COMPUTATIONAL DESIGN SOFTWARE: PRODUCT DESIGN TO MANUFACTURING

EXPLOITING ADVANCED MANUFACTURING CAPABILITIES: TOPOLOGY OPTIMIZATION IN DESIGN

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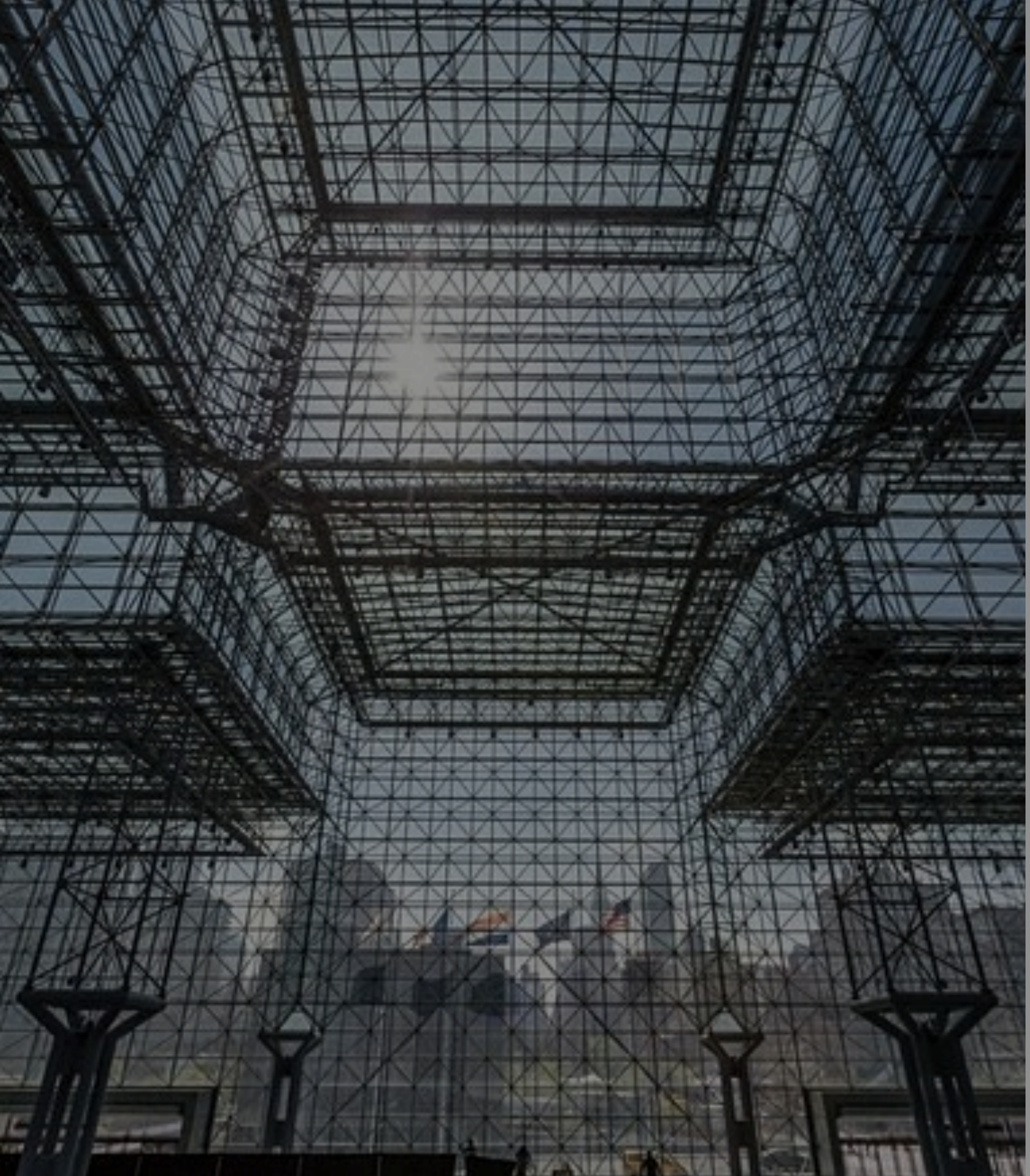
Why Design Tools?

- Limited design tools because additive manufacturing technology hasn't been able to **execute on designs.**
- Carbon's process and material can produce manufacturing quality parts. Innovation in: Hardware, software, materials and **design**.
- Software tools **enable customization** — automatic generation of the design specific to user/patient data, software QC to ensure the mechanical performance.



Lattice designs have previously only been available to architects and bridge builders

Design Parameter Optimization : Inverse Design

INPUTS

MATERIAL PROPERTIES
+
USER-DEFINED MECHANICAL RESPONSE
+
DESIGN CONSTRAINTS

Resin viscosity
Final material properties (e.g. modulus)

Force to be applied
Expected deformation

Length, width, height, weight, pore size, etc.

CARBON SOFTWARE
+
LATTICE LIBRARY

=

OUTPUT

FINAL PART DESIGN

1) 3D MANUFACTURING READY
2) MULTIPLE FUNCTIONAL ZONES

Unit cell
Min/max size of cell
Cell gradients
Strut thickness
Printability

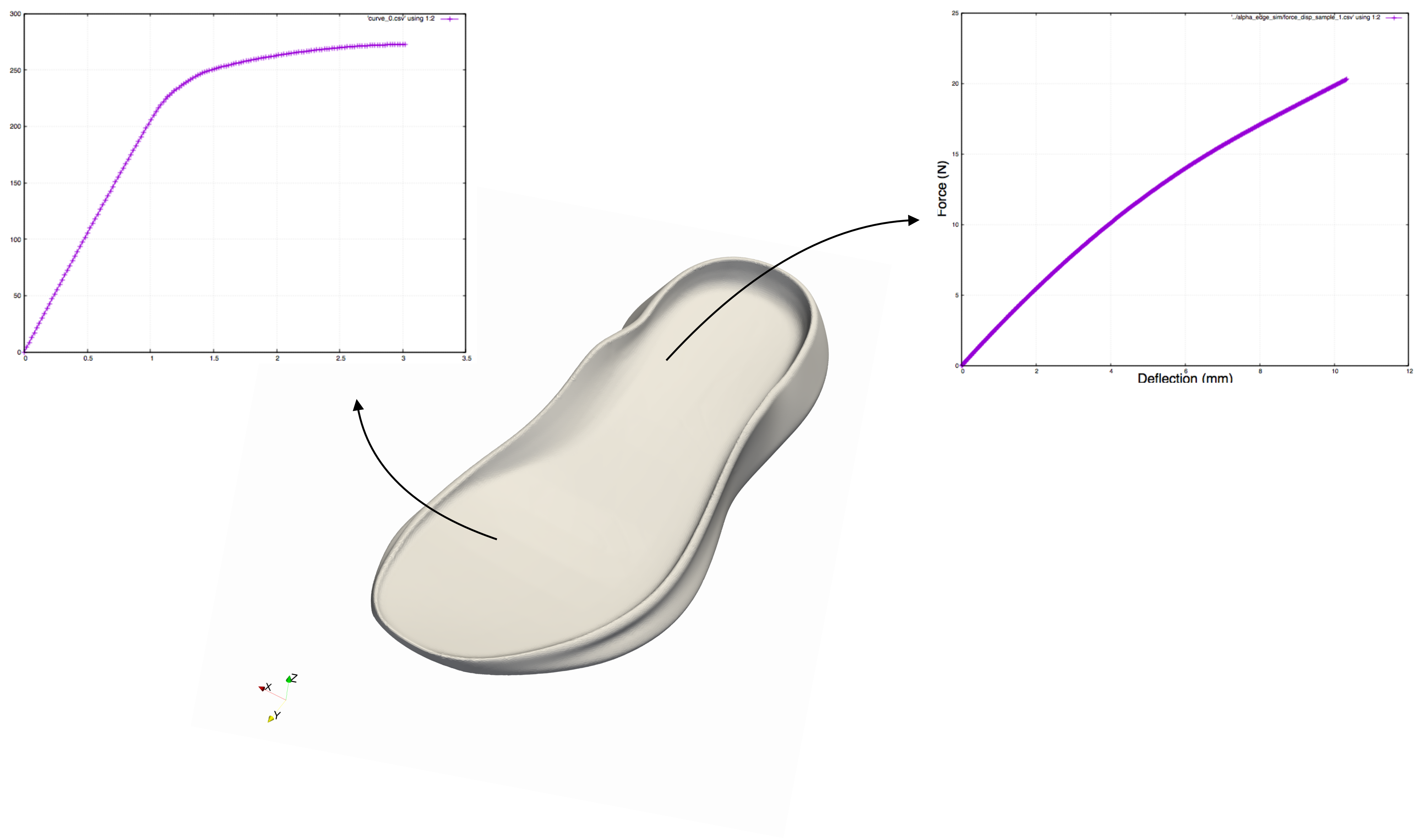
Design Parameter Optimization : Inverse Design

INPUT

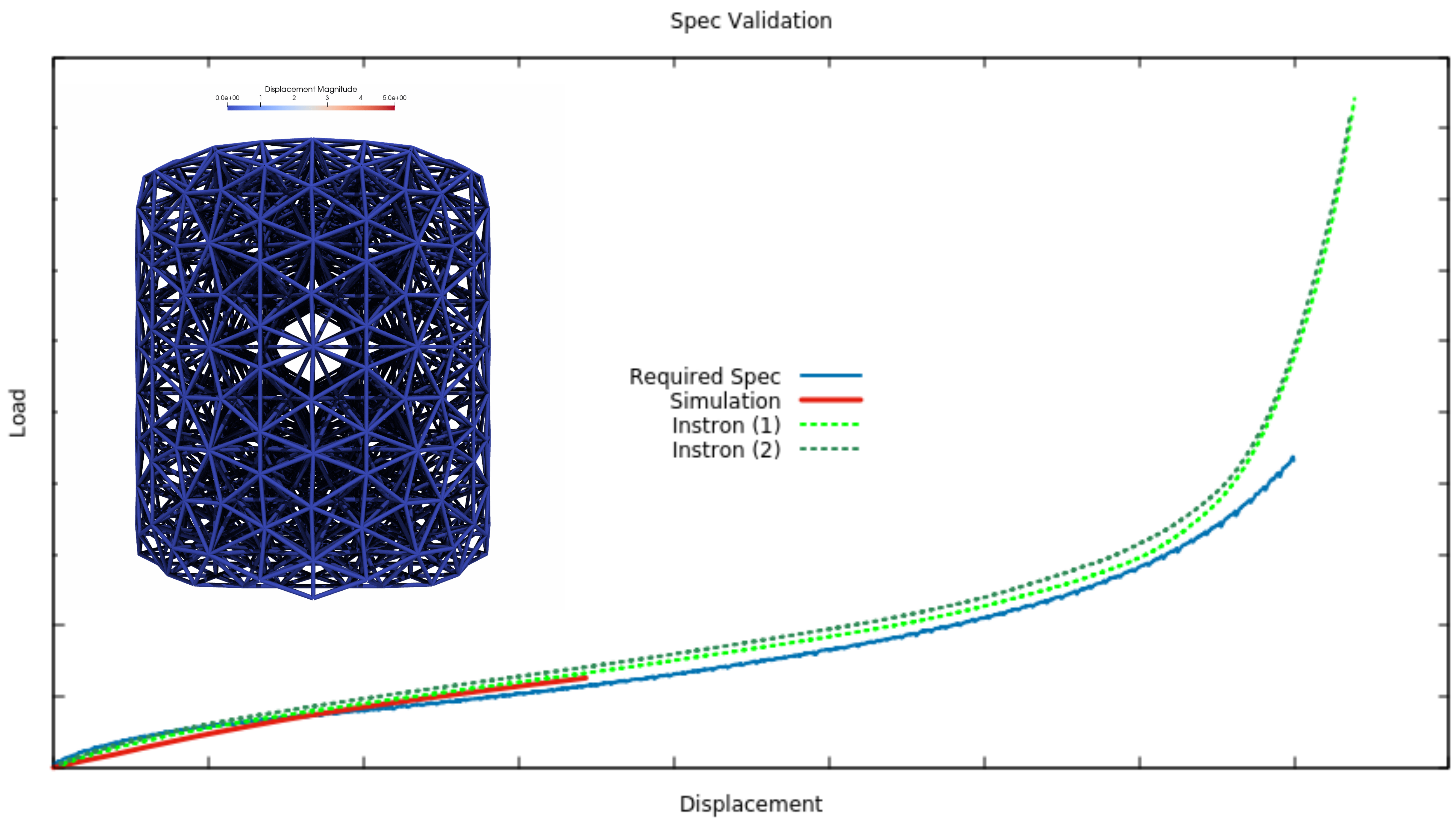
CAD of primitive, the loading conditions and desired mechanical responses, the cost function (optimize for weight, speed …)

OUTPUT

DLS manufacturable latticed design(s) with different materials



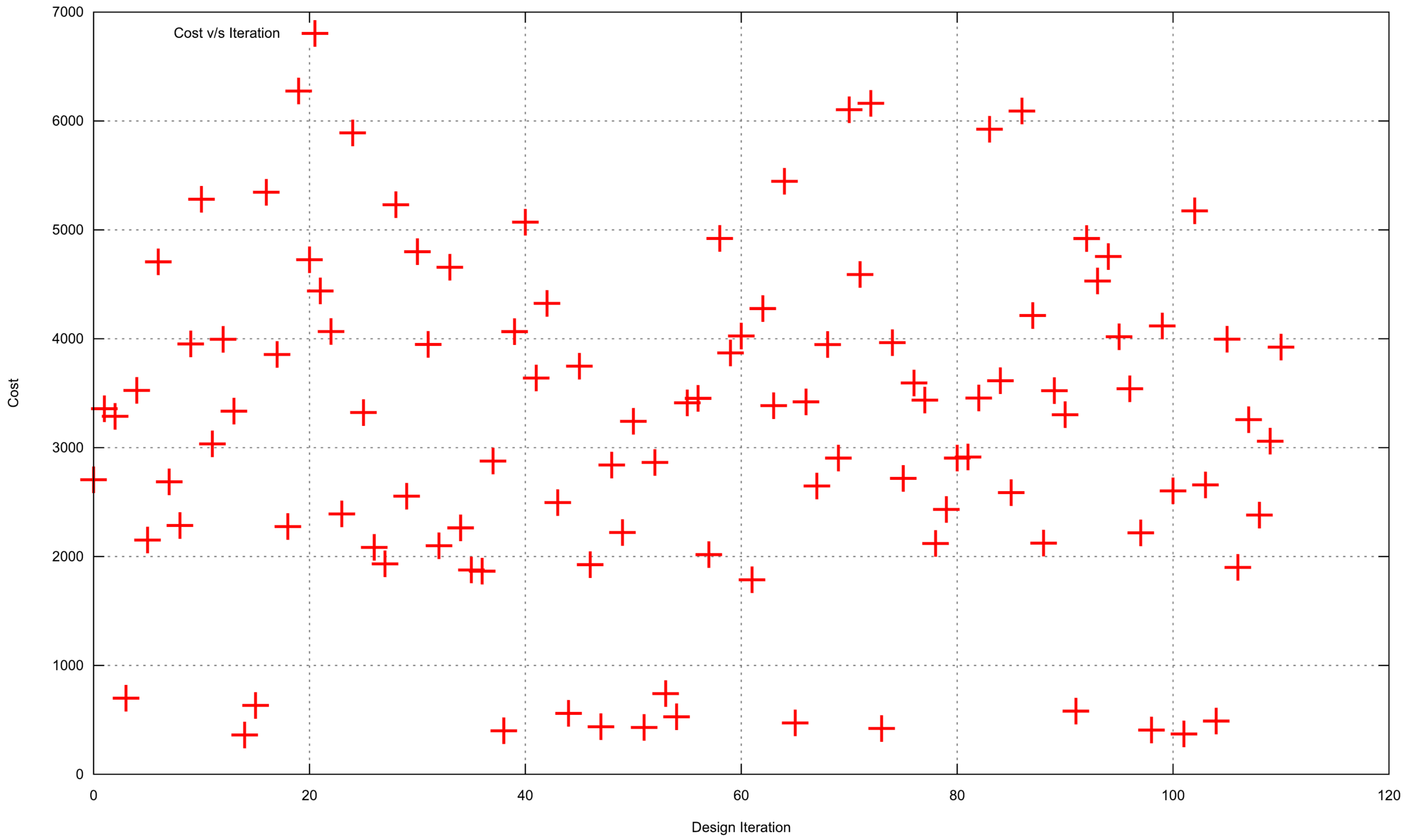
Design Parameter Optimization : Inverse Design



- Users provide the **expected mechanical response of the part**: stress-vs-strain curve
- Carbon software module runs a number of design optimization simulations to find **the set of lattice parameters and resin** that can achieve the spec in a **single design iteration**

Design Parameter Optimization : Inverse Design

- Run **continuous / discrete** variables optimization — GA / SGD.
- Robust **lattice population** for any CAD
- Robust **volumetric discretization** — e.g. tet/hex mesh
- Physical simulation — FEA.
- Everything runs on AWS Elastic Computing

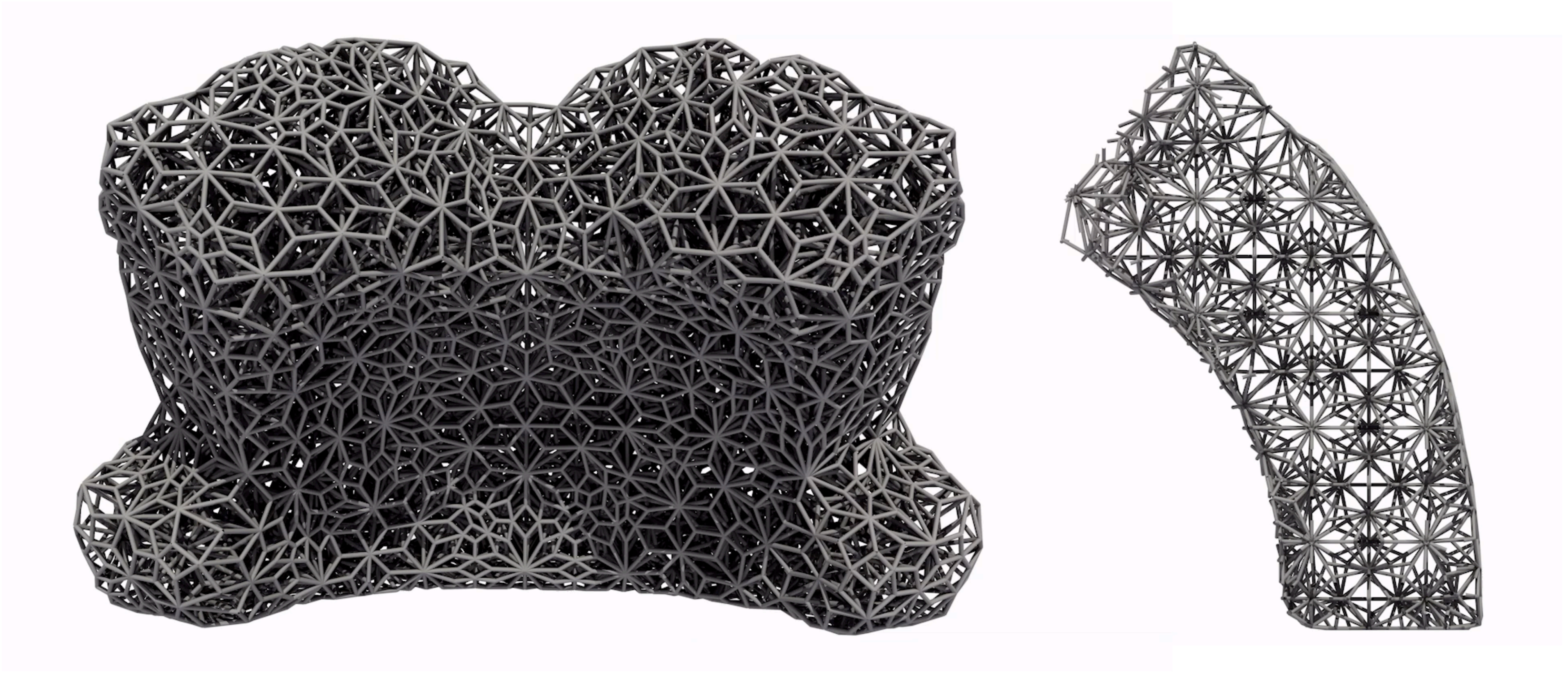


Advantages of Designing with Lattice Structures

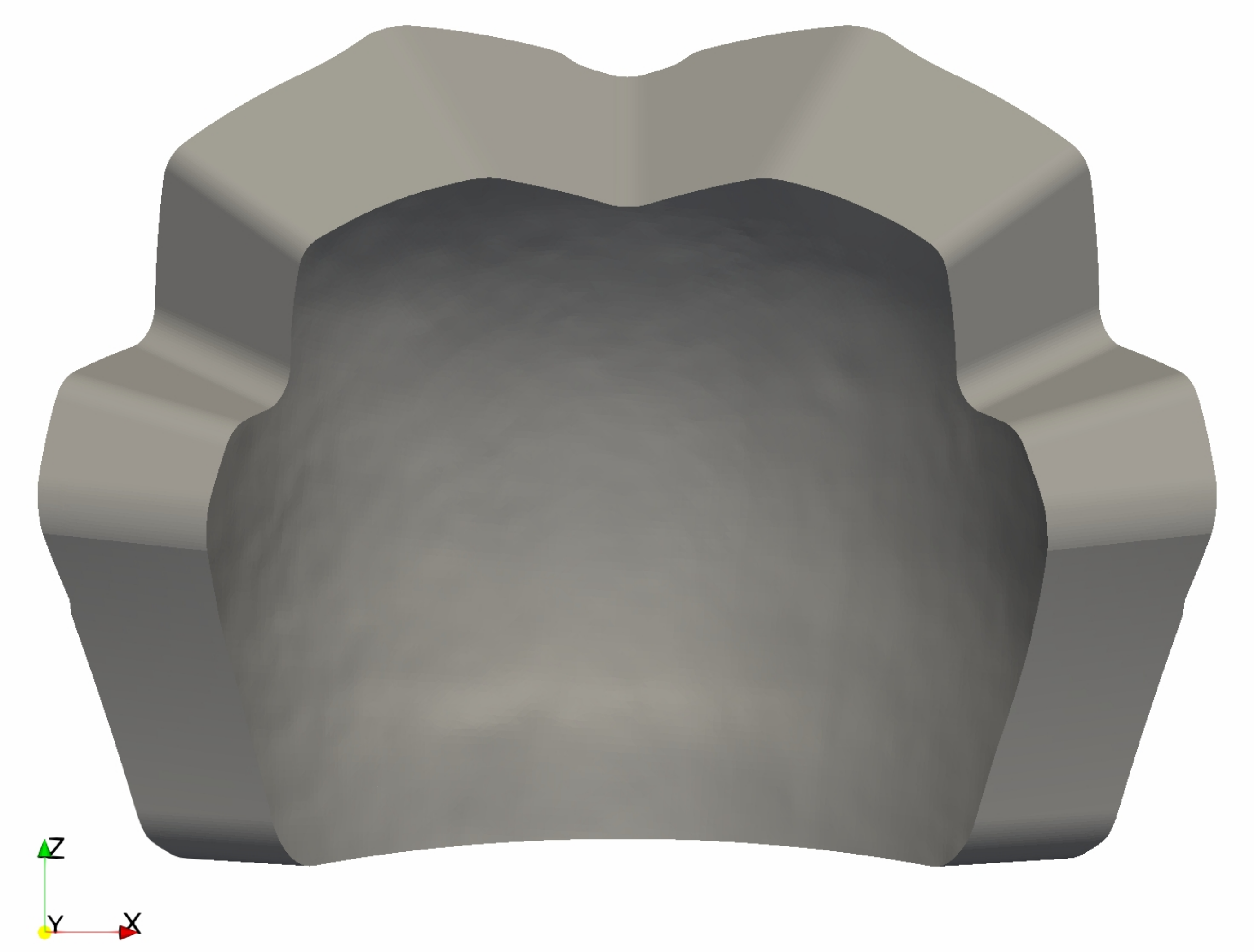
1. Automated customized design generation and manufacturing workflow
2. Controlling linear & rotational energy absorption
3. Reducing peak pressure — improve stress distribution over a surface/tissue
4. Adapting the design to the customized environmental loading conditions
5. Multiple mechanical responses within a single part with the same material
6. Lattice Cosmos: Controlling stiffness/mass, strain densification, anisotropic stress vs strain behavior

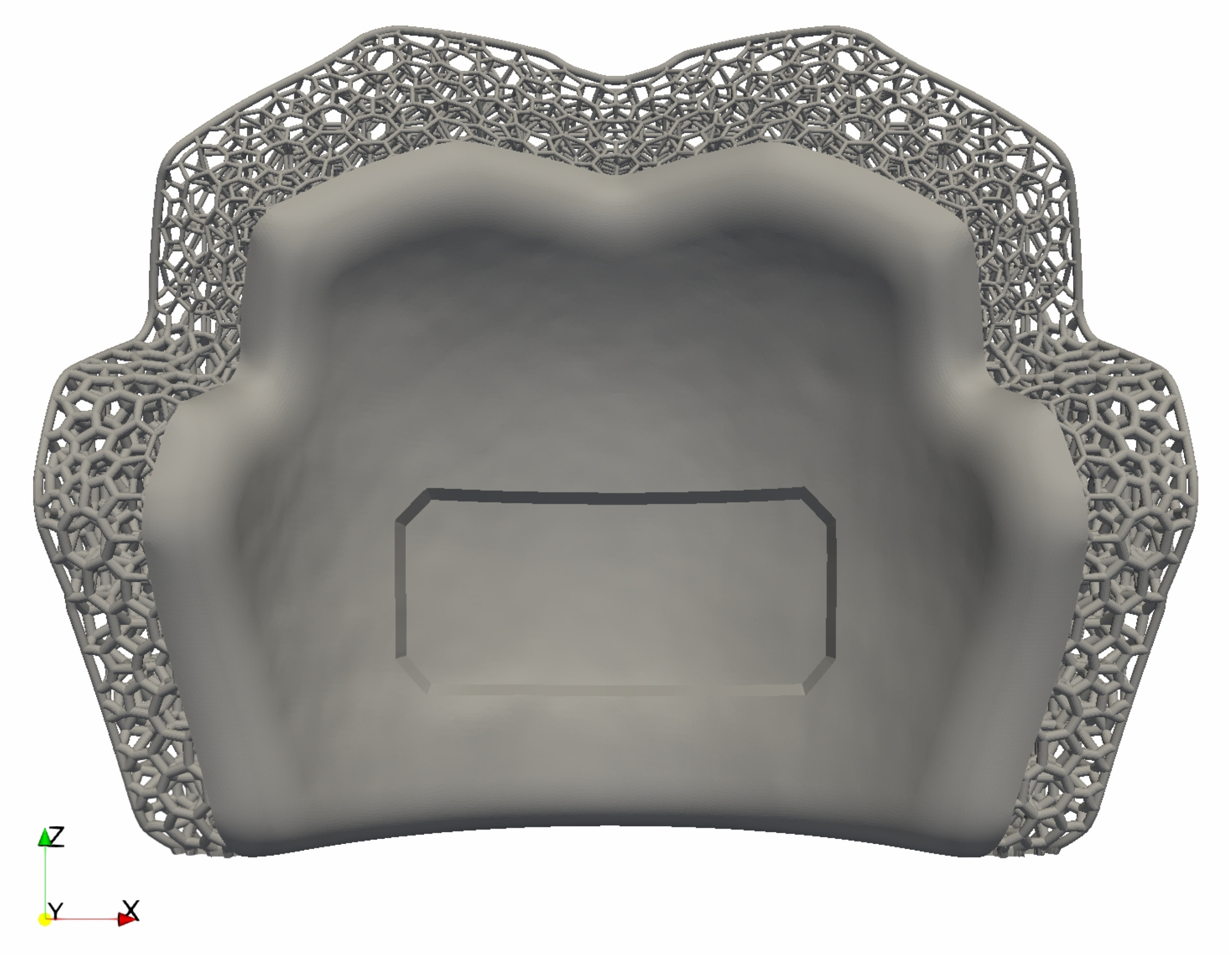
1. Custom Design Generation: NFL Helmet Pads

- **7000+ lattice parameters explored for each pad design**
- **Finite element simulations autonomously performed** on cloud to evaluate each set of design parameters
- **30x faster product design** cycles — 10+ designs in just two weeks
- **Optimized** for print/manufacturing process parameters
- **Custom designs** for each player from *Day 0*
- **Reduced # of parts** from 12 pads to 7 = fewer assembly steps



1. Customized Manufacturing Workflow

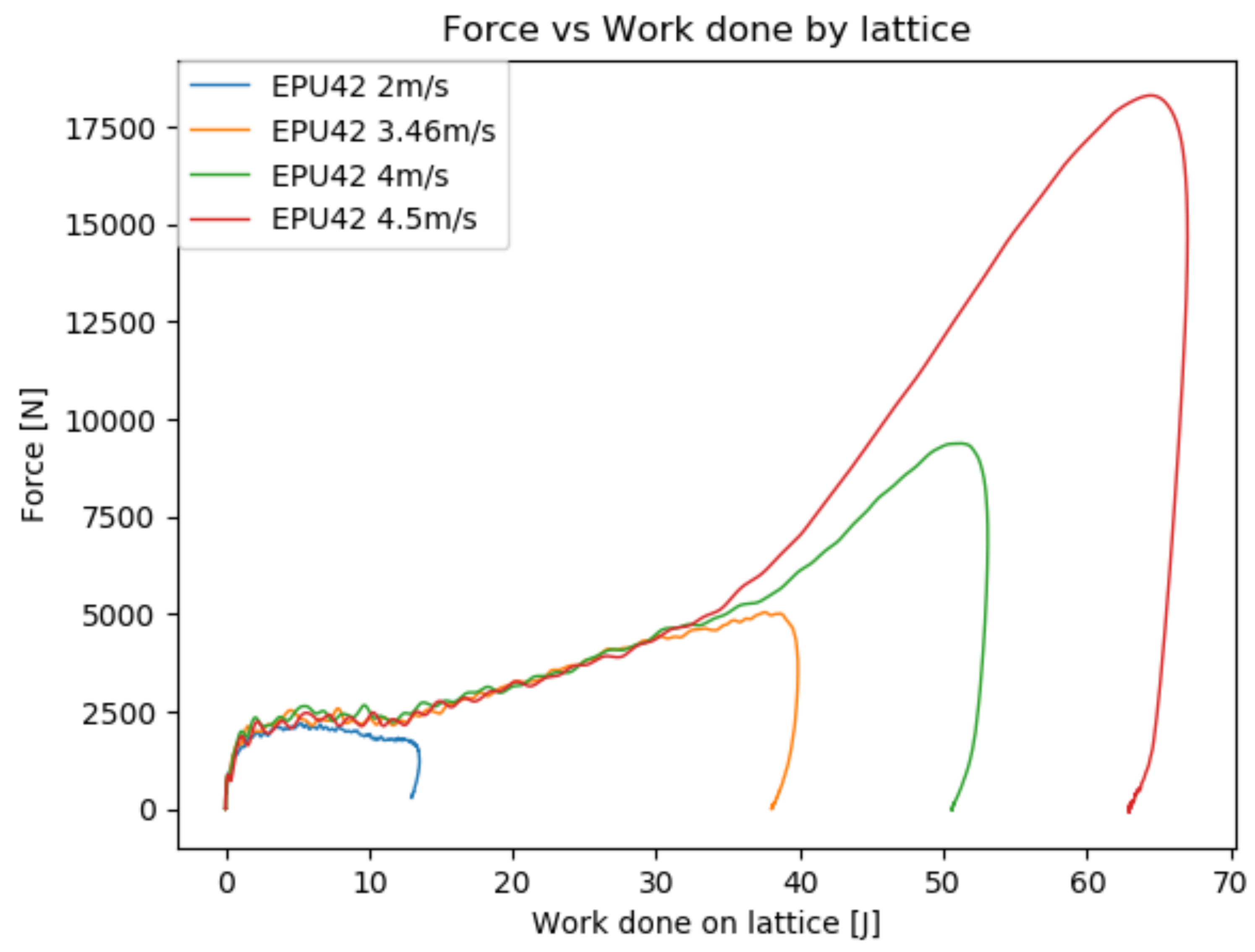


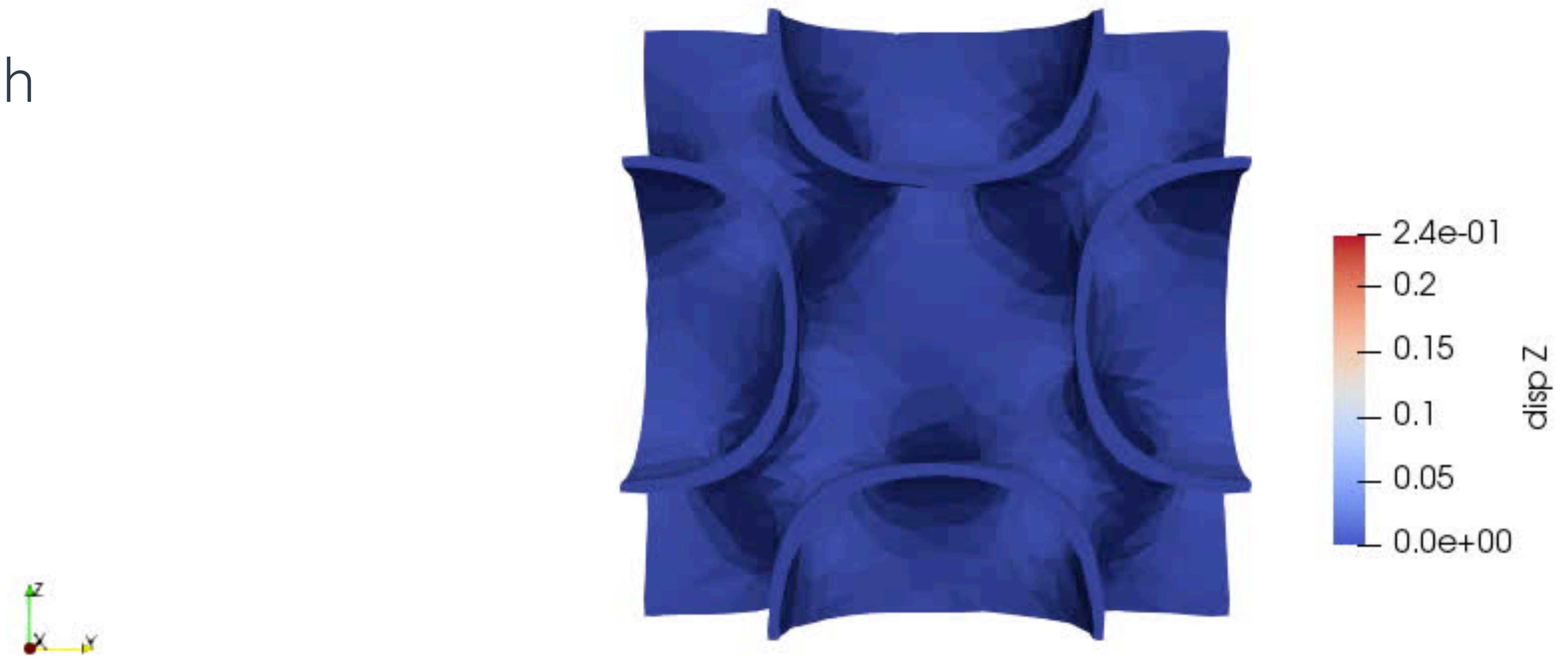


- **Input:** provided by the customer for each player — specific CAD
- **Automated Pipeline:** Creates a smooth CAD on subset of surface, generates a surface skin, builds surface parameterization to create recesses (applying textures), populate the performance related lattices, and also performs quality control checks for each part before it is sent to the printer
- Simple tool can be used by manufacturing technicians **(700+ helmets)**
- **Eventually completely automatic —** no human intervention needed in the pipeline.

2. Controlling linear & rotational energy absorption

- Minimize peak linear and rotational acceleration
- **30% performance improvement vs. foam** with same volume and mass - for peak acceleration
  - Explored 100s structures to achieve the performance from Schwarz, Gyroid, FRD, A15, ...
  - Optimized for a range of impact energy.
- Durability: repeated impacts (100k cycles) with elastomer resins
- 2-3 impacts with semi-rigid resins





Wohlgemuth et al 2001, Macromolecules

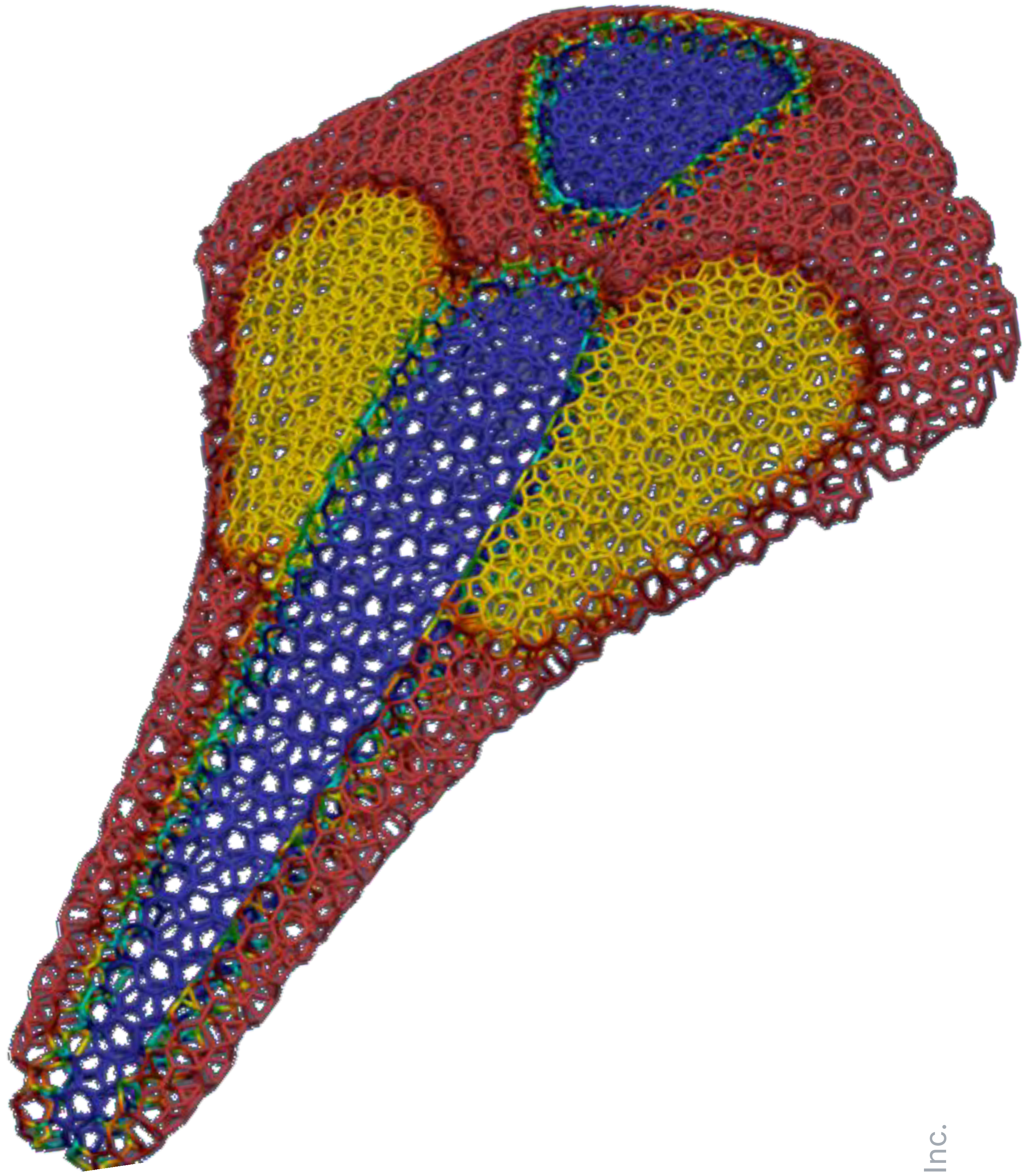
3. Reducing Peak Pressure / Improve Stress Distribution

PERFORMANCE / COMFORT

- **Reduce peak pressure** at the sit bones by >20%
- **Maintain shear strength** for stability
- **Thermally cooler** / breathability

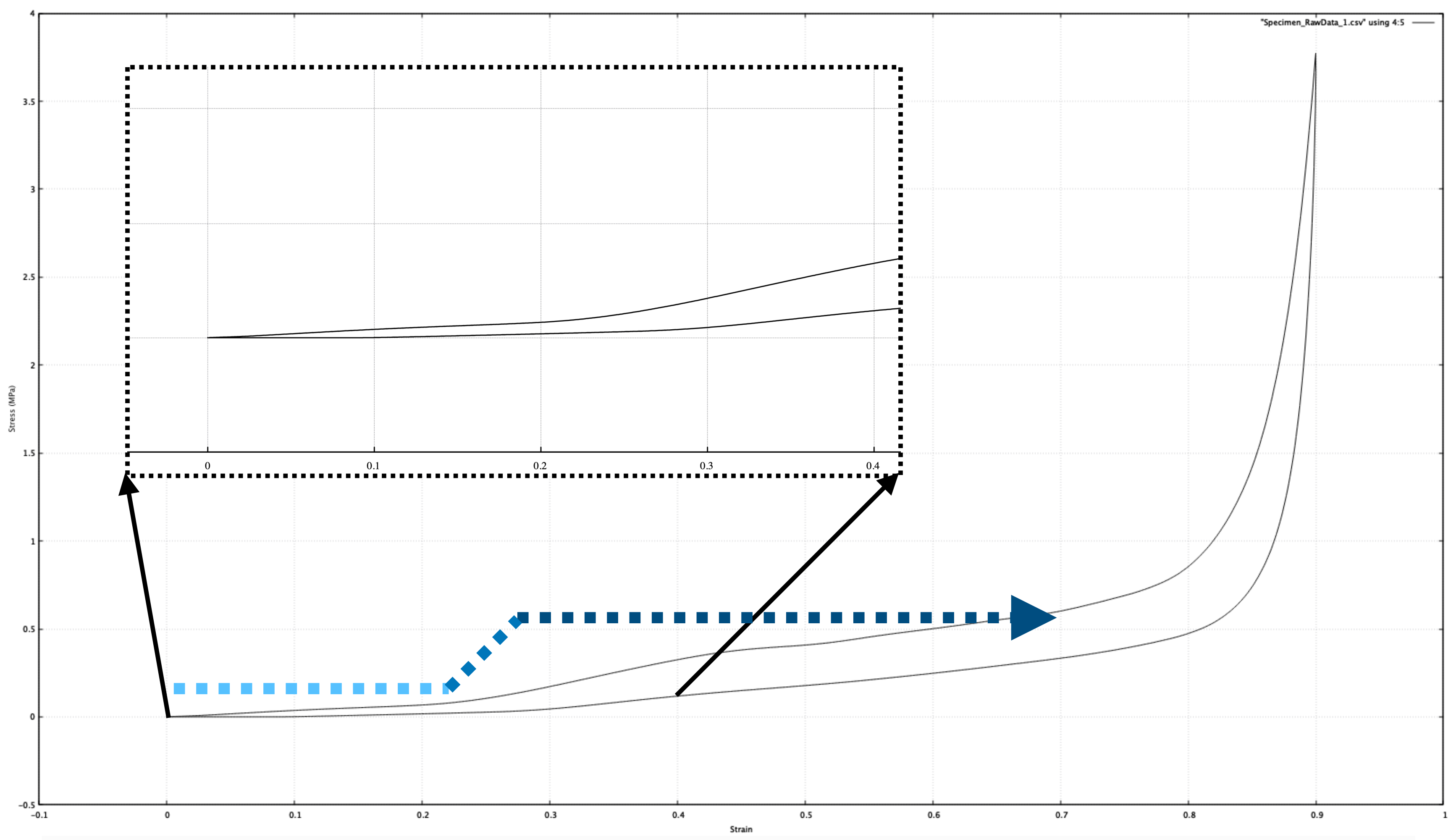
PRODUCTION EFFICIENCY + SUPPLY CHAIN

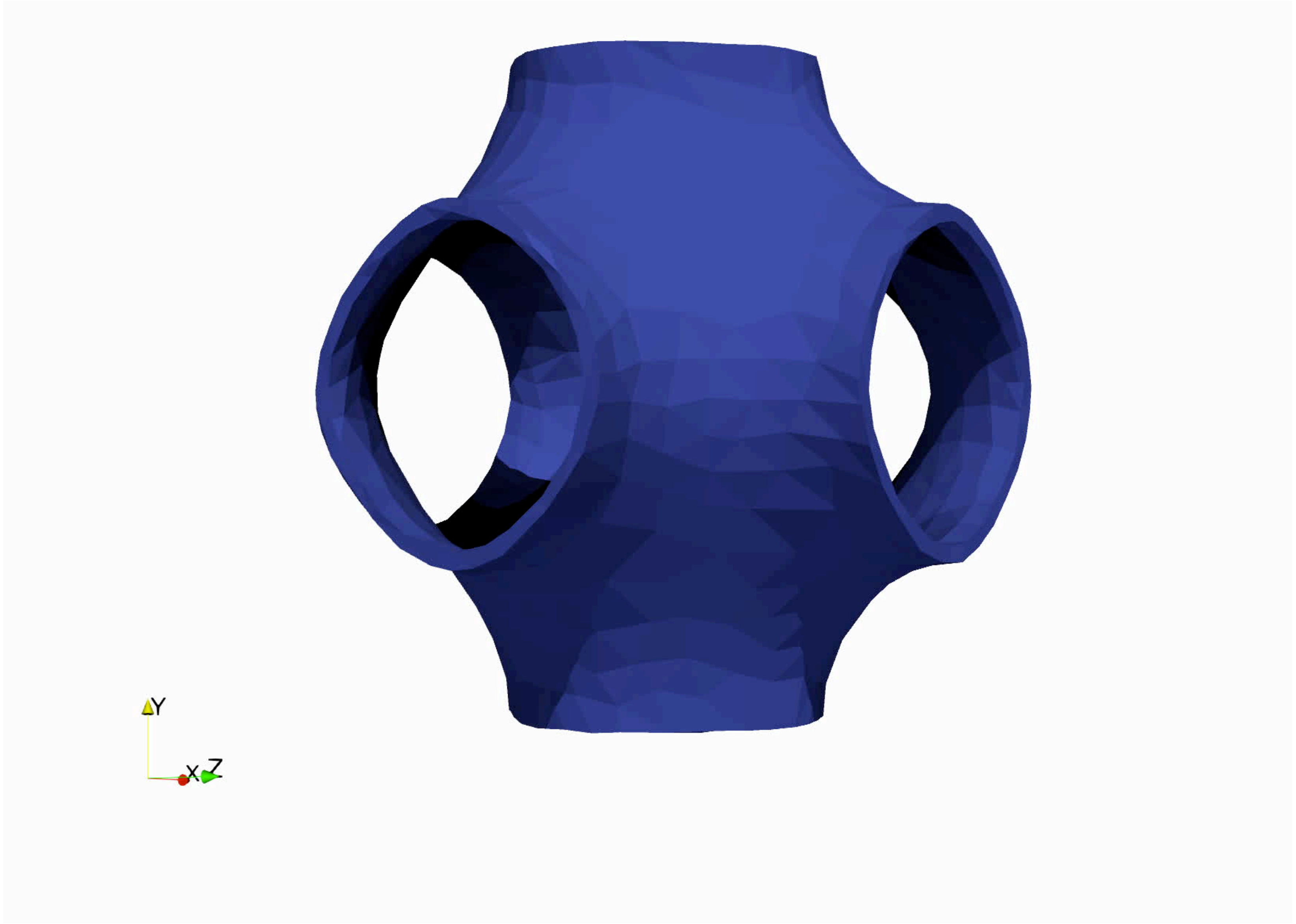
- **Multiple stiffness zones in a single part with same material**
- **Reduce** time from product concept to pilot production



4. Controlling Strain Densification

- Design **adapts to the customized environmental loading condition** (patient specific head/tissue shape)
- Densification can be **postponed up to 70%, volume fraction ~ 0.25**
- **Staircase stress - strain:** mix and match structures and their transitions to achieve a complex mechanical response
- Controlled **surface to volume ratio to control degradation.**



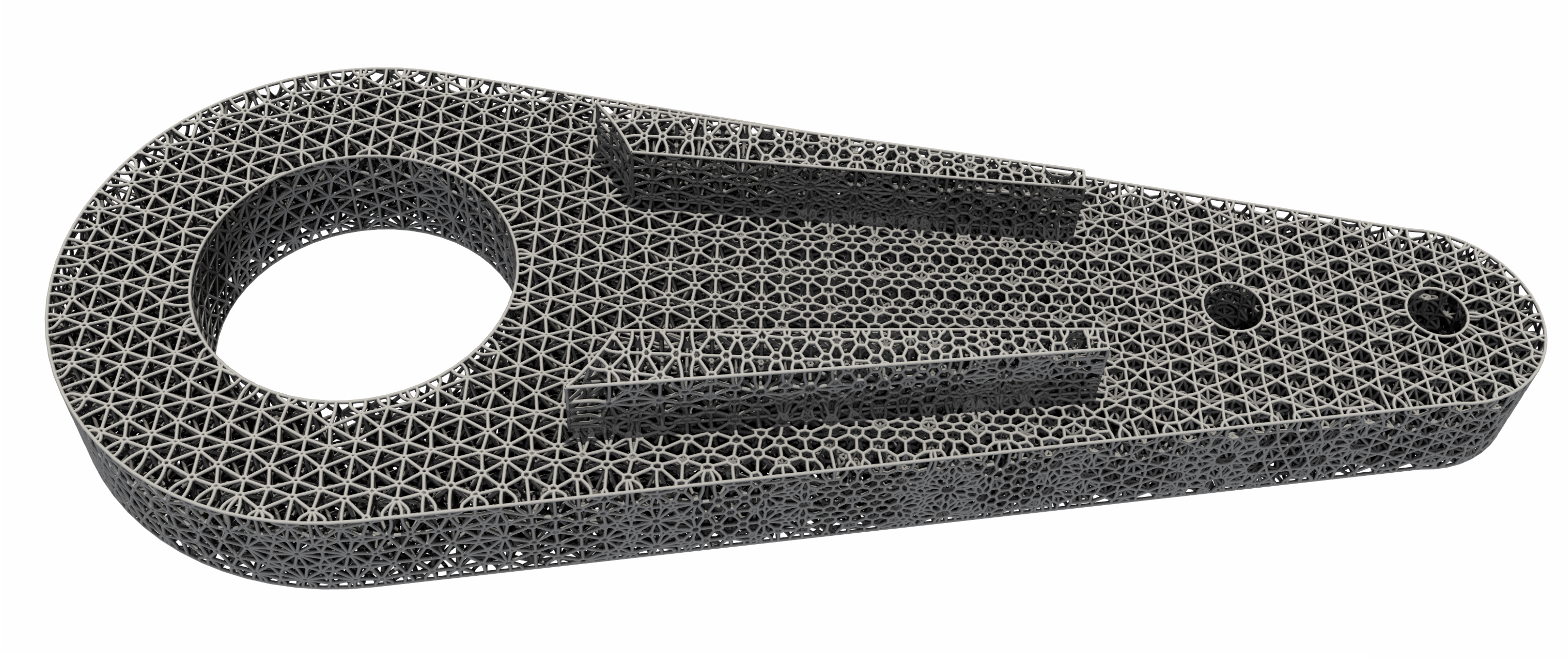


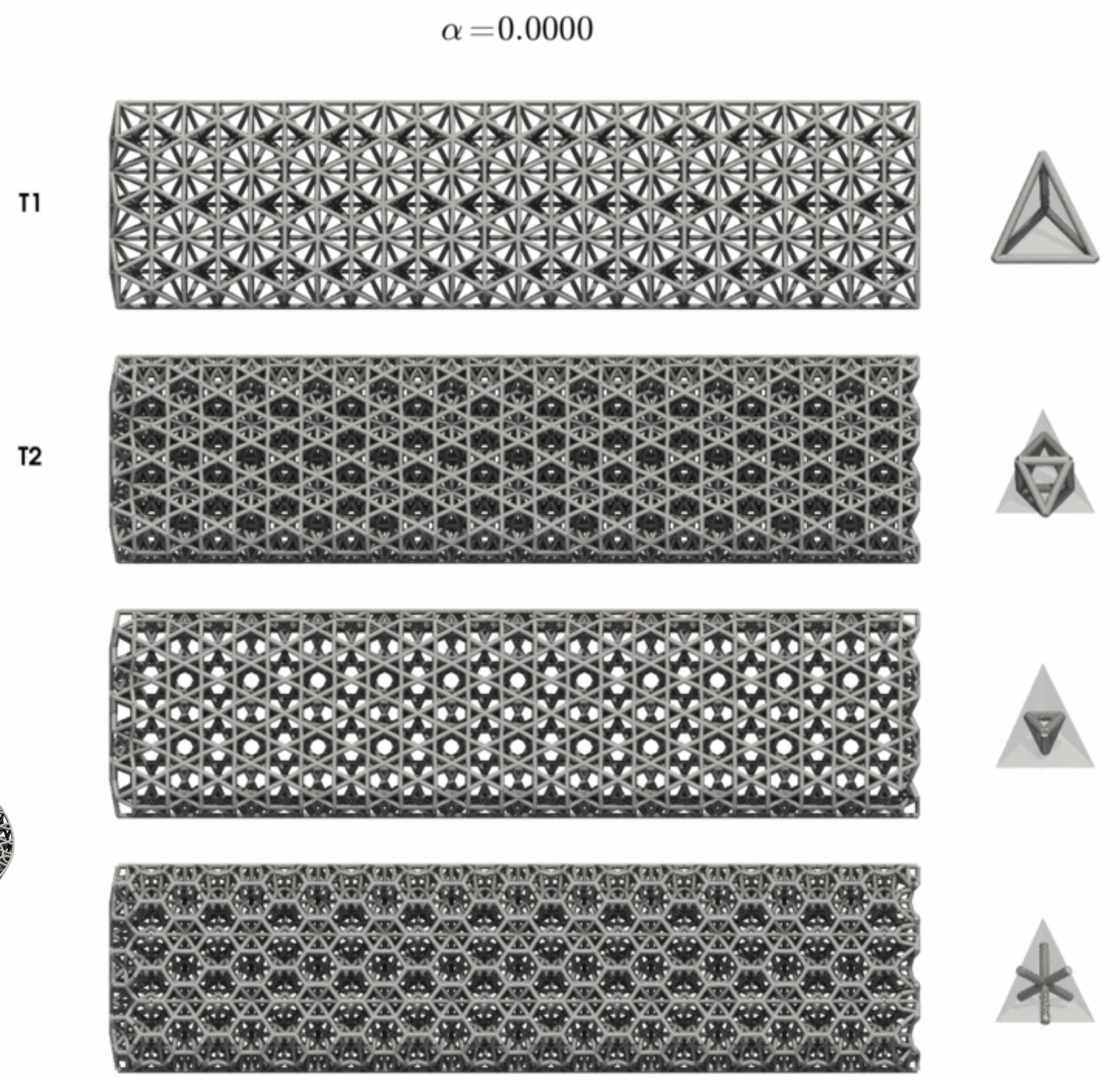
5. Multiple mechanical responses within a single part with the same material

Customized mechanical response within a single part with the same material.

Smooth transition via **topology parametrization enabled by automatic and robust geometric discretization.**

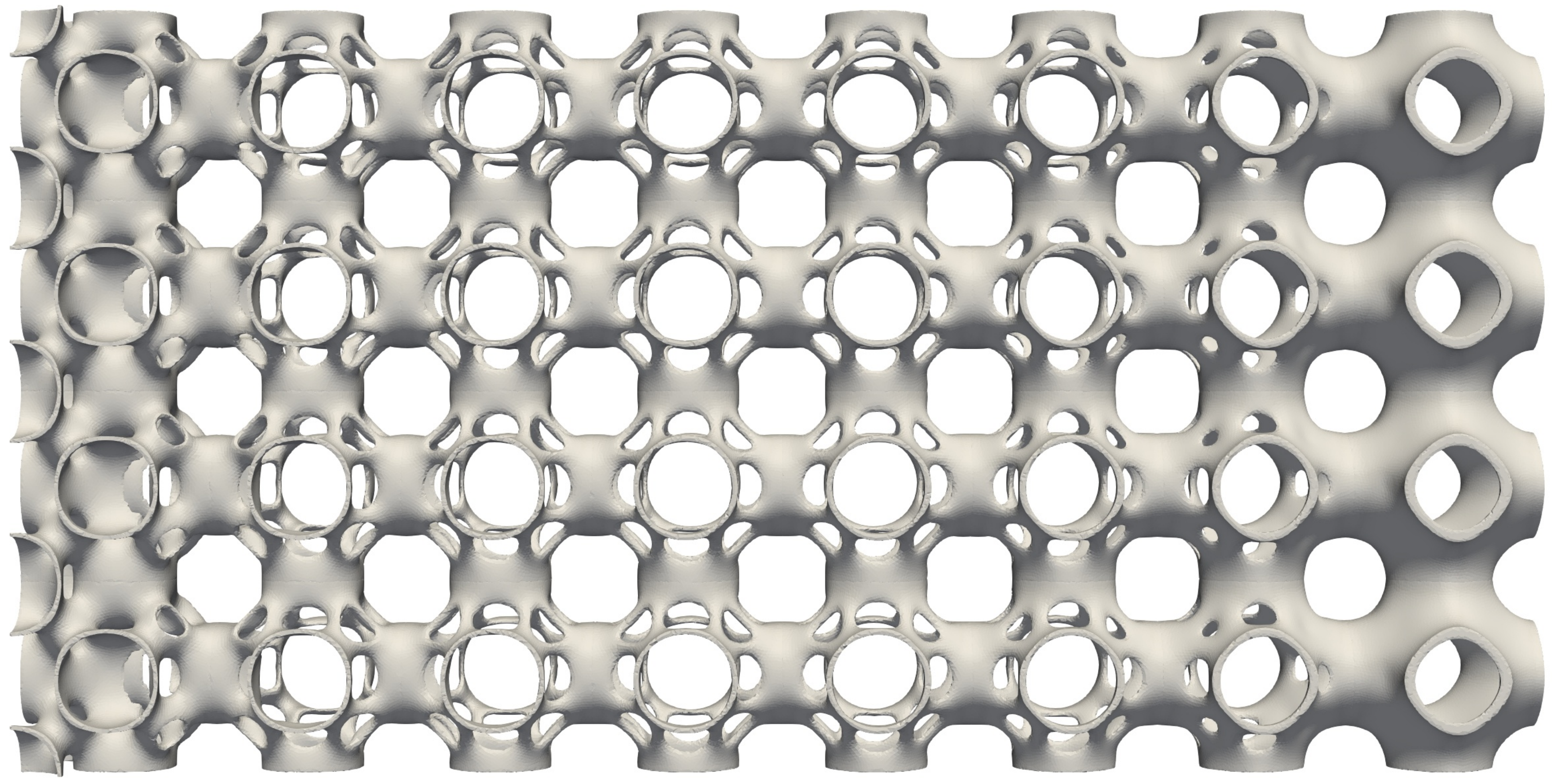
- Better performance
- Reduced assembly steps

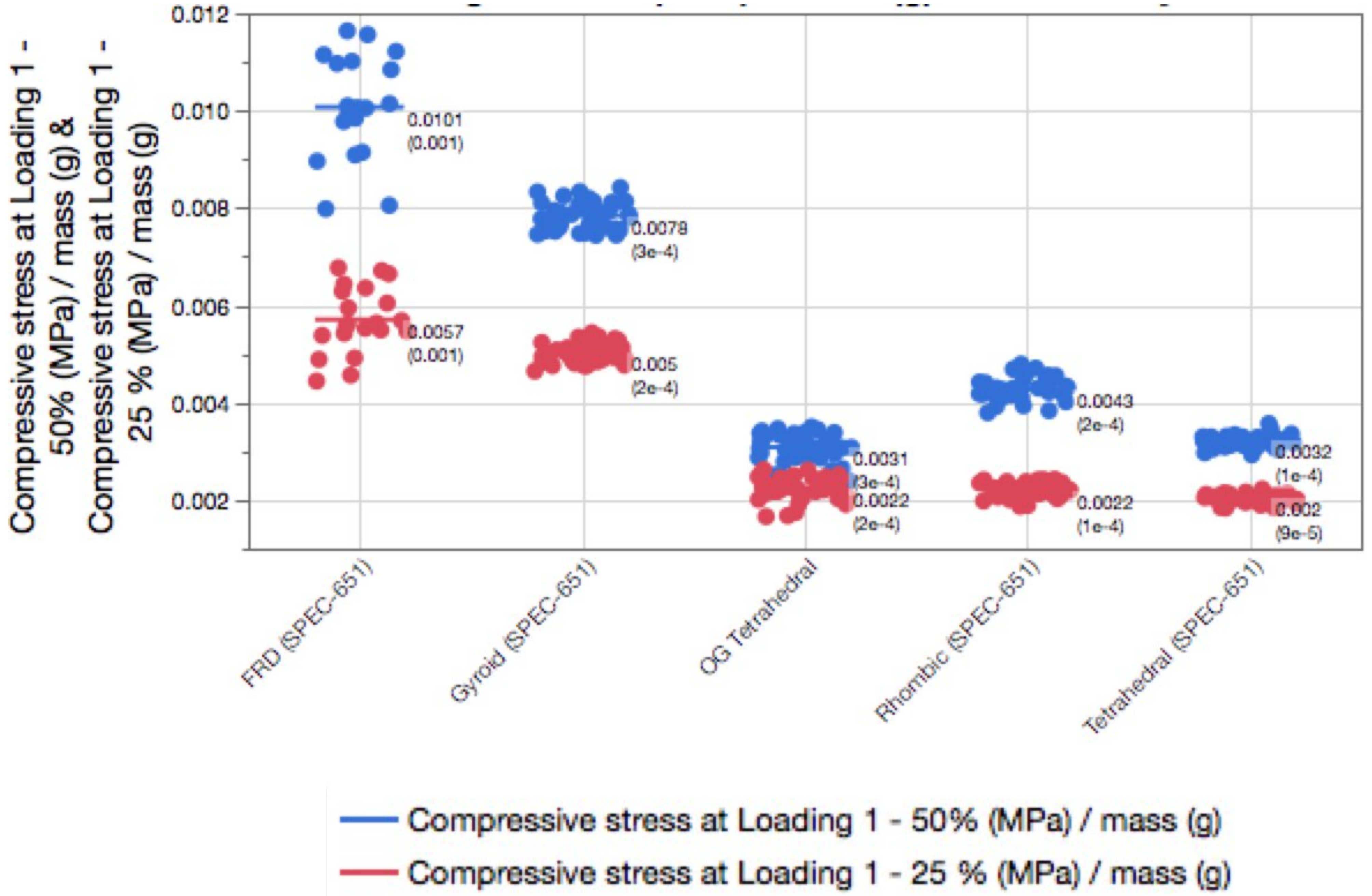




5. Multiple mechanical responses within a single part with the same material

- Transitions between well studies TPMS, controlled by a smooth parameter. Optimization method can be a simple gradient descent
- Can achieve 3x different stiffness / mass ratio using the same bulk material — e.g. elastomeric polyurethane.





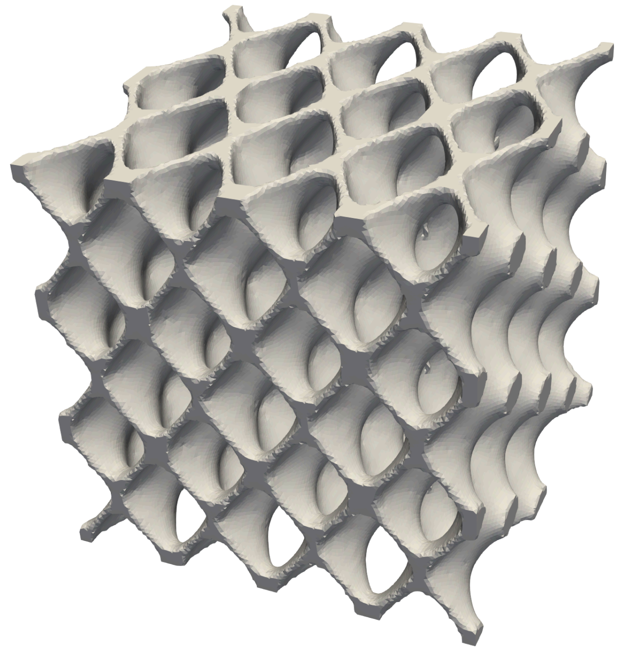
6. Controlling stiffness/mass, strain densification, anisotropic stress vs strain behavior

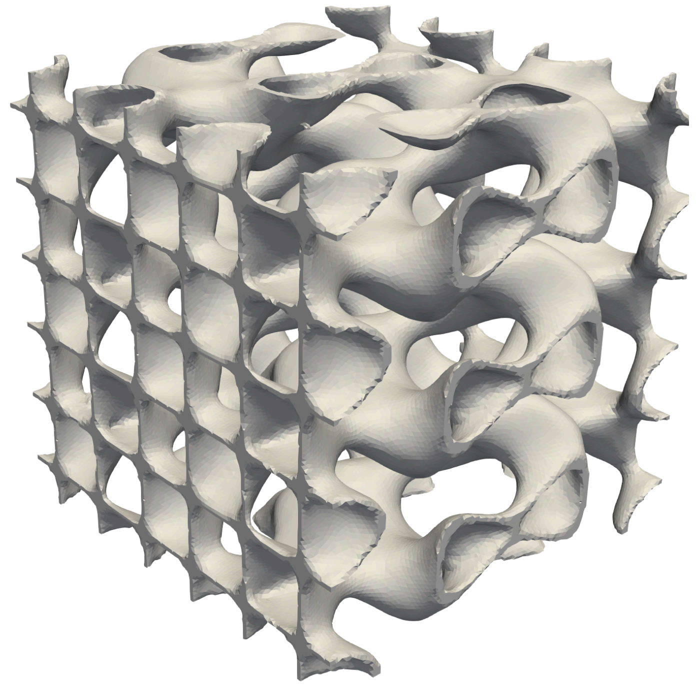
- **Maximize stiffness to mass ratio** — can achieve 98% of the theoretical upper bound (HS ratio) using FRD structure

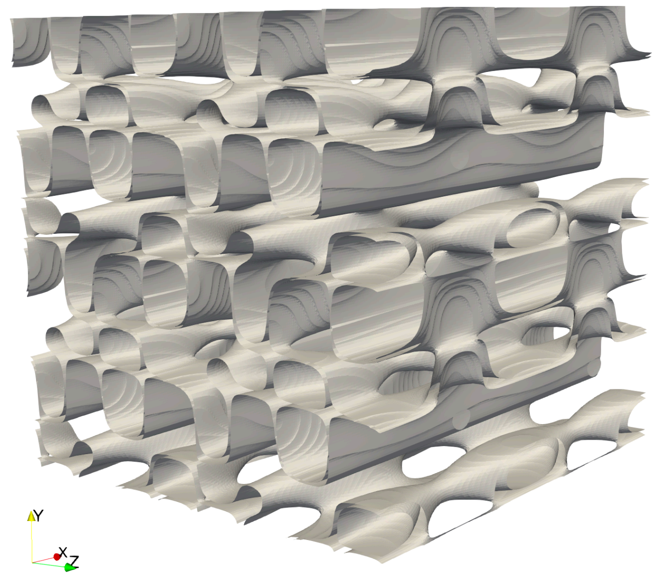
- **Anisotropic behavior:** stiffness in Z direction can be 8-10x stiffness in XY plane or share

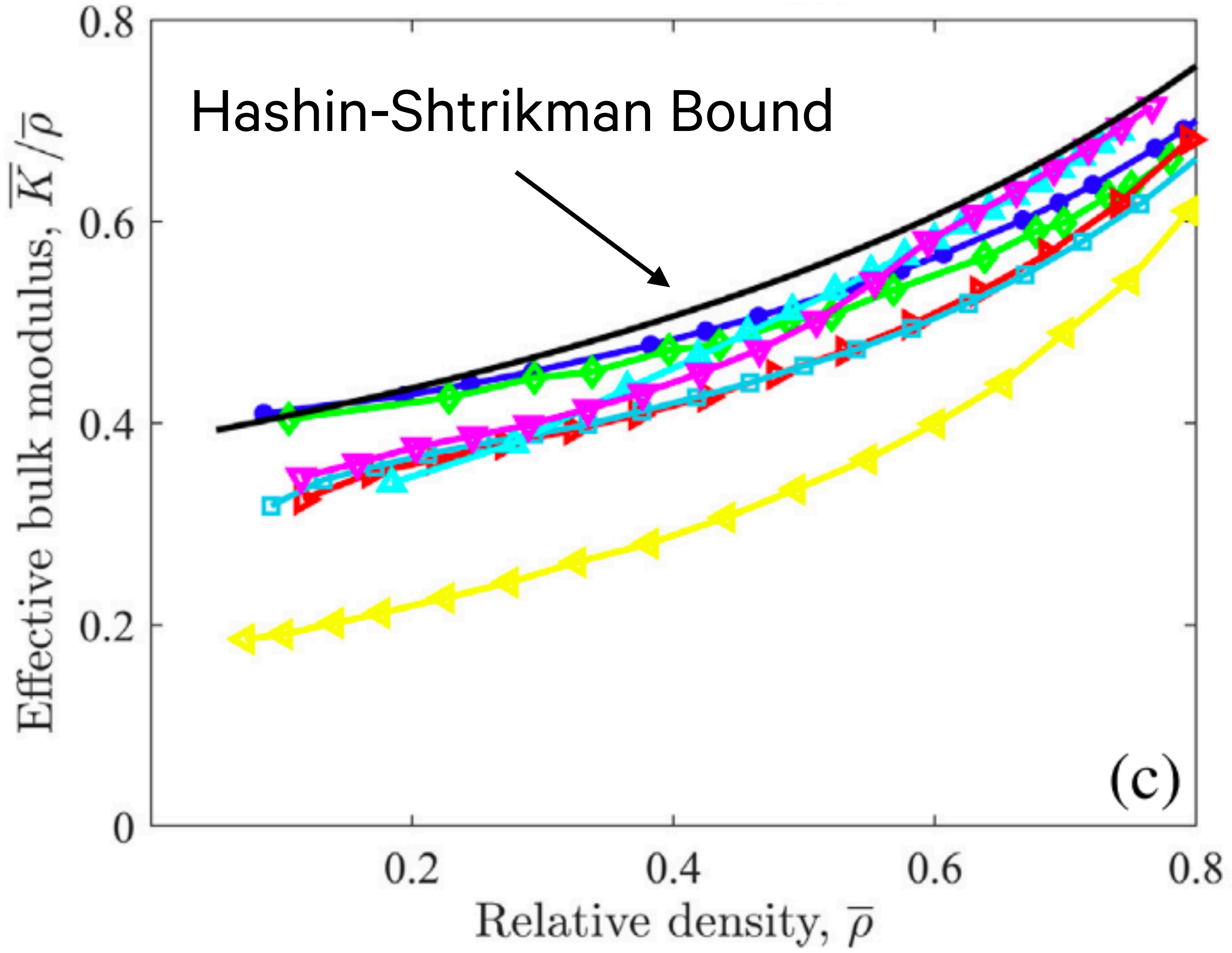
- Controlled **bending v/s buckling mode of deformation** — energy dissipated / recovered in static as well as dynamic usage

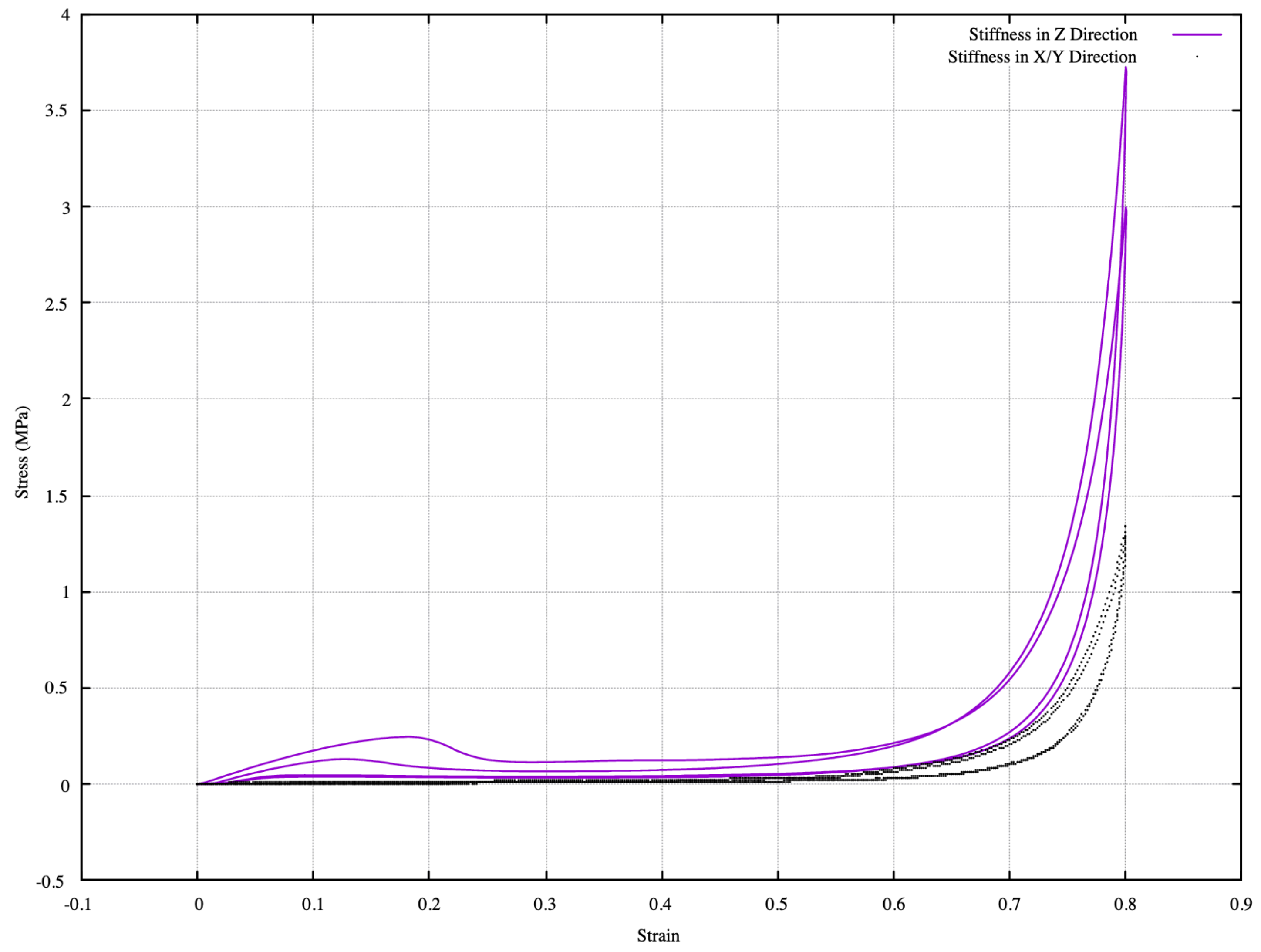
- Controlled **porosity of the structure** to promote tissue growth











Chen et al 2019, Materials and Design

6. Lattice Cosmos: Search For Similar Shapes and Mechanical Properties

General representation of all TPMS, Potential # of unique structures : **10^{16}**

$$f(x,y,z) = \left(c + \sum_{i=1}^{N} w_i p_i(h_i x) q_i(k_i y) r_i(l_i z)\right)^2 - t^2$$

$$\sum_{i=1}^{N} w_i = 1$$

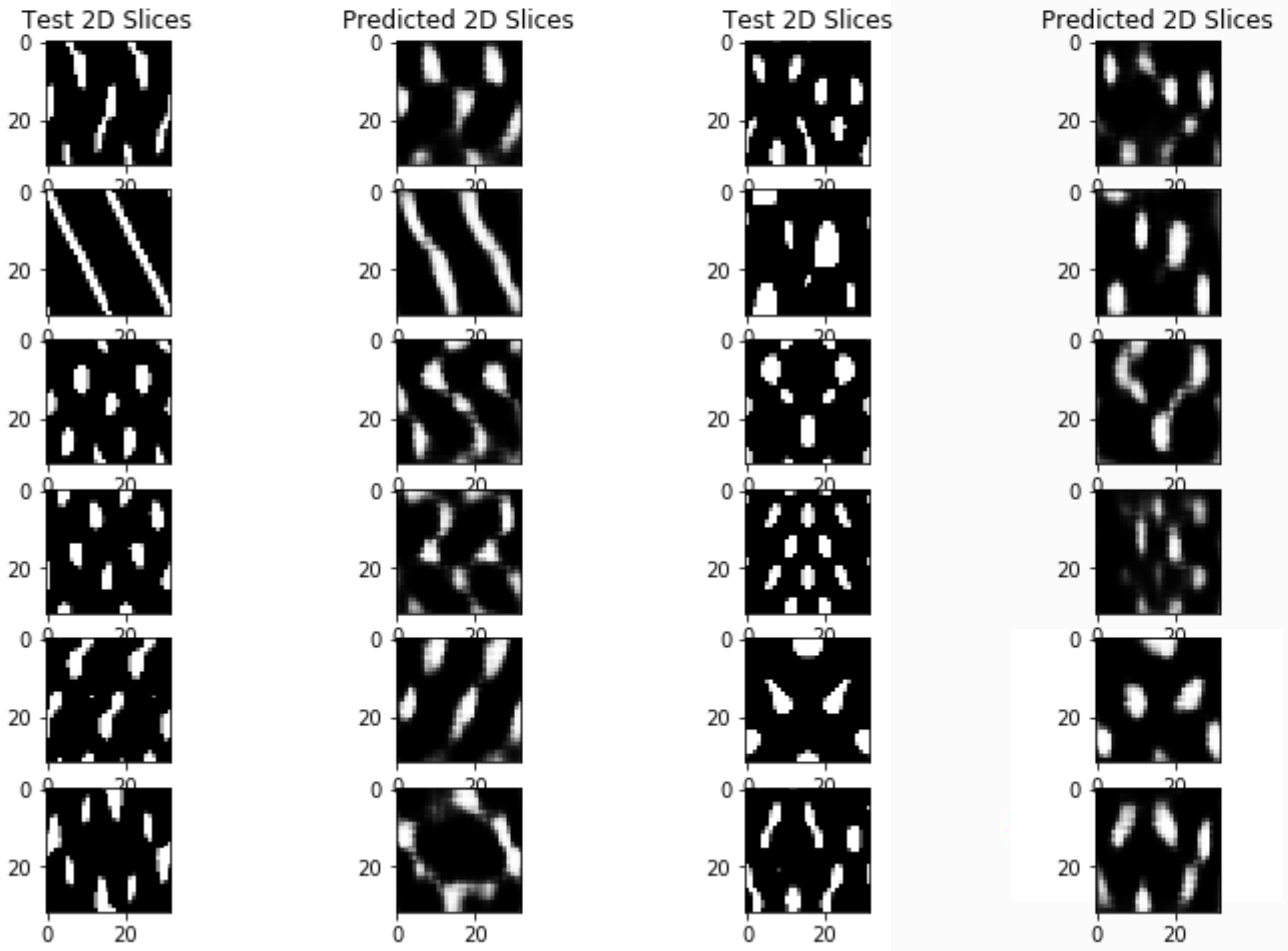
Where the variables are...

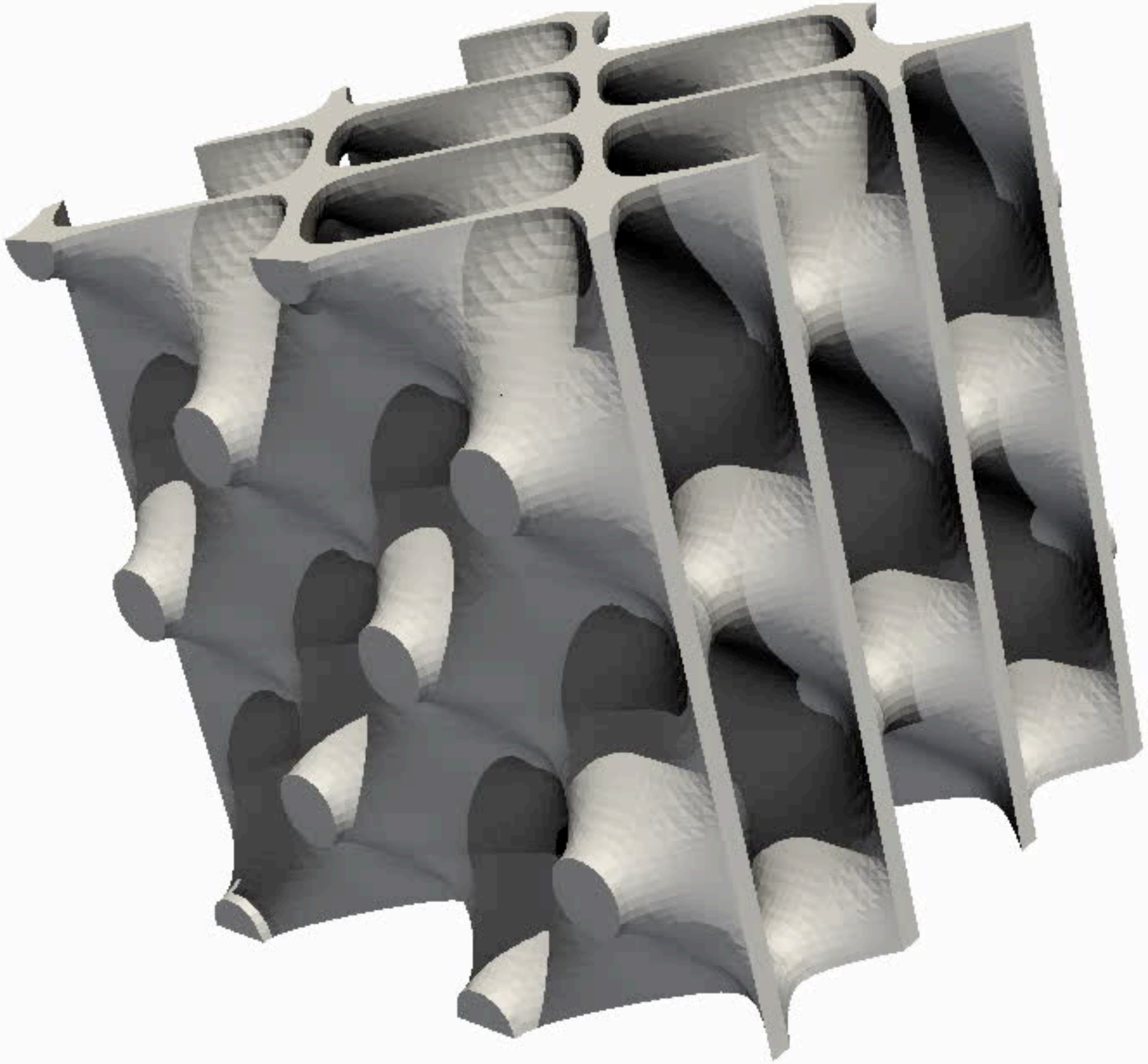
Variable	domain	Number of choices?	Approx num choices
p_i, q_i, r_i	each is a function: $\cos$ or $\sin$	For each i, 2^3 choices	8^N choices
h_i, k_i, l_i	integers in $[0,4]$	For each i, 5^3 choices	125^N choices
w_i	real numbers (possibly negative!) that sum to 1	Infinite, but if we discretize in units of size $\frac{1}{m}$ for some integer *m*...	$\sim N^{2m} \cdot e^N$
c	$c \in [-0.3, 0.3]$	Discretize: 10 choices?	10?
t	$t \in (0, 0.5]$	Discretize: 10 choices?	10?
Total:			$100 \cdot e^N 10^{3N} N^{2m}$

6. Lattice Cosmos: Search For Similar Shapes and Mechanical Properties

Gyroid works, but is it optimal for a single directional impact based cost function?

- CNN driven auto encoder and a similarity metric
- Find shapes similar to gyroid
- Run simulations on selected set





THANK YOU!

APPENDIX