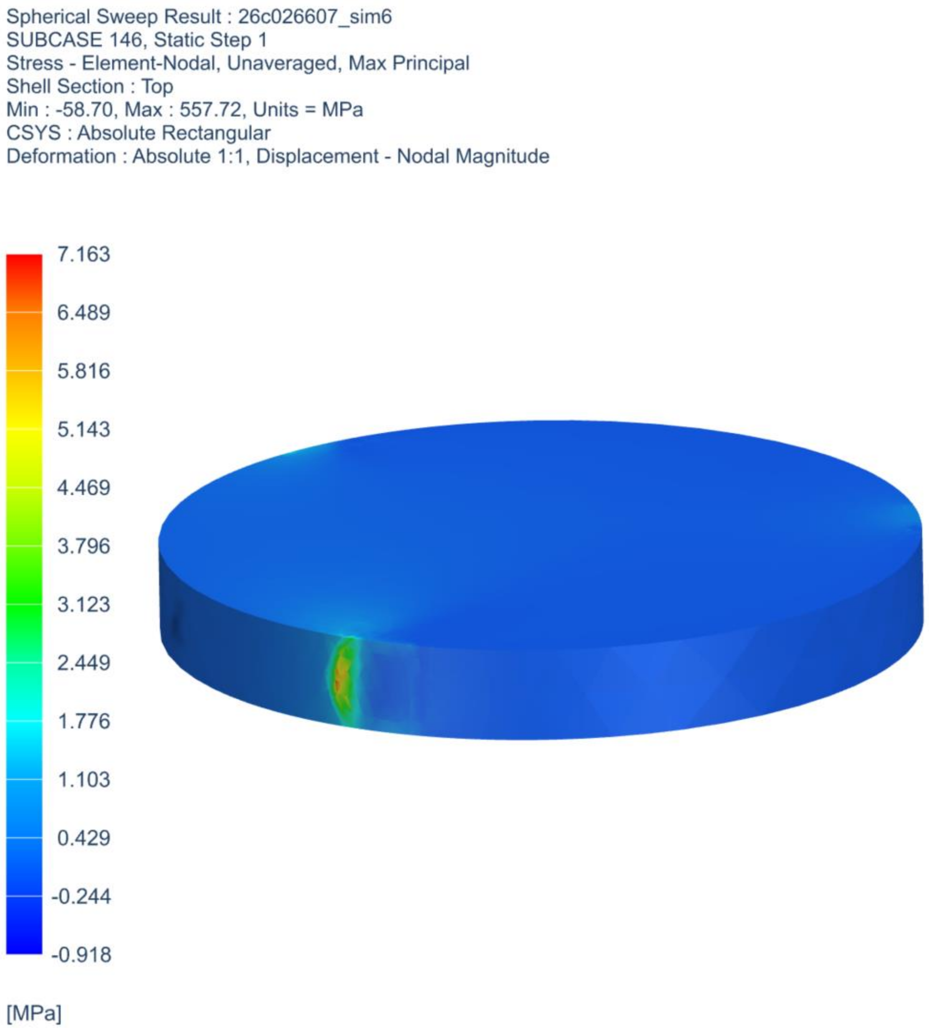


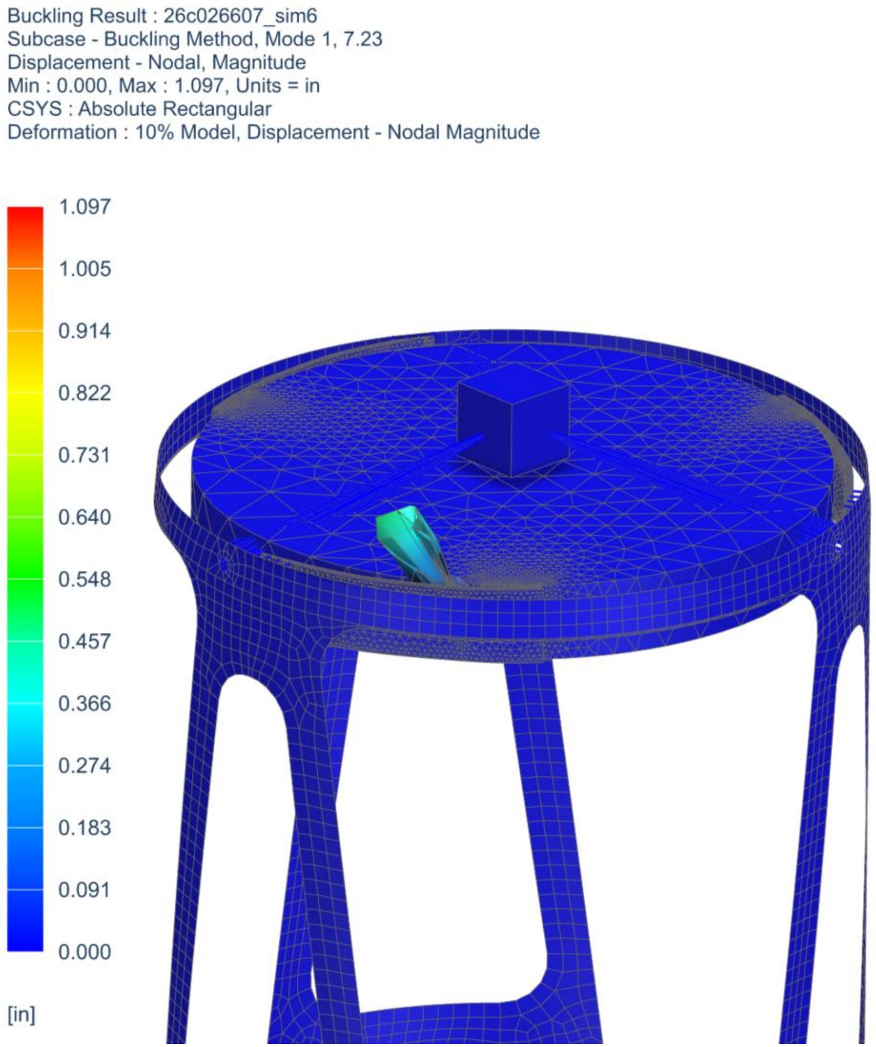




Analysis

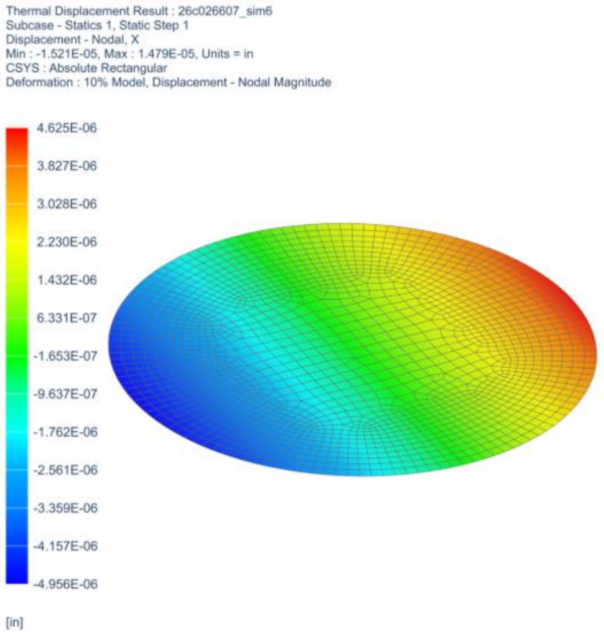
Spherical Sweep: Ultimate Stress < 10.54 MPa and Buckling Eigenvalue > 4

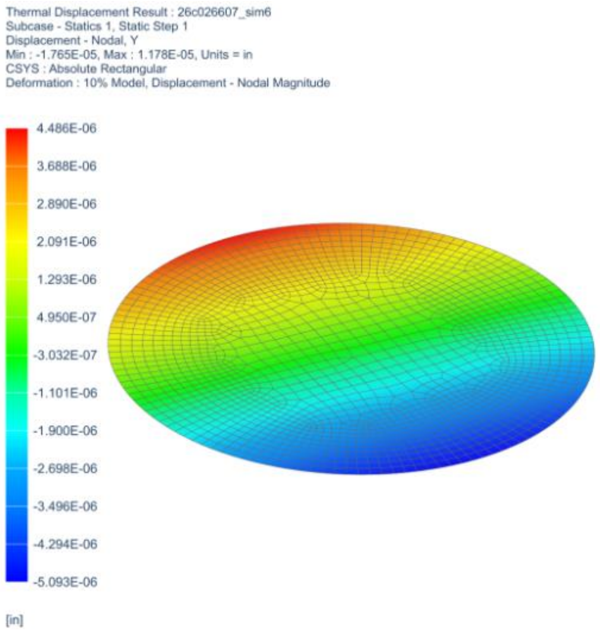


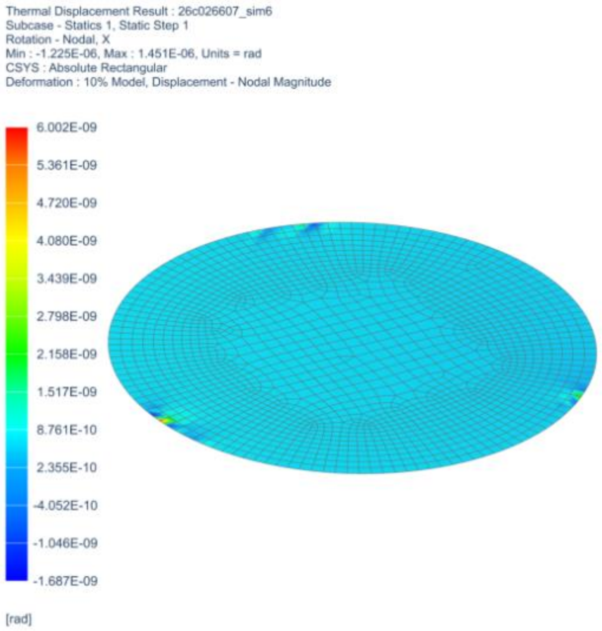


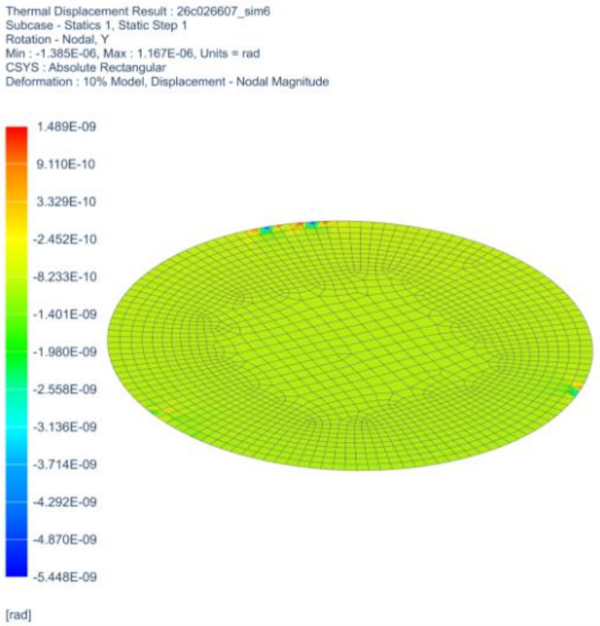
Analysis

Isothermal Displacement: Displacement RSS < 7.87 µin and Rotational RSS < 0.9 µrad







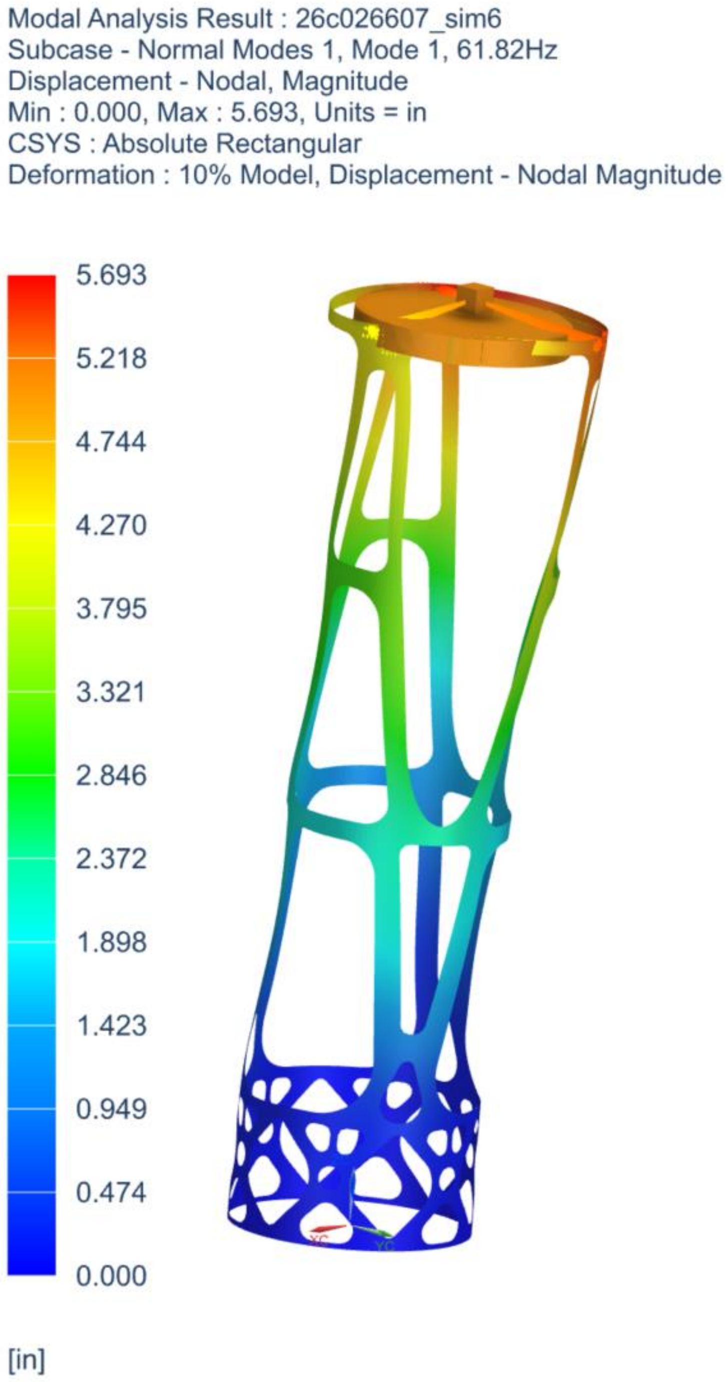


$$RSS_d = \sqrt{(-4.956 * 10^{-6})^2 + (-5.093 * 10^{-6})^2} = 7.11 \text{ µin}$$

$$RSS_r = \sqrt{(6.002 * 10^{-9})^2 + (-5.448 * 10^{-9})^2} = \mathbf{0.008 \text{ µrad}}$$

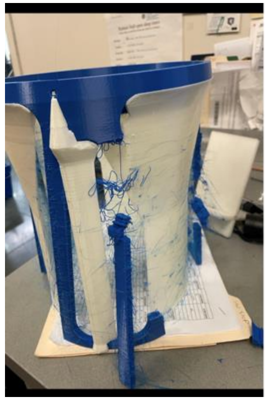
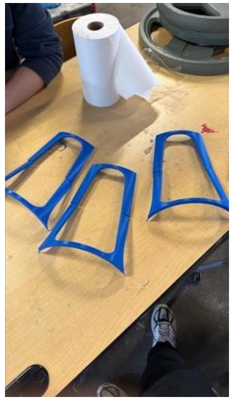
Analysis

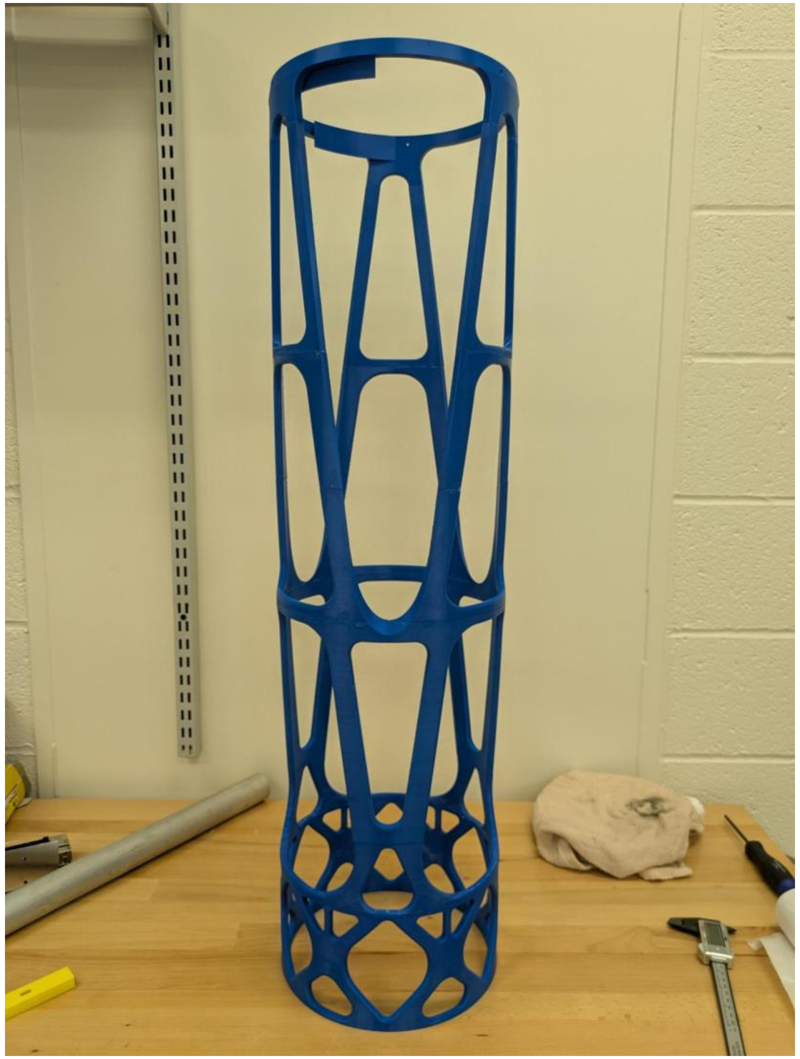
Modal Analysis: First Mode > 60 Hz



Manufacturing

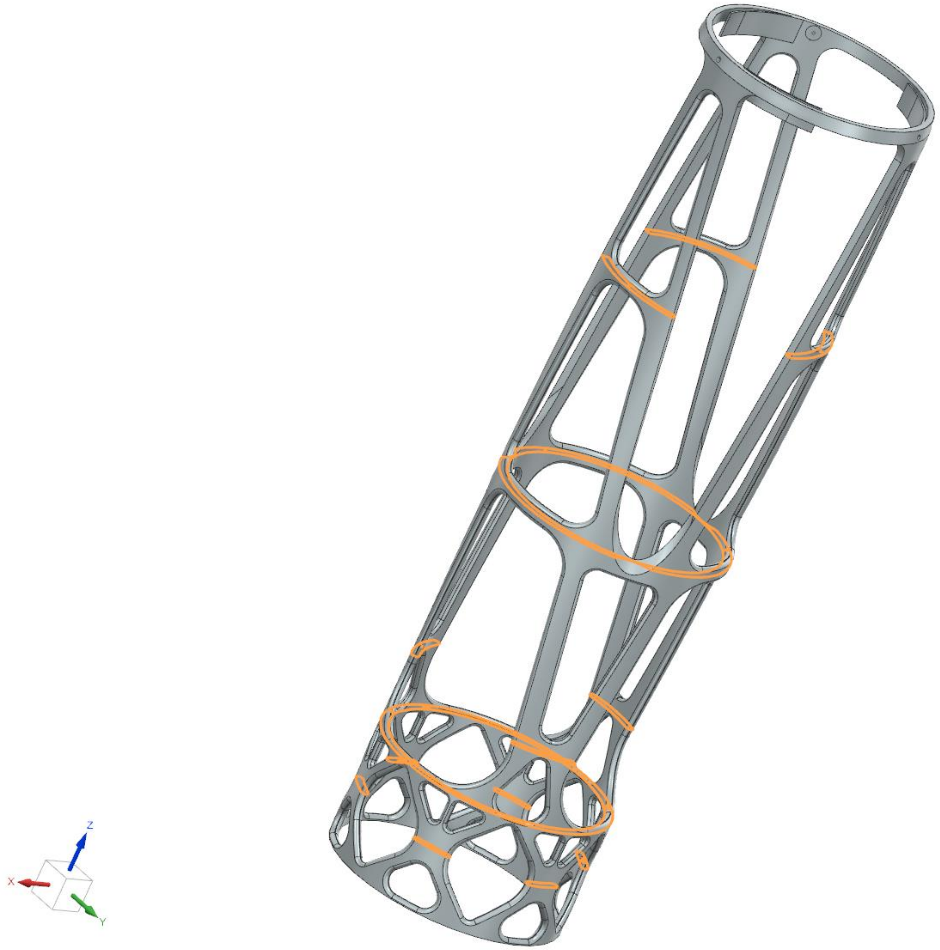
- The final full-scale prototype required multiple print jobs because the FMS was divided into separate sections.
- GrabCAD Print estimates were used to record print time, ABS material usage, and QSR support material usage for each section.
- These values were important for estimating manufacturing cost and understanding the practical time commitment required to produce the full-scale prototype.
- While the ABS prototype was not equivalent to the intended DMLS Invar structure, the print-time and material data provided a realistic manufacturing estimate for the physical system delivered by the team.

Print Time and Material Usage

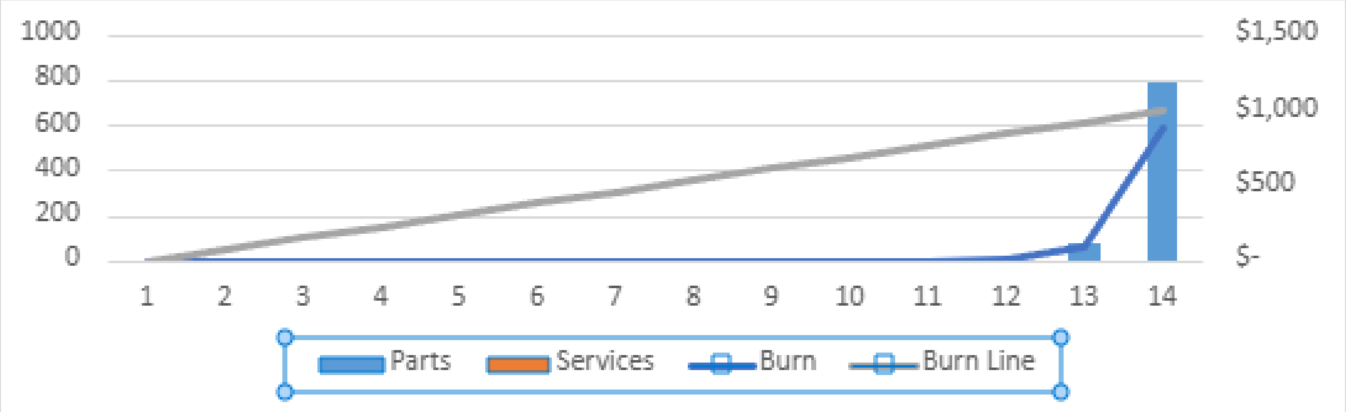
Section	Print Time (hr:min)	ABS Material (in^3)	QSR Support Material (in^3)
1	10:01	9.345	4.273
2	09:49	10.143	4.046
3	07:25	5.54	3.828
4	18:07	16.238	5.506
5	16:01	16.498	3.466
6	17:41	16.028	7.366
Subtotal	**79:04**	**73.792**	**28.485**

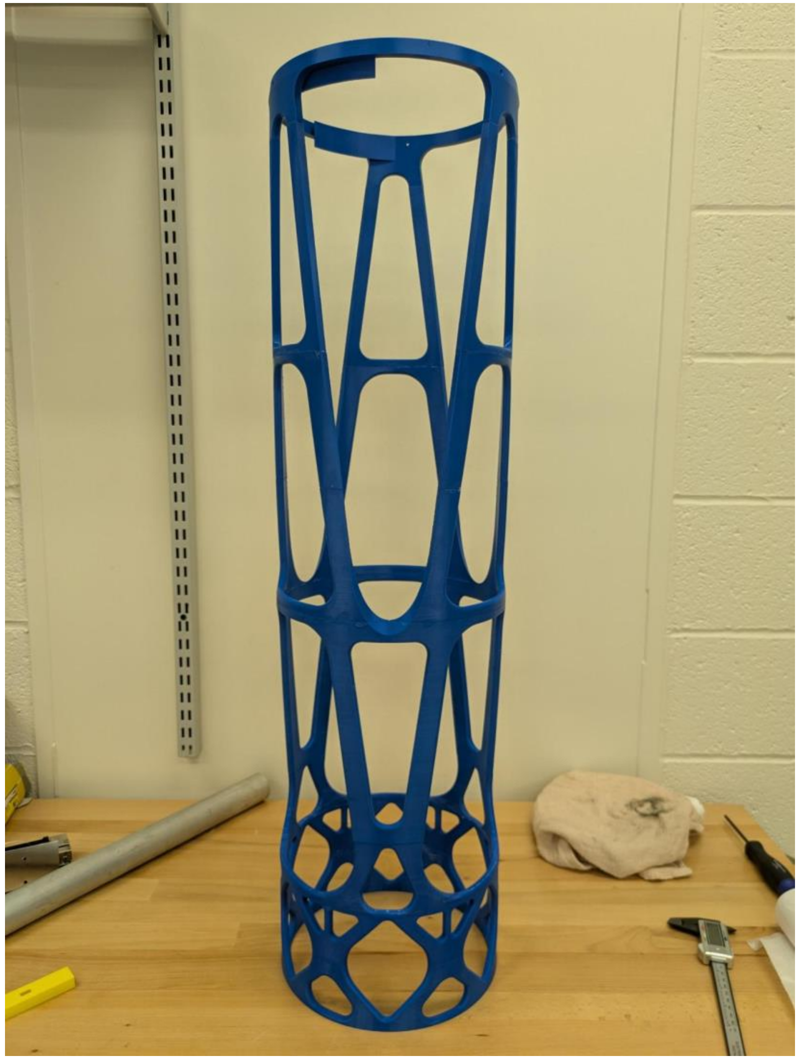


Cost Estimate

Item	Cost
ABS Material	$786.85
QSR Material	$108.24 (estimated)
Total	**$895.09**

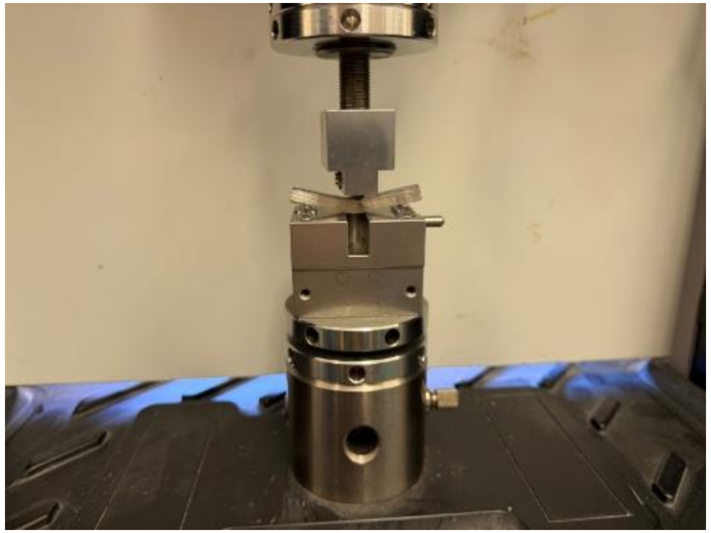
~$3.80 / in³ average QSR ABS cost rate online

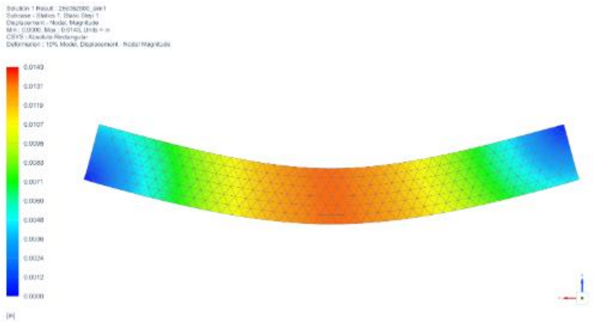




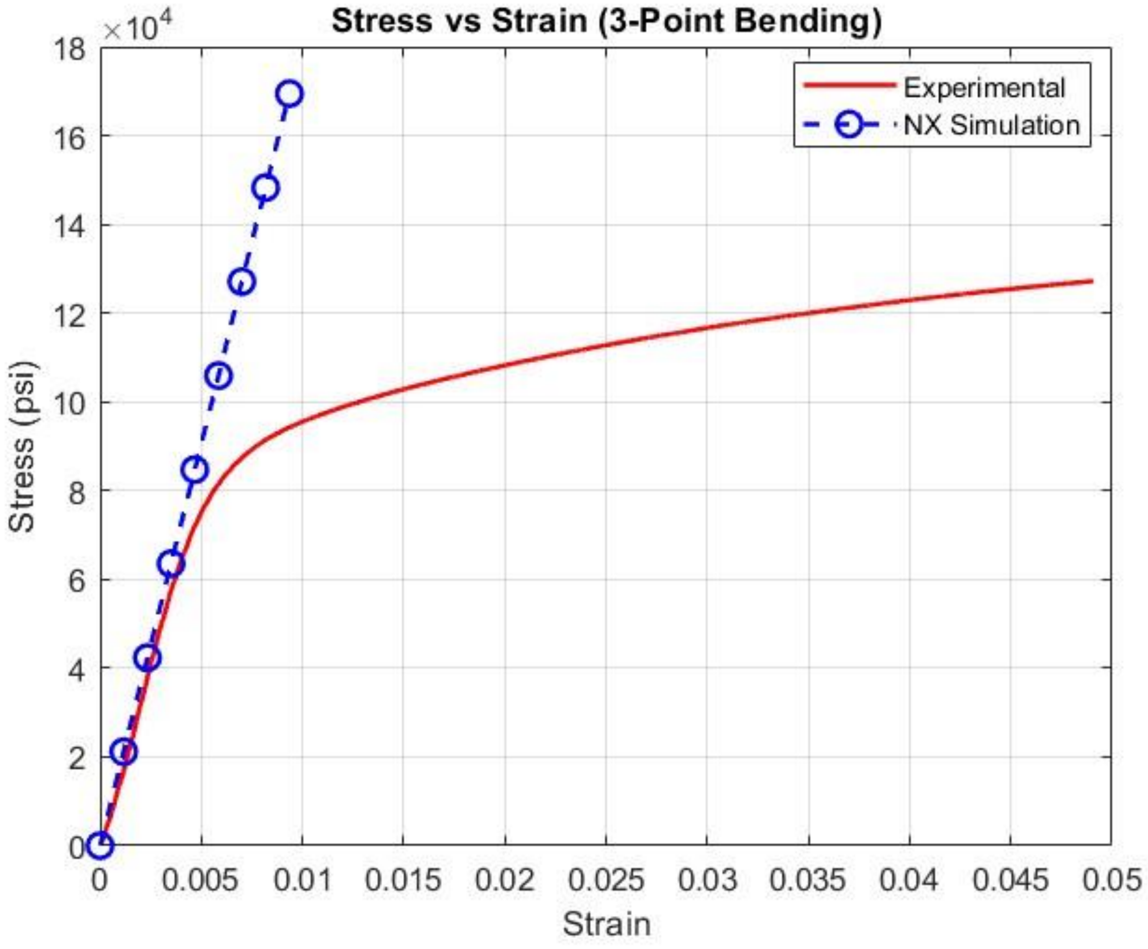
Material Test

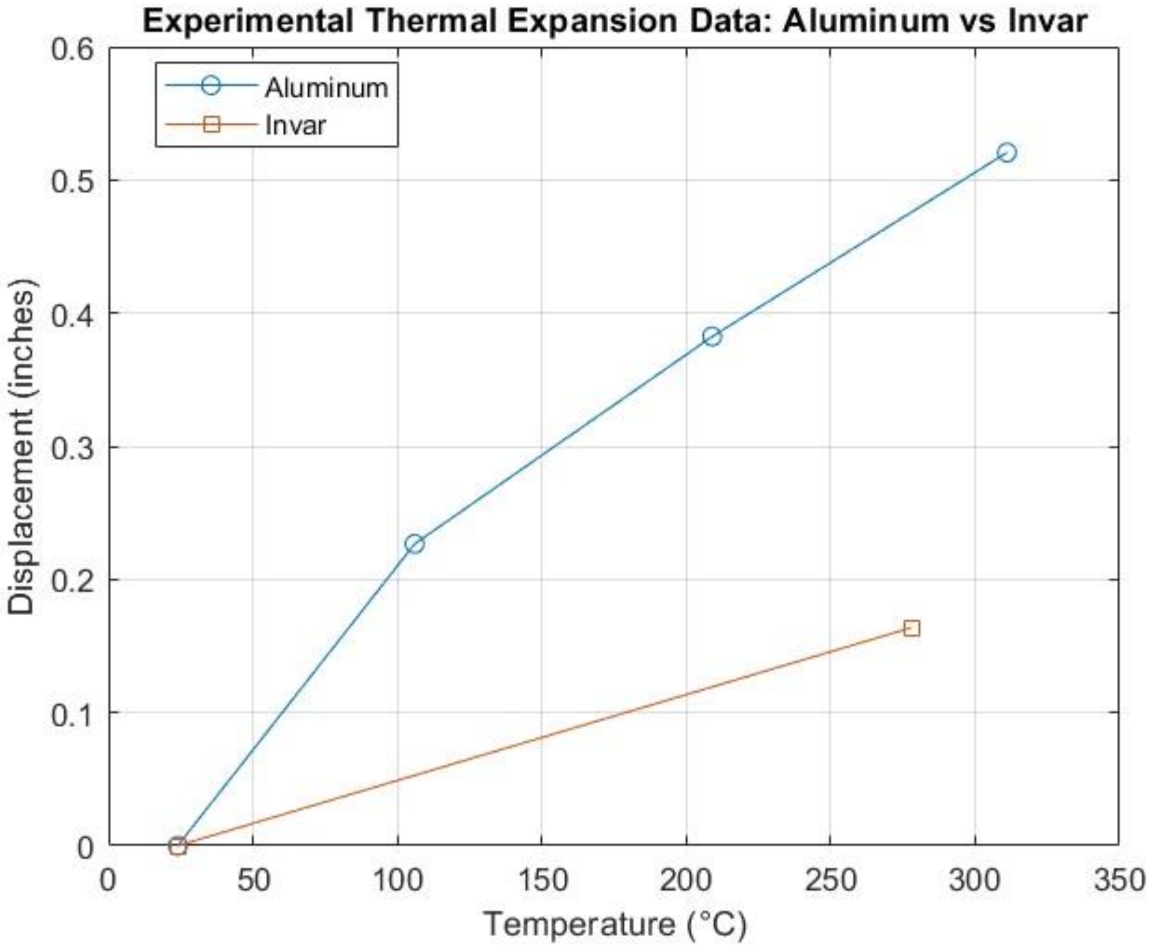
- A significant portion of this project was dedicated towards material testing to validate the performance of the FMS prior to manufacturing.
- This testing was performed on a subtractive manufactured sample of Invar because the team was unable to acquire DMLS (PBF) Invar 36.
- It’s important to note that the team recognizes that these tests don’t exactly mirror PBF data.
    - Instead, the objective of these tests was to cover a framework that demonstrates how these evaluations would be conducted to validate material.
- Two tests were performed:
    1. 3-Point-Bend
    2. CTE





Material Data



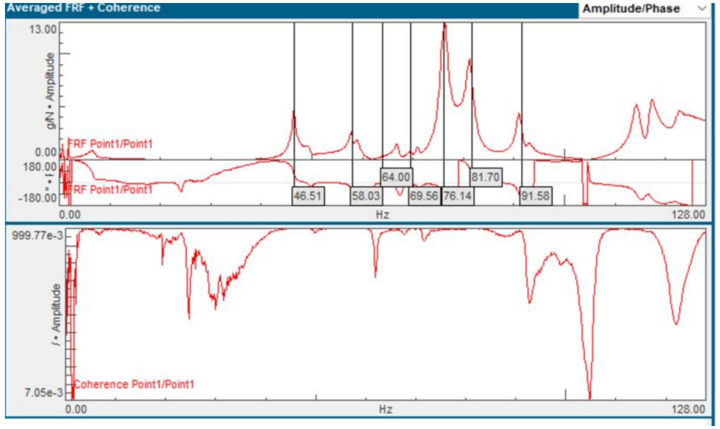


Vibration Test/Model Correlation

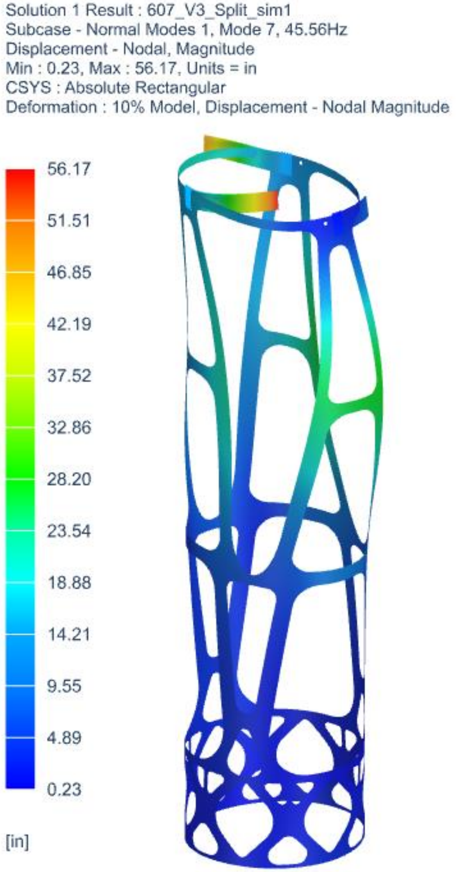
- A vibration test on the printed scale was performed to verify CAD model simulations

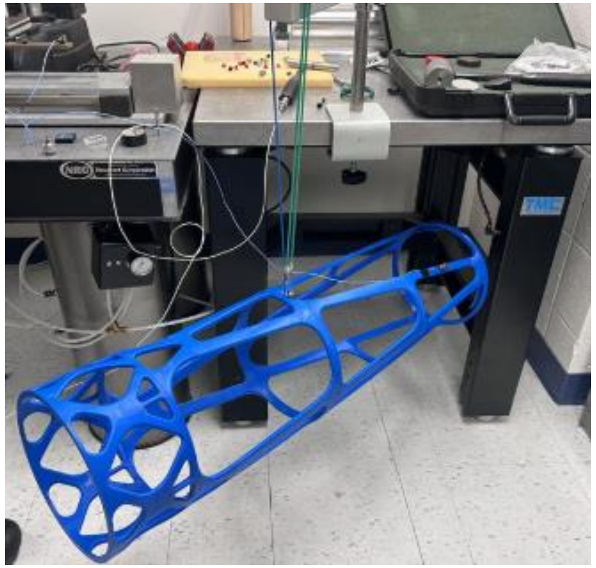
- Physical model was weighed and density was used for correlation simulation

- ABS Spec sheet density: 1.05 g/cm^3
- ABS Tested density : 0.971 g/cm^3



	Simulation with test density	Test 1	% Error
1st Mode	45.56	46.51	2%





Conclusions/Future Work

Future Work

If the team had more time or the opportunity to revisit the project, the following areas would be the highest priorities for continued development:

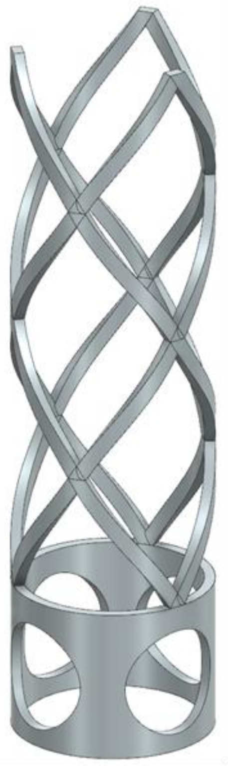
- Reduce obscuration to meet the final requirement
- Continue MATLAB + NX optimization and design refinement
- Further tailor the geometry to additive manufacturing capabilities
  - Reduce support-structure needs and 90° overhangs
- Improve member alignment with the optical path
- Manufacture a more representative DMLS Invar/substitute metal prototype for testing correlation

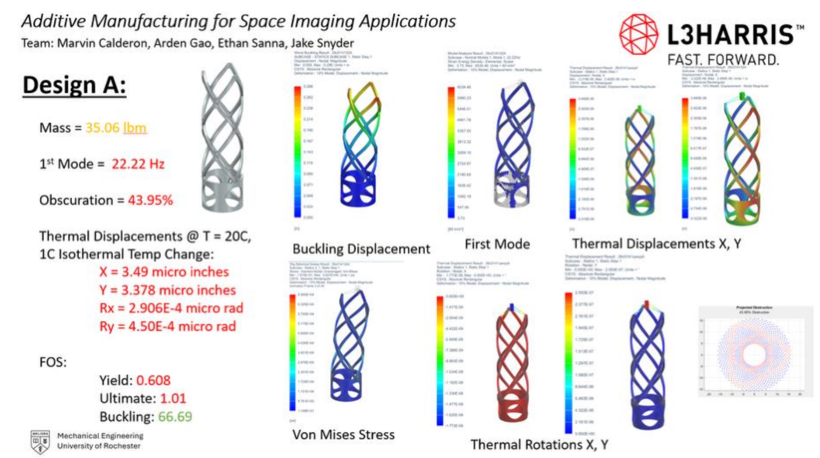
Acknowledgements

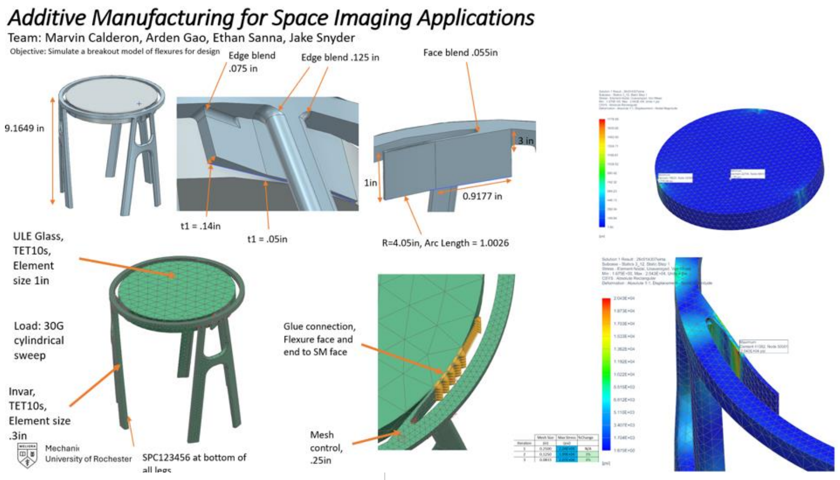
The ME205 L3Harris Senior Design Team would like to first thank our sponsor, L3Harris, and the team members Patrick Ellsworth, Steve Sutton, Devin Woodyard, and Pat Zinter for their technical expertise and support. The authors would also like to acknowledge and thank Professor Muir, along with Jim Alkins, Chris Pratt, Ed Herger and Angel Bermudez for their mentorship and guidance throughout this semester. Finally, the authors would like to thank our peers in senior design, who have now been our classmates for the past four years in Mechanical Engineering at the University of Rochester. This project would not have been made possible without their willingness to share ideas, constructive feedback and insight.

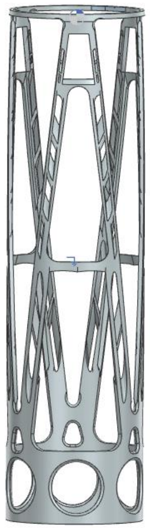
Individual Contribution: Marvin Calderon

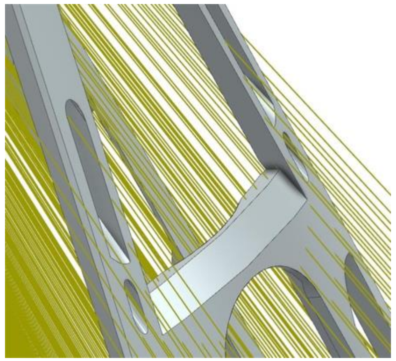
- Developed design A for down selection
- Designed various iterations leading to final design, collaborating with team members to meet specification
- Conducted FEA to push design forward
- Expanded on the provided Obstruction MATLAB scripts, to incorporate geometry into NX
  - Streamlined future design of allowing for obstruction optimization
- Responsible for early to near end stage design of FMS to SM interface
- Contributed to writing and content for Gates B, C and D
- Responsible for the initial splitting of parts for printing, including slicing and printing of the first two partsAssisted construction of 3D printed assembly







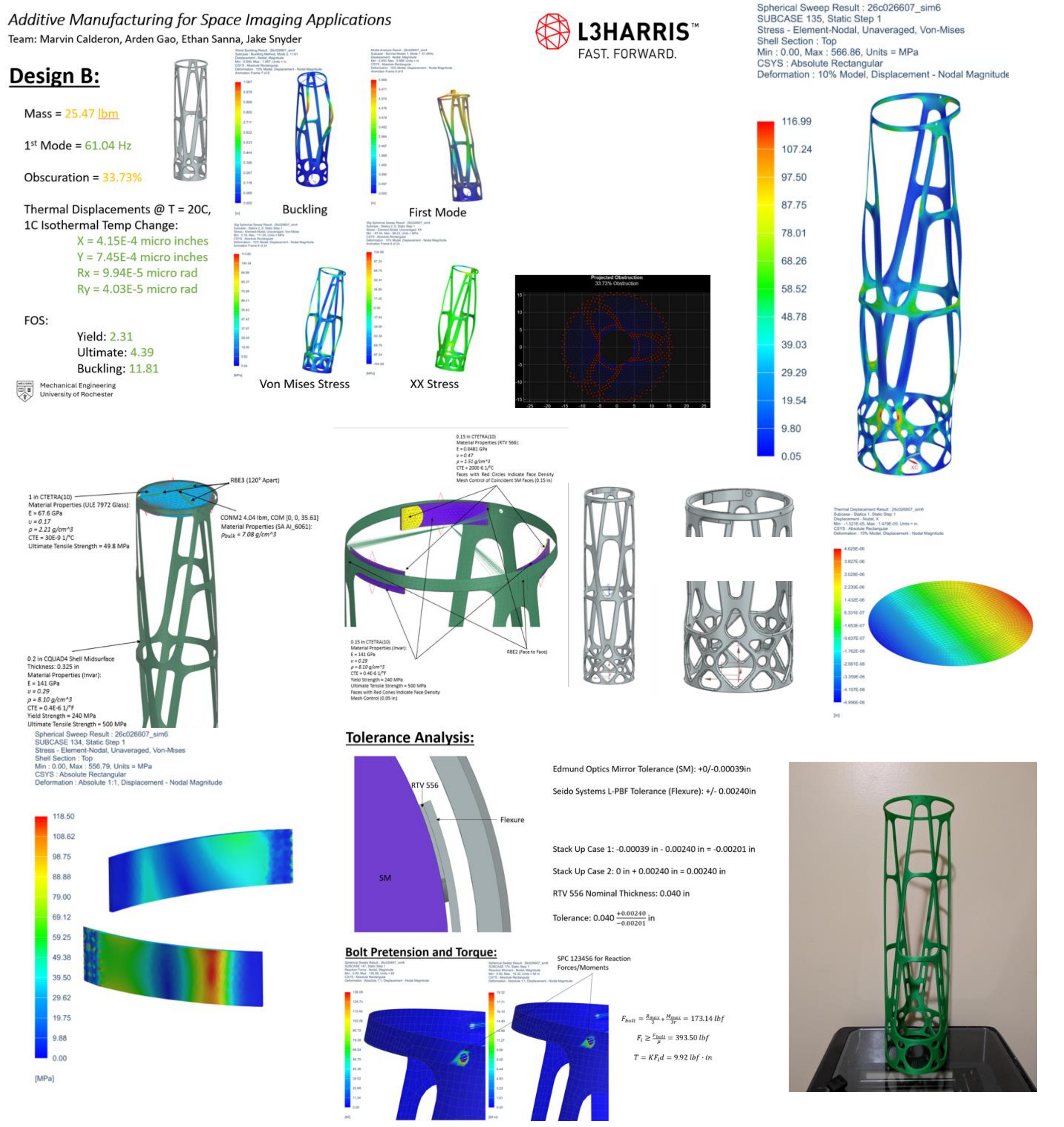




ME205 - Advanced Mechanical Design

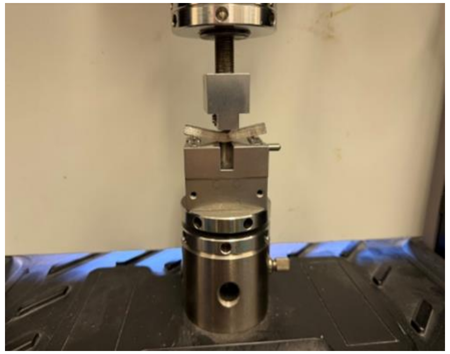
Individual Contribution: Arden Gao

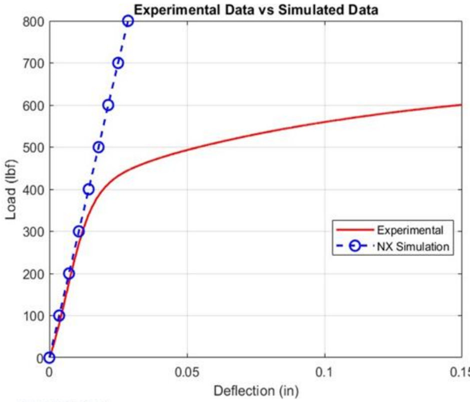
- Created Design B for the down selection
- Designed PDR version of the FMS and conducted all FEM/SIM setups to meet requirements
    - Wrote these sections for the PDR
- Characterized and researched all materials for analysis from multiple sources
    - Conducted case study on RTV CTE
- Incorporated design ideas from group members to improve initial Gate B design and FDR design through multiple iterations/concepts
    - Printed/post-processed 2 iterations for display
    - Designed SA interface
- Ran all FEM/SIM analysis and optimization for the Final Design to meet requirements
- Conducted bolt pretension/torque, fastener hand calculations, and fatigue life analysis in FDR
    - Wrote about each FEM/SIM setup for FDR
- Conducted simulation for test correlation
- Assisted in assembly of Design Day print

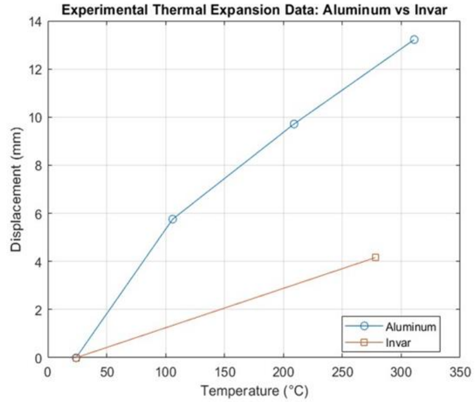


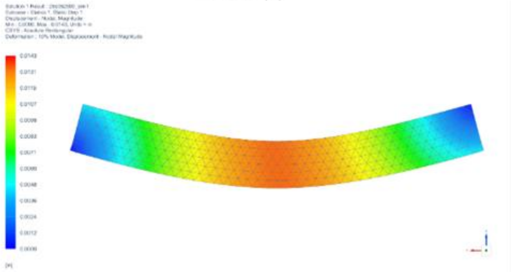
Individual Contribution: Ethan Sanna

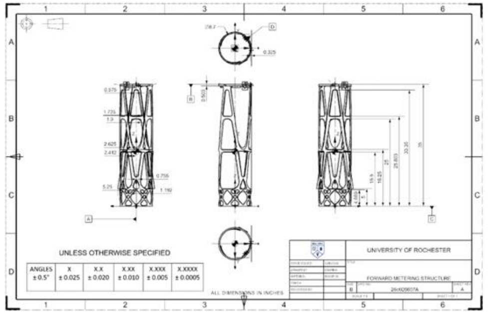
- Connected with past L3Harris Alum (Declan Bhagwat, Angel Bermudez as well as L3 representative Patrick Zinter
- Gate A
  - Created several of the initial concept design
  - Problem Statement, Requirements, Specifications, and Deliverables
- Gate B
  - Pugh Matrix comparison for PDR
  - Wrote several sections of the PDR
- Gate C
  - Created the BOM
  - Created 2D CAD Drawings for Parts
  - Managed and submitted all purchase orders
- Gave technical presentation to ME120 students
- Performed material testing with Chris Pratt, Jim Alkins and Ed Herger
- Created all weekly update PowerPoints
- Assisted in manufacturing assembly / design day
- Gate D
  - Managed both FDRs and wrote several sections

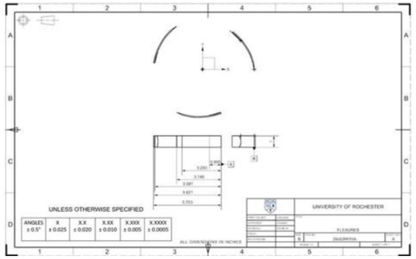






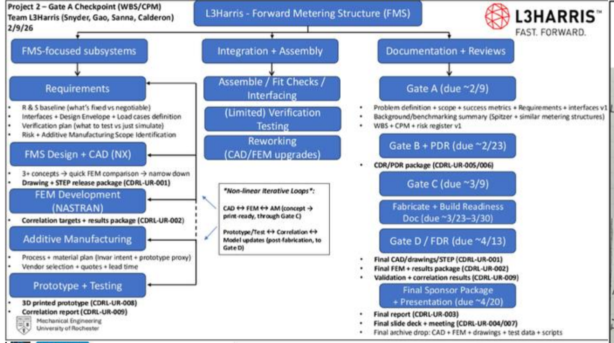


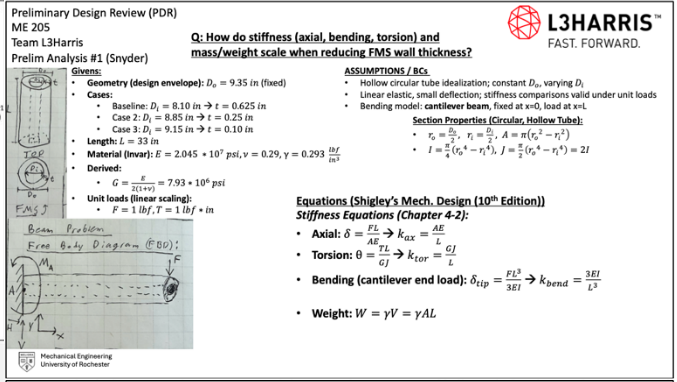


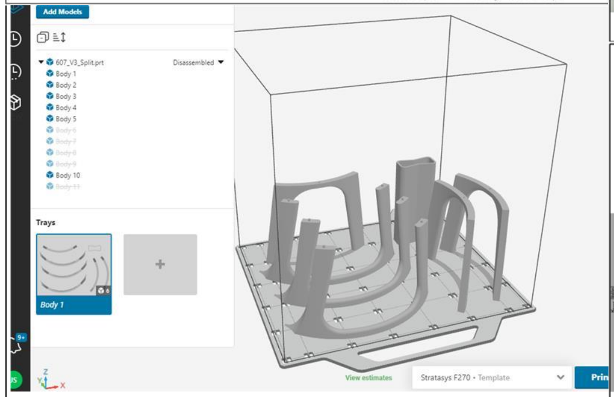


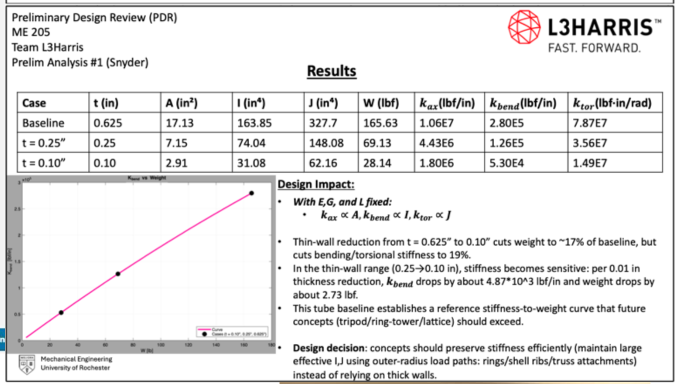
Individual Contribution: Jake Snyder

- Original team lead during project kickoff; **helped define sponsor expectations, meeting schedule, and project direction**
- Led most of **Gate A**, including **WBS**, **critical path planning**, dependency matrices, and MATLAB-based project planning tools
- Major contributor to **early concept generation**, design down selection, and **preliminary FMS mechanical analysis**
- **Built early CAD/FEM models**, ran simulations, supported flexure development, and helped drive optimization decisions
- Wrote major portions of the **PDR/Gate B** and presented a significant share of the L3Harris technical review
- Led **external vendor outreach**, quote comparison, and **metal AM feasibility discussions**
- **Owned much of the full-scale ABS prototype planning**, slicing, sectioning, and **shop coordination**
- Wrote key **Gate D/FDR** sections and created the team's final project website









Case	t (in)	A (in²)	I (in⁴)	J (in⁴)	W (lbf)	k_{ax}(lbf/in)	k_{bend}(lbf/in)	k_{tor}(lbf-in/rad)
Baseline	0.625	17.13	163.85	327.7	165.63	1.06E7	2.80E5	7.87E7
t = 0.25"	0.25	7.15	74.04	148.08	69.13	4.43E6	1.26E5	3.56E7
t = 0.10"	0.10	2.91	31.08	62.16	28.14	1.80E6	5.30E4	1.49E7

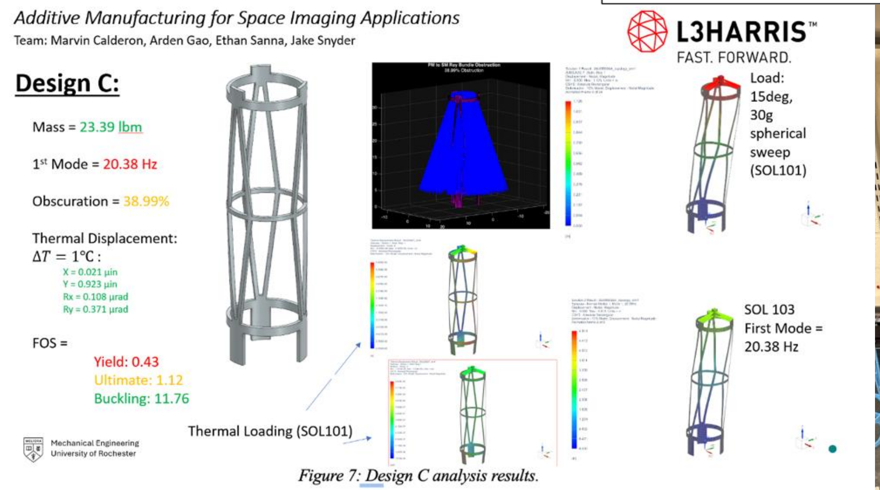


Figure 7: Design C analysis results.

Mechanical Engineering
University of Rochester

ME205 - Advanced Mechanical Design

A	B	C	D	E	F	G
Project Hours	Marvin	Arden	Ethan	Jake		
Hours Last Week	15	15	15	15	Total	Cost
Total Hours	138	147	103	112	500	$50,000.00