Process-informed Design Optimization for Additive Manufacture

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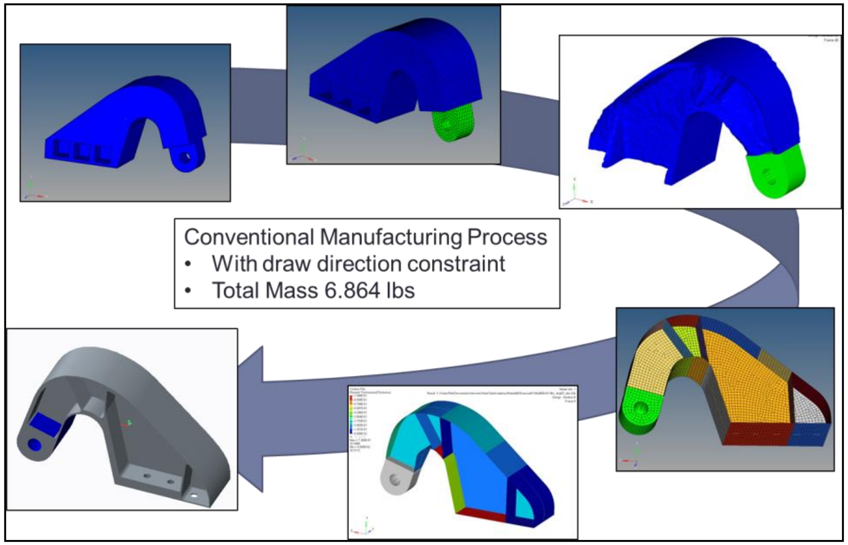
Introduction

- Structural design driven by
  - *Performance*—min weight, s.t. strength, stiffness, stability requirements
  - *Certification*—ensure safety throughout design life within range of variability due to operational environment and material, process, analysis, and inspection capabilities
- Robust structural design for AM
  - Must account for process variability/capability during component configuration design and sizing

Structural Component Optimization

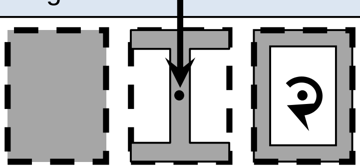
Optimize for structural performance

- Minimum weight
- S.t. strength, stiffness, stability requirements
- For given loads, material, boundary conditions



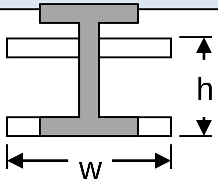
Topology Optimization

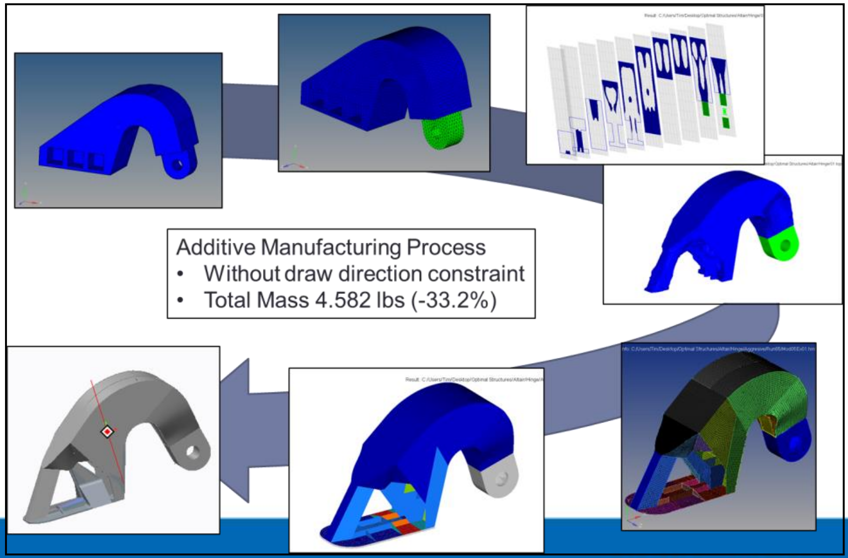
- Determine best arrangement of a limited volume of structural material within a given spatial domain
- Regions with high strain energy are allocated greater densities



Shape Optimization

- Adjust boundary definitions
- Shape basis vectors treated as design variables in gradient-based algorithm





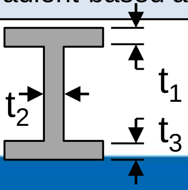
Design must also account for

- Process limitations
- Process-induced variability

Martinez, Taylor, McCloskey, "Leveraging Geometric Shape Complexity in Optimal Design for Additive Manufacturing," 2015

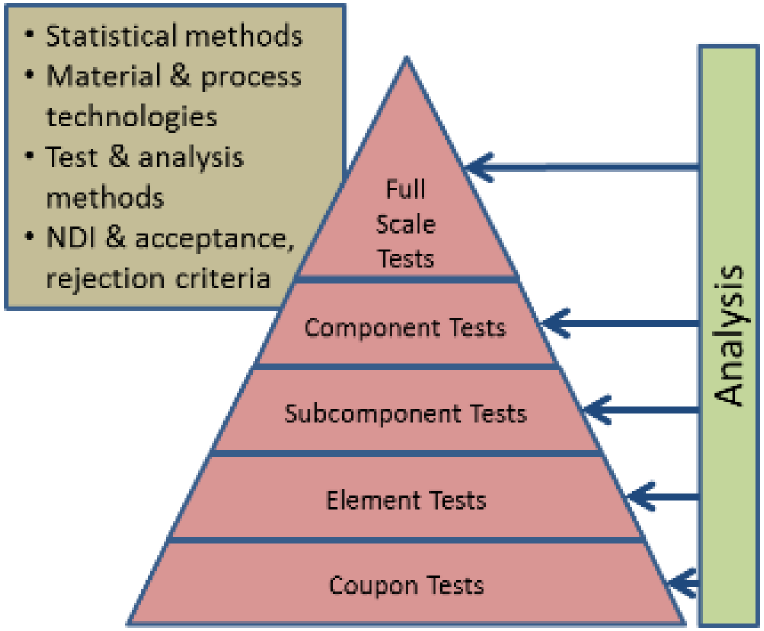
Size (Gauge) Optimization

- Adjust entries on finite element property cards
- Property card entries treated as design variables in gradient-based algorithm



Aerospace Structural Certification

- Strain-based certification
  - Correlate strains to FE-based predictions and standard analysis approaches
- Building Block Approach
  - Test-Model-Analyze-Test Correlation
  - Feasible, economical
  - Hierarchical
    - Material
    - Individual part
    - Part of full scale component
    - Part of a full-scale airframe
    - Full scale airframe



Taylor, Manzo, Flansburg, "Certification Strategy for Additively Manufactured Structural Fittings," Solid Freeform Fabrication Symposium, Austin, Texas, 2016.

Compare Composite Structure Certification

- Process sensitivity
  - Material only achieves usable state through component fabrication process
  - Process control critical to achieve predicted performance
- Only laminate level, non-interactive failure criteria used for margin-of-safety calculations
  - Nonhomogeneous materials
    - Micromechanical approaches—inadequate probability of predicting failure onset, uneconomical
    - Lamina level criteria—insufficient generality and robustness to capture complex interactions between laminae
  - Statistical basis allowables developed from fiber-dominated laminates—prevent matrix, interactive failure modes
  - Captures manufacturing and inspection process capabilities
- *Develop and apply properties at scale where interactions and manufacturing effects effectively embedded and characterized*

Value
- Theoretical foundation
- Process optimization
- Design rules
- Failure mode characterization

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AM Structure Design and Certification

- ***Building block approach***—test-model-analyze-test correlation
- ***Qualified manufacturing process*** is required
  - Controlled, consistent materials --statistical basis material properties, allowables for structural design and analysis
  - As-built porosity levels depend on material state—powder size, shape factors, and agglomerates – probabilistic approach (powder metal structures)
  - Account for geometric sensitivity through geometry-specific process qualification (welded struct.)
- ***Develop and apply properties at scale*** where interactions and manufacturing effects effectively embedded and characterized (composite structures)
- ***Process sensitivity mitigation*** (cast, powder metal structures)
  - Post process heat treatment
  - Additional safety factors, testing, inspection
  - Part-specific manufacturing process qualification for critical applications
  - Life prediction methodology based on probabilistic damage tolerance (powder metal structures)
- ***Mechanical property degradation*** (i.e. low elongation/ductility) ***mitigation*** (cast, powder metal structures)
  - Allowable reductions
  - Preclude use of certain analysis methods (i.e. plastic bending analysis).
- ***Robust, comprehensive standards***—mfg processes, testing, inspection, design, & analysis

Taylor, Manzo, Flansburg, "Certification Strategy for Additively Manufactured Structural Fittings," Solid Freeform Fabrication Symposium, Austin, Texas, 2016.

Laser AM Component Design

- Effective design for AM must account for AM process capability
  - Characterize sensitivity w.r.t significant process parameters
  - Process-structure-property models
    - Needed for parameter optimization, sensitivity studies, DOE levels
    - Too cumbersome for design application
- Macro-scale material characterization and geometric sensitivity
  - Lightweight analytical models
    - Efficiently assess designs
    - Integrate with automated optimization tools
  - Semi-empirical
  - Part zoning based on geometric sensitivity
  - Life prediction system based on probabilistic DT
  - Key process sensitivities

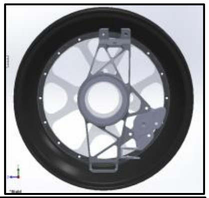
- Process capability studies
- Design of Experiments (DOE) approach
- Replication for appropriate confidence interval
- Geometric feature specific
- Optimized process parameters
- Response surface models

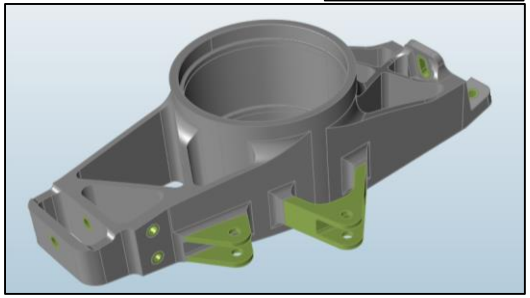
Residual stress

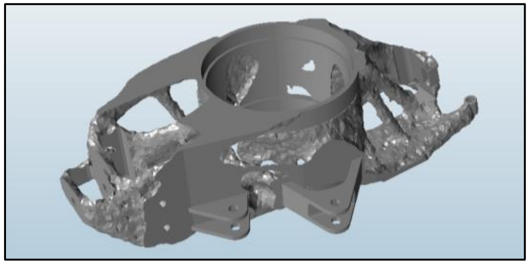
Surface quality

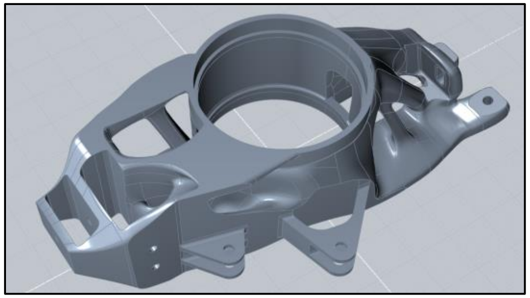
Voids/porosity
- Location
- Type—gas pores vs lack of fusion

Mechanical properties
- Stiffness
- Strength
- Toughness









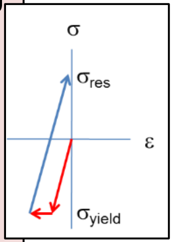
Martinez, UT Arlington, “Design Optimization of Race Car Steering Knuckle for Additive Manufacturing,” 2017

Residual Stresses in Laser AM

- Cause
  - Thermal history during layer buildup develops internal stress gradient
  - Internal stress gradient induces bending moment that causes parts to curl upwards
  - Bending moment magnitude is fn of geometry (height, width)
  - Curvature radius proportional to height
- Characterization
  - X-ray
  - Neutron diffraction
  - Contour method
  - Feature deformation—bridge, overhang
- Control
  - Parameter optimization
  - Connect to build plate at base
  - Support structure for overhangs
  - Geometry changes

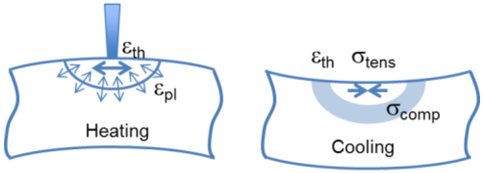
<u>Mercelis, 2007</u>

- Laser heats material
- Material thermal expansion partially blocked by surrounding colder material
- compressive stress exceeds yield strength→compressive plastic strain
- Material cools, shrinks when laser leaves
- Tensile residual stress surrounded by compressive stress zone

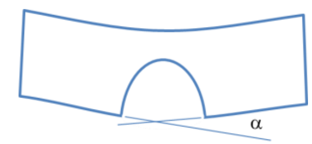


<u>Issues</u>

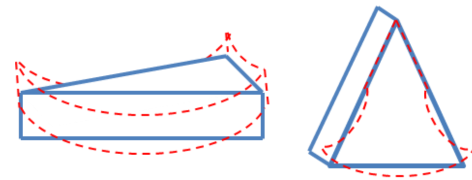
- Post-processing
- Material
- Time
- Damage/finish
- Design restrictions



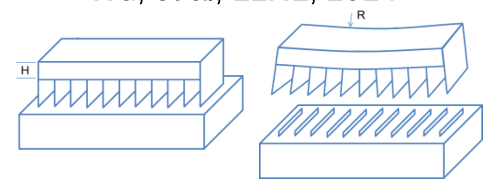
Mercelis & Kruth, Univ. Leuven, 2006



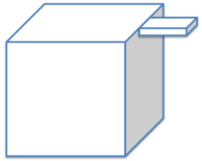
Kruth, et al, Univ. Leuven, 2012



Wu, et al, LLNL, 2014



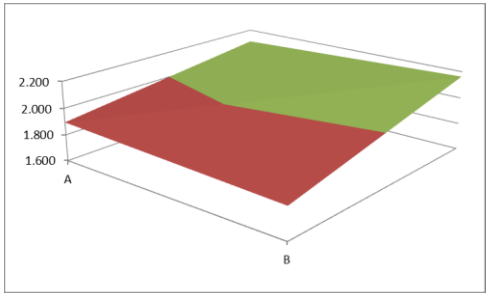
Safronov, et al, Moscow St Univ Tech, 2017

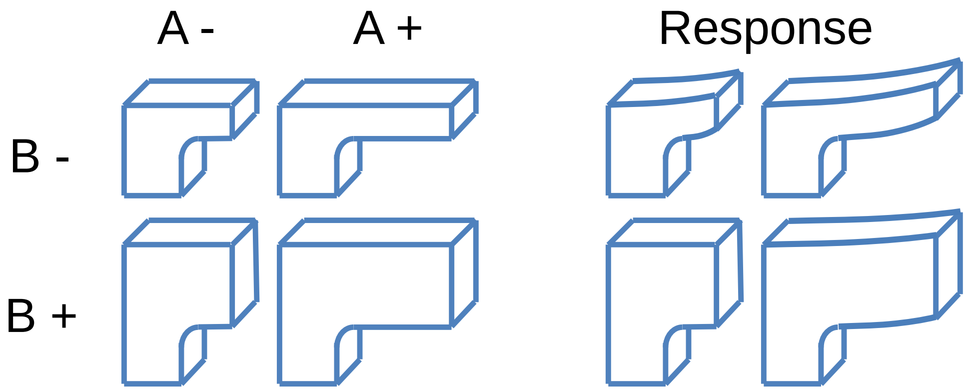


Patterson, UAH, 2014

DOE/Response Surface Methodology

- Factors: overhang geometric feature dimensions
- Response: feature deformation—driven by residual stress
- Approximation function: fit through experimental response





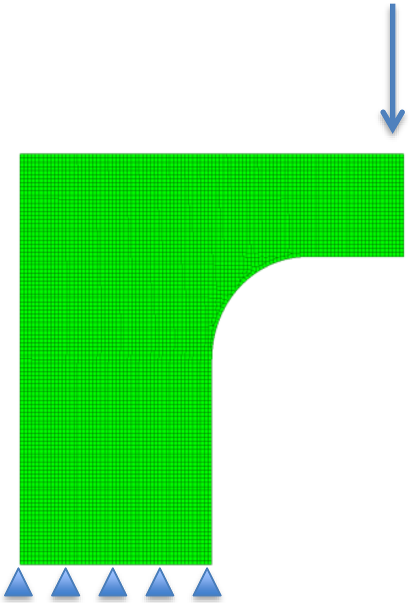
Run#	Run Order	Factor Assignment						
		A	B	C	D=AB	E=AC	F=BC	G=ABC
1		-	-	-	+	+	+	-
2		+	-	-	-	-	+	+
3		-	+	-	-	+	-	+
4		+	+	-	+	-	-	-
5		-	-	+	+	-	-	+
6		+	-	+	-	+	-	-
7		-	+	+	-	-	+	-
8		+	+	+	+	+	+	+

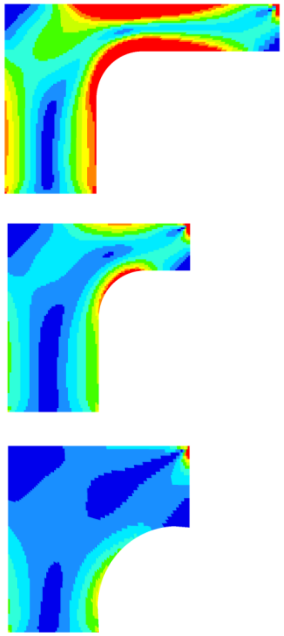
$$F(x)=a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_1x_2 + a_5x_2x_3 + a_6x_3x_1 + a_7x_1x_2x_3 + \text{error}$$

Note work of Patterson, Univ Alabama Huntsville, used uncalibrated thermal FE for experimental response model "Design of Experiment to Analyze Effect of Input Parameters on Thermal Stress and Deformation in Overhanging Part Features Created with the SLM Additive Manufacturing Process," 2014

Process Constraints in Shape Optimization

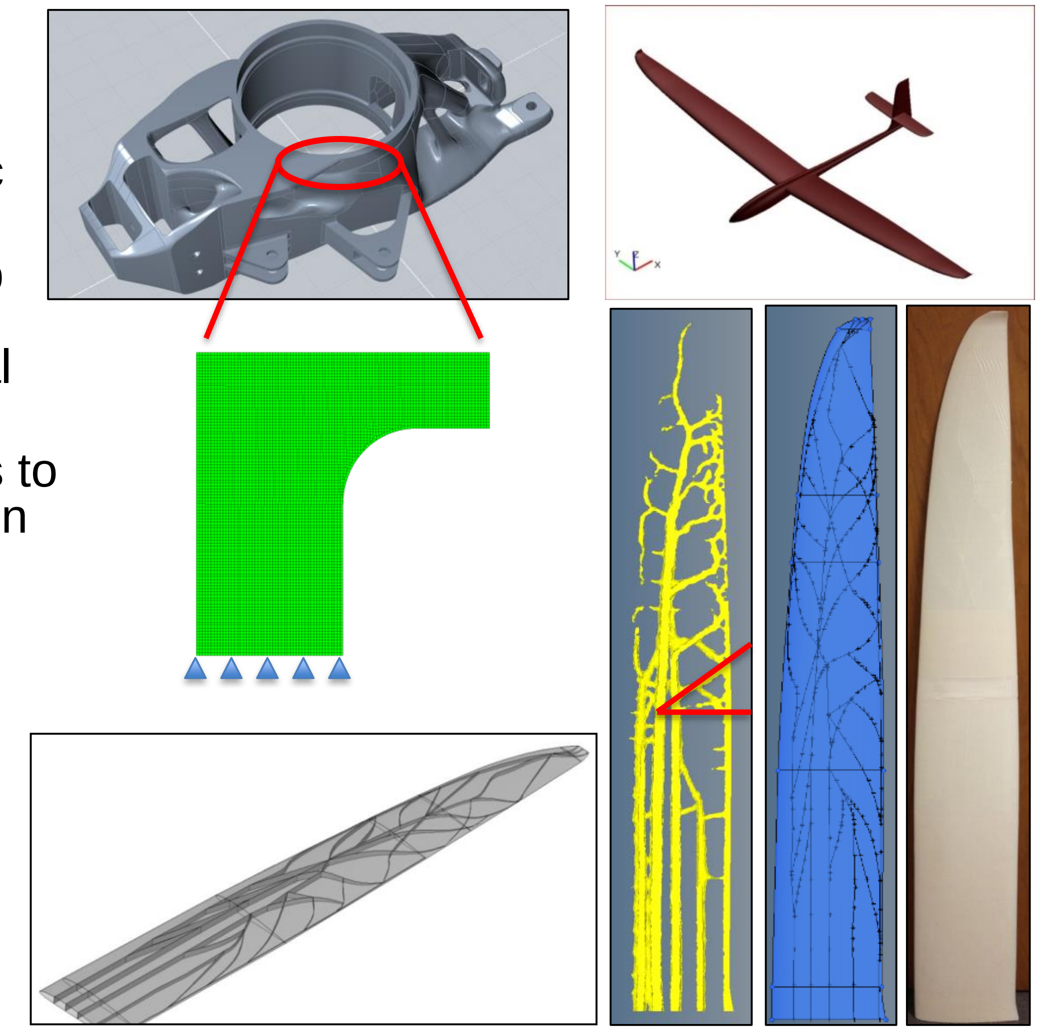
- Optimize for structural performance
  - Minimum weight
  - S.t. strength, stiffness, stability requirements
  - For given loads, material, boundary conditions
- Implement in shape optimization model (in-progress)
  - Design variables defined by shape basis vectors
  - Design variable changes morph geometry to determine optimized shape
- Constrain based on process capability
  - DOE-derived approximation function
  - DRESP2, DEQATN in OptiStruct takes shape variable state as input
  - DCONSTR defines allowable deformation vs. feature dimension





Current and Future Work

- Complete shape optimization model implementation for basic geometry
- Execute DOE builds to develop response functions for specific geometries sensitive to residual stress
- Apply basic geometry functions to full geometry shape optimization model based on localized geometric parameters
- Other geometry-process sensitivities in design
  - Overhang feature angle
  - Porosity (need in-situ metrology data)
- Topology optimization implementation



UTA Senior Capstone Design Report, “Fused Deposition Modeling of Thin-walled Aircraft Structures, 2016