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Title: R&D Lattice Modeling, Manufacturing, and Inspection

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R&D Lattice Modeling, Manufacturing, and Inspection

Masters Degree Final Presentation

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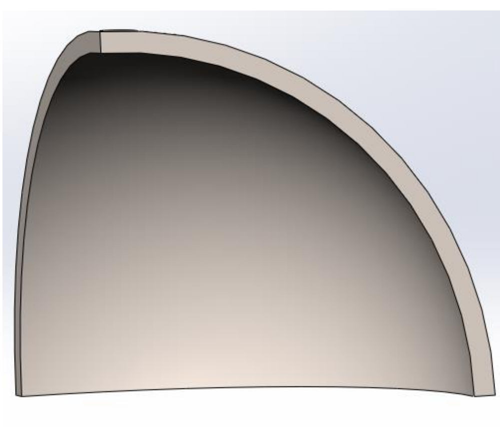
03/30/2020

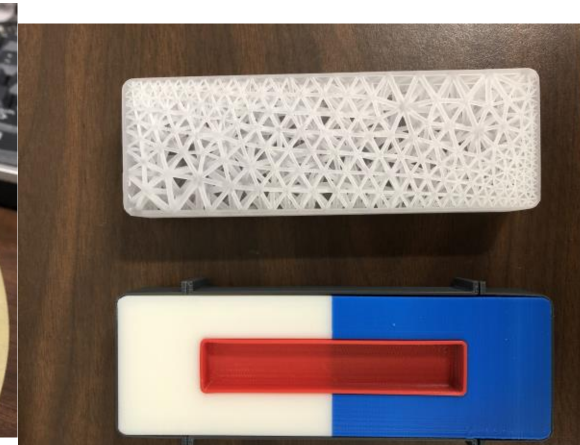
Slides Outline

- Project Background
- Lattice Fundamentals and Basic Research
  - Maxwell Criterion
  - Approximations and Analytical Lattice Solutions
  - Testing
  - Testing Results v. Analytical solutions
- Materials, Methods, Modeling, and Inspection
  - Polymers and Metals
  - Additive Processes and Limitations
  - Limitations of Modeling
  - Inspection techniques and Limitations

Project Background

- Mechanical mocks are useful when substituting components in tests of Large assemblies, when that component isn't specifically being tested.
  - Useful when components are rare, expensive, or hazardous and can be replaced in the test
- Simplest mocks match mass properties. More complex mocks match mechanical properties as well.
  - Varying wall thickness, lattice density, and unit cell changes response while keeping mass the same
- We are asking how to make responses match instead of how low can we go



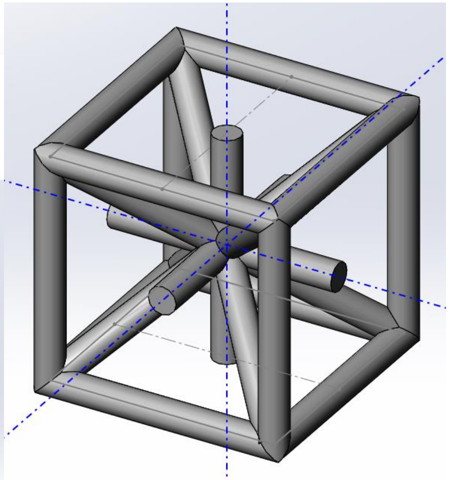


Lattice Fundamentals and Basic Research

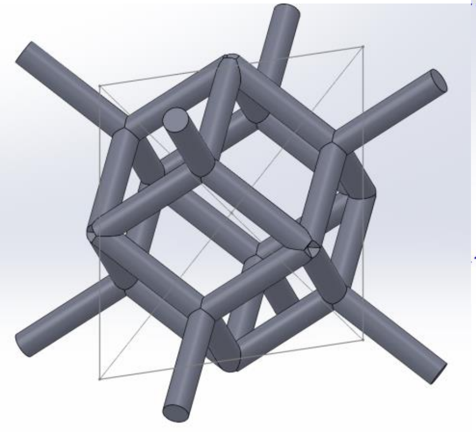
Lattice Fundamentals-Stretch vs. Bend Dominated

- Lattices can be divided into Stretch and Bend dominated
- Division is based on the results of the 3D Maxwell Criterion [1]
  - M=b-3*j+6
    - b is the number of struts (beams)
    - j is the number of joints
  - If M is greater than or equal to 0 the lattice is stretch dominated.
    - Lattice is self-supporting if pin joint assumption is made
    - Struts are primarily in tension and compression
  - If M is less than 0, the lattice is bend dominated
    - Lattice is not self-supporting with pin joint assumption
    - Struts are primarily in bending

Octet--M=0



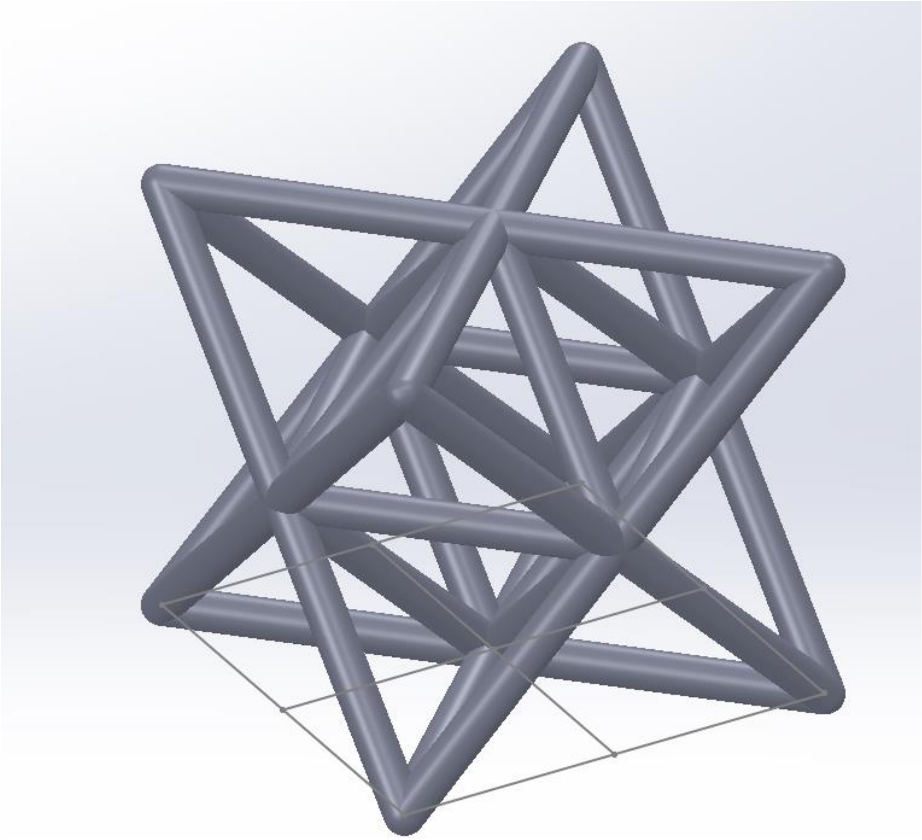
Iso-truss– M=5



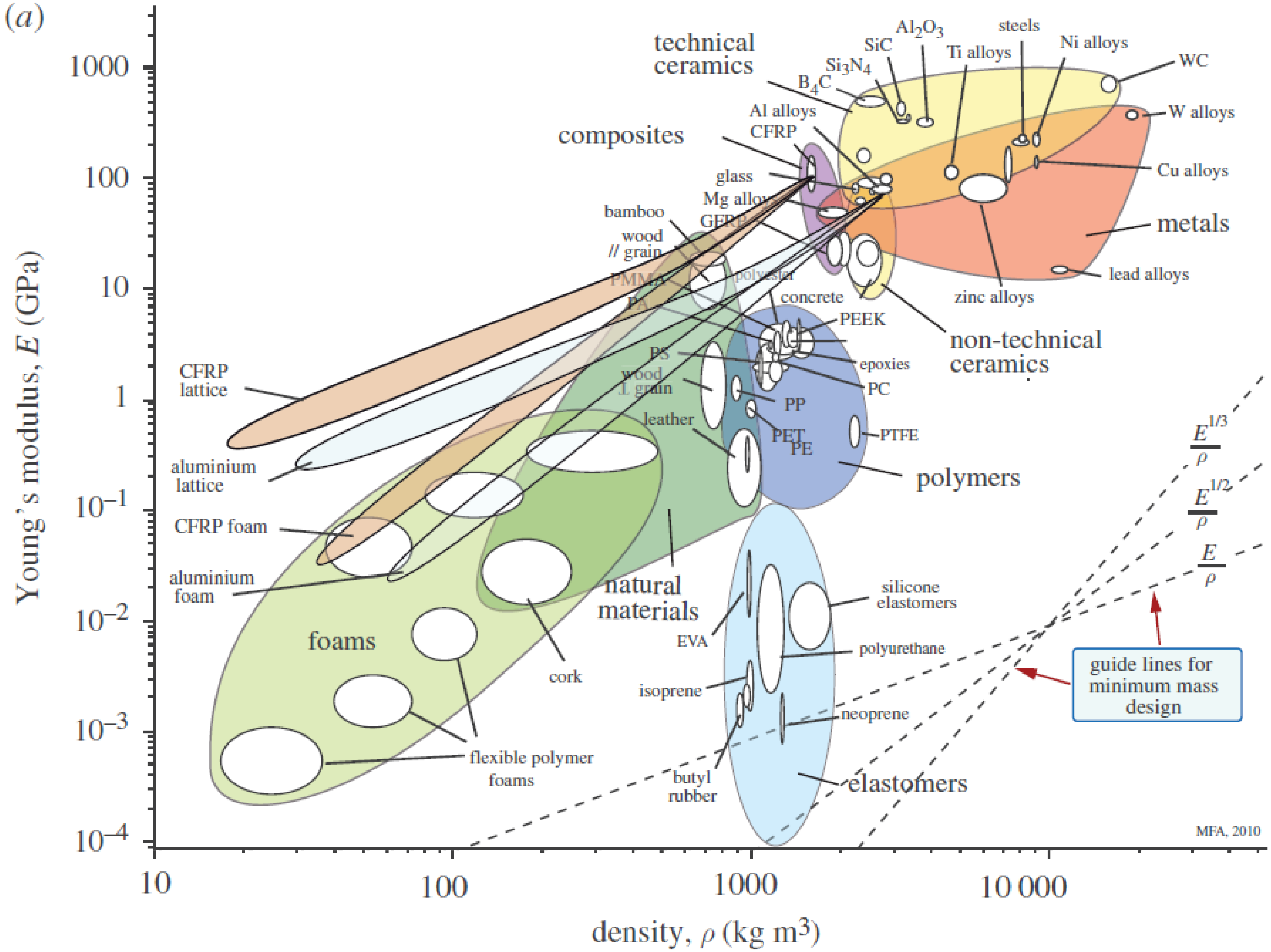
Rhombic Dodecahedron M=-4

Lattice Fundamentals-Maxwell Criterion example

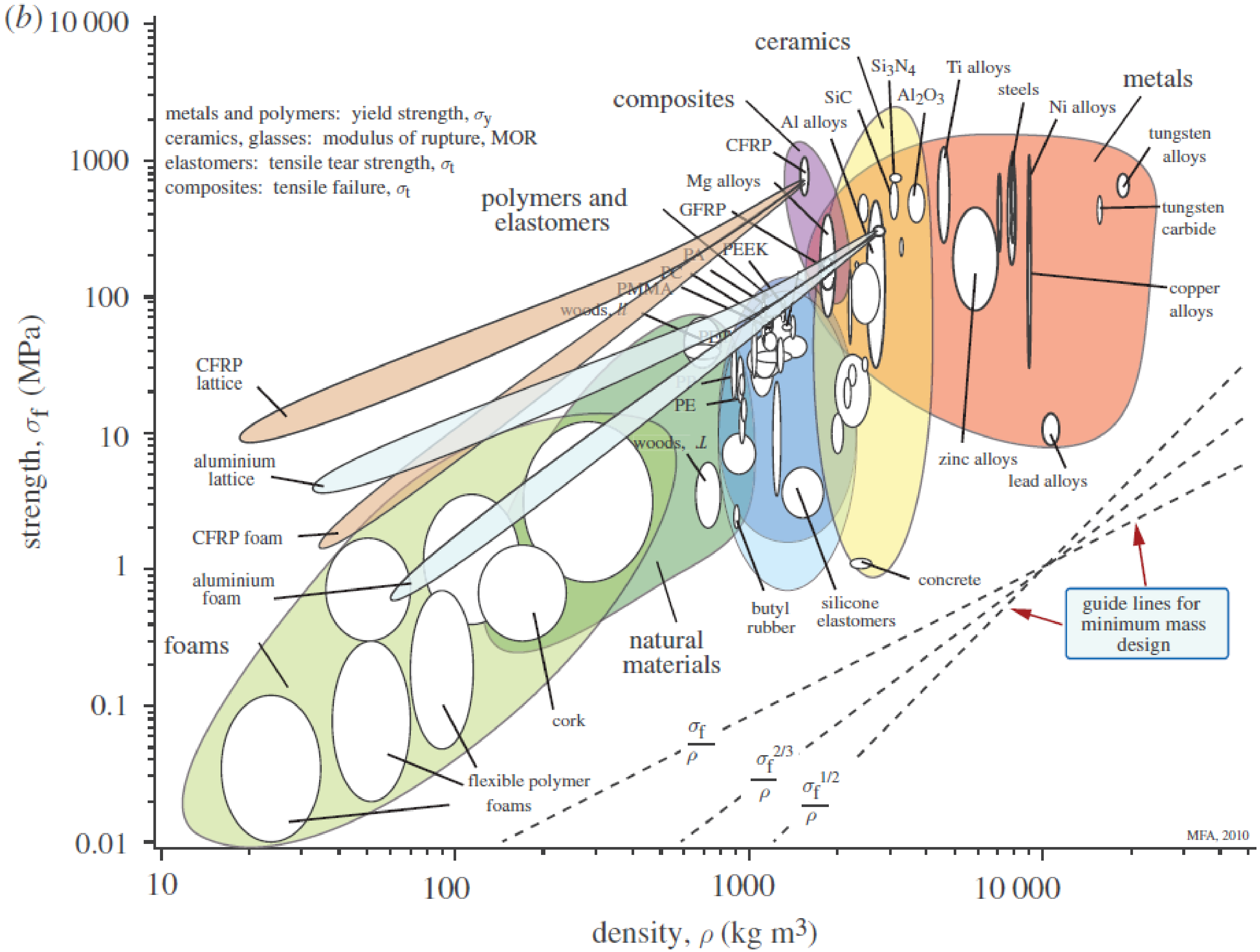
- The octet unit cell has
  - b=36
  - j=14
- M=b-3*j+6
- M=0
- Octet is statically determinate
- Using the pin joint assumption, octet could be solved using the method of joints from statics.



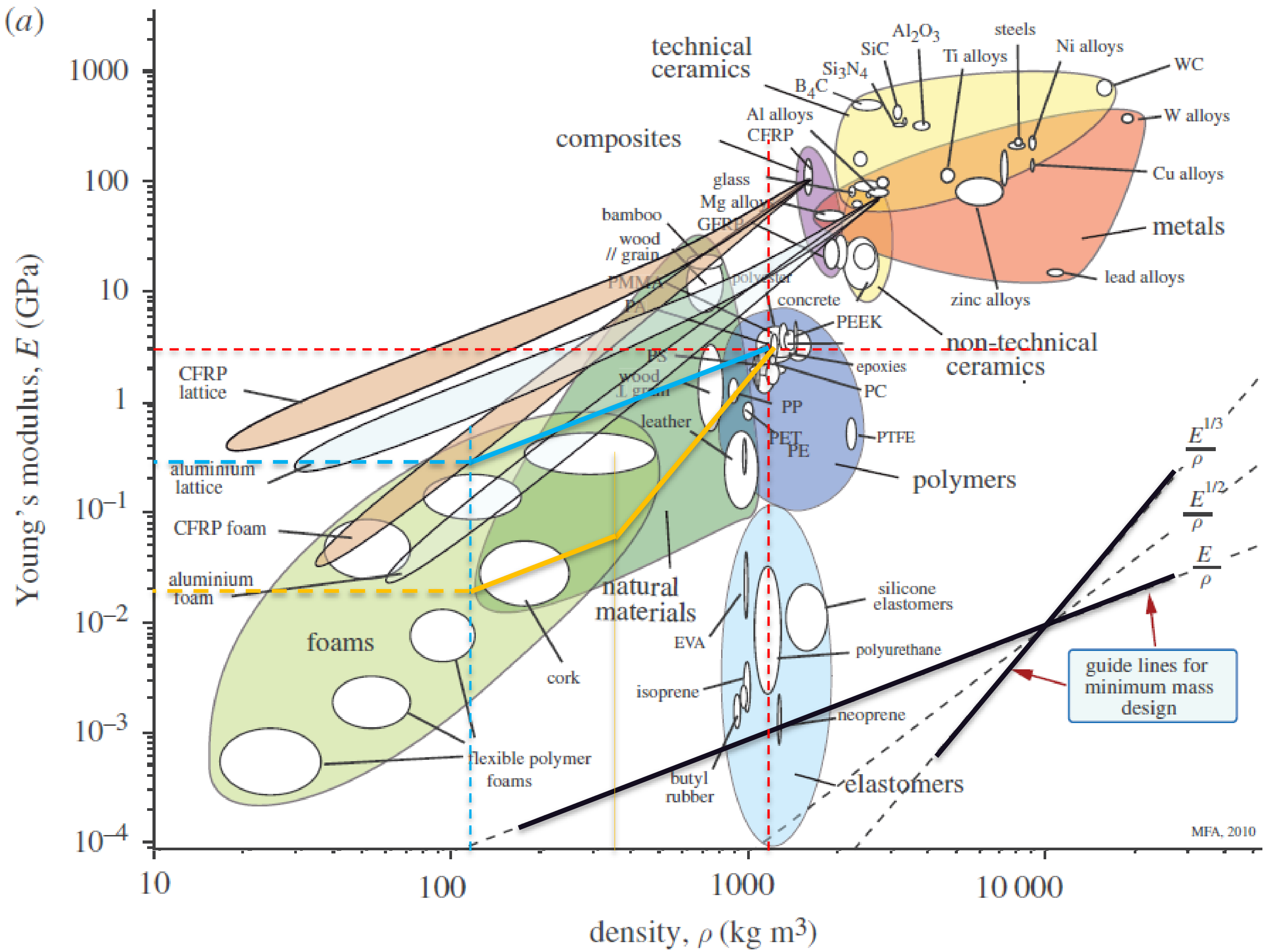
Effective Modulus and Strength-Ashby chart [2]



Effective Modulus and Strength-Ashby chart [2]



Ashby Chart Example—10% Octet Lattice, Formlabs Clear SLA Resin (ρ=1200 kg/m^3, E=2.8 Gpa) [2]



Effective Modulus and Strength-Octet analytical solutions

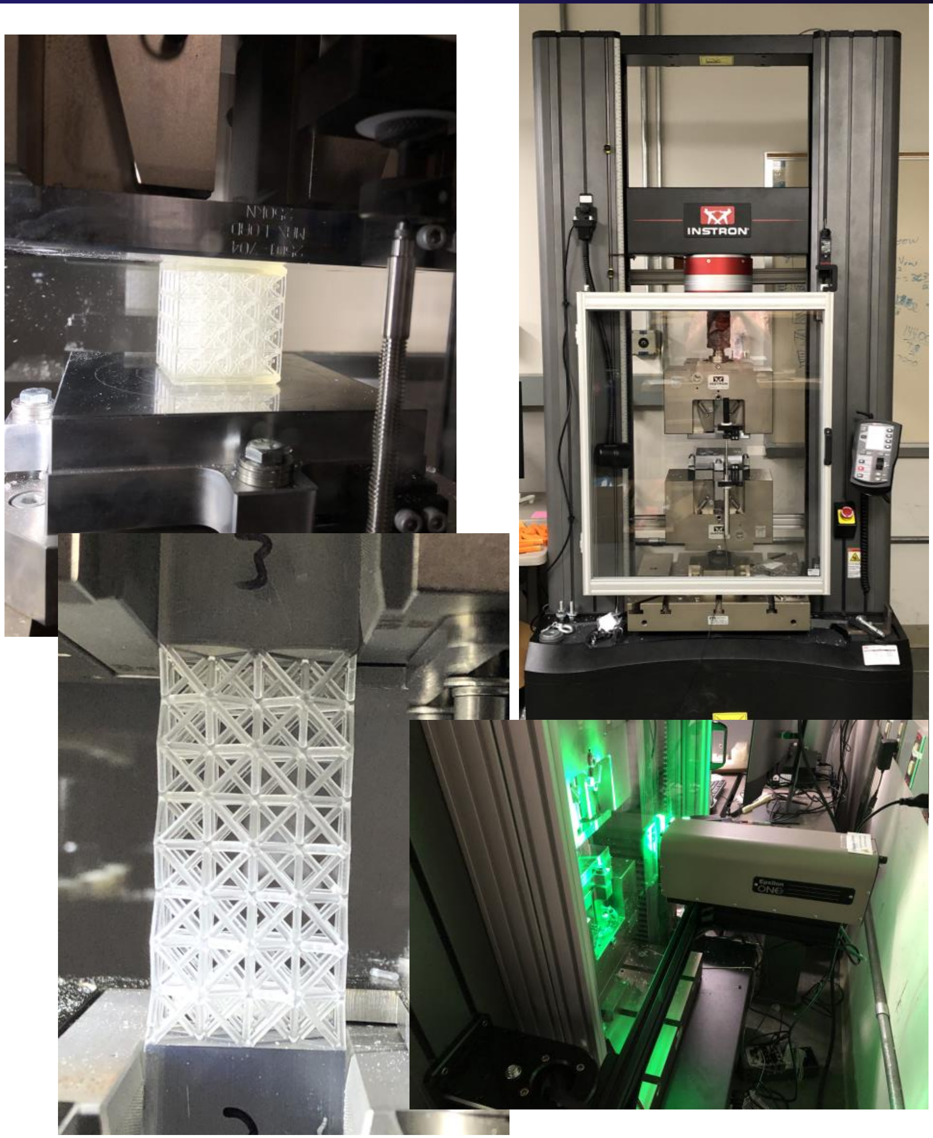
- From Messner “Wave propagation” [3]The approximate relative density for an octet lattice is given by:
  - $\bar{\rho} = \frac{6\sqrt{2}A}{l^2}$
    - Where A is cross sectional area of the strut, l is length of the strut,
    - This equation assumes that the volume of the nodes negligible.
- The effective modulus for an octet lattice with a load applied on an axis can be gained from Messner’s stiffness tensor and is:
  - $E_{eff} = \frac{E\bar{\rho}}{6}$
  - This equation assumes that the octet nodes are pin jointed, and therefore, cannot sustain a moment.
  - Valid for low relative densities (<10%)

Effective Modulus and Strength-Octet analytical solutions

- Deshpande claims in “Effective properties of the octet-truss lattice” [1] that the effective modulus is:
  - $E_{eff} = \frac{E\overline{\rho}}{9}$
  - However, in his compliance tensor a few lines later, the effective modulus simplifies to $E_{eff} = \frac{E\overline{\rho}}{6}$
  - Since this paper contains conflicting information, Messner’s work is used
- An equation that estimates the strength of an octet lattice can be gained from Fig. 3 of “Effective properties of the octet-truss lattice” paper as well.
  - $\sigma_{eff} = \frac{\sigma_y\overline{\rho}}{3}$

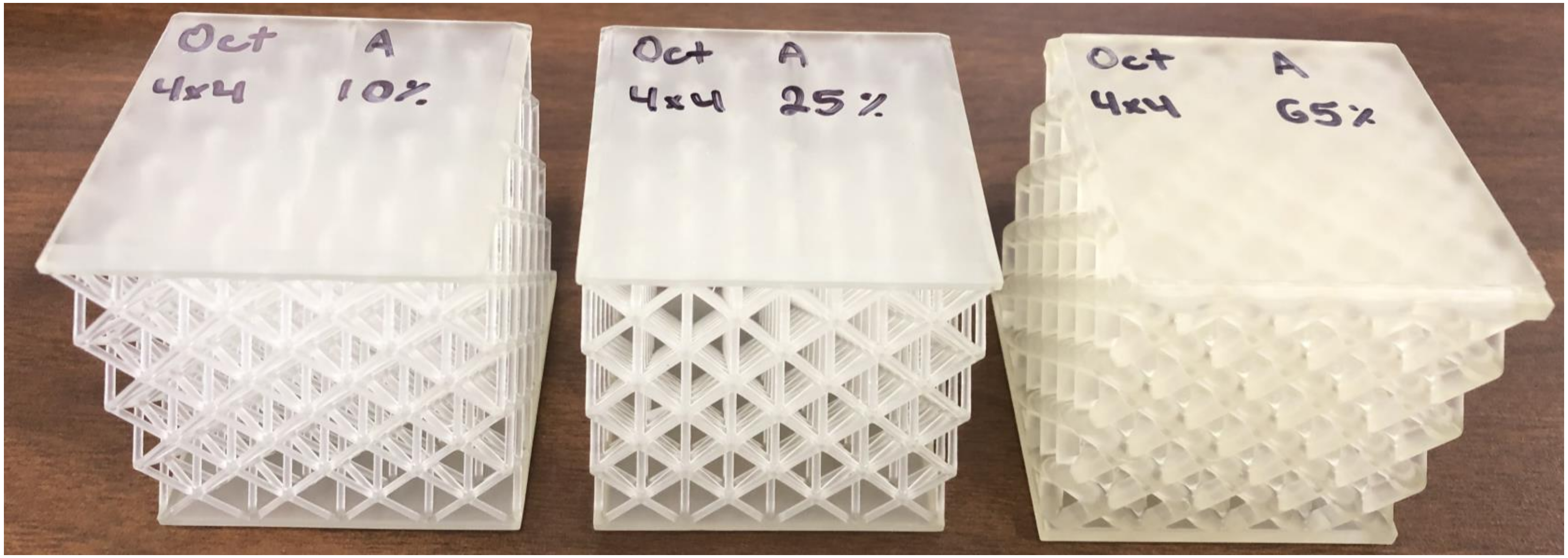
Experimental Setup

- Instron 5985 Dual column test frame with 250 kN capacity
- EpsilonOne Non-contact extensometer gauge length of 10-50mm (class B-1)
- Compression specimen
  - 2” cube with 0.5” unit cells (SLA)
  - 2” cube 4.2 mm unit cells (Ti-5533)
  - 10%, 25%, 65%
- Tensile specimens
  - 1”x1”x2” test section
  - Same lattice properties as compression



Effective Modulus and Strength-Actual Results

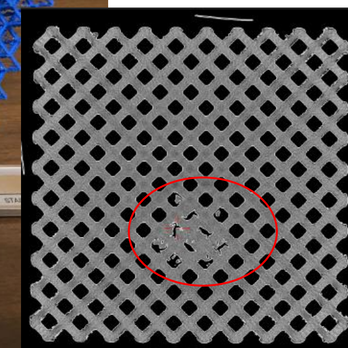
Actual Octet Compression Results v. Approximations and Analytical solutions--Formlabs Clear SLA Resin (MPA)					
Relative density	Messner	Ashby chart M1	Ashby chart M2	LANL FEA	LANL tests
10%	38.3	280	20	32.4	31.4
25%	95.8	800	50	106.4	129.7
65%	249.2	1900	480	545.9	628.8

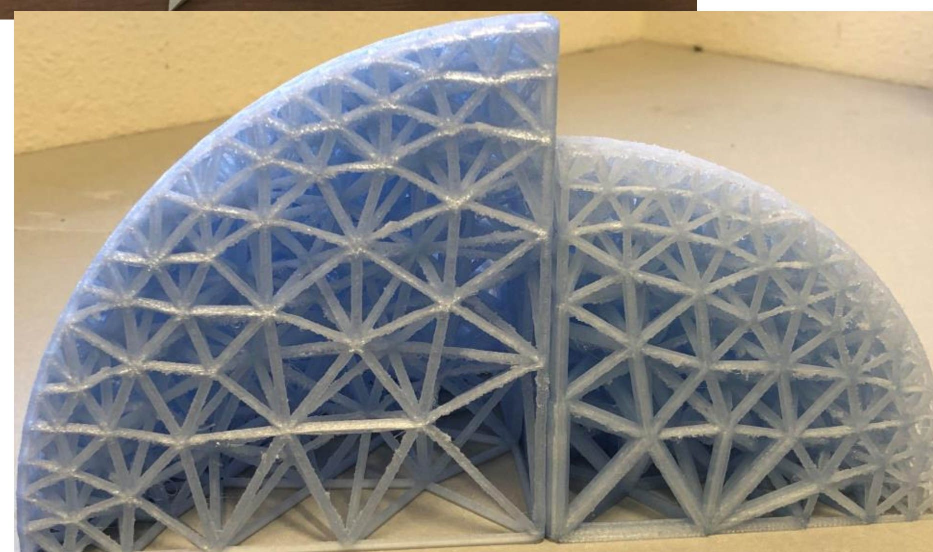


Materials, Processes, Modeling, and Inspection

Materials—AM Polymer

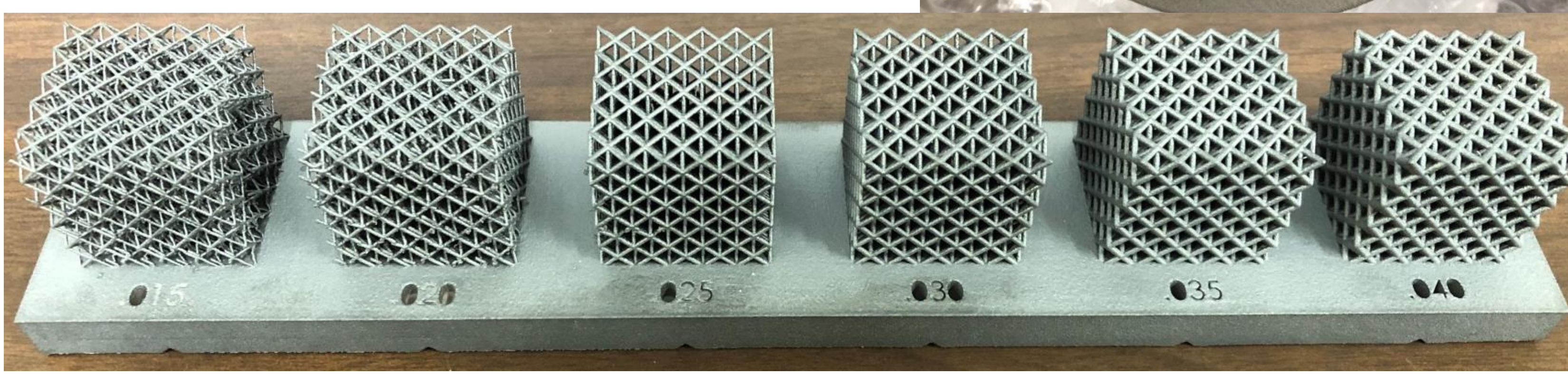
- **SLA resin**
  - High detail prints
  - Isotropic behavior
  - Can be "doped" with different materials to change properties (density, modulus, conductivity)
    - Tungsten, hollow glass spheres, chopped glass and carbon fibers
  - Occludes at high density (>65%) and small cell size (~3mm)
  - Limited to smaller build volumes (5" cube is common, larger available)
- **FDM**
  - Low detail compared to SLA
  - Anisotropic behavior ~10% weaker along build layers
  - Soluble support allows for long unsupported strut lengths
  - Many unfilled and filled materials commercially available
  - Very large build volumes are possible
    - Up to 36"x24"x36" at LANL with soluble support





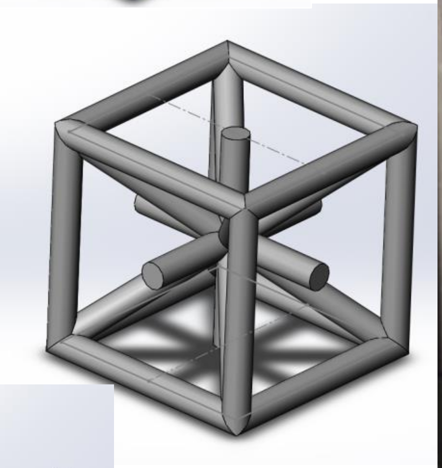
Materials—Metals, Laser Powder bed

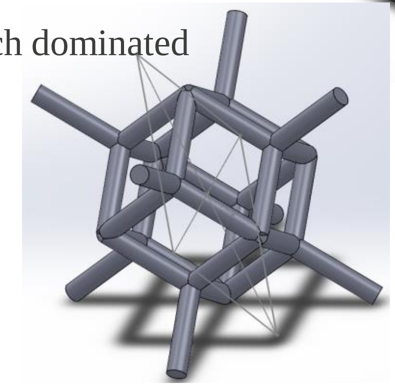
- **Ti-6Al-4V**
  - Large Body of research on properties of AM material
  - Areas of high stress cause distortion and build failures, especially on small diameter struts, porosity
- **Ti-5Al-5V-5Mo-3Cr**
  - Less prone to distortion than Ti-64
  - Typically has higher yield strength
- **Other Materials of interest**
  - 316/316L Stainless
  - Aluminum Alloys (AlSi10Mg, A360)
  - Copper

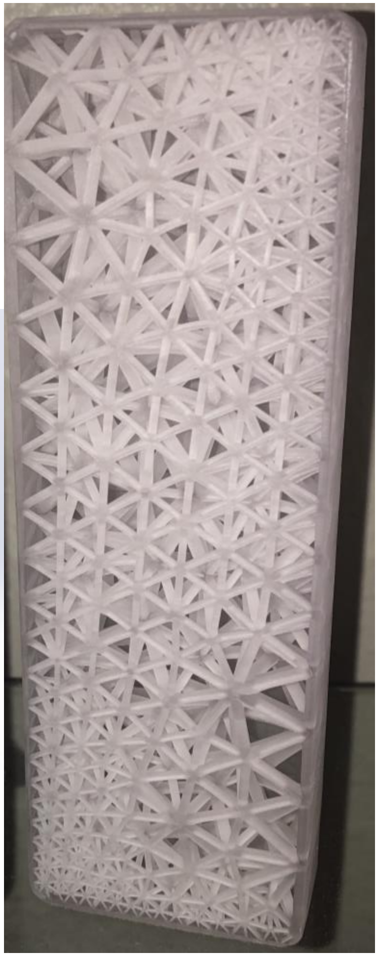


Lattice Types

- **Octet**
  - Orthotropic Stretch Dominated Lattice (M=0)
  - Has horizontal struts
- **Iso-truss**
  - Projected to have nearly isotropic behavior
  - Stretch dominated (M=5)
- **Unstructured Tetrahedral**
  - Stretch Dominated (M=3?)
  - Conformal geometry easily produced from FEA meshes
- **Rhombic Dodecahedron**
  - Bend Dominated (M=-4)
  - Has no horizontal or low angle struts
- **Other Lattice Types**
  - CORC—(M=-54), but approaches stretch dominated properties
  - Myriad of Cubic Cells
  - Other unit cell base shapes
    - Hexagonal Close packed

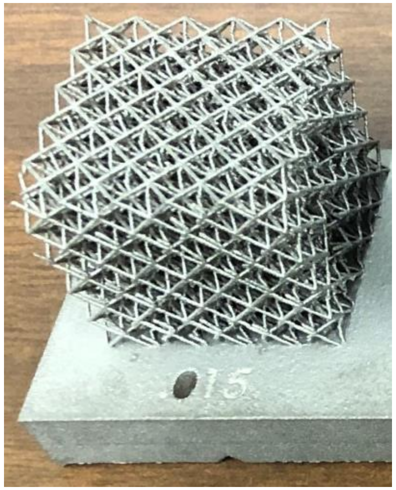




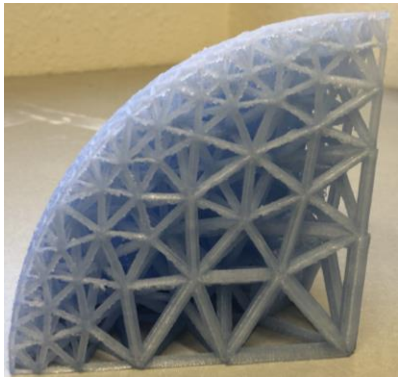


Printing Limitations

- **Metal**
  - Maximum Part Size-~400mm cube
  - Maximum unsupported horizontal length-~3-6mm
  - Minimum angle for unsupported struts-~45deg
  - Minimum strut Diameter-~350um
    - Laser width
    - Strut warp/ catch by recoater blade
  - Minimum/Maximum practical relative density-~8%-65%
  - Anisotropy in printing process
  - Cleaning out powder and parasitic material
  - Strut warping/broken struts

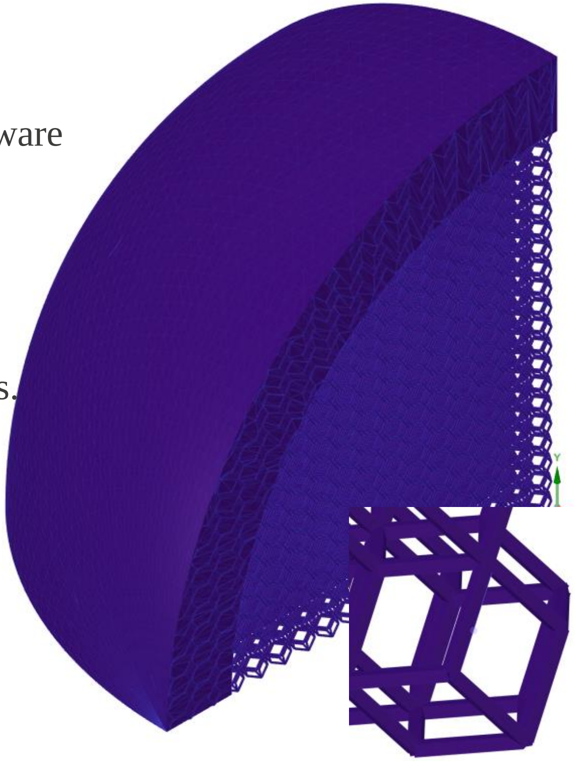


- **Polymer**
  - Max part size
    - SLA-5.7"x5.7"x7.3 inches (larger is possible)
    - FDM- Up to 36"x24"x36"
  - Maximum unsupported horizontal length
    - SLA~.5"(dependent on strut diameter)
    - FDM- nearly unlimited with use of soluble support
  - Minimum Strut Diameter
    - SLA~125 um
    - FDM~1.5mm
  - Minimum/Maximum Relative Density
    - SLA-<5%-65%
    - FDM
  - Material warping
  - Resin Occlusion
  - Broken Struts



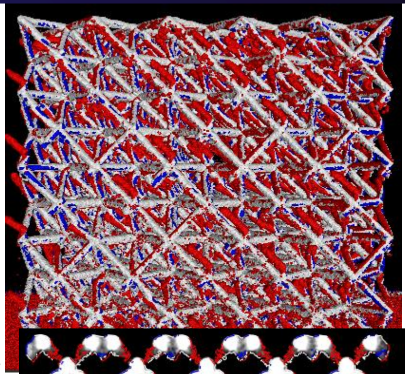
Design and manufacturing Software Limitations

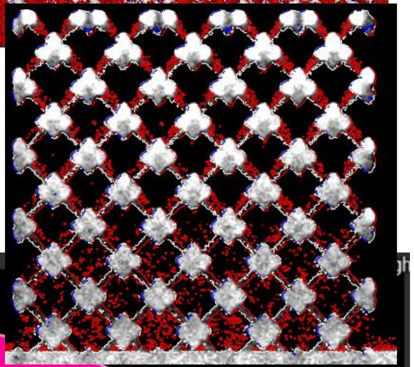
- **CAD Programs**
  - Solidworks
    - Primarily single threaded application therefore it bogs down significantly as part size increases.
    - 3” hemisphere is the largest successfully made part in Solidworks
      - Solidworks had significant issues with the part and crashed many times
    - Only able to generate non-conformal lattices so far
    - Currently limited to single cell size/density and geometry
  - Kansas City National Security Campus Geometry Conformal Lattice Software
    - Generates conformal lattice structures
    - Still under development
    - Limited unit cells.
- **TO Programs**
  - Ansys will create lattices, but unit cells are limited to their predefined cells.
    - Can create variable density lattices based on Ansys TO resultes
  - Octet is the only cell from the earlier list that is available for use
  - All available lattices have horizontal struts
- **Slicing Software**
  - CAD programs tend to leave artifacts in STL file when exporting lattices
  - Programs hang or crash with large STL sizes
  - Many are single threaded when generating support and tool paths.
- 1/8 sphere took over 24 hours to generate and is 35 MB, square struts used to reduce size

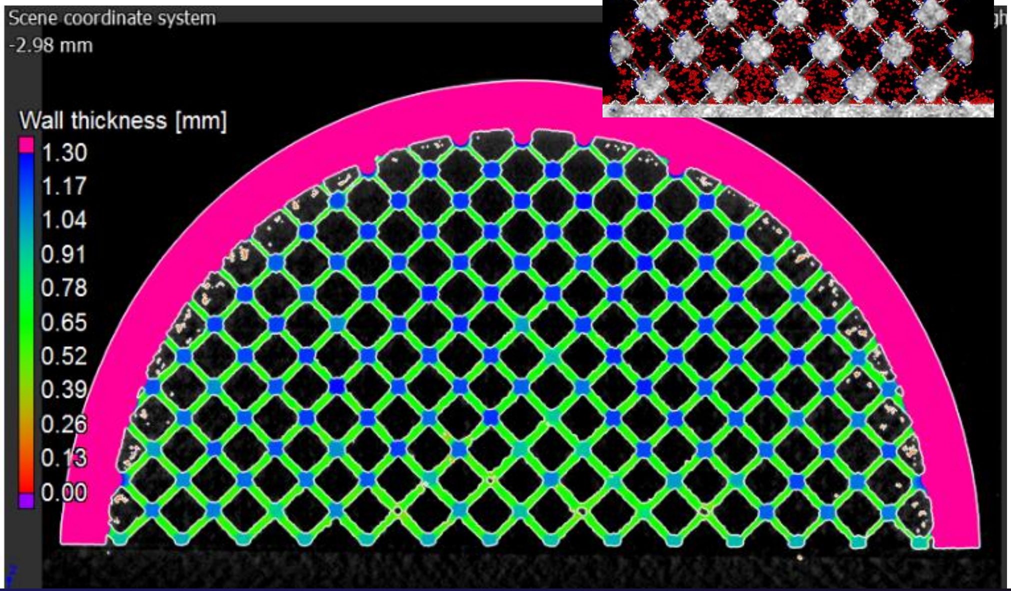


Inspection Limitations

- **Weight/relative density**
  - Few limitations in measuring weight and volume
  - If doing a submerged volume test, must make sure all air is removed from lattice structure
- **Optical Scanning**
  - Only capable of inspecting visible struts in the first few layers of cells
  - Cannot see the back side of struts so assessing the roundness of a strut would be difficult
- **CT Scanning**
  - Noise caused by x-ray scatter
    - Orange disconnected blobs in image
  - Lack of penetration in metals
    - Voids at lattice nodes
  - Part envelope of 20-30” machine dependent
  - High density parts require higher power which reduces scan resolution
  - For Ti parts, max practical size may be only 6-8” in diameter (with current equipment)
  - Images must be meticulously studied for flaws
    - May be possible to automate this process.
- **Other internal imaging techniques may be possible**



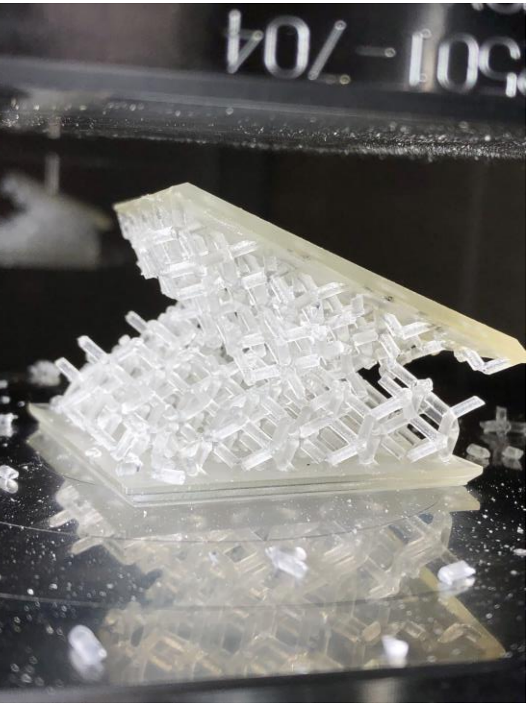


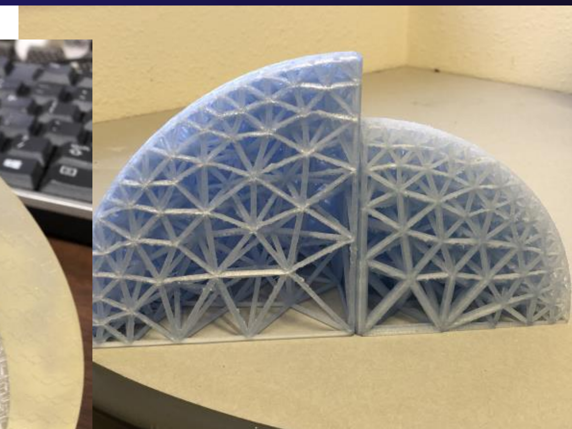


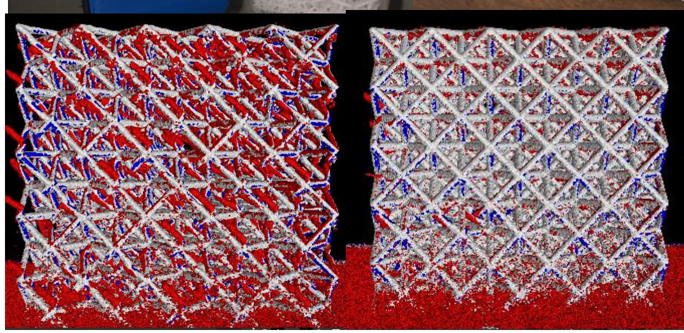
References

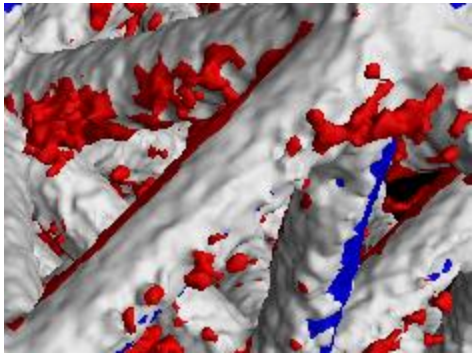
- [1] Deshpande, V. S., Fleck, N. A., & Ashby, M. F. (2001). Effective properties of the octet-truss lattice material. *Journal of the Mechanics and Physics of Solids*, *49*(8), 1747-1769
- [2] Fleck, N. A., Deshpande, V. S., & Ashby, M. F. (2010). Micro-architectured materials: past, present and future. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *466*(2121), 2495-2516.
- [3] Messner, M. C., Barham, M. I., Kumar, M., & Barton, N. R. (2015). Wave propagation in equivalent continuums representing truss lattice materials. *International Journal of Solids and Structures*, *73*, 55-66.

Questions?

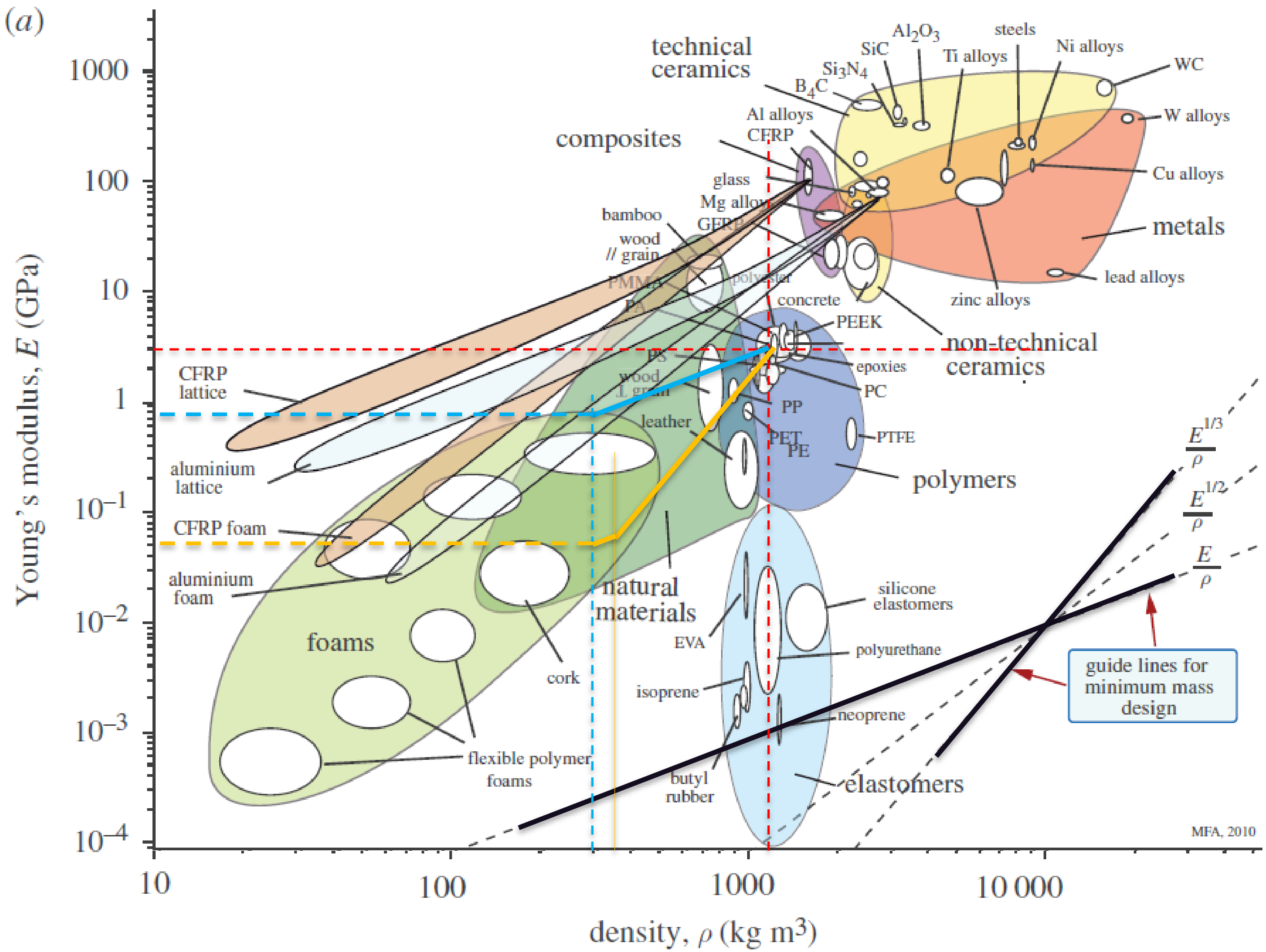








Ashby Chart Example—25% Octet Lattice, Formlabs Clear SLA Resin (ρ=1200 kg/m^3, E=2.8 Gpa) [2]



Ashby Chart Example—10% Octet Lattice, Formlabs Clear SLA Resin (ρ=1200 kg/m^3, E=2.8 Gpa) [2]