A Design-Validation-Production Workflow For Aerospace Additive Manufacturing

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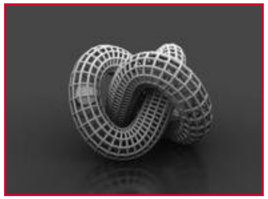
Why we look at the Additive Manufacturing Technology?

They are cool

fancy stuff



Structural freedom

Individual design

democratic design

complexity is for free

functional integration

No tooling

lot size 1

custom made parts

spare parts on demand

“Do you benefit from the structural freedom?”

Why Aerospace?

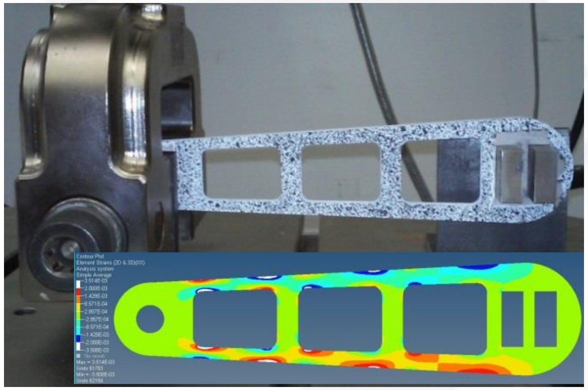
- Overall Goals:
  - Reduce Weight
  - Improve Performance
  - Reduce Costs
- Main Advantages:
  - Can use geometric complexity in achieving design goals without cost or time penalty
  - Part consolidation, feature integration is possible to avoid assembly issues
  - Direct production from 3D data enables customization
  - Pursue multimaterial, multifunctional designs along with geometric complexity
  - Ignore constraints of conventional manufacturing—learn constraints of AM processes

Project Impetus

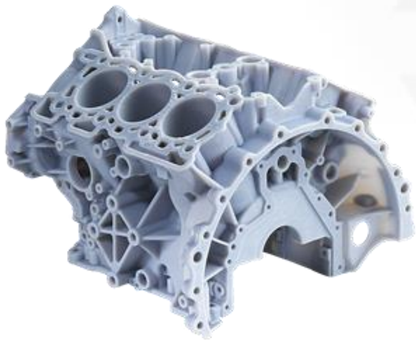
- Increased interest in Additive Manufacturing
  - In-field deployment of 3D printed metal parts
  - Competition to metal castings
- Concern about anisotropy based on build plane and direction
  - Are printed parts different from conventionally manufactured parts?
  - Can FEA solvers simulate them with accuracy
- Concern about failure

Objective

- Validation - Create an intermediate design step where we prove we can simulate with accuracy



- Upfront Design- Once we prove simulation accuracy, we create novel parts with confidence knowing that the simulation represents reality.

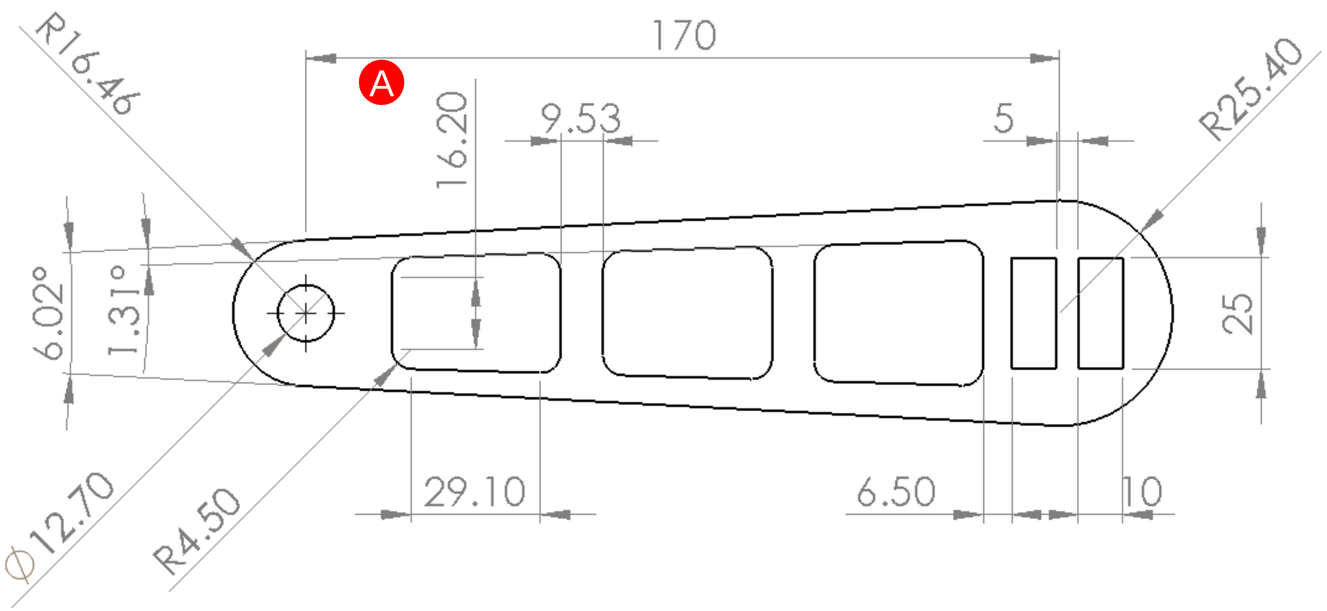


Current Work

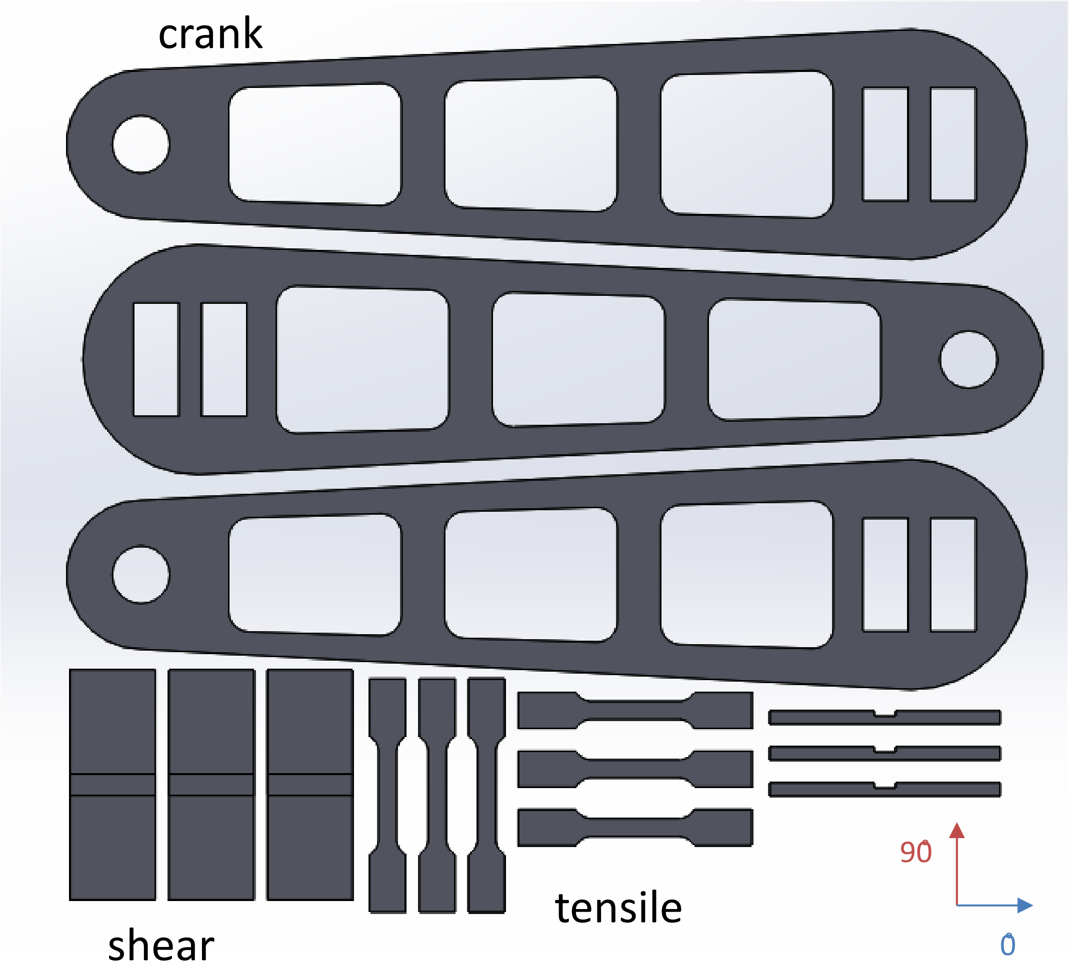
- Create a ‘standardized’ 3D geometric shape
- Print geometric shape using DMLS
- Print and test tensile bars- stress-strain
- Validate elastic behavior of geometric shape with DIC strain measurement
- Break geometric shape
- Simulate and compare to experiment
- Quantify simulation accuracy

Altered Bike Crank Geometry

- Forces failure to the front (left) of the crank



Layout of print job



Direct Metal Laser Sintering

- CAD drawing discretized into geometric layers
- Laser sinters a layer of powder for the CAD geometry layer
- More powder is added for the next layer

Courtesy: Incodema3D

DMLS Parameters

Scan Speed (mm/s)	1300
Laser Power (W)	370
Laser Diameter (µm)	100-500
Hatching Distance (mm)	0.19
Layer Thickness (µm)	30
Hatching pattern offset	66°

Material

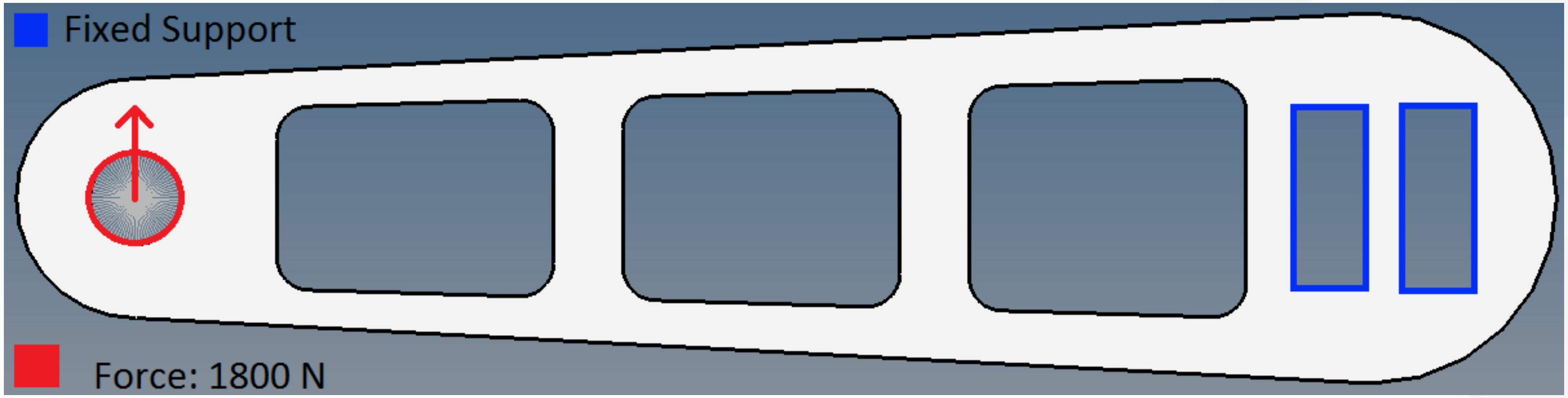
EOS Aluminum AlSi10Mg

Element	Measured Concentration (%)
Silicon	9.7
Magnesium	0.35
Iron	0.19
Manganese	0.07
Copper	<0.001
Zinc	<0.002
Titanium	0.004
Aluminum	Balance

Validating Elastic behavior

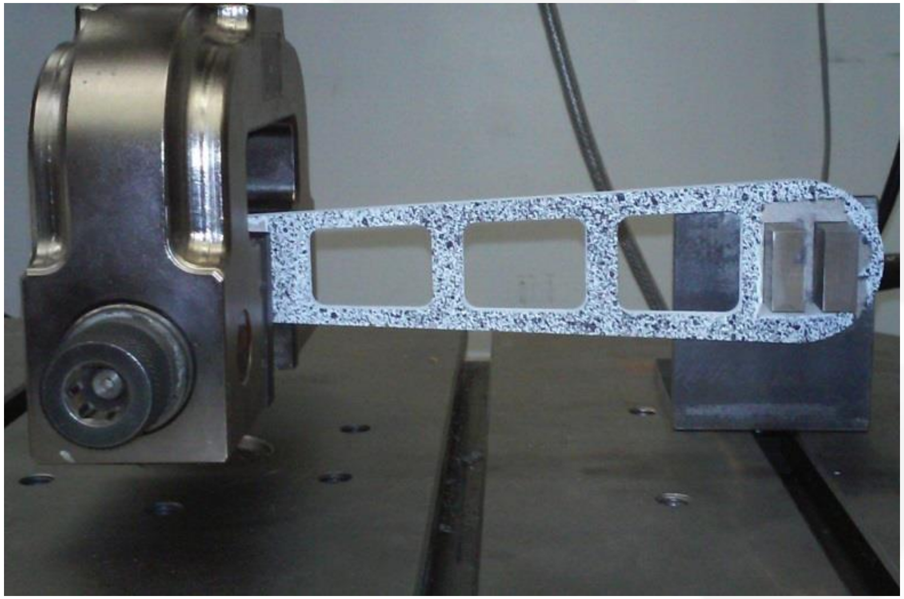
Elastic Model-OptiStruct

- Mat1 elastic material models used
- Linear Static analysis used
  - Small strains

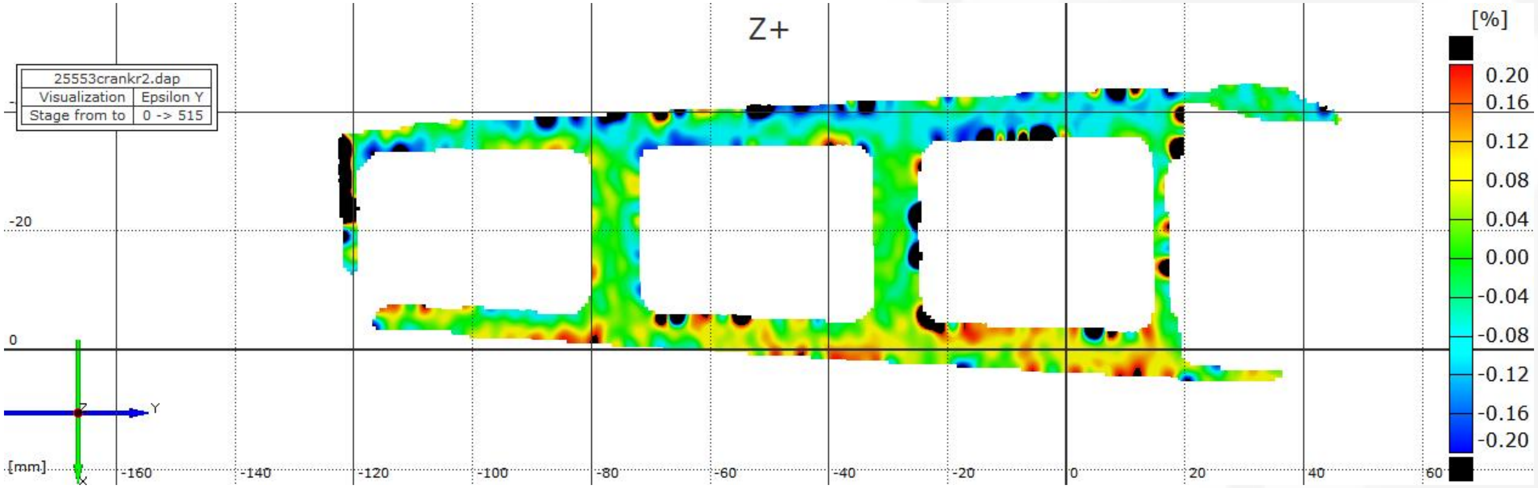


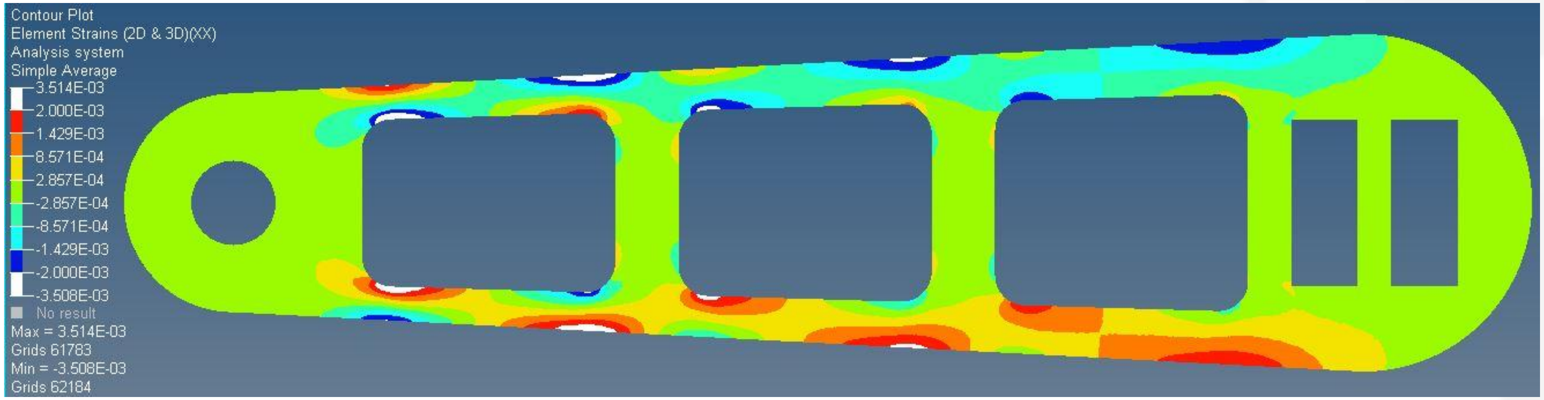
Experimental setup

- Specimens are coated with a speckle pattern



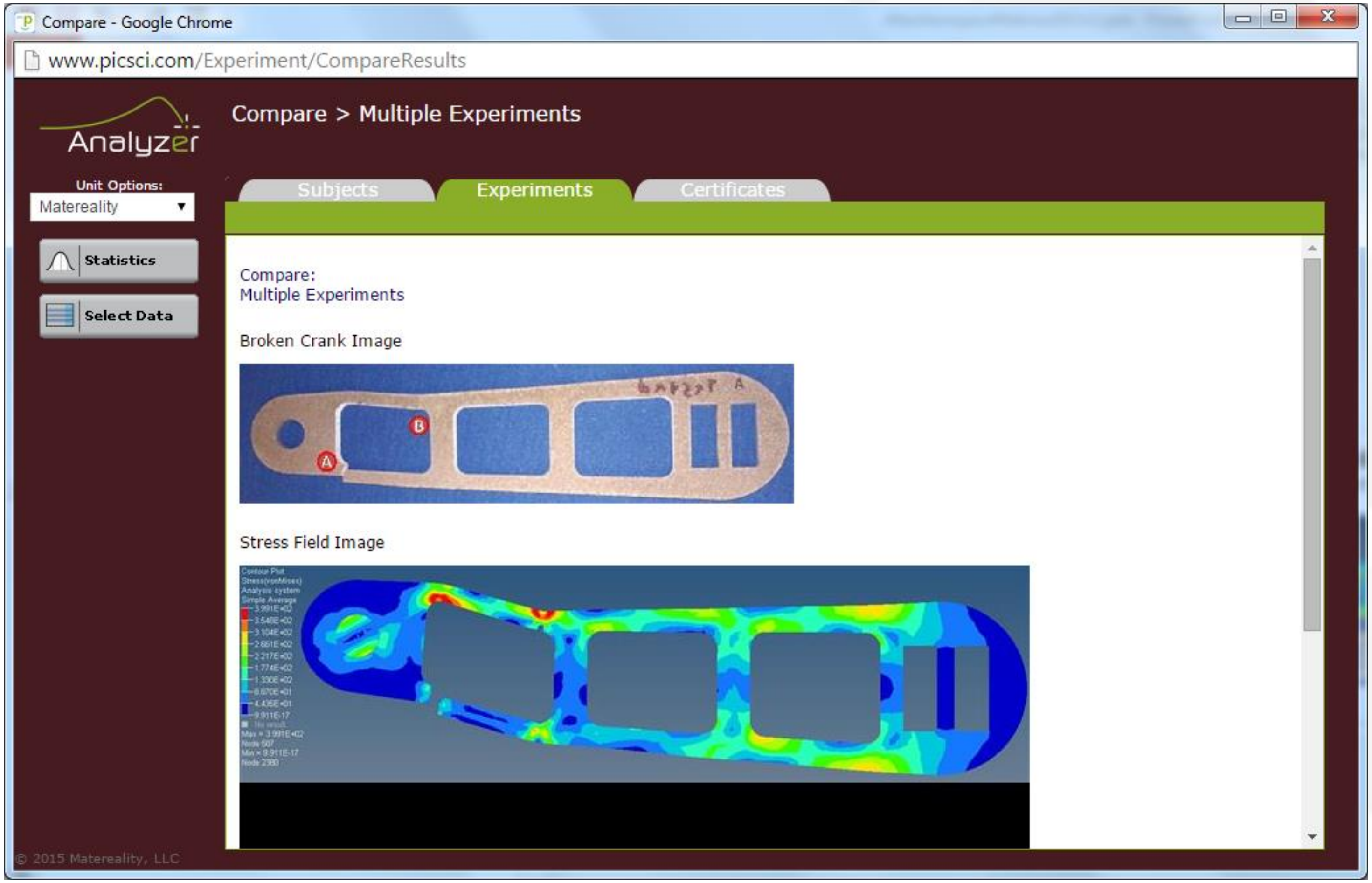
Elastic Validation
Measured Modulus (65.6 GPa)





Validating Failure

Failure Validation
Comparing Simulation to Experiment



Technical conclusions

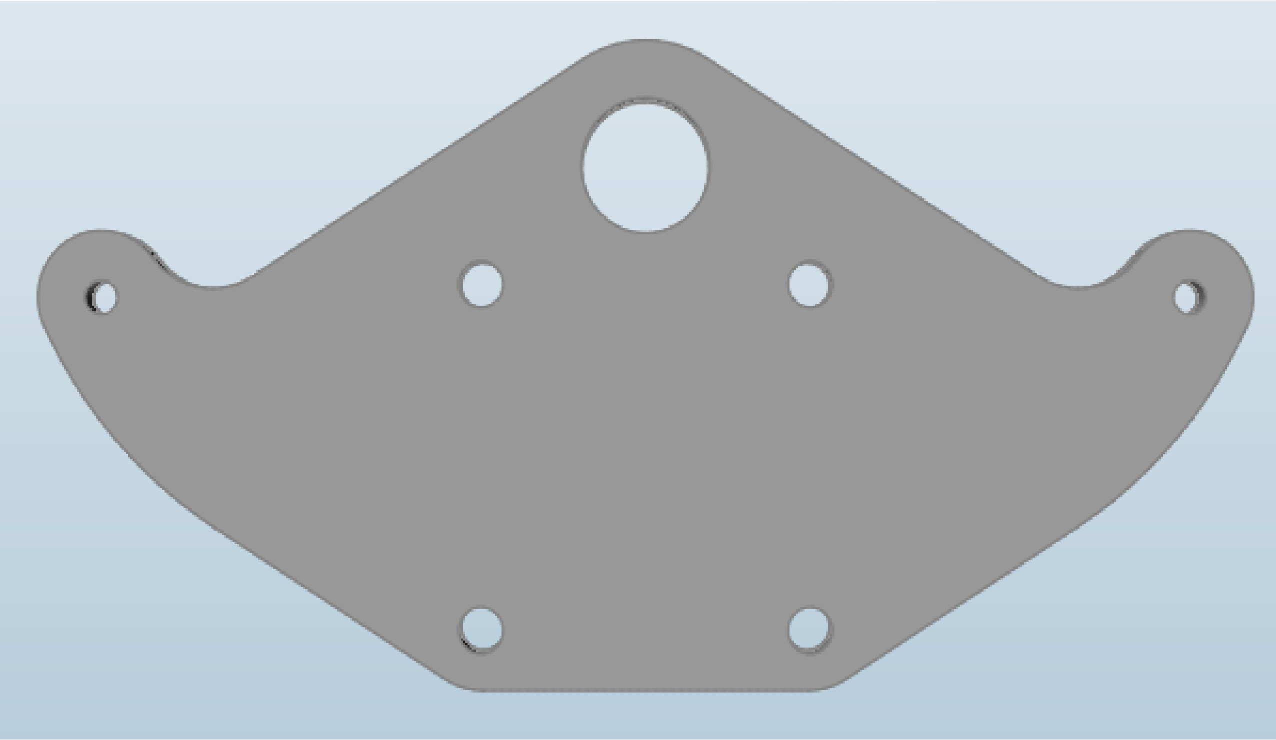
- There is a measurable difference between x and y direction material properties in the printing plane
  - Not significant enough to affect simulation for small strains
- DMLS parts can be simulated the same way as conventional products under similar conditions
  - OptiStruct can predict strain contours on DMLS specimens for small strains in the elastic region
  - RADIOSS can predict the progression of failure

Business Implications

- Validation is an essential step for 3D printing
- Validation confirms the ability of FEA to capture:
  - Printing anisotropy
  - FEA Solver accuracy
  - Material behavior : Elastic, Plasticity, Failure
- A ‘standardized’ geometry and load case must be used for quantifying simulation accuracy
- Helps manage risk with this novel process

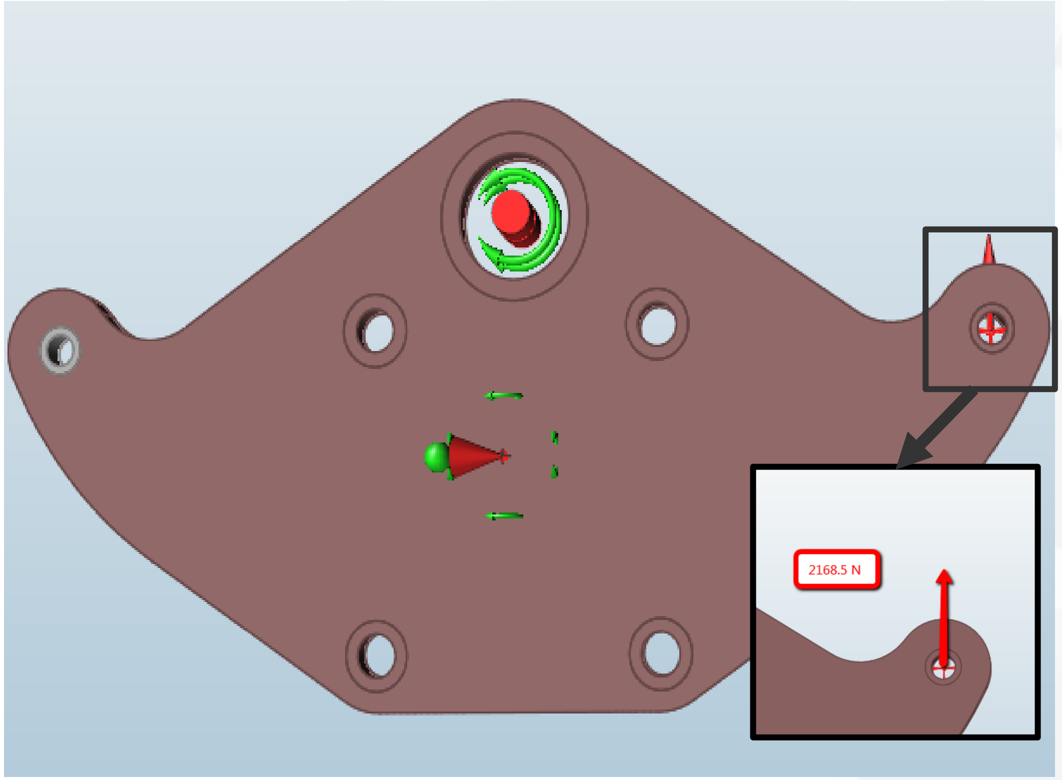
Optimization and Analysis of 172 Cessna Bellcrank

Baseline Design



Loads and Boundary Conditions

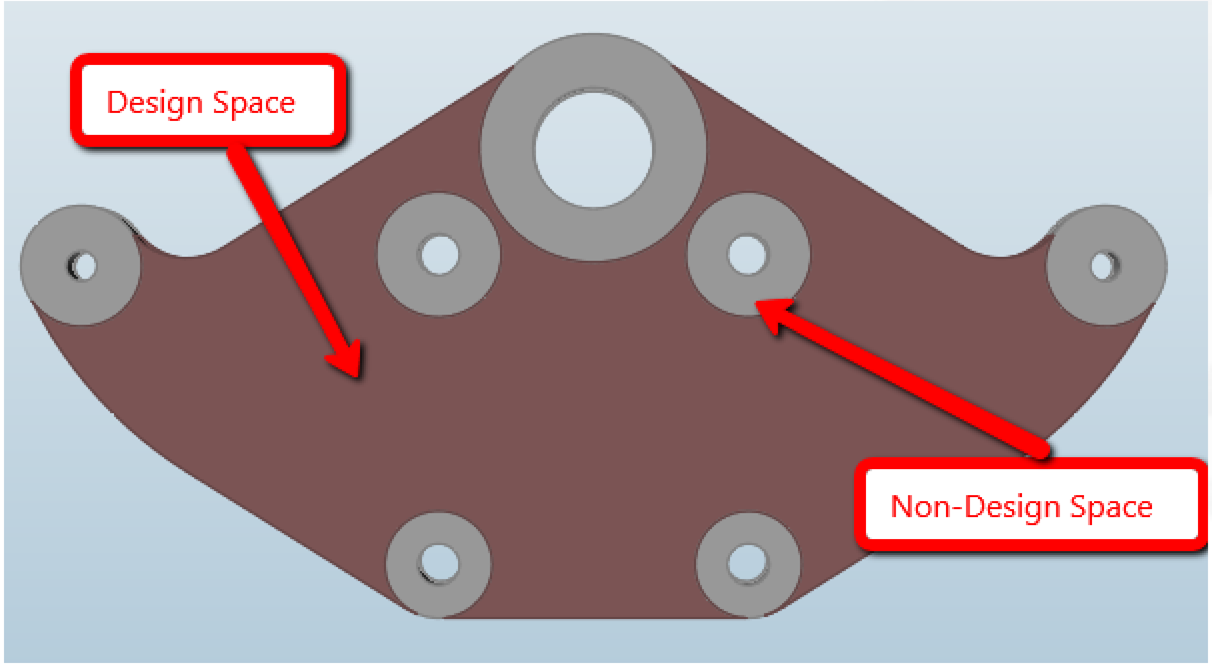
- Load: 2168.5 N
- Fixed Translation at bolt holes
- Rotation allowed on top bolt hole



Design Objective

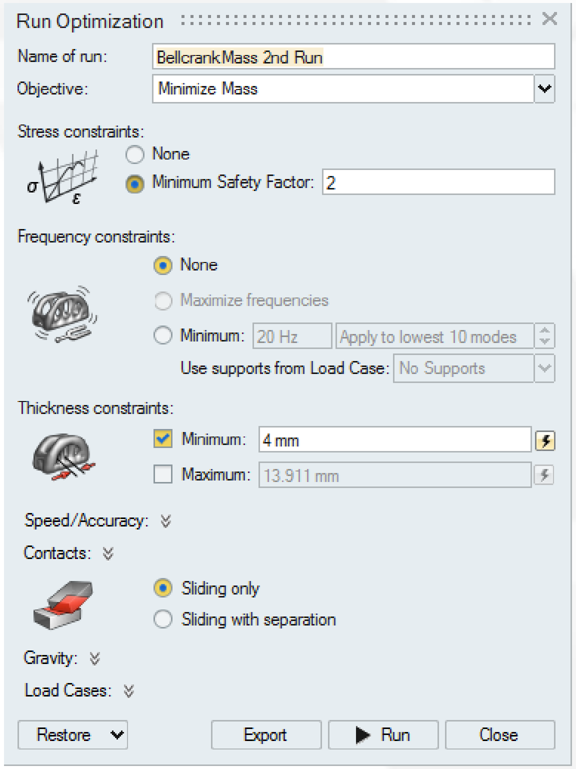
- Reduce volume/weight of part
- Ensure at least a safety factor of 2
- Prevent deflection from exceeding 1/8"

Optimization Setup

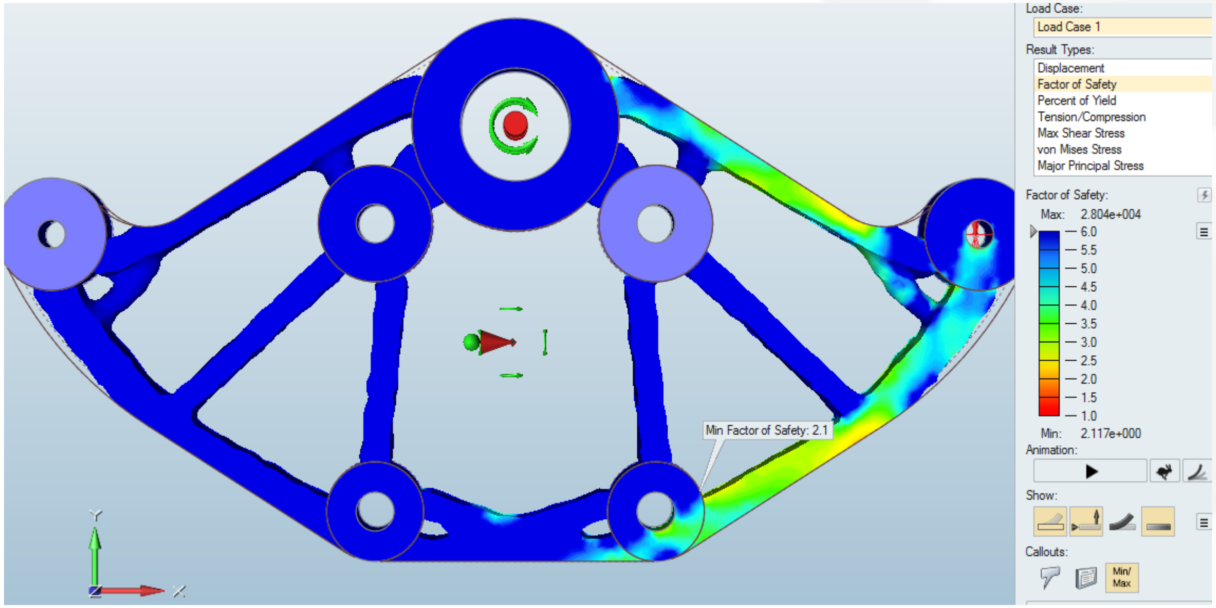


Optimization Setup

- Objective:
  Minimize Mass
- Constraints:
  - Safety Factor 2
  - Minimum member size of 4 mm

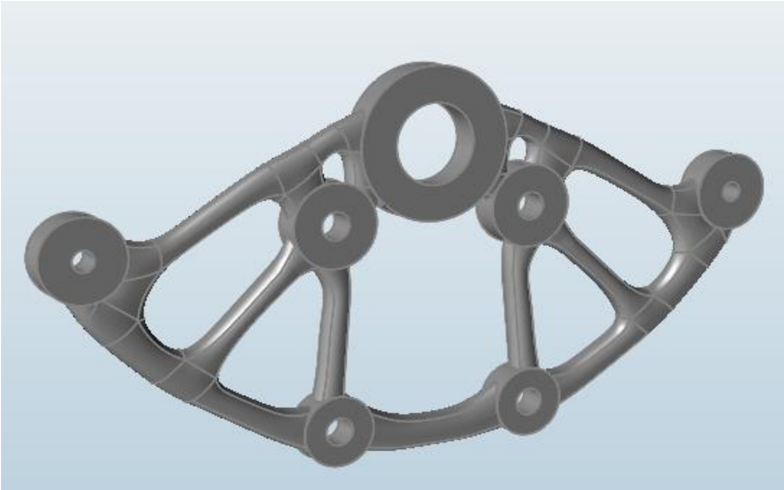


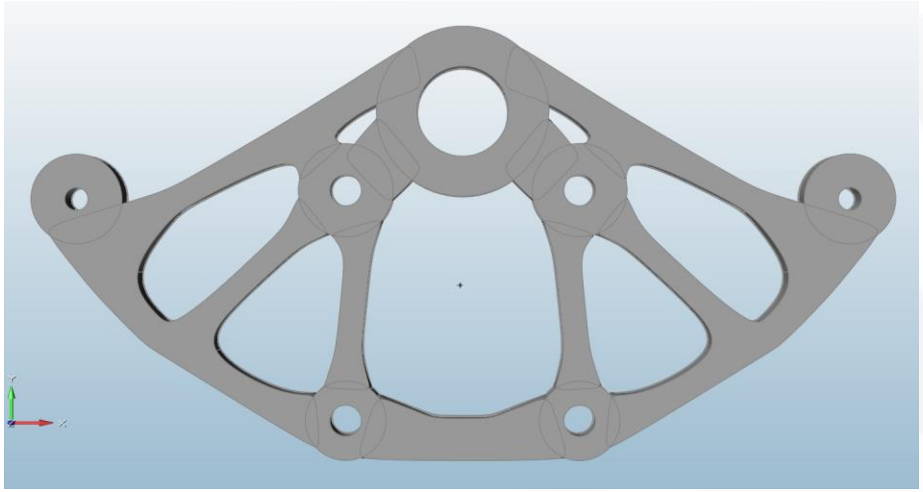
Initial Optimization Results



Baseline Design	Optimized Design
Max Deflection	
0.002"	0.006"
Peak Stress	
55.6 Mpa	100.6 Mpa
% Mass Reduction	
52.6	

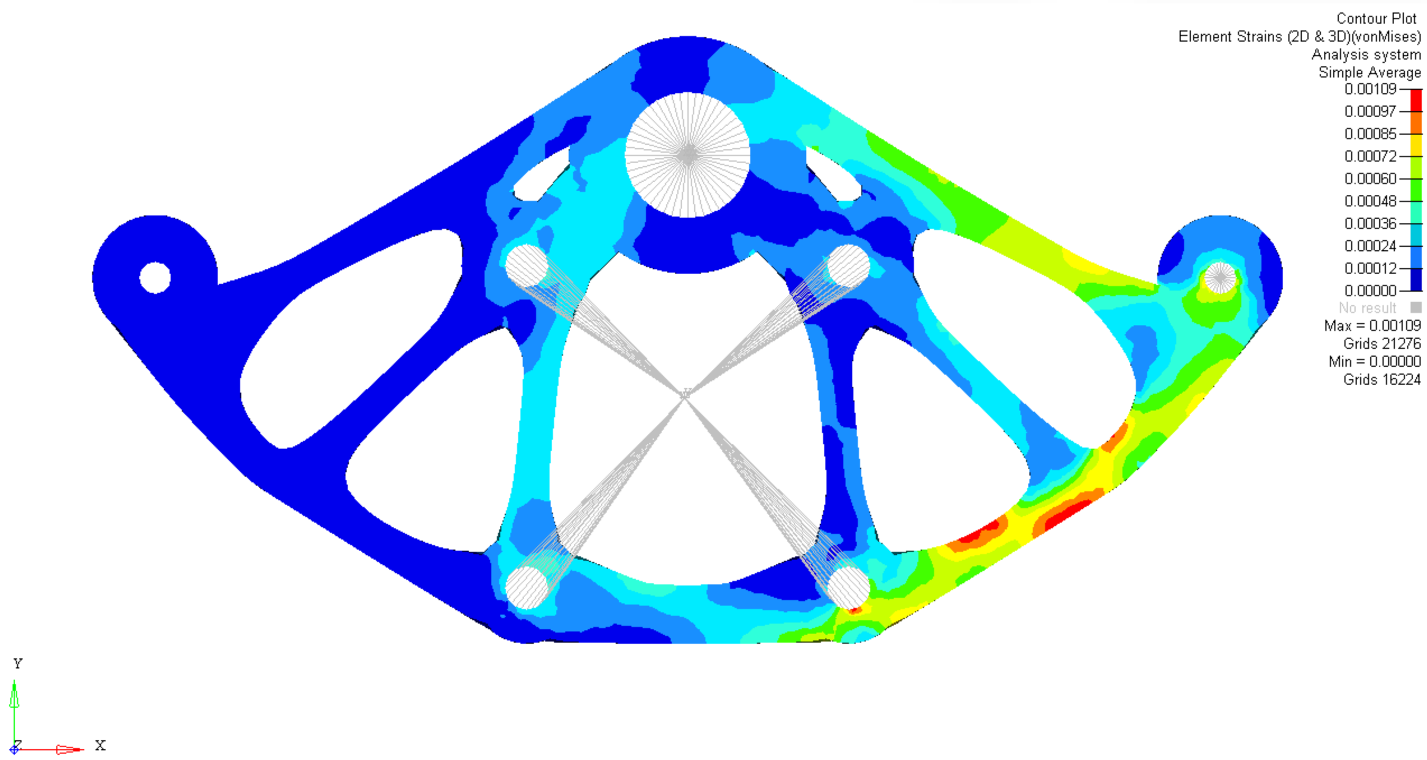
PolyNURB Translation to Geometry



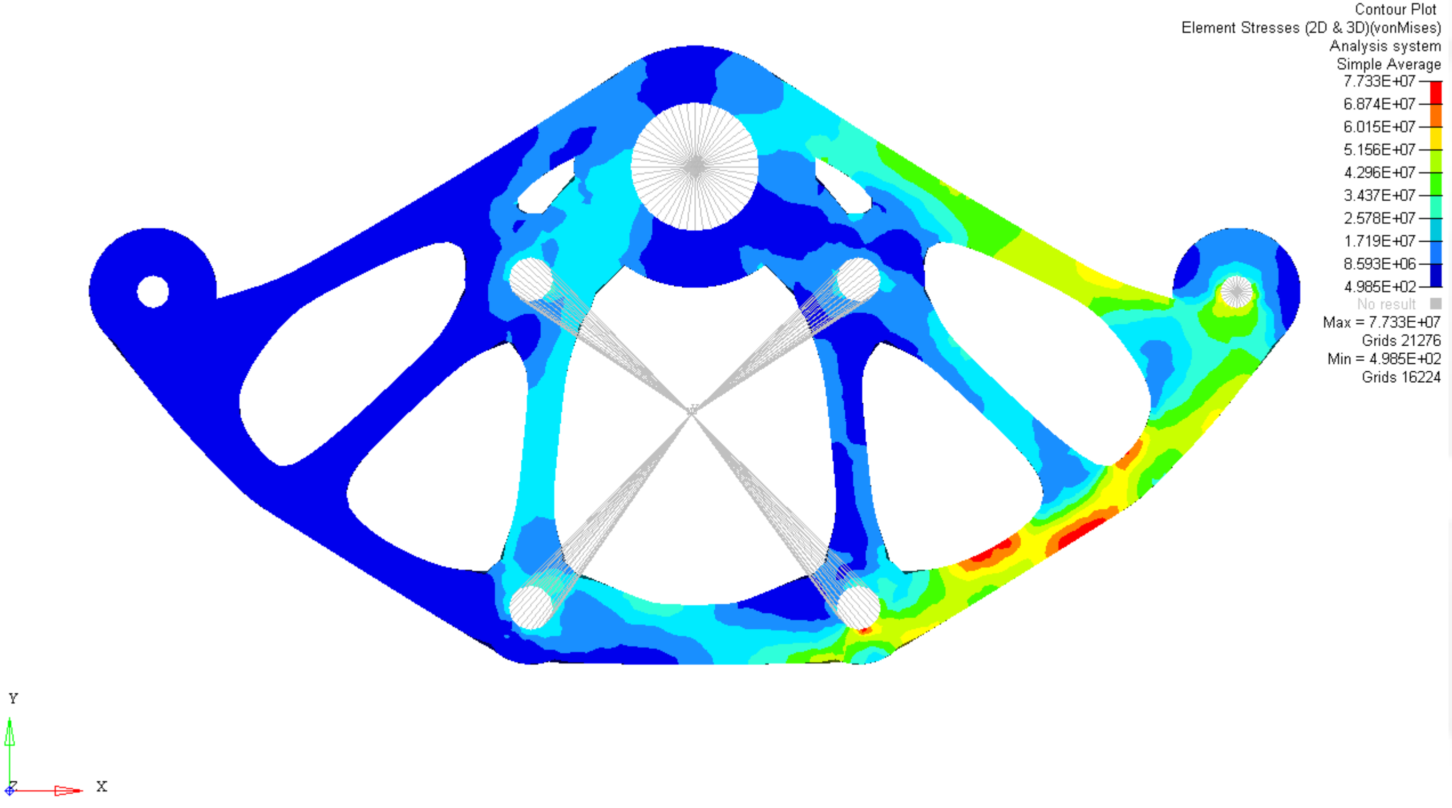


Printed Design had vertical walls – eliminated need for post-processing to reduce stair steps

Analysis Results: Von Mises Strain



Analysis Results: Von Mises Stress



Lab Work on Bellcrank

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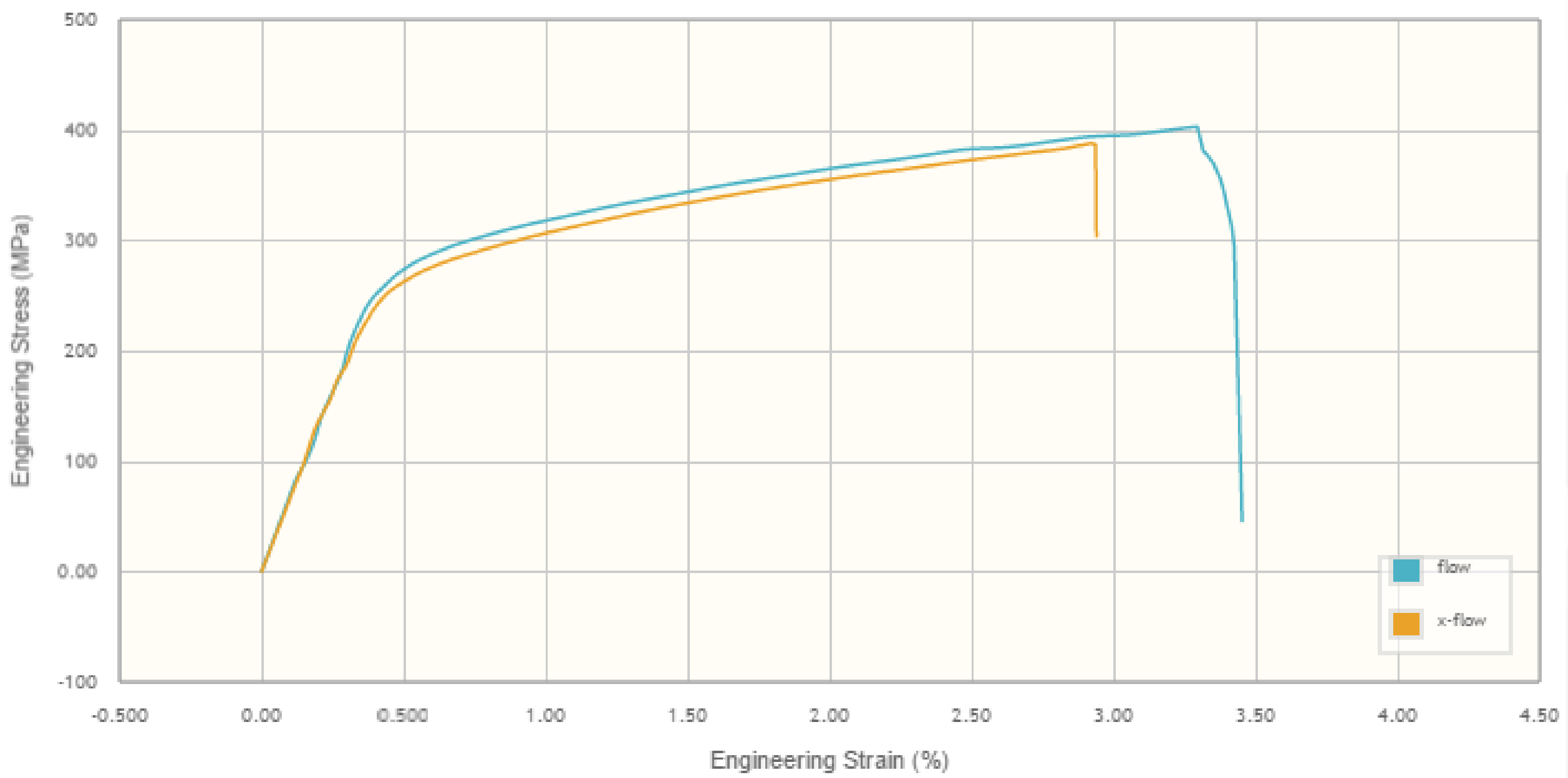
Aluminum	Balance

Material Properties



Material information

Material	AlSi10Mg	
Young's Modulus	63122	MPa
Yield Stress	213.0041	MPa
Poisson’s Ratio	0.331	
Failure Plastic Strain	0.02247295	mm/mm
Density	2.63E-09	tonne/mm^3

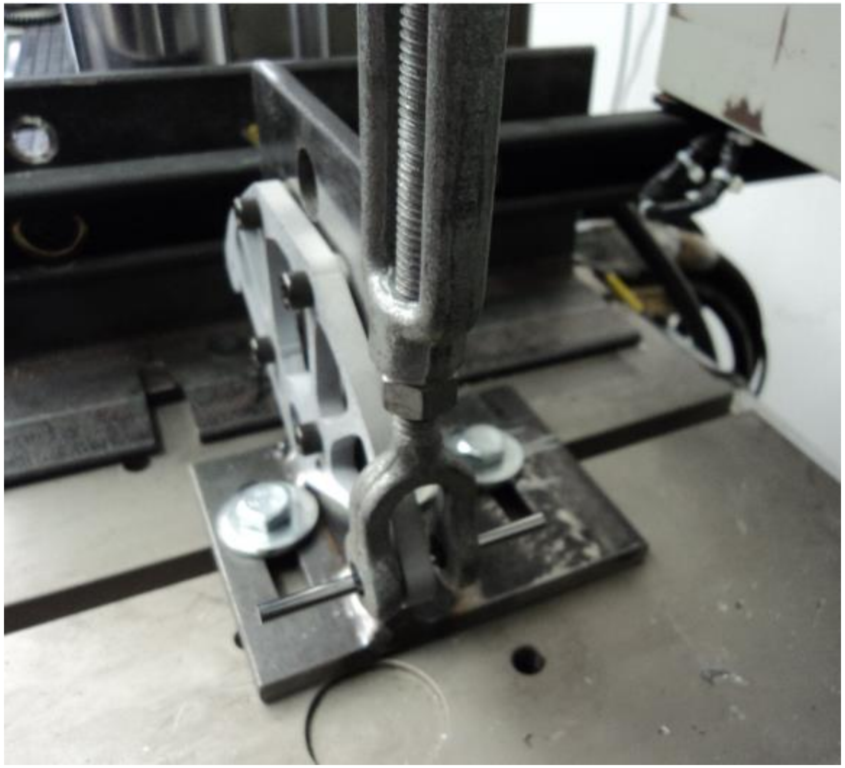
Chemical Analysis

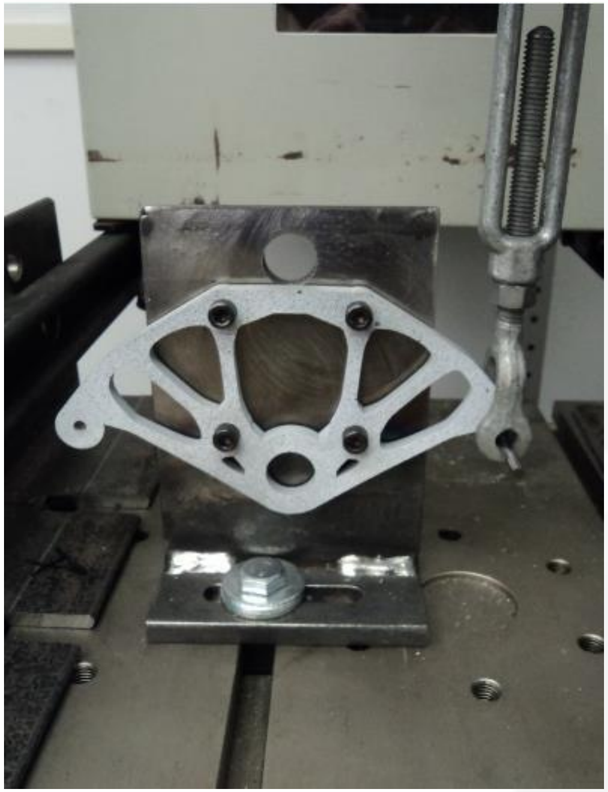
Element	Measured Concentration (wt%)
Aluminum	Balance
Copper	<0.05
Iron	0.13
Magnesium	0.36
Manganese	<0.01
Nitrogen	<0.20
Nickel	<0.01
Lead	<0.01
Oxygen	0.10
Silicon	9.80
Tin	0.01
Titanium	<0.01
Zinc	<0.01
Other	<0.05

Test setup

- Bolted 4 pattern to t-shaped bracket
- Used pin+turn buckle to push down crank
- Set force cutoff at 2170N (crosshead velocity 4mm/min), in Universal Testing Machine Instron

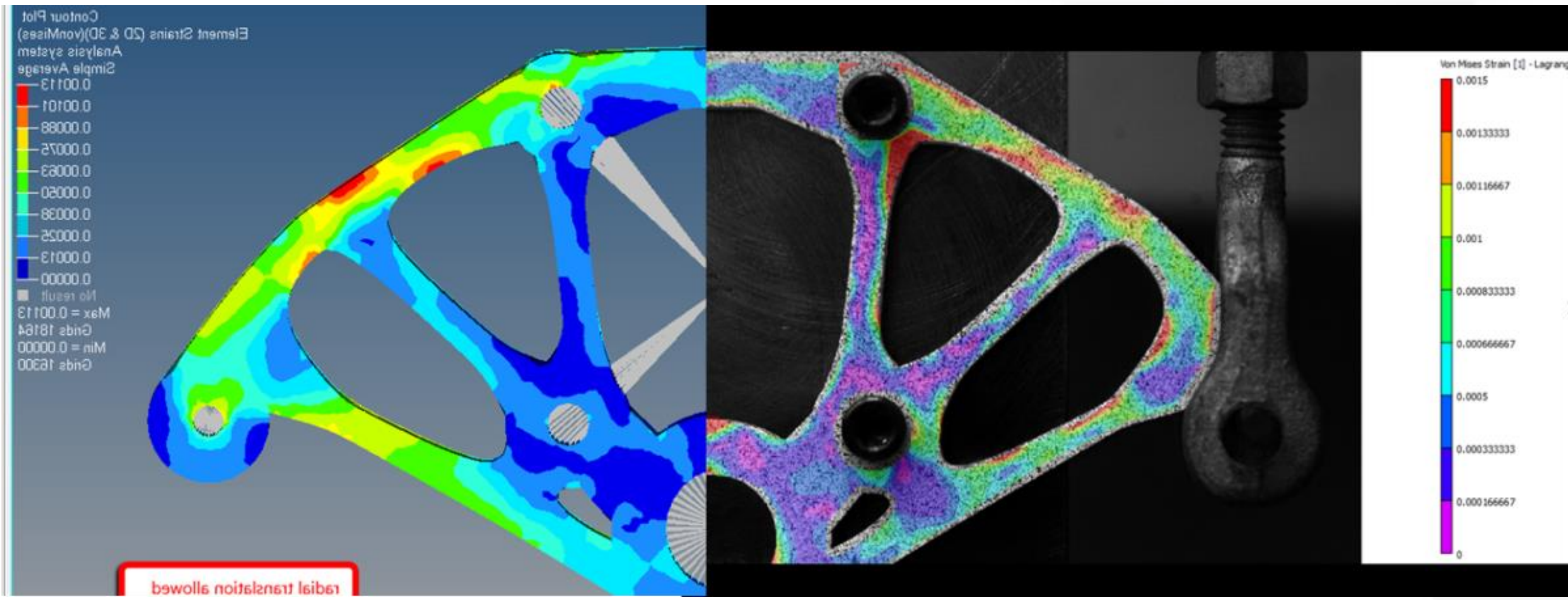
Setup Pictures





Elastic Validation

Comparing DIC von Mise’s Strain using VIC 2d software



Final Performance Results

	Original	Optimized
Max Deflection (mm)	.051	.127
Peak Stress (Mpa)	55.6	86.7
Mass (kg)	0.138	0.080

- Significant Overdesign for Original Design
  - Factor of Safety and Peak Stress Constraints relaxed for Design Optimization
- 45% Mass Reduction

Conclusions

- Procedure Established to Validate Workflow for Design, Testing, Validation, and Certification for Aerospace DMLS Fabricated Parts
- Certification by Analysis with Experimental Substantiation is Viable
- Anisotropy of Material should be considered in future during optimization
- Significant opportunity for weight reduction using AM methods