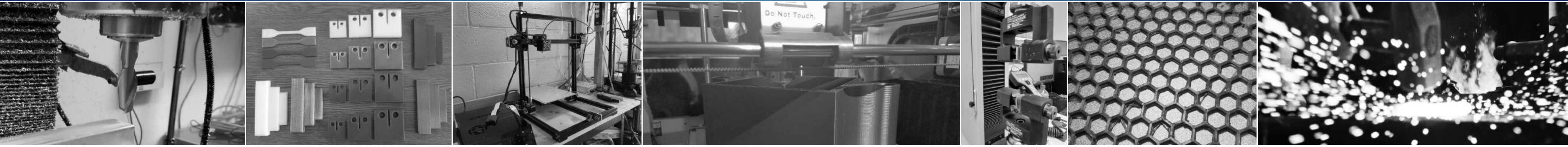
Designing Manufacturable Meso-Scale Architected Materials for Scanning-Type Additive Manufacturing



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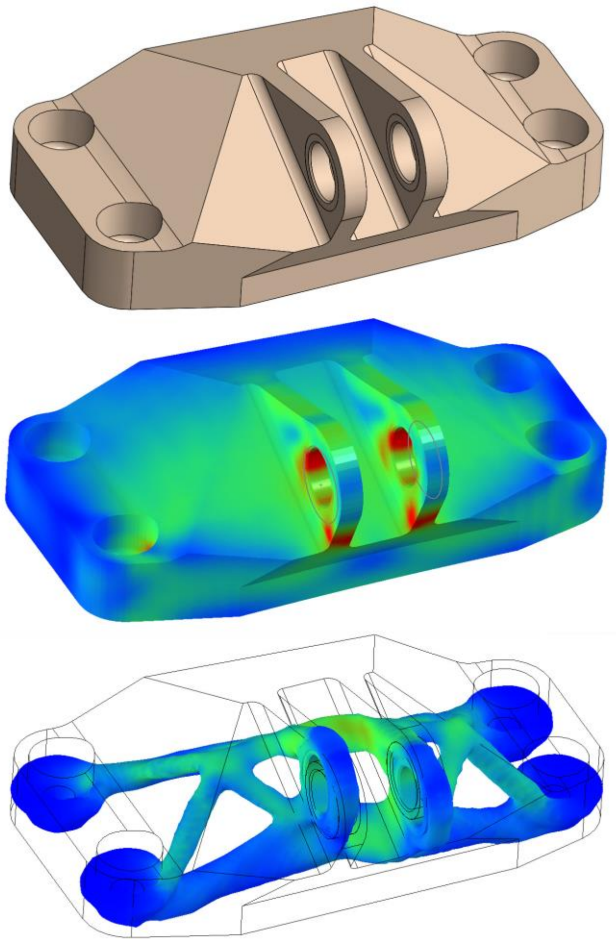
Manufacturability-Driven Design (MDD)

- **Design and manufacturing methods have rapidly advanced in recent years**
  - Additive manufacturing and advanced casting/molding methods
  - Algorithm-based design methods
    - topology optimization, generative design, optimal design, analytical target cascading (ATC)
  - Design freedom
  - Additive manufacturing is both a help and a major cause of the problem
- **Previously: Design-for-manufacturing (DFM) methods were used**
  - Simple design, cheap materials, liberal tolerances, etc.

Topology Optimization



https://www.fetraining.net/topology-optimization-part-1/

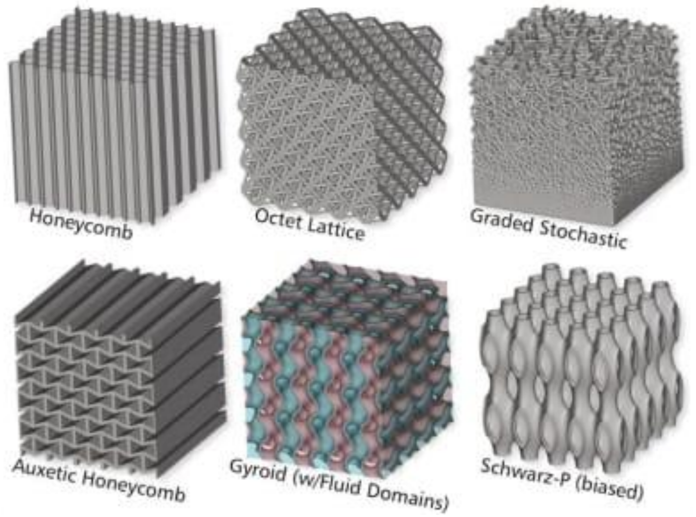
Manufacturability-Driven Design (MDD)

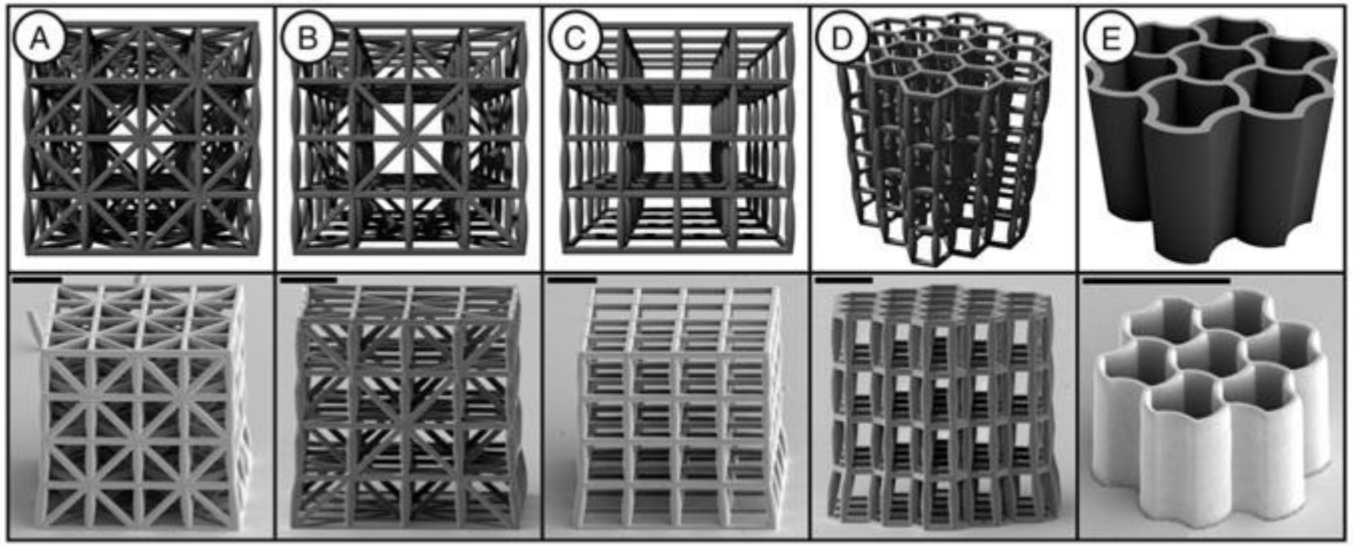
- **Manufacturability-Driven Design (MDD) is a design perspective in which manufacturability is the prime or co-prime requirement**
  - Using advanced design methods can produce far superior designs, even when restricted for manufacturability
  - Explicit or implicit constraints: Purely mathematical, purely expert, or hybrid problem formulation
  - Process-induced material effects
- Major advantages:
  - Take advantage of process characteristics
  - Can be iteratively improved and automated after first round!
  - More accurate design representation and more stable problem formulation

Manufacturability-Driven Design (MDD)

❑ Manufacturing Process-Driven Structured Material (MPDSM)

- ❑ Structured or architected material were the prime design constraint is manufacturability
- ❑ Restrict design candidates to manufacturable options before performance or cost objectives applied



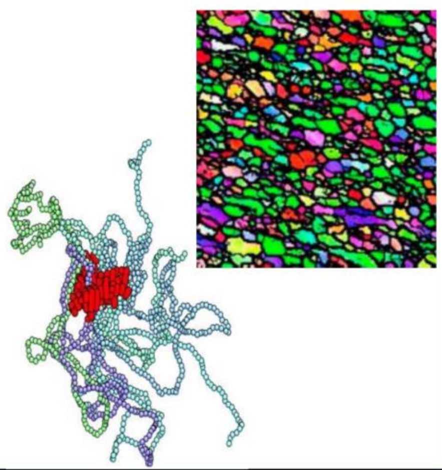


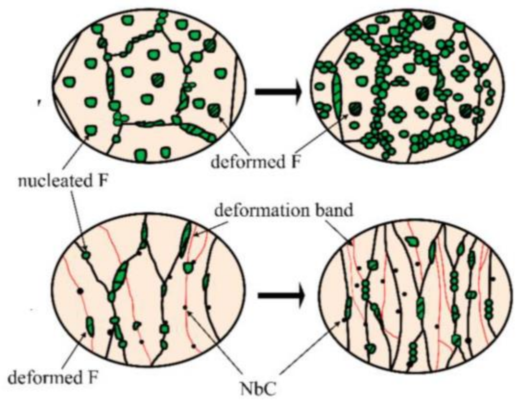
https://www.techbriefs.com/component/content/article/tb/pub/features/articles/35824

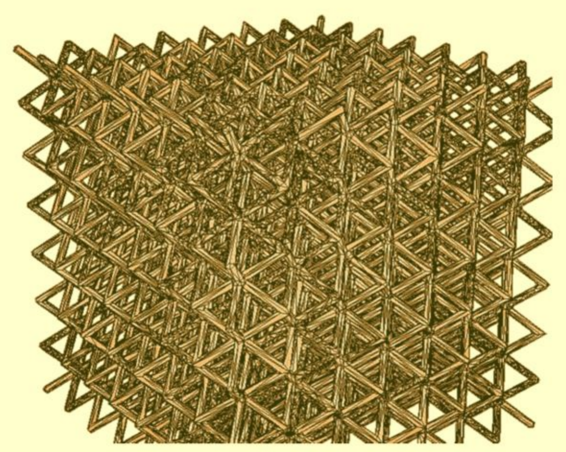
https://3dprintingindustry.com/news/german-scientists-3d-print-lightweight-material-stronger-steel-23300/

Material Architecture Design Levels

Natural material — *Source of Dominant Properties* — Structure and processing

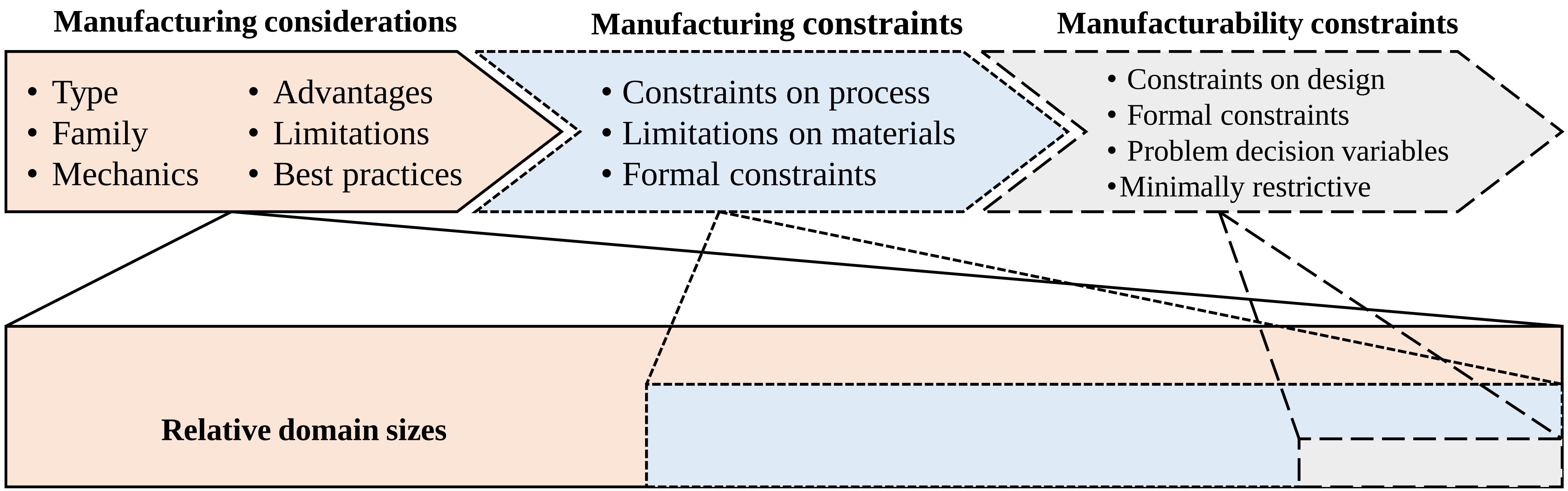






Sub-microstructure	Microstructure	Mesostructure	Macrostructure
❑ Natural material structure on atomic, crystal, or molecular level ❑ May be influenced by processing conditions ❑ **Examples**: Polymer chains, grain structure details in metals	❑ Structure observable using an optical microscope, heavily influential on macro-scale properties ❑ Strongly influenced by processing conditions ❑ **Examples**: Porosity, metal grain layout, scan structure in 3-D printed materials	❑ Designed or patterned structure, may be generated by element layout or designed inclusions/defects/voids ❑ Solid, homogeneous materials do not have a mesostructure ❑ **Examples**: Honeycomb structure, metamaterial, unit cell-based lattice	❑ In design, typically the “useful level” ❑ Generally the final component or product that is to be made from the designed material ❑ For homogeneous solid materials, microstructure drives macrostructure properties (no mesostructure)

Manufacturability Constraint Mapping



Patterson, A.E. & Allison, J.T. (2022). Mapping and enforcement of minimally restrictive manufacturability constraints in mechanical design. *ASME Open Journal of Engineering, 1*: 014502.

Manufacturability Constraint Mapping

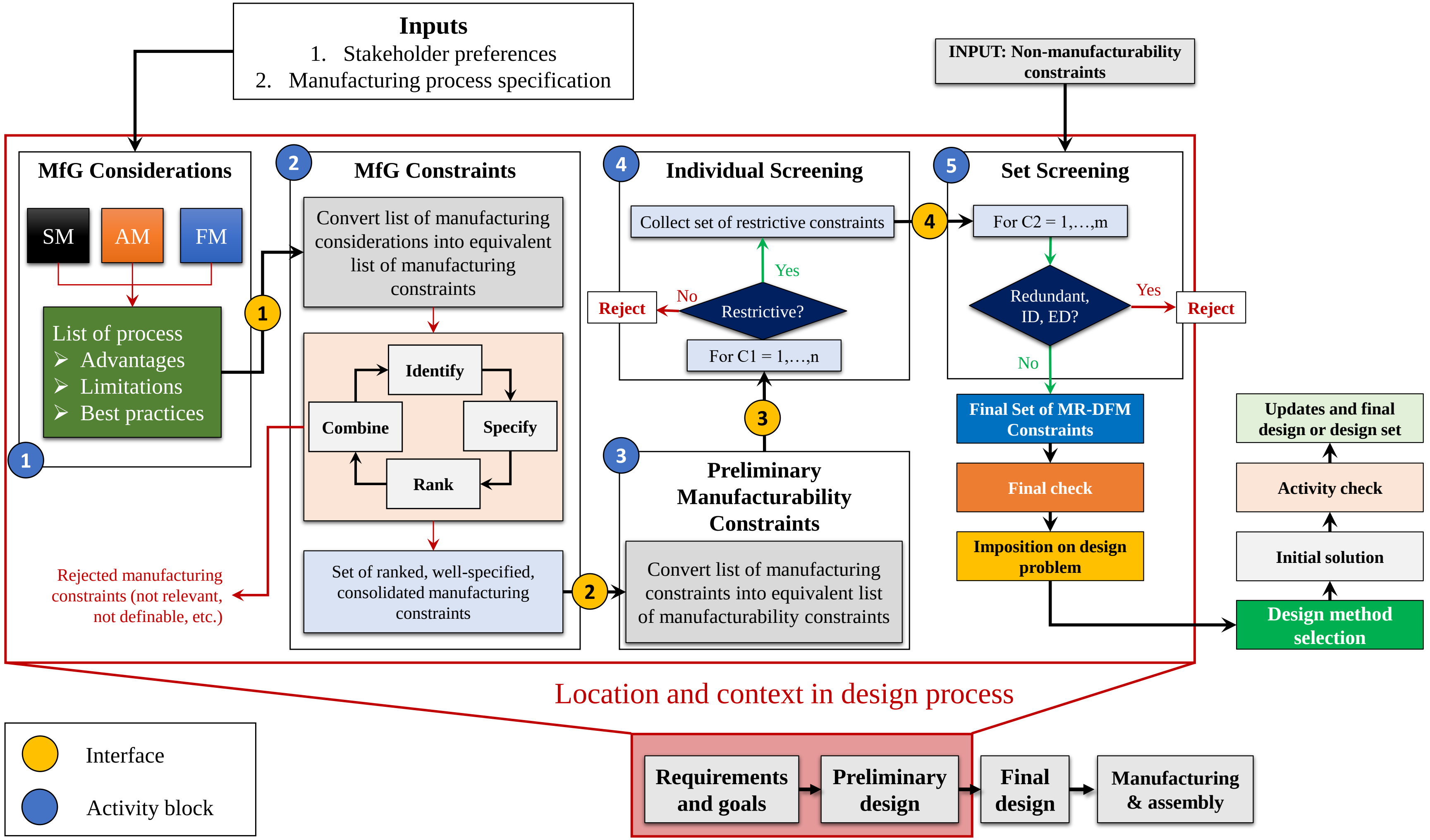
1. **Input**: Given
Output: Raw set of mfg considerations

2. **Input**: Raw set of mfg considerations
Output: Ranked, ordered, specified manufacturing constraints

3. **Input**: Full set of manufacturing constraints
Output: Full set of manufacturability (design-specific) constraints

4. **Input**: Full set of manufacturability constraints
Output: Set of (nominally) active manufacturability constraints

5. **Input**: Set of active manufacturability constraints
Output: Set of useful manufacturability constraints



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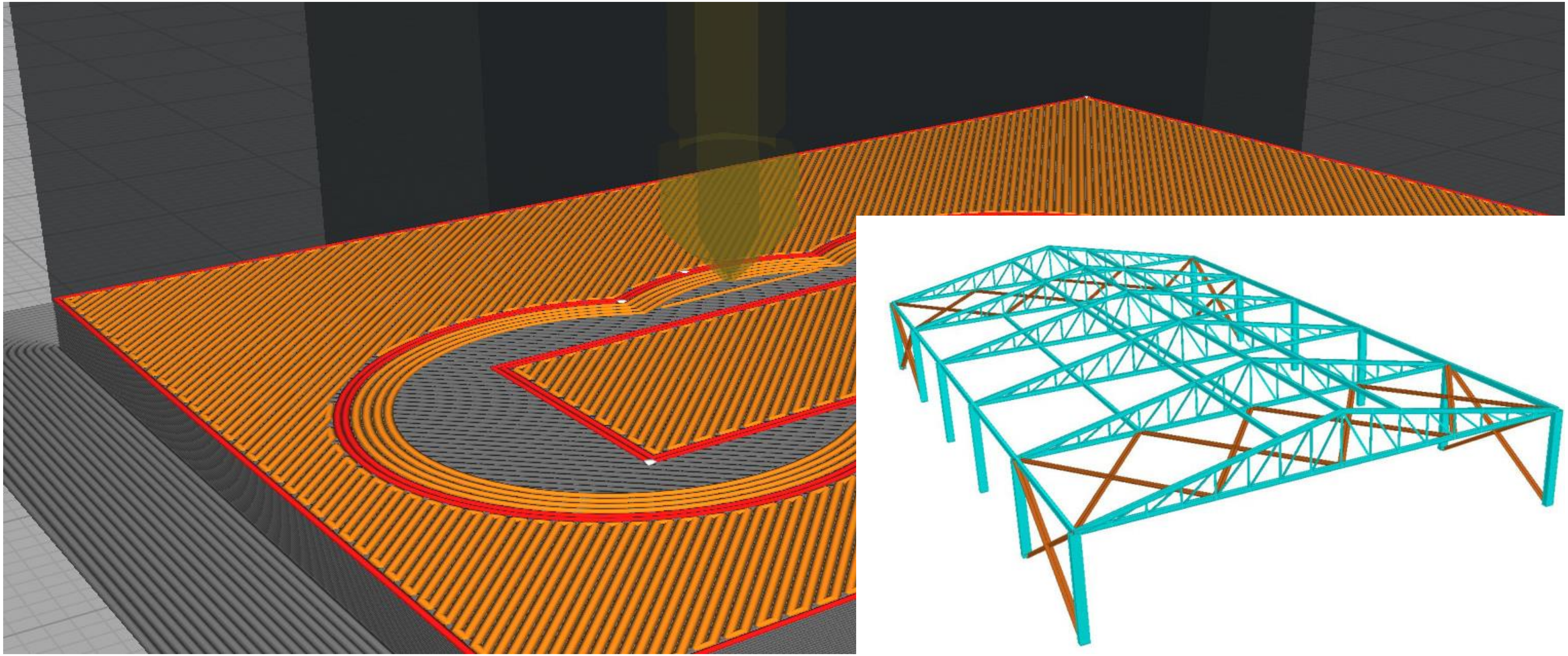
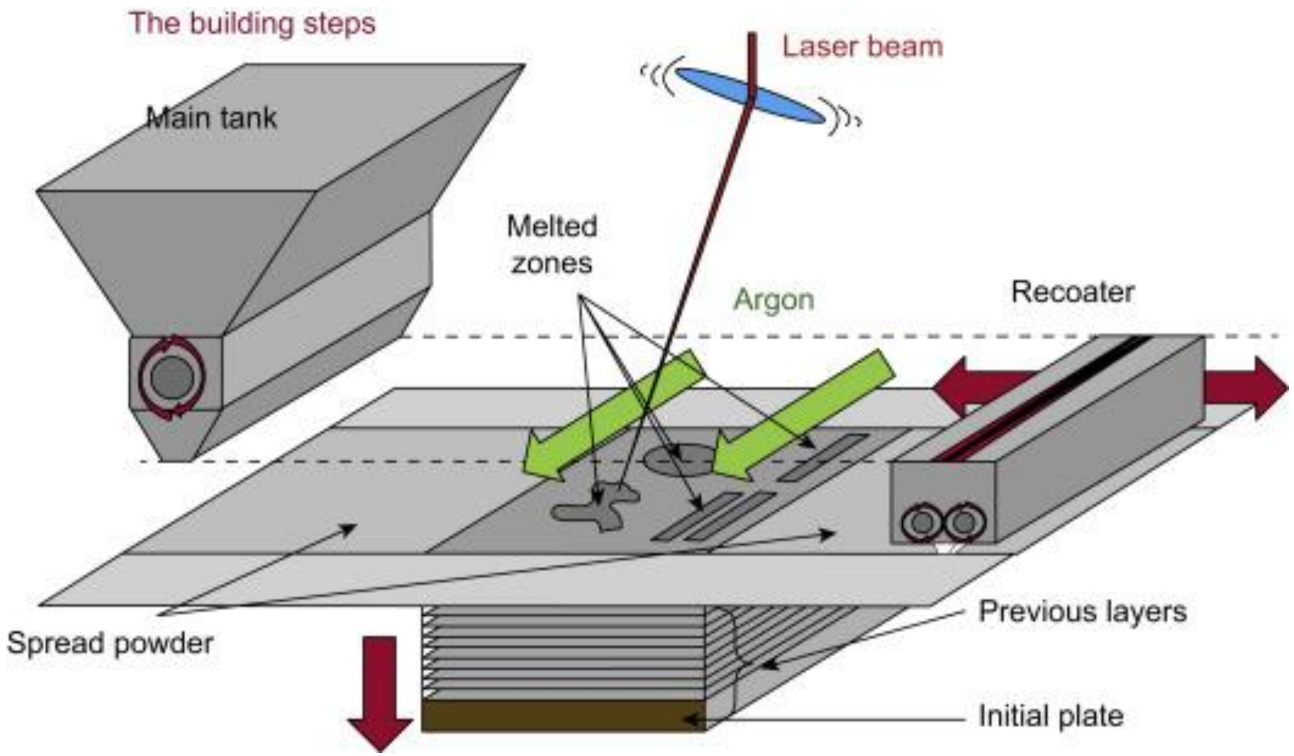
Scanning-Type Additive Manufacturing

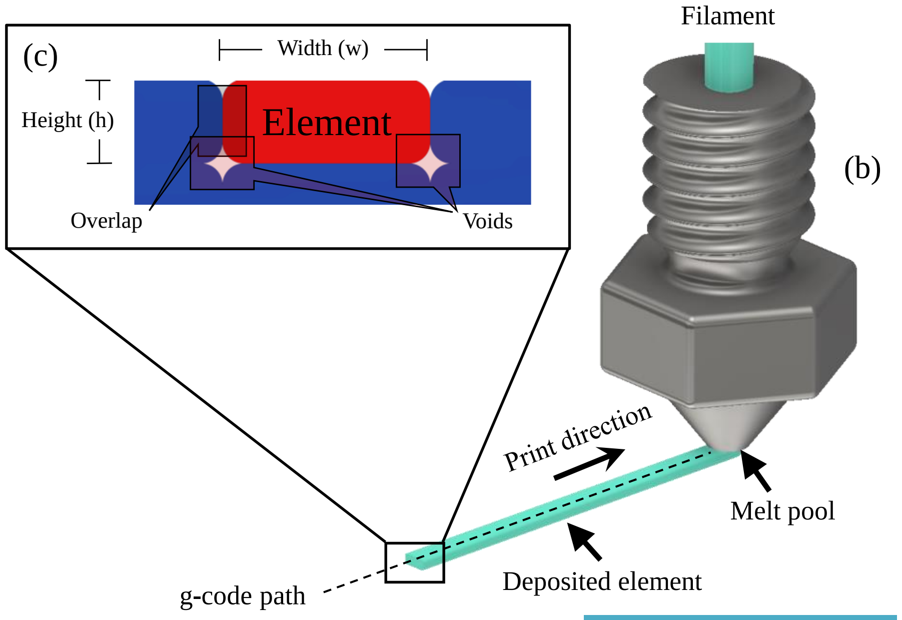


Scanning-Type Additive Manufacturing

Powder Bed Fusion AM



Material Extrusion AM



g-code!

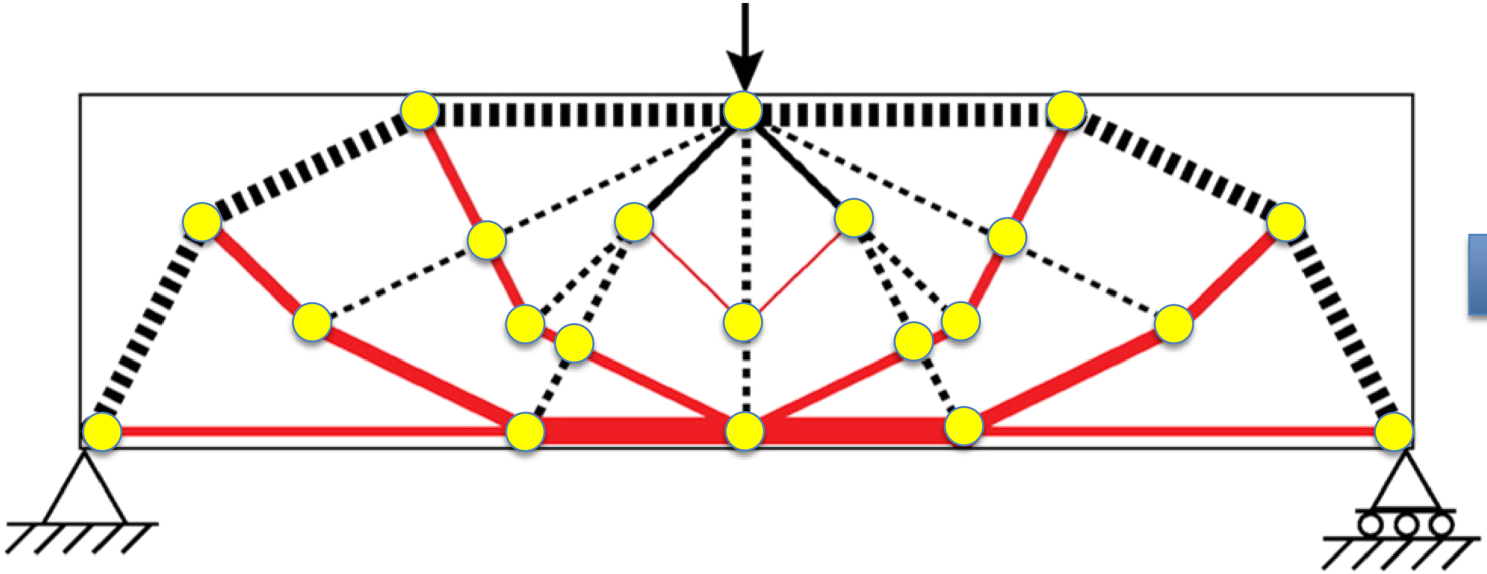
Isotropic and constant CS!

Zhang, Y., Yang, S., & Zhao, Y.F. (2020). Manufacturability analysis of metal laser-based powder bed fusion additive manufacturing – a survey. *The International Journal of Advanced Manufacturing Technology, 110*: 57-78.

Patterson, A.E., Chadha, C., & Jasiuk, I.M. (2022). Identification and mapping of manufacturability constraints for extrusion-based additive manufacturing. *Journal of Manufacturing and Materials Processing, 5*(2): 33.

Design Strategy– Meso-Scale Truss Design

Case Study: Truss Method



G-code

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G1 F750 X68.421 Y96.615 E0.02275
G1 X68.932 Y96.419 E0.0455
G1 X69.466 Y96.3 E0.06825
G1 X69.895 Y96.262 E0.08615
G1 X70.181 Y96.253 E0.09805
G1 X70.299 Y96.251 E0.10296
G1 X149.293 Y96.25 E3.38714
G1 X149.347 Y96.25 E3.38939
G1 X150.041 Y96.26 E3.41825
G1 X150.586 Y96.308 E3.44099
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G1 X152.101 Y96.912 E3.50928
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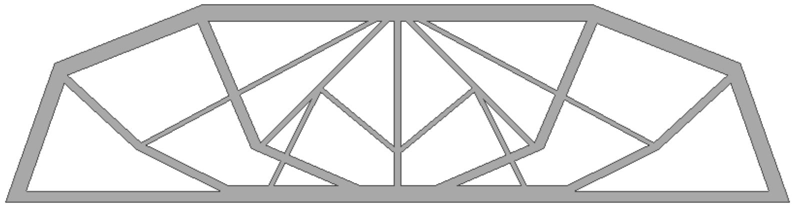
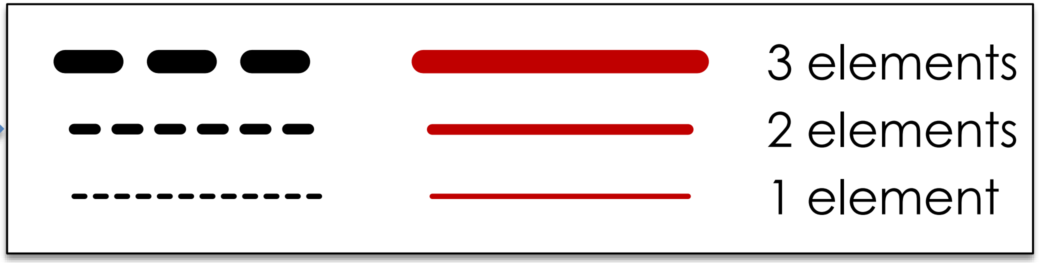
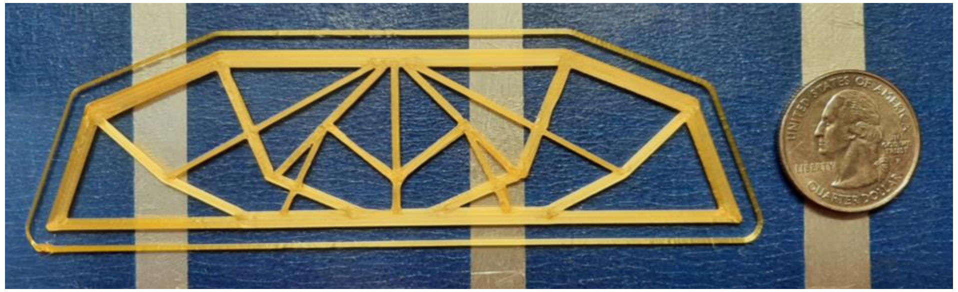


Truss Designs





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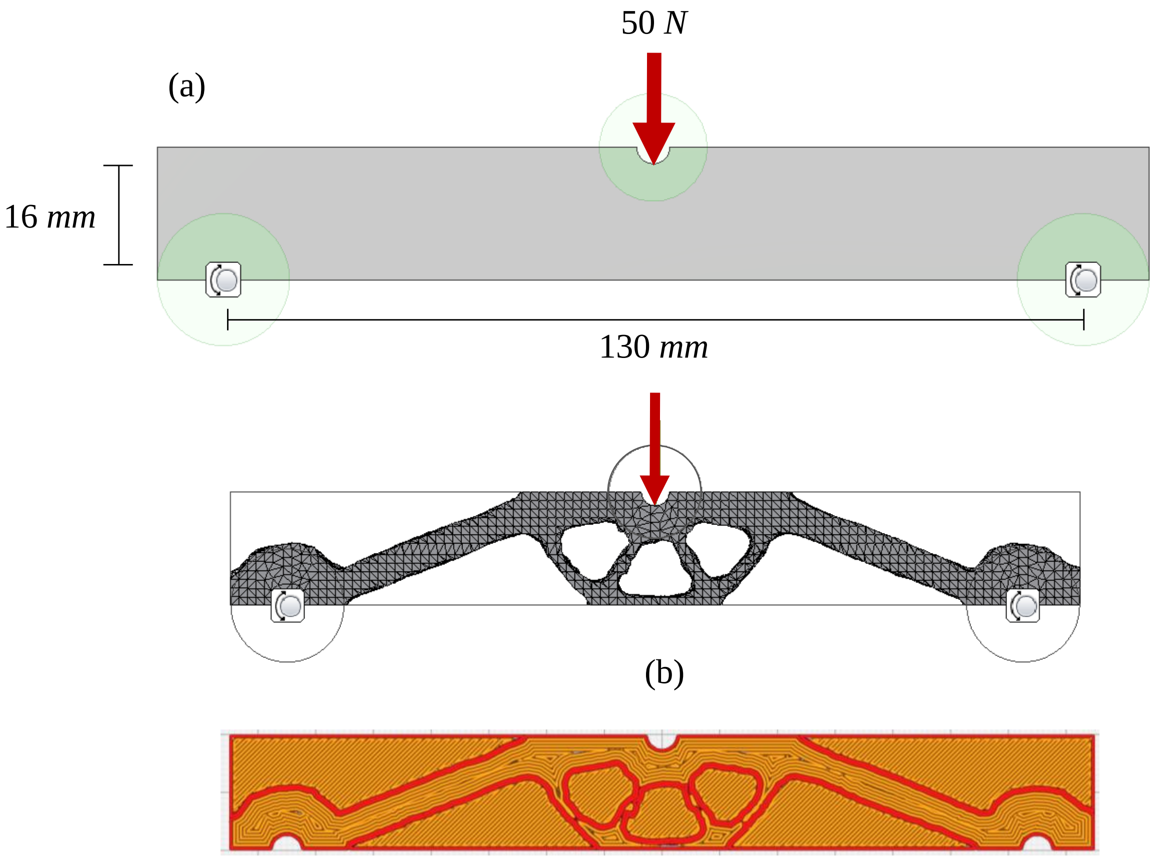
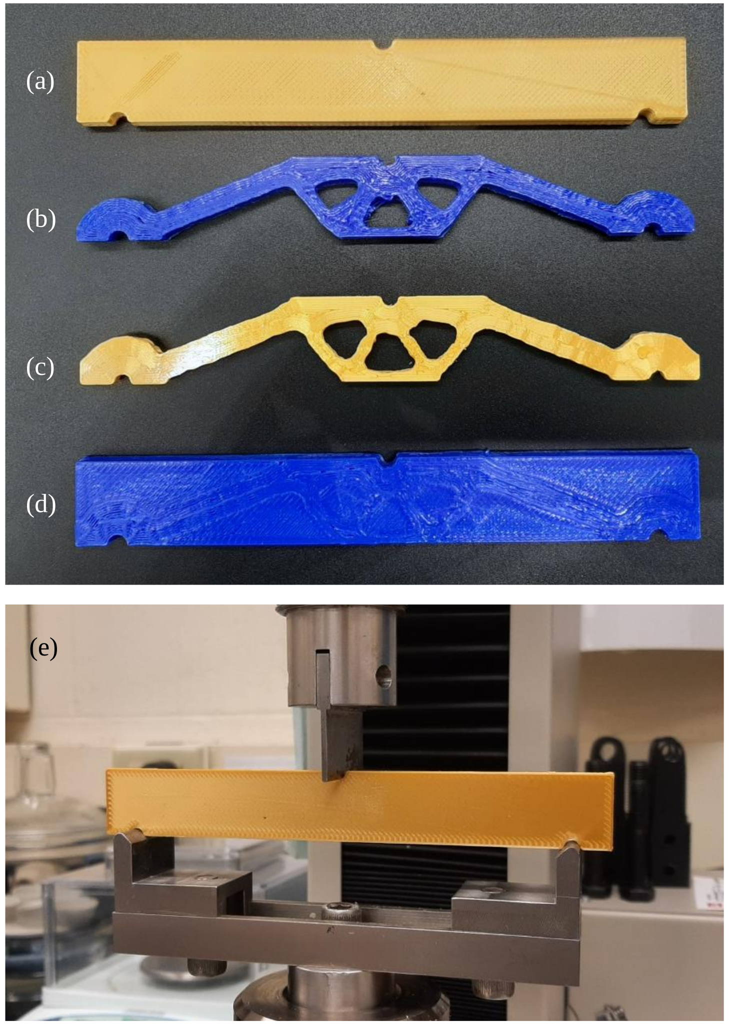
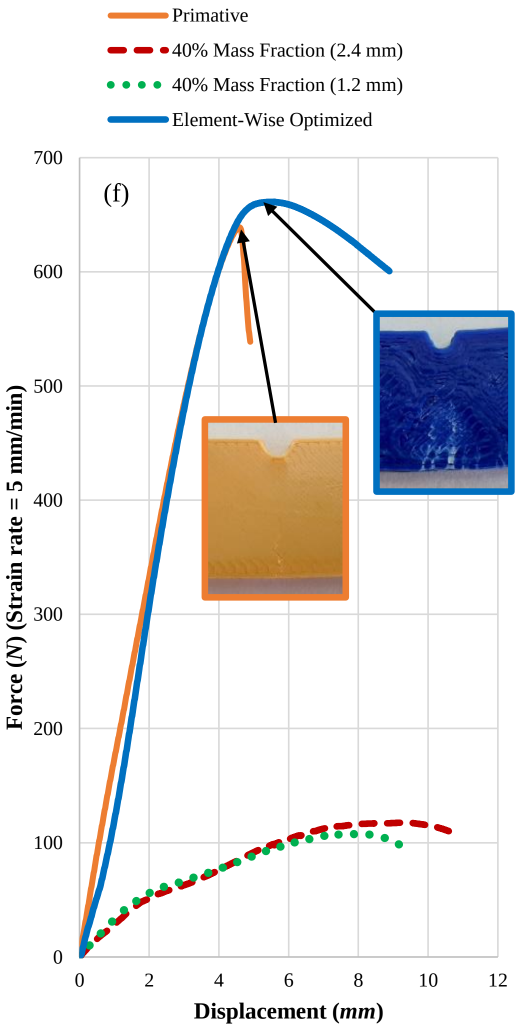
Design Strategy – Designed Regions







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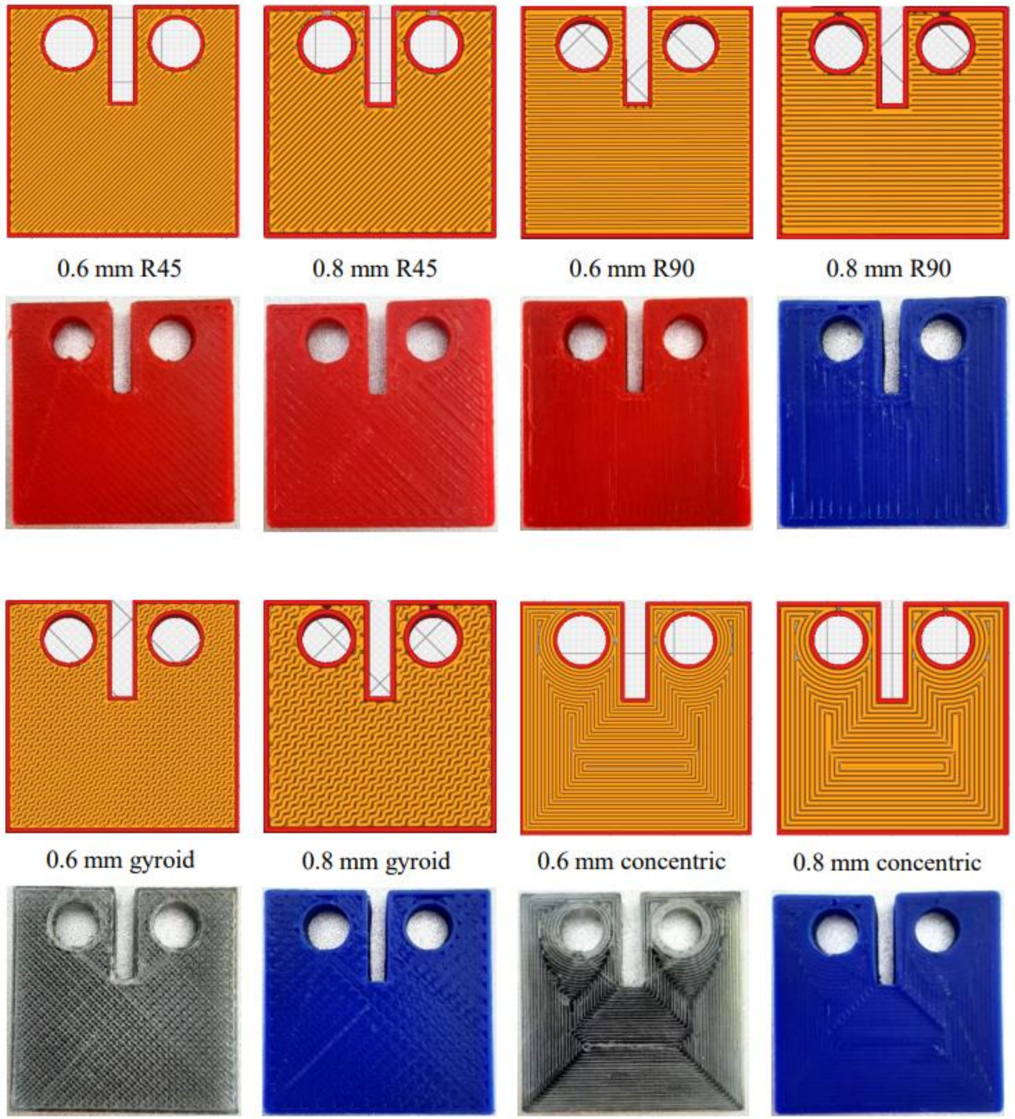
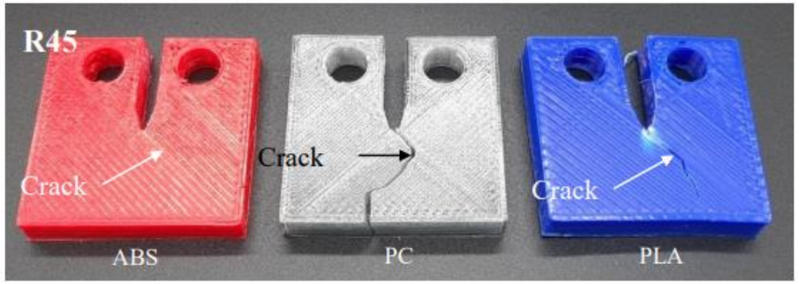
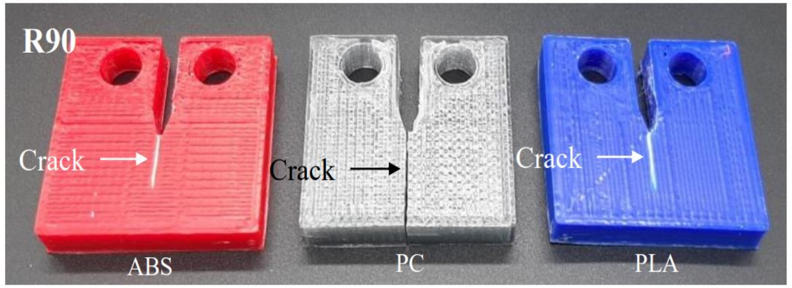
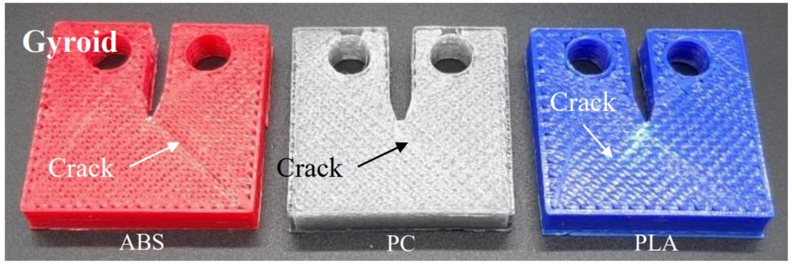
Design Strategy: Parametric Material Layout

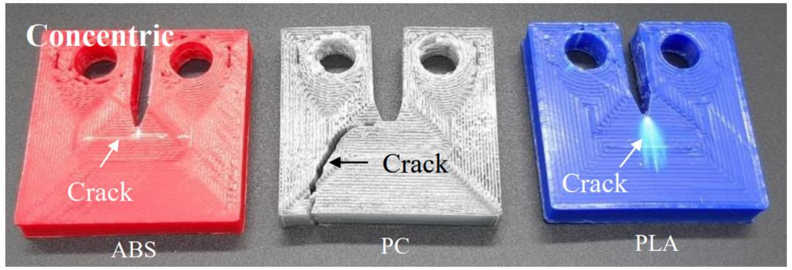


ABS: K_Q + 38%
PLA: K_Q + 34%
PC: K_Q + 52%









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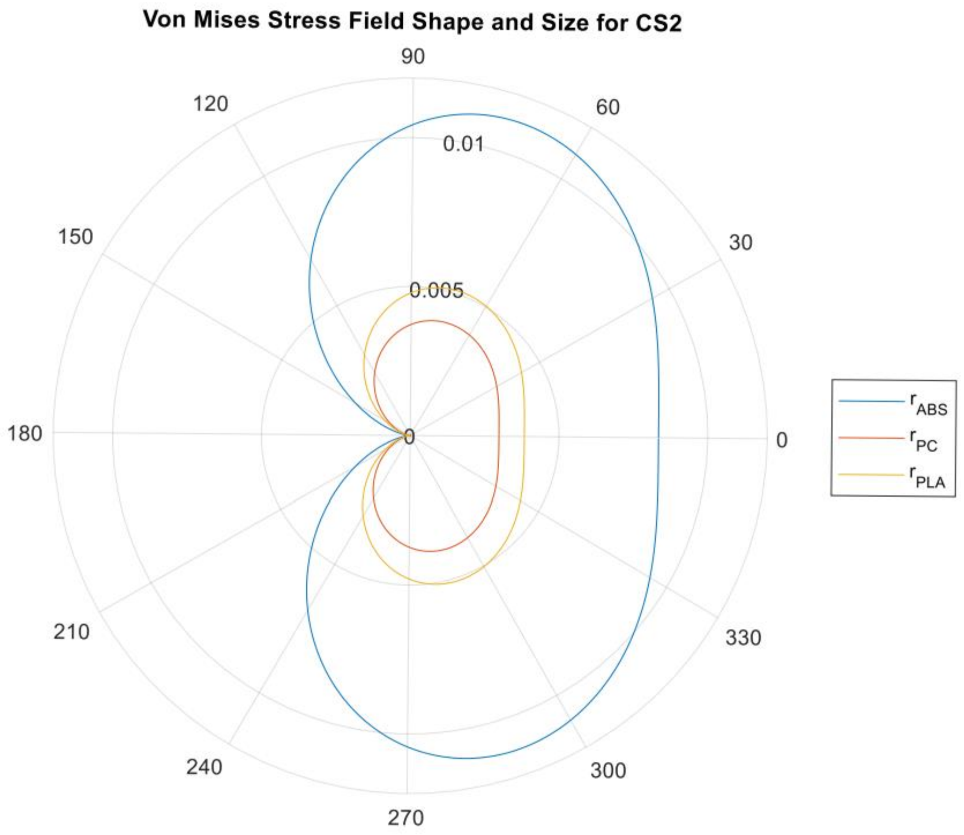
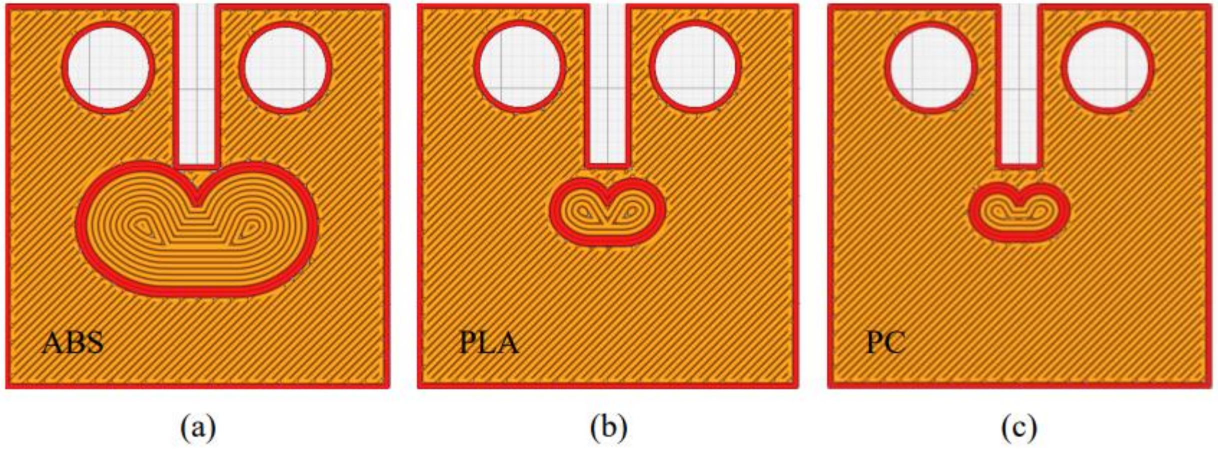
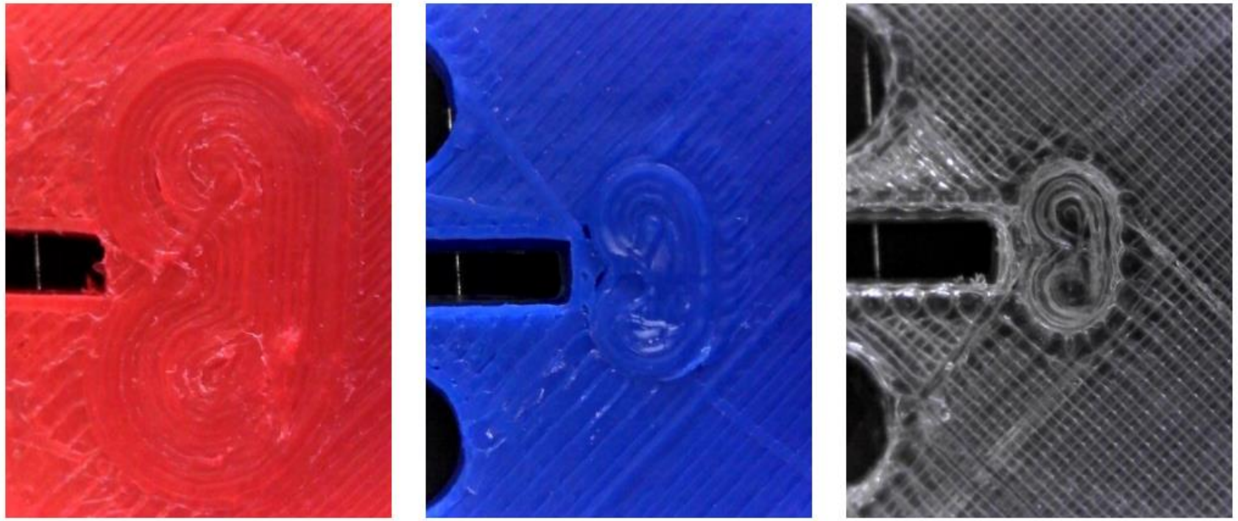
Design Strategy: Analytical Stress Field







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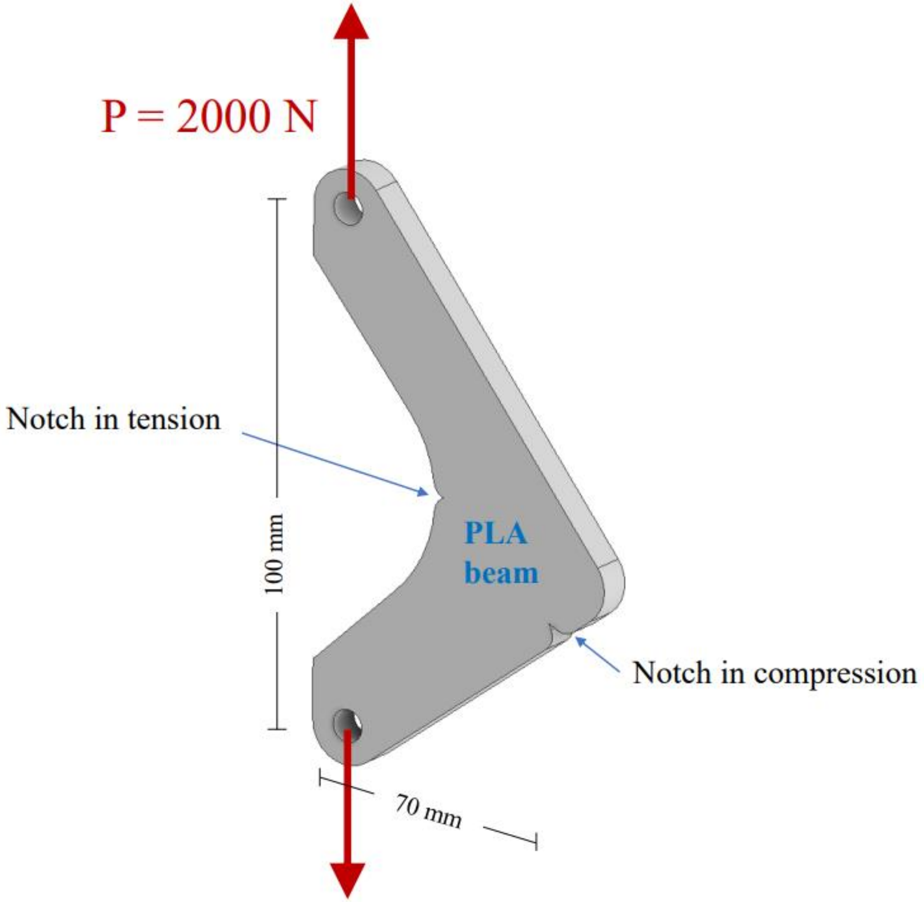
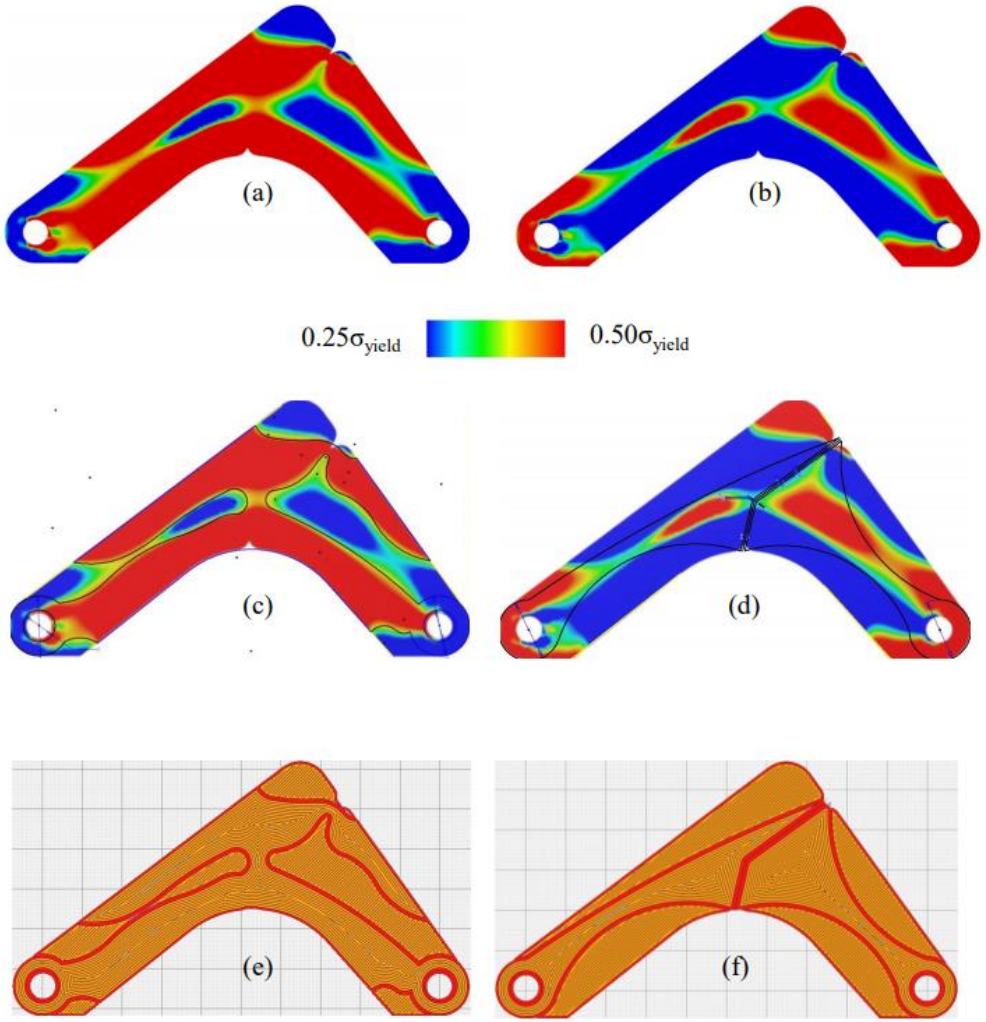
Design Strategy: Regional w/ Crack Path



Designed to arrest fracture



Designed to follow crack path

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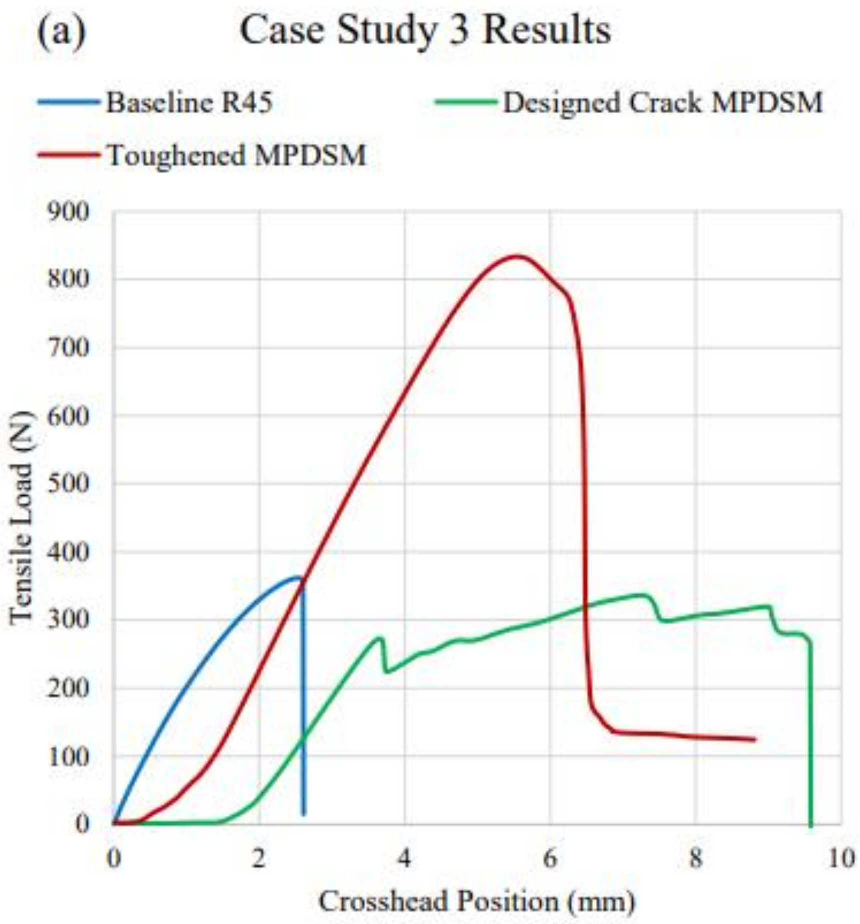
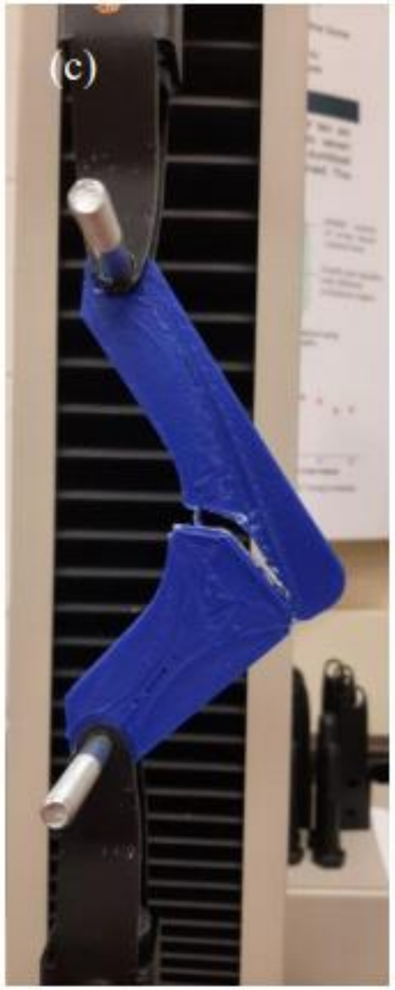
Design Strategy: Regional w/ Crack Path





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Discussion and Conclusions

- Examples shown used FFF, but these principles apply to any ST-AM processes using a variety of materials.
- Assuming that each bead/element of materials is isotropic or transversely isotropic with a uniform cross-section allows the use of beam and truss theory for design.
- MPDSMs are a promising approach for improving manufacturability outcomes for architected materials.
- Manufacturability is the most important constraint and ensures that all the design candidates are producible using one or several manufacturing processes.
- Many different approaches discussed in this presentation, all of which are effective. Many more approaches and better design automation possible.

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