ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

ED+C ENGINEERING DESIGN AND COMPUTING

Computational Evaluation and Optimization of Mechanical and Form Properties of 3D-Printed Bone Tissue Engineering Scaffolds

Max Engensperger

Supervised by Dr. Paul Egan and Prof. Dr. Kristina Shea

Introduction

Problem

- Medical case requires that bone is grown

Spinal Fusion

Major Fractures

sources: http://www.newhealthadvisor.com/spinal-fusion-recovery.html
http://images.radiopaedia.org/images/3030426/6d91c93a6a565320a67ff78ad8b240_jumbo.JPEG
http://d10k7sivr61qqr.cloudfront.net/content/royinterface/6/Suppl_3/S341/F8.large.jpg

Introduction

Problem

- Medical case requires that bone is grown
- The space is too big for bone to grow naturally

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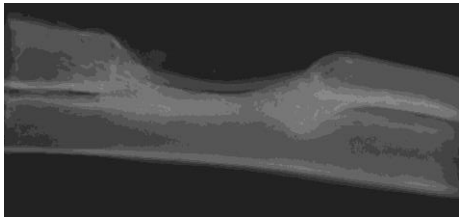
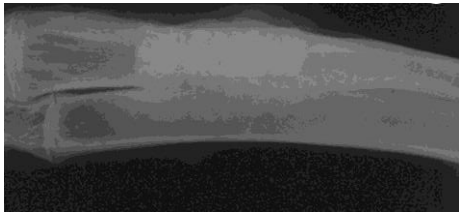
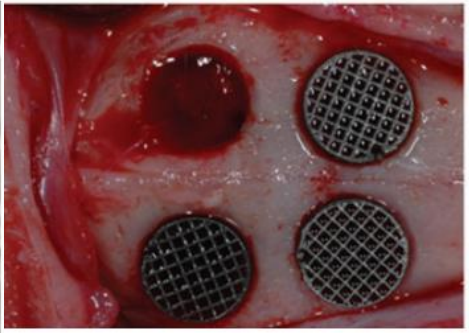
Introduction

Problem

- Medical case requires that bone is grown
- The space is too big for bone to grow naturally
- The bone cells requires a scaffold to grow and proliferate







sources: Wild, M. D., Schumacher, R., Mayer, K., Schkommodau, E., Thoma, D., Bredell, M., . . . Weber, F. E. (2013). Bone Regeneration by the Osteoconductivity of Porous Titanium Implants Manufactured by Selective Laser Melting: A Histological and Micro Computed Tomography Study in the Rabbit. Tissue Engineering Part A,19(23-24), 2645-2654. doi:10.1089/ten.tea.2012.0753

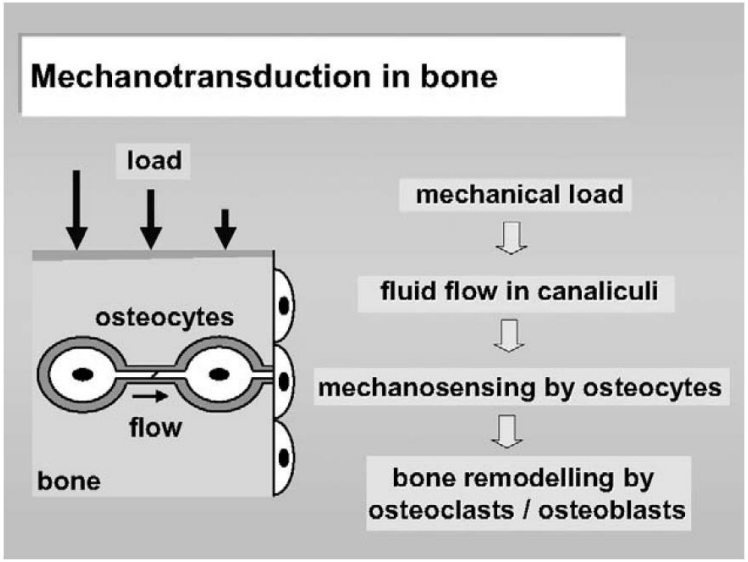
Introduction

Research Questions

- What are interesting properties for a BTE-scaffold from an engineering point of view?
- Can we design BTE-scaffolds according to those properties?
- Can we automate this design process?

Background

Mechanobiology of Bone Tissue



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Banaszkiewicz, P. A. (2013). Porous-Coated Hip Replacement. The Factors Governing Bone Ingrowth, Stress Shielding, and Clinical Results. Classic Papers in Orthopaedics, 51-55. doi:10.1007/978-1-4471-5451-8_12

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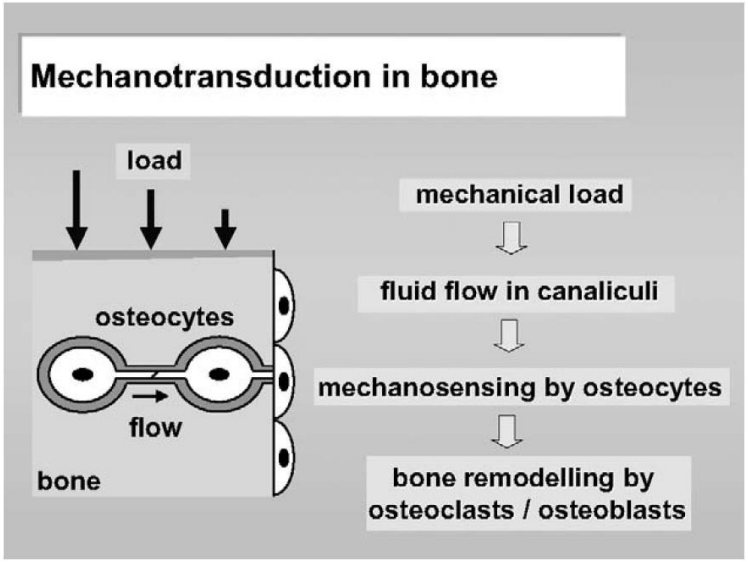
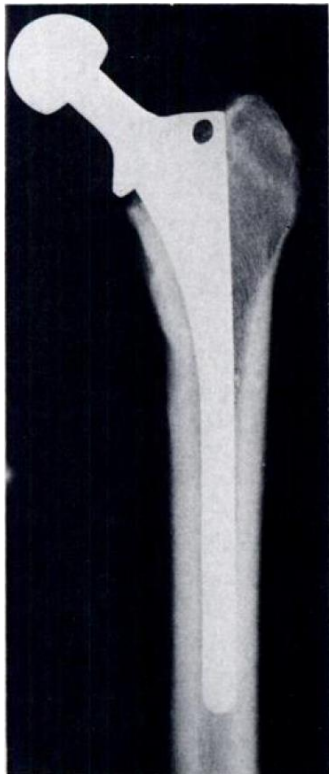


No Loads on Bone

Stress Shielding



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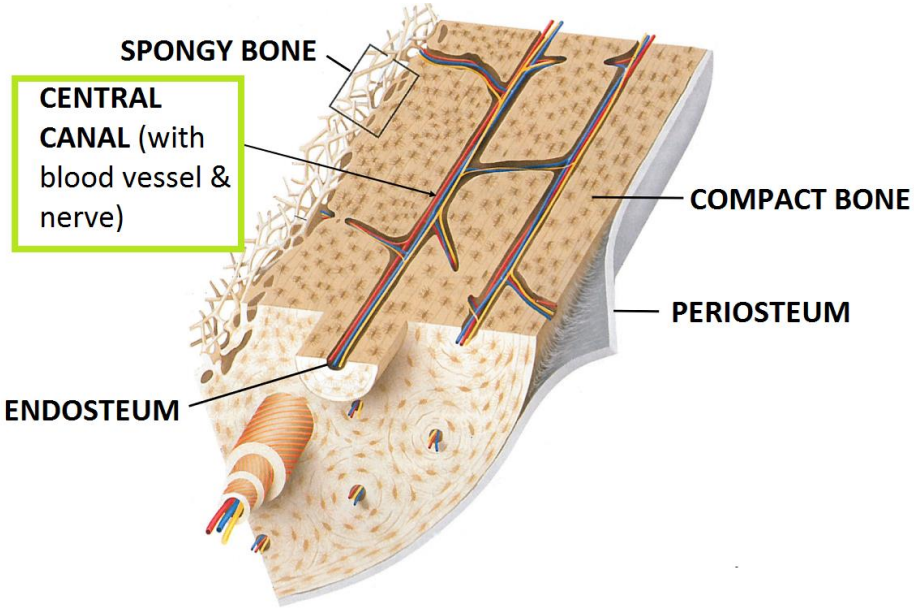
Background

Nutrient Flow in Bone



sources: https://classconnection.s3.amazonaws.com/921/flashcards/4154921/png/screenshot_(52)-1455E9A7B7962DA7895.png
http://www.pitt.edu/~rph18/Pictures/bone.jpg

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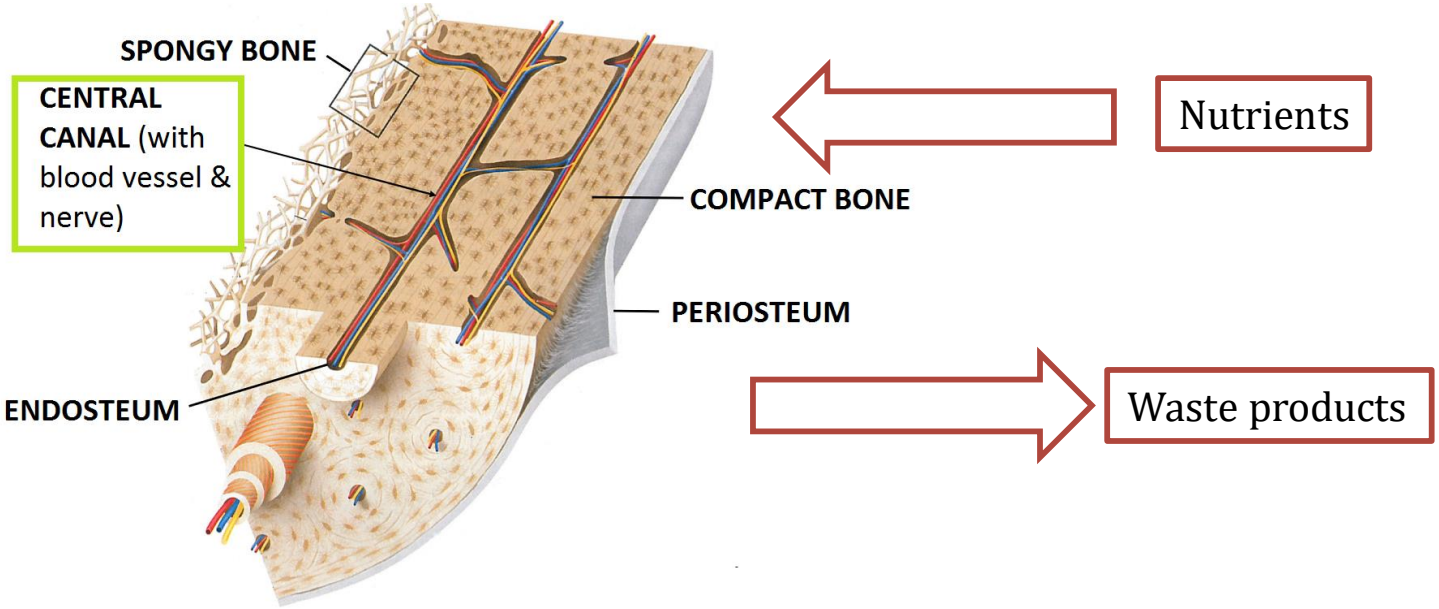
Nutrient Flow in Bone



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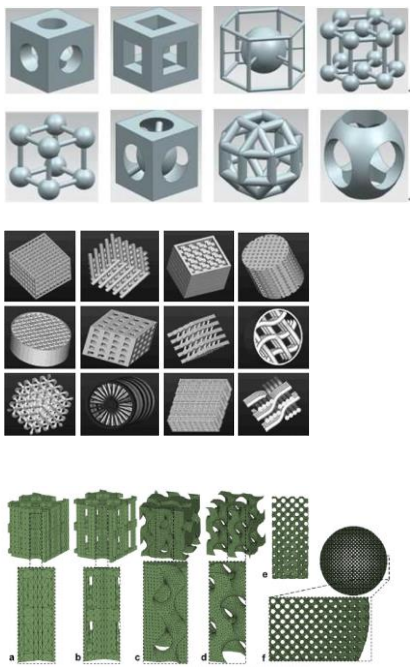
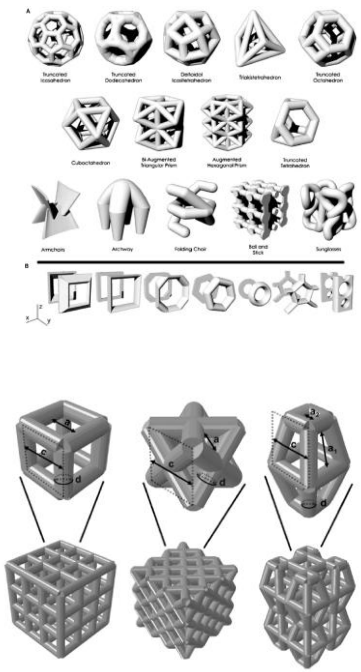
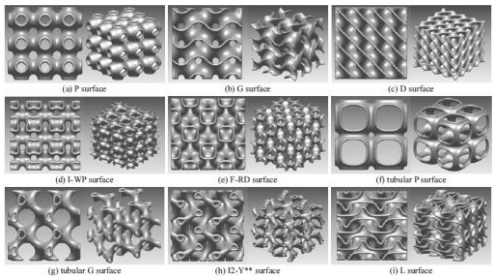
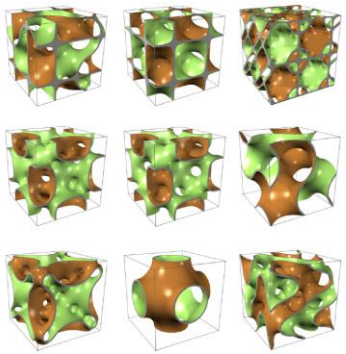
Background

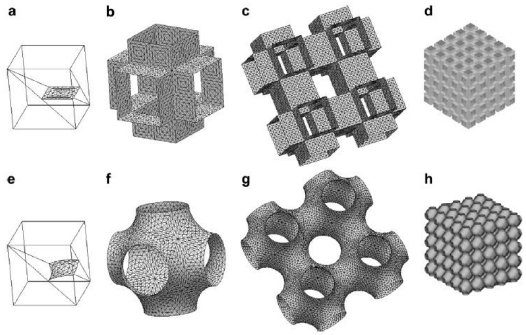
Scaffold Designs from other Research

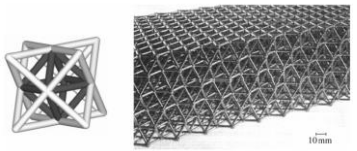










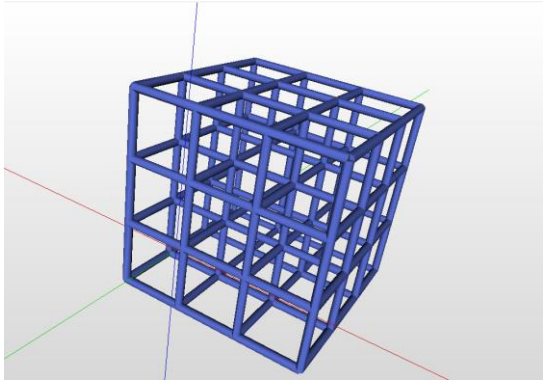


sources: Master's Thesis to this Presentation: Computational Evaluation and Optimization of mechanical Properties of 3D-Printed Bone Tissue Engineering Scaffolds
Appendix A.2 Topologies from other research

Goals

Procedure

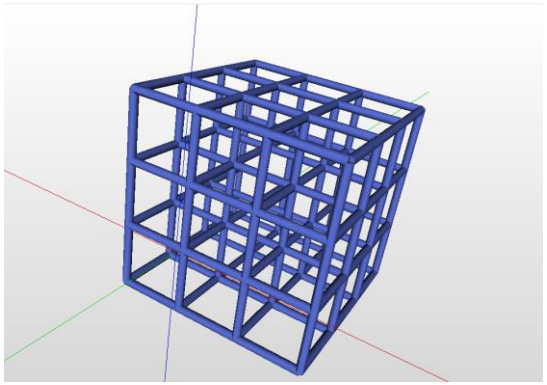
- Generate scaffolds

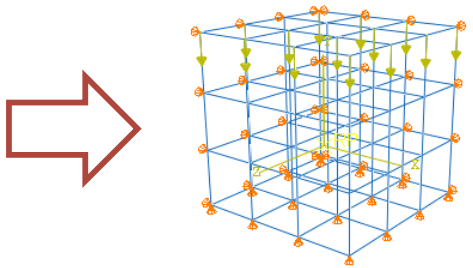


Goals

Procedure

- Generate scaffolds
- Evaluate scaffolds

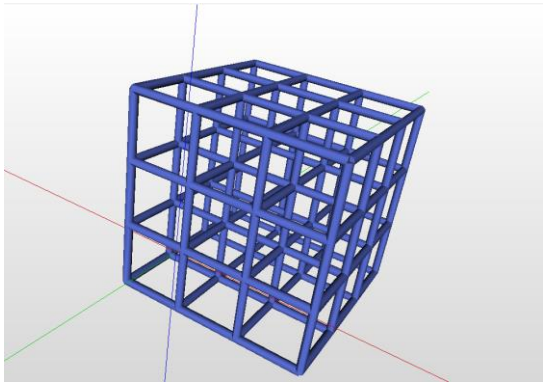


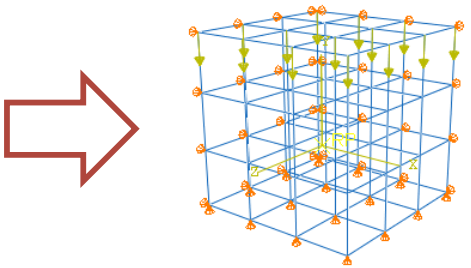


Goals

Procedure

- Generate scaffolds
- Evaluate scaffolds
- Optimize scaffolds



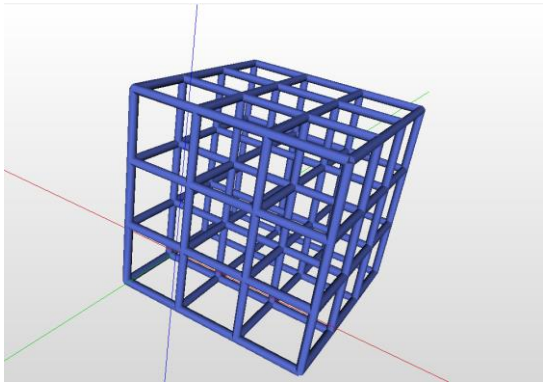


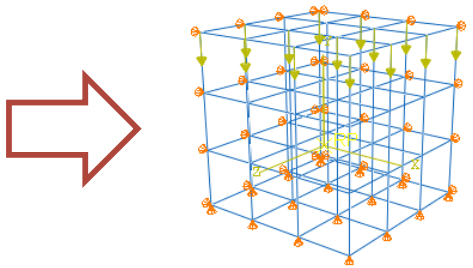
$$
\begin{aligned}
\min_{x} \quad & f(x) = w_1 E_1(x) + w_2 E_2(x) + \dots \\
s.t. \quad & g_1(x) \leq 0 \\
& g_2(x) \leq 0 \\
& \vdots \\
& h_1(x) = 0 \\
& h_2(x) = 0 \\
& \vdots
\end{aligned}
$$

Goals

Procedure

- Generate scaffolds
- Evaluate scaffolds
- Optimize scaffolds





Requirements

- Mechanical properties equal to bone (stress shielding)
- Ideal porosity for bone growth (nutrient transport)

$$
\begin{aligned}
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Goals

Evaluation Outputs

Mechanical Properties
- Elastic moduli
- Shearing moduli
- Poisson's ratios

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- Elastic moduli
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Compliance of the meta-material

$$\begin{pmatrix}\epsilon_{11}\\ \epsilon_{22}\\ \epsilon_{33}\\ \gamma_{23}\\ \gamma_{31}\\ \gamma_{12}\end{pmatrix} = \epsilon = C * \sigma = \begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16}\\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26}\\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36}\\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46}\\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56}\\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66}\end{pmatrix} * \begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \tau_{23}\\ \tau_{31}\\ \tau_{12}\end{pmatrix}$$

$$E_{11} = \frac{1}{c_{11}} \quad E_{22} = \frac{1}{c_{22}} \quad E_{33} = \frac{1}{c_{33}}$$

$$\nu_{12} = -\frac{c_{12}}{c_{11}} \quad \nu_{23} = -\frac{c_{23}}{c_{22}} \quad \nu_{31} = -\frac{c_{31}}{c_{33}}$$

$$\nu_{21} = -\frac{c_{21}}{c_{22}} \quad \nu_{32} = -\frac{c_{32}}{c_{33}} \quad \nu_{13} = -\frac{c_{13}}{c_{11}}$$

$$G_{23} = \frac{1}{c_{44}} \quad G_{31} = \frac{1}{c_{55}} \quad G_{12} = \frac{1}{c_{66}}$$

E_{xx}: Elastic Modulus
ν_{xy}: Poisson's ratio
G_{xy}: Shearing Modulus

Goals

Evaluation Outputs

Mechanical Properties
- Elastic moduli
- Shearing moduli
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Form Properties
- Porosity
- Surface area
- Pore size

Compliance of the meta-material

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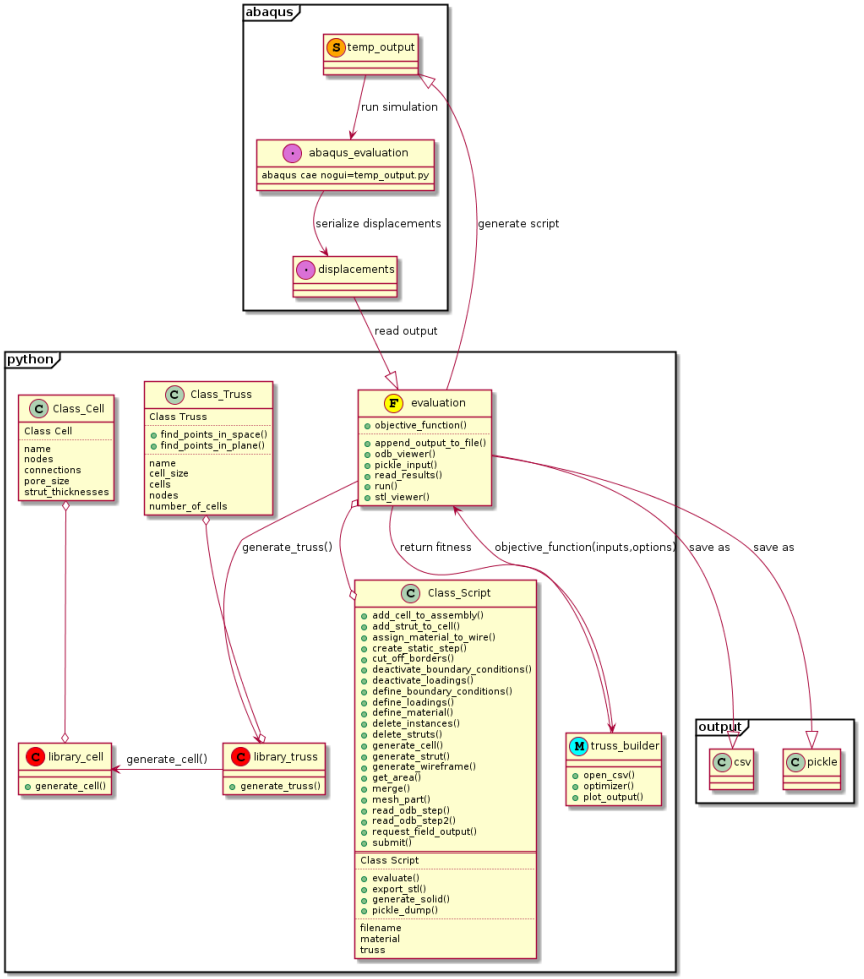
Methods

Tools

- Abaqus scripting with Python
- FEM-Solver Abaqus
- Optimization toolbox SciPy



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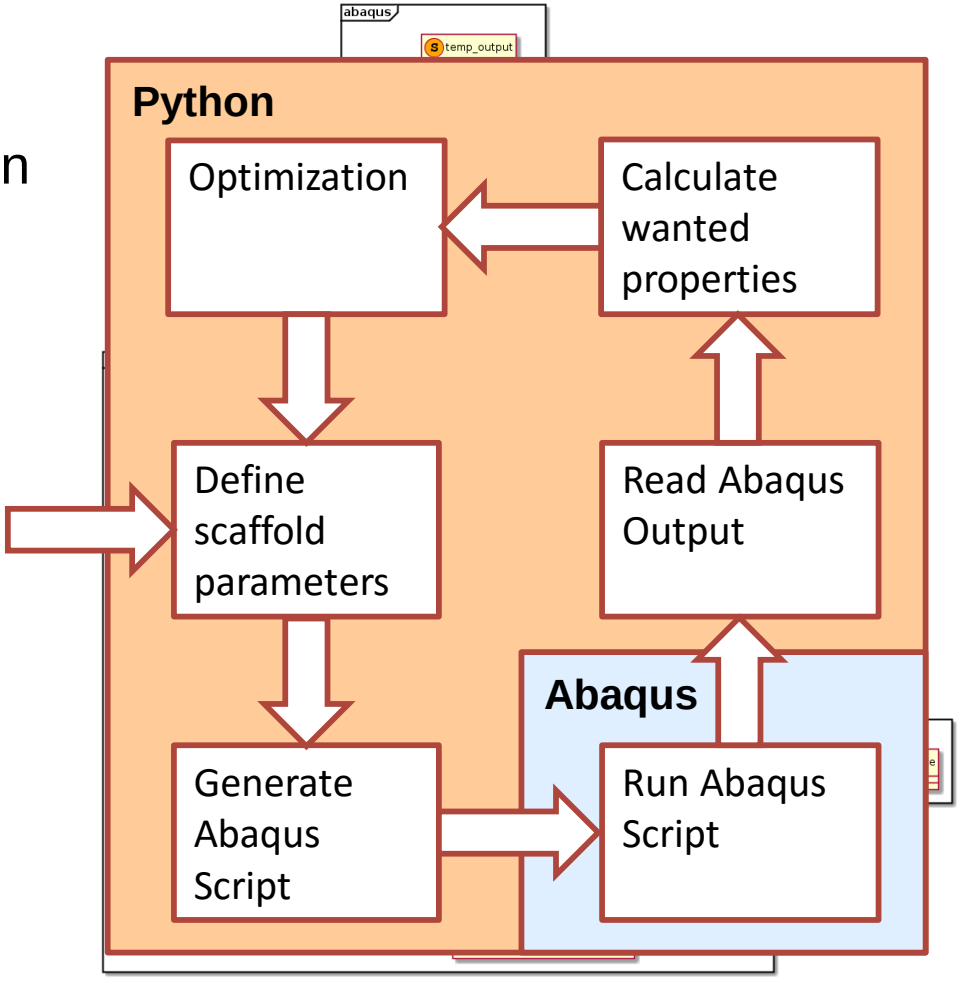

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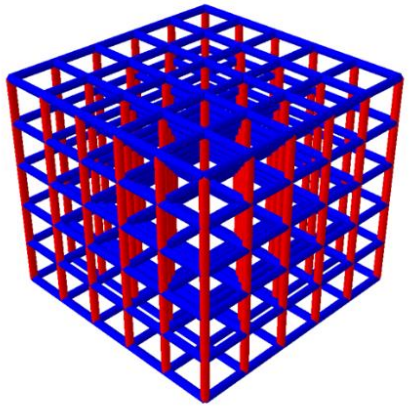
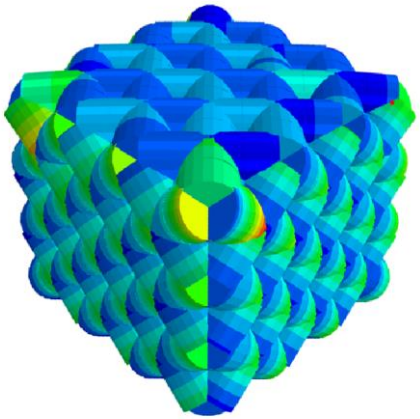
FEM-Model

- Beam elements





Methods

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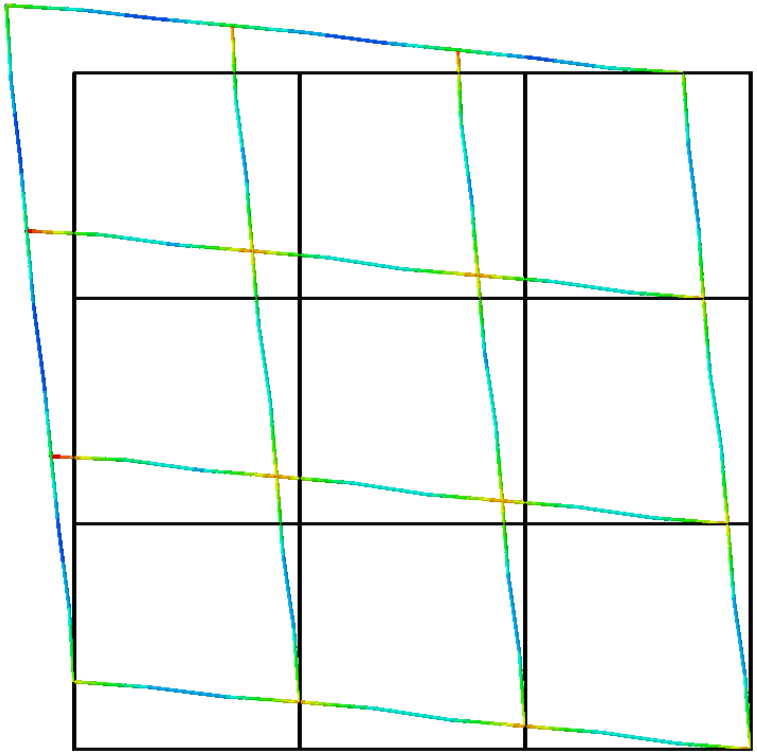
FEM-Model

- Beam elements
- Quadratic shape functions



Methods

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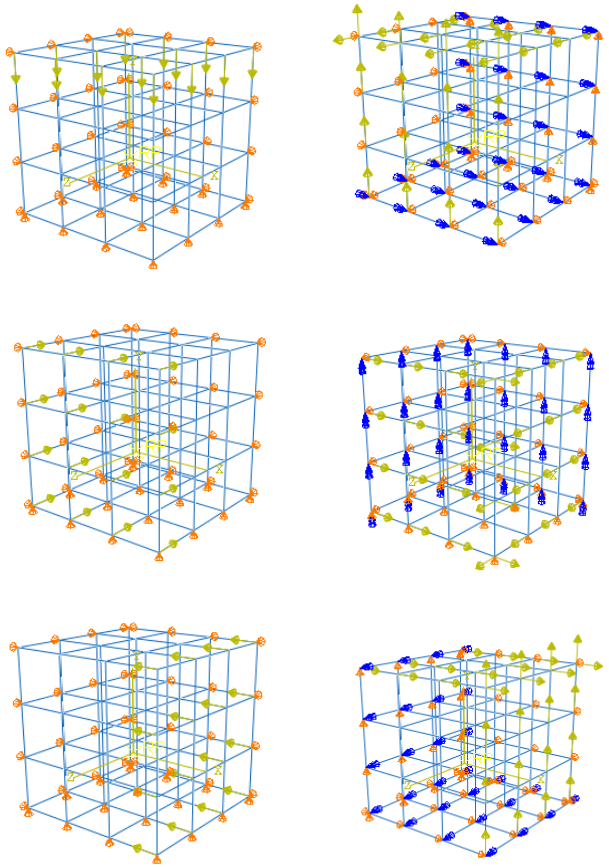
FEM-Model

- Beam elements
- Quadratic shape functions
- Six loading states



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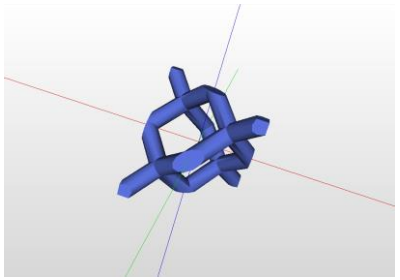
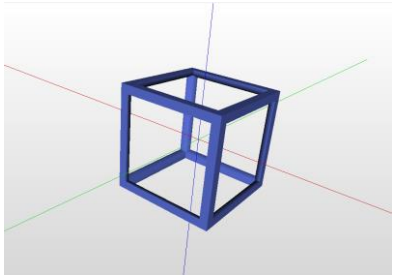
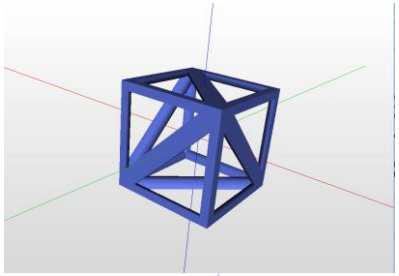
$$d_{11}/l_{scaffold} = \epsilon_{11} = c_{12} * \sigma_{22} = c_{12} * \frac{F}{A_{scaffold}} \longleftrightarrow c_{12} = \frac{d_{11} * A_{scaffold}}{F * l_{scaffold}}$$

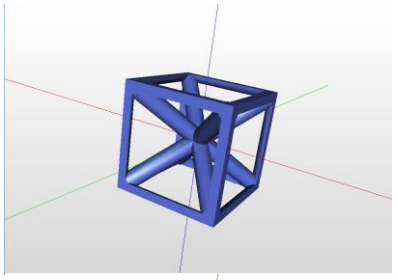
d_{11}:	displacement
$l_{scaffold}$:	length of the scaffold
F:	applied force
$A_{scaffold}$:	area of the scaffold

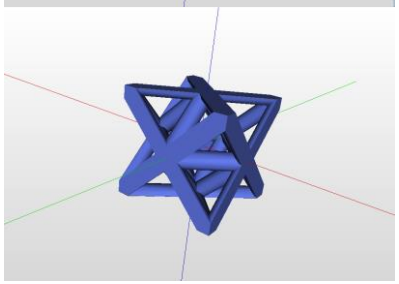
Topologies

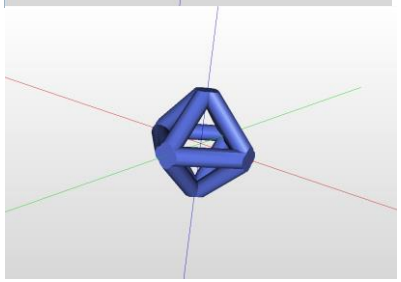


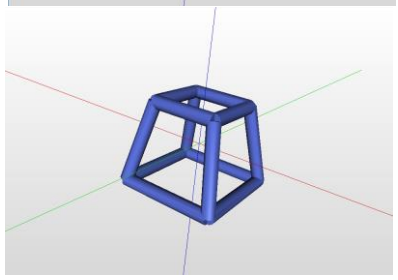


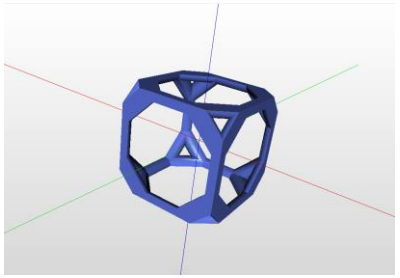


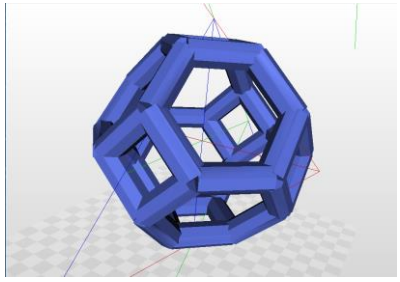












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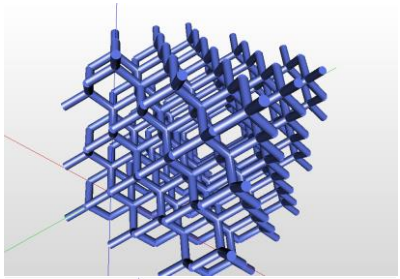
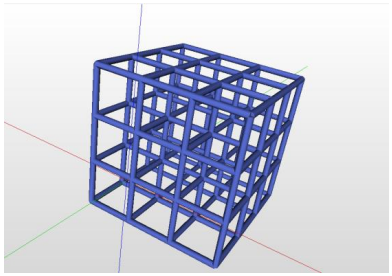
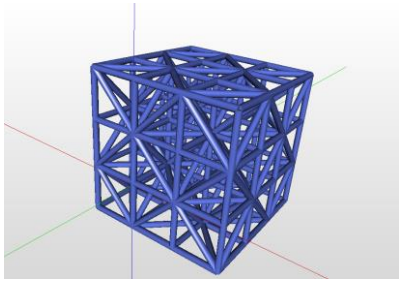
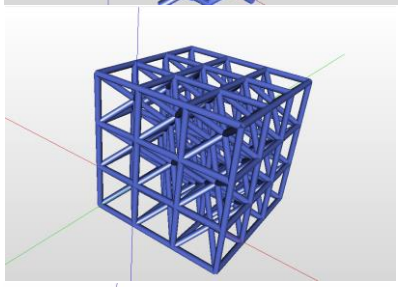
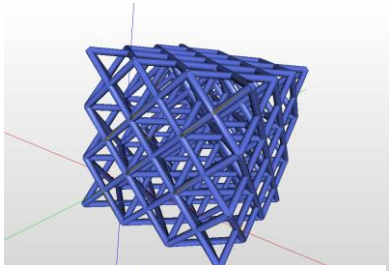
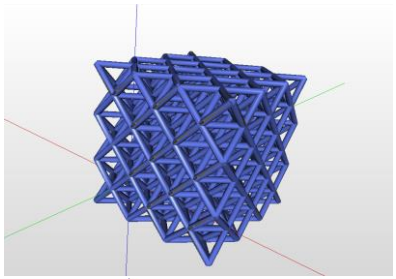


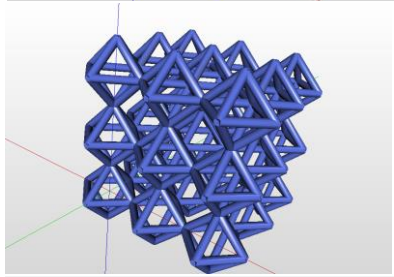


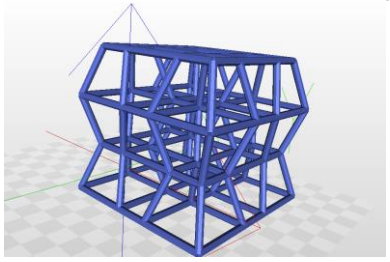


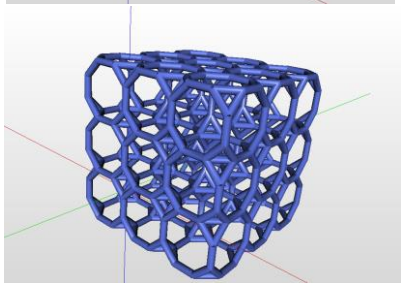


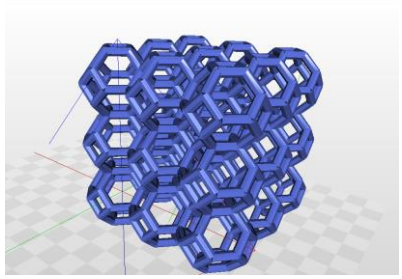












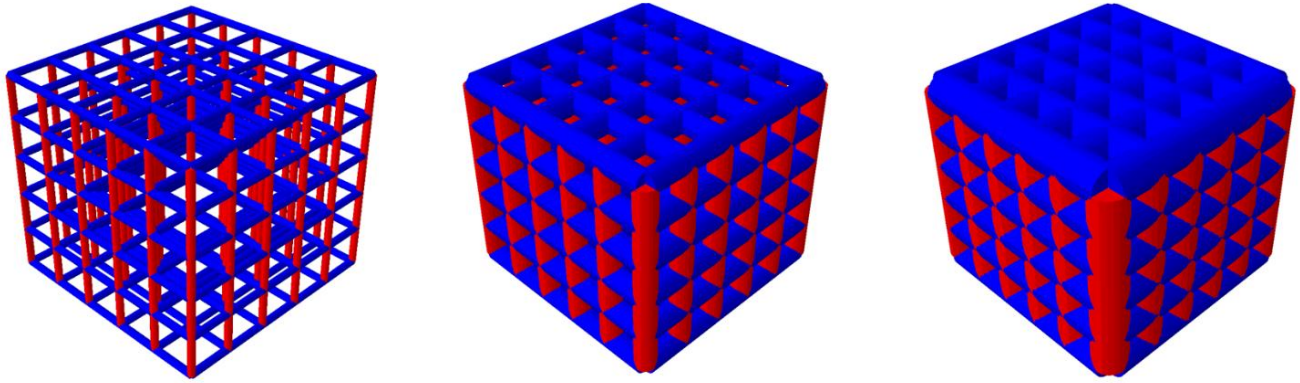
Results

Basic Optimization

Results

Basic Optimization

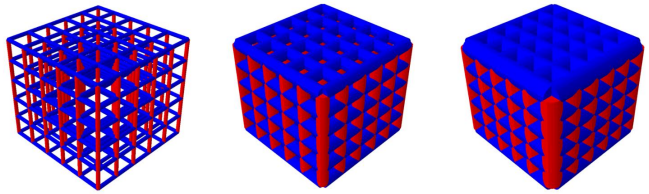
- Thickness scaling

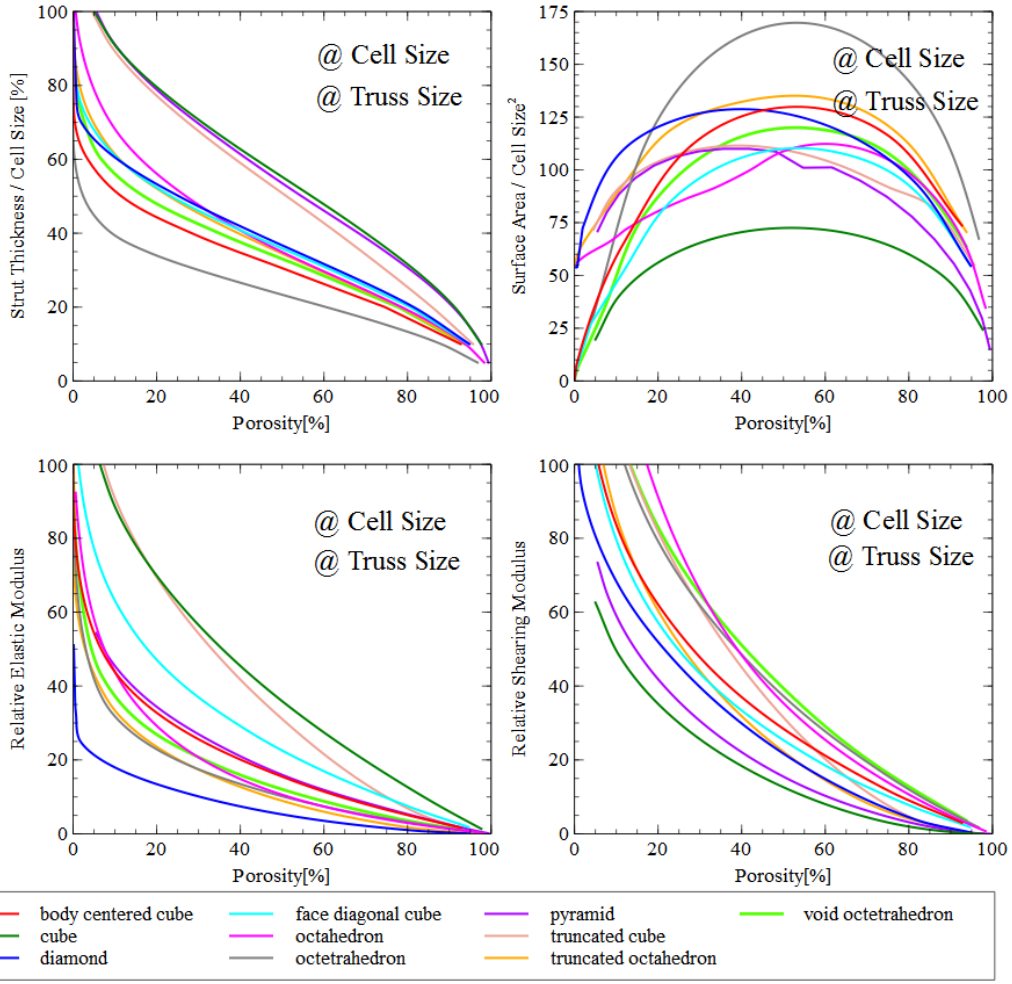


Results

Basic Optimization

- Thickness scaling

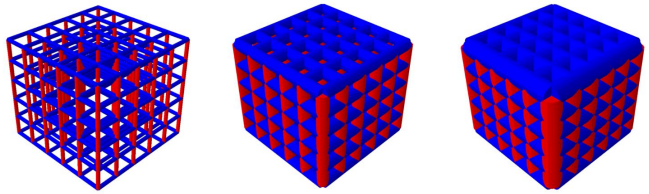


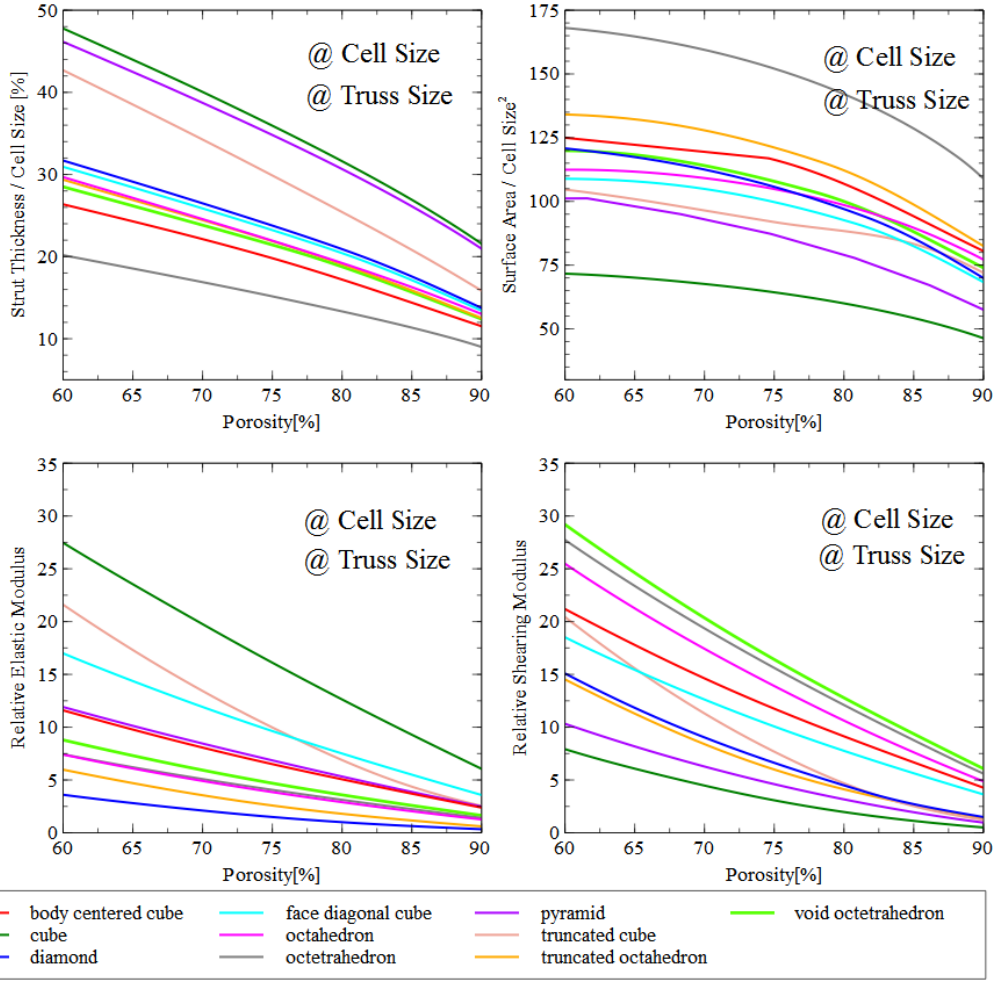


Results

Basic Optimization

- Thickness scaling

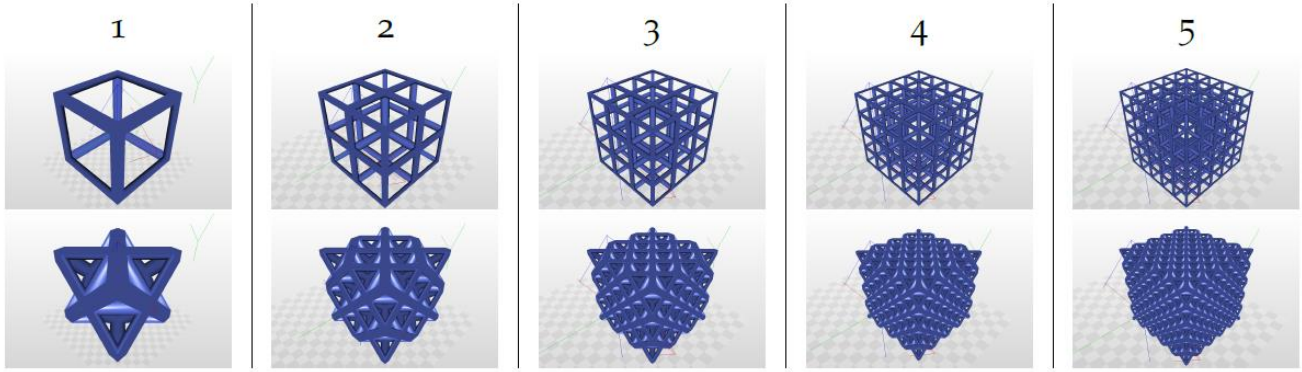




Results

Basic Optimization

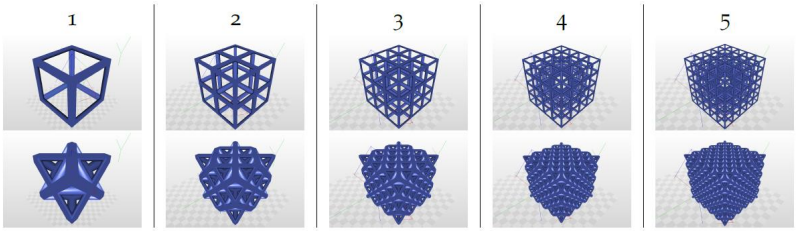
- Thickness scaling

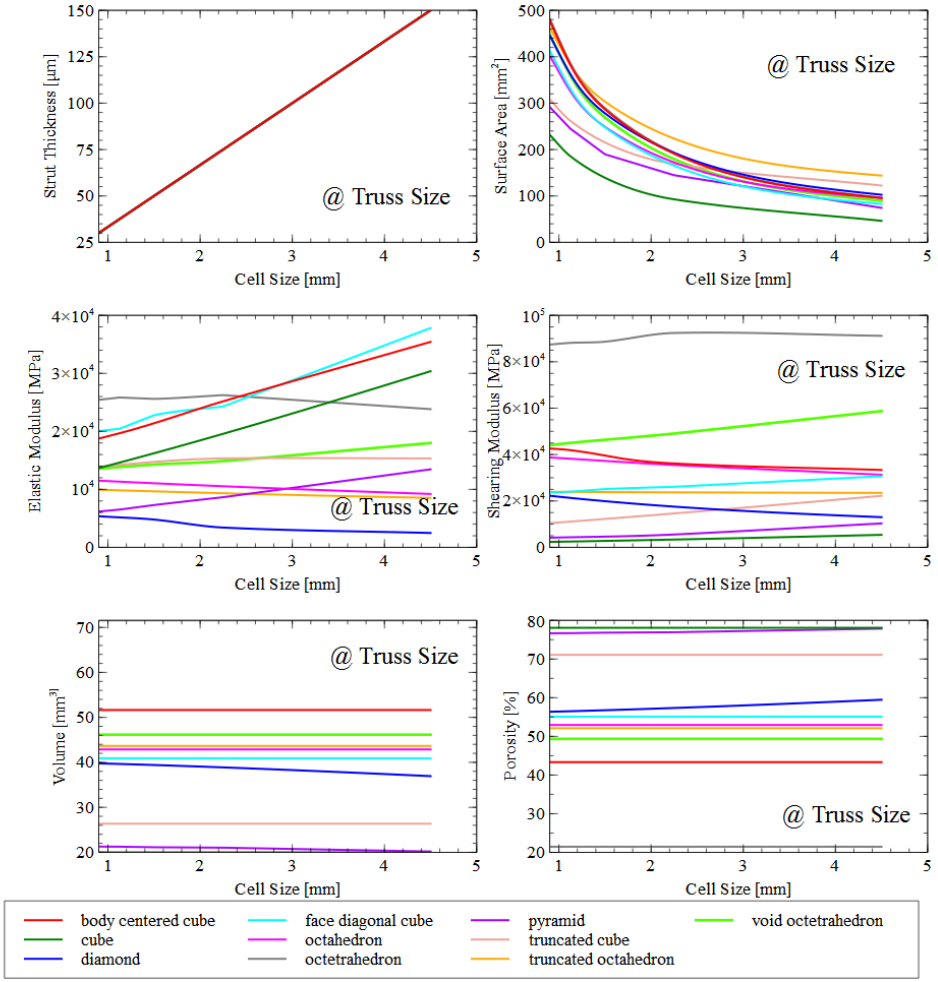


Results

Basic Optimization

- Thickness scaling





Results

Basic Optimization

- Thickness scaling

Optimization Goals

- Maximize sigma Z

$$\begin{aligned} \min_{x} \quad & f(x) = E_x(x) + E_y(x) - E_z(x) \\ s.t. \quad & g_1(x) = x_1 \geq 0 \\ & g_2(x) = x_2 \geq 0 \\ & \vdots \end{aligned}$$

$f(x)$: Objective Function
$g_n(x)$: Inequality constraint

$x_1, x_2, \ldots, x_n$: Strut Diameters

Results

Basic Optimization

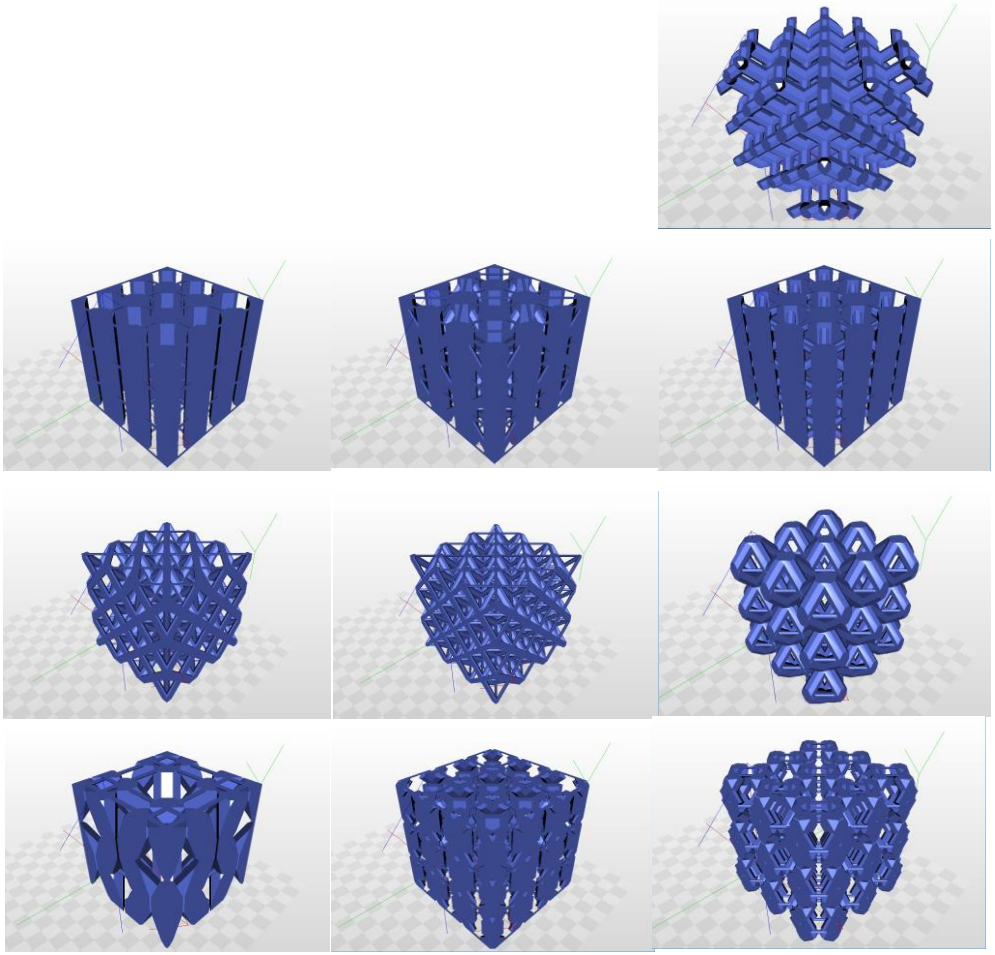
- Thickness scaling

Optimization Goals

- Maximize sigma Z

$$\begin{aligned} \min_x \quad & f(x) = E_x(x) + E_y(x) - E_z(x) \\ s.t. \quad & g_1(x) = x_1 \geq 0 \\ & g_2(x) = x_2 \geq 0 \\ & \vdots \end{aligned}$$

$f(x)$: Objective Function
$g_n(x)$: Inequality constraint



Results

Basic Optimization

- Thickness scaling

Optimization Goals

- Maximize sigma Z

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$f(x)$: Objective Function
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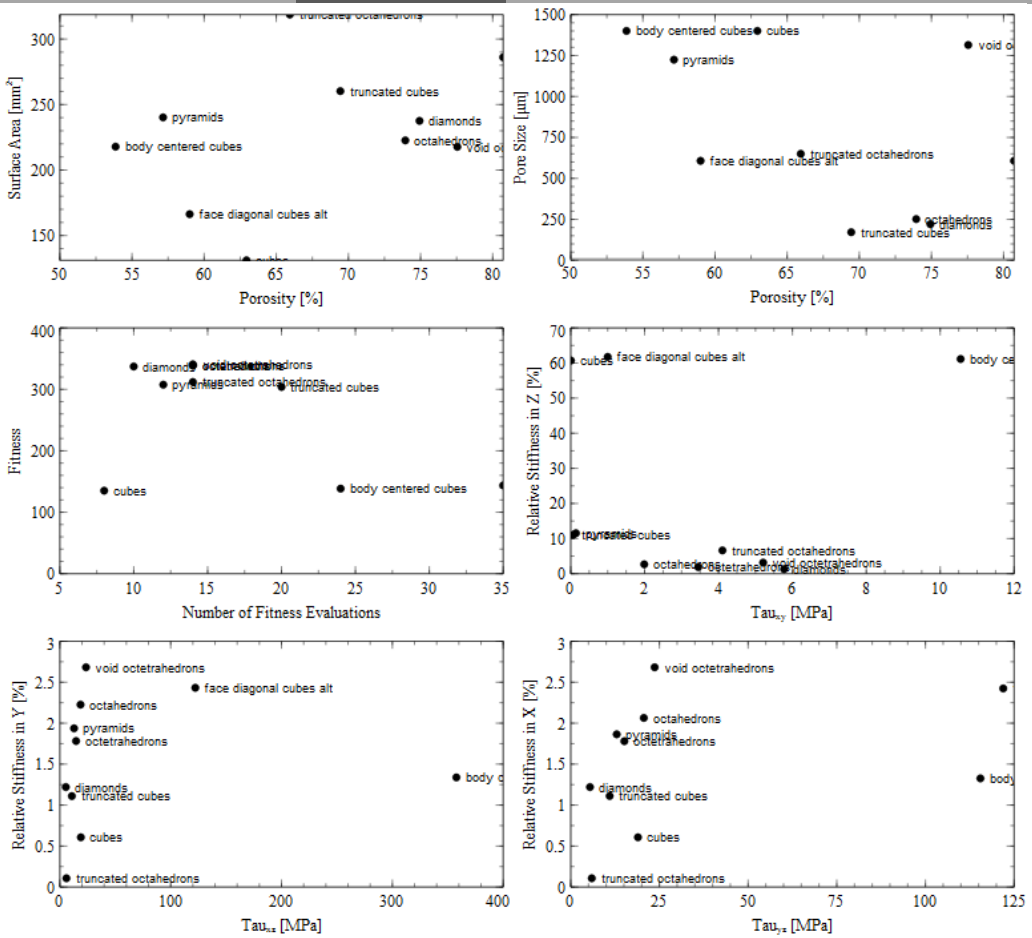


Results

Basic Optimization

- Thickness scaling

Optimization Goals

- Maximize sigma Z
- Biomimetic approach

$$\begin{aligned} \min_{x} \quad & f(x) = \tfrac{1}{300}|E_x(x) - 12GPa| + \tfrac{1}{300}|E_y(x) - 12GPa| + \tfrac{1}{300}|E_z(x) - 15GPa| \\ s.t. \quad & g_1(x) = x_1 \geq 0 \\ & g_2(x) = x_2 \geq 0 \\ & \vdots \end{aligned}$$

Results

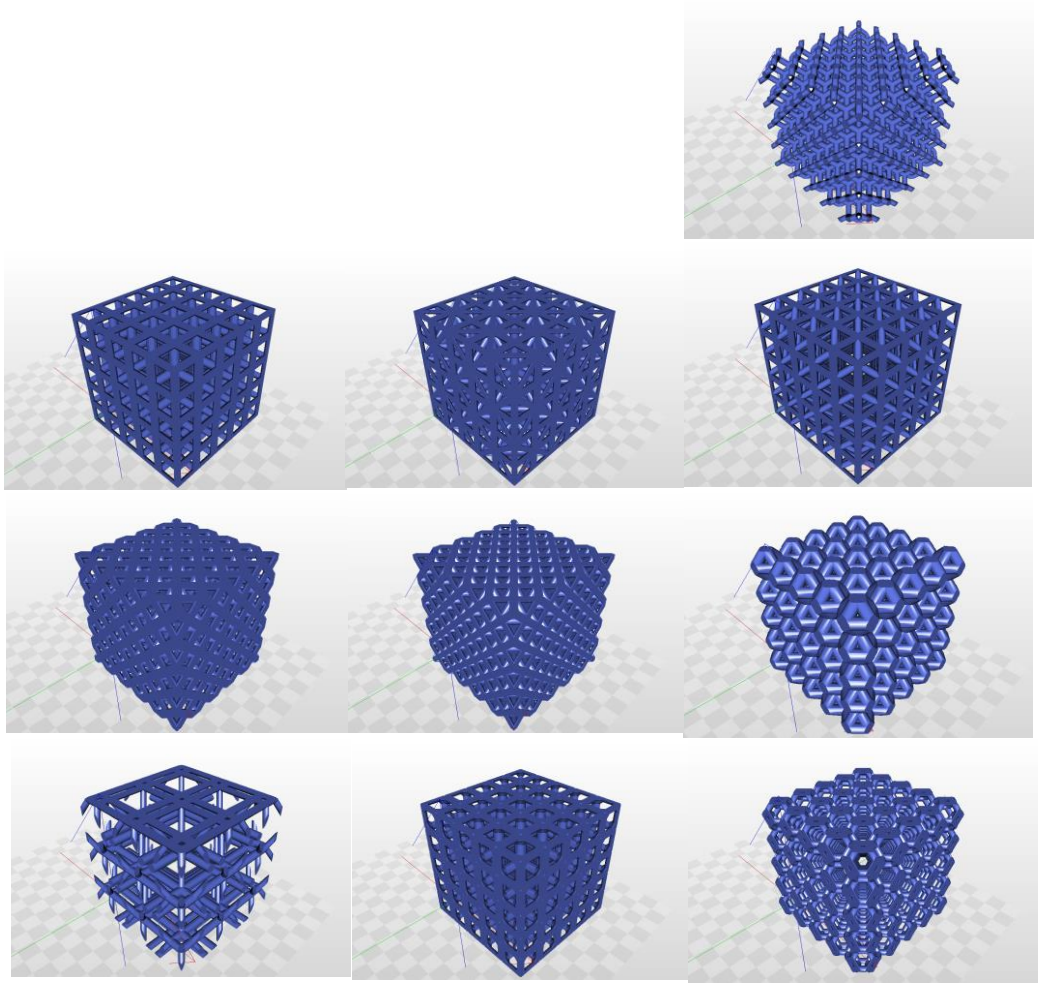
Basic Optimization

- Thickness scaling

Optimization Goals

- Maximize sigma Z
- Biomimetic approach

$$\begin{aligned} \min_{x} \quad & f(x) = \tfrac{1}{300}|E_x(x) - 12GPa| + \tfrac{1}{300}|E_y(x) - 12GPa| + \tfrac{1}{300}|E_z(x) - 15GPa| \\ s.t. \quad & g_1(x) = x_1 \geq 0 \\ & g_2(x) = x_2 \geq 0 \\ & \vdots \end{aligned}$$



Results

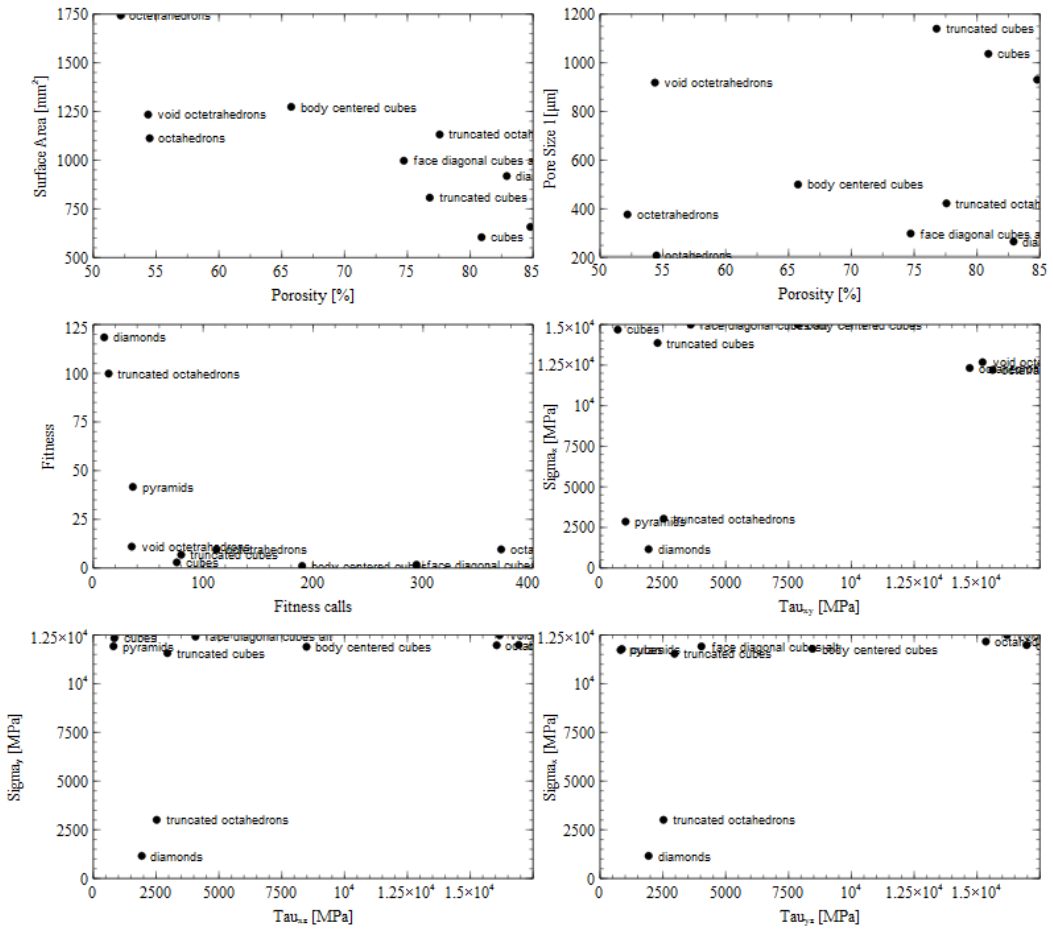
Basic Optimization

- Thickness scaling

Optimization Goals

- Maximize sigma Z
- Biomimetic approach

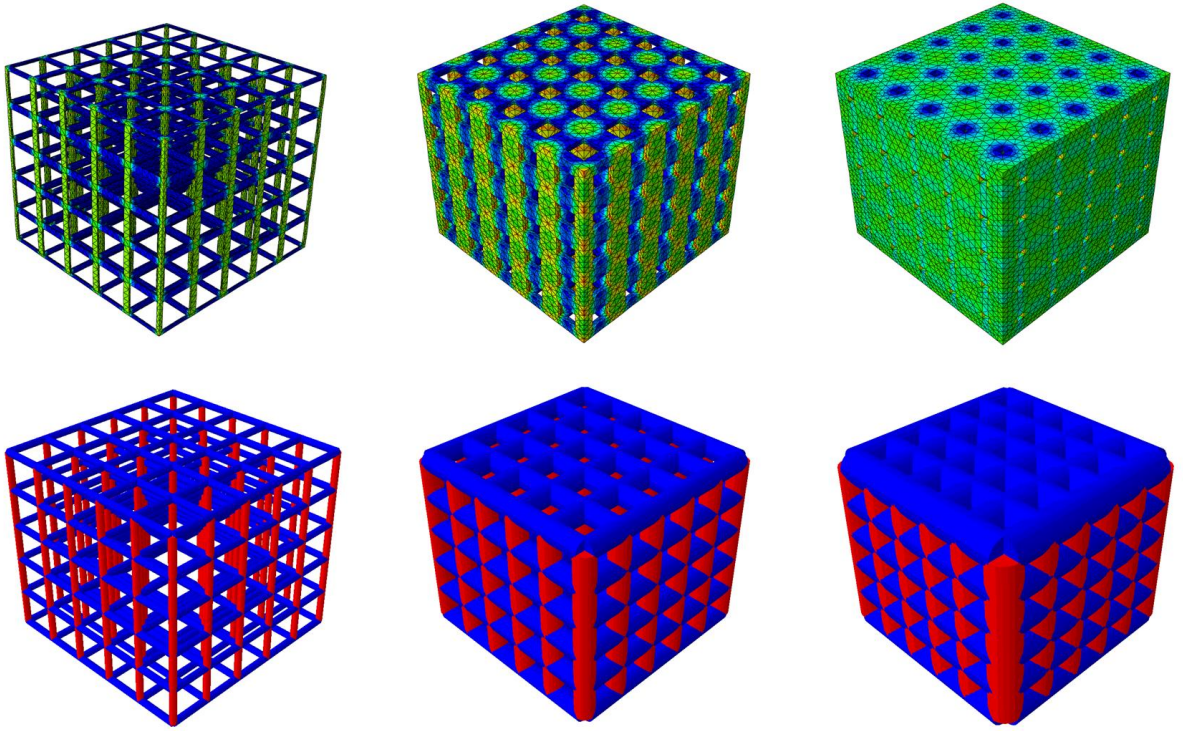
$$\begin{aligned} \min_{x} \quad & f(x) = \tfrac{1}{300}|E_x(x) - 12GPa| + \tfrac{1}{300}|E_y(x) - 12GPa| + \tfrac{1}{300}|E_z(x) - 15GPa| \\ s.t. \quad & g_1(x) = x_1 \geq 0 \\ & g_2(x) = x_2 \geq 0 \\ & \vdots \end{aligned}$$



Discussion

Validity

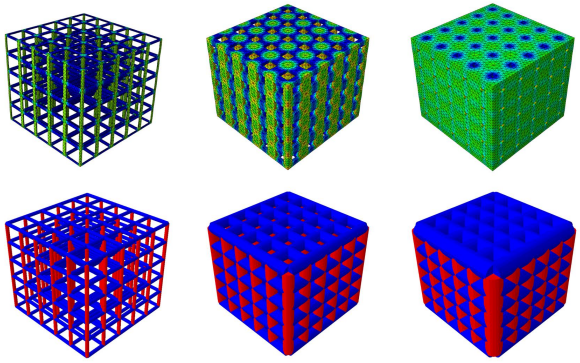
- Sensitivity analysis

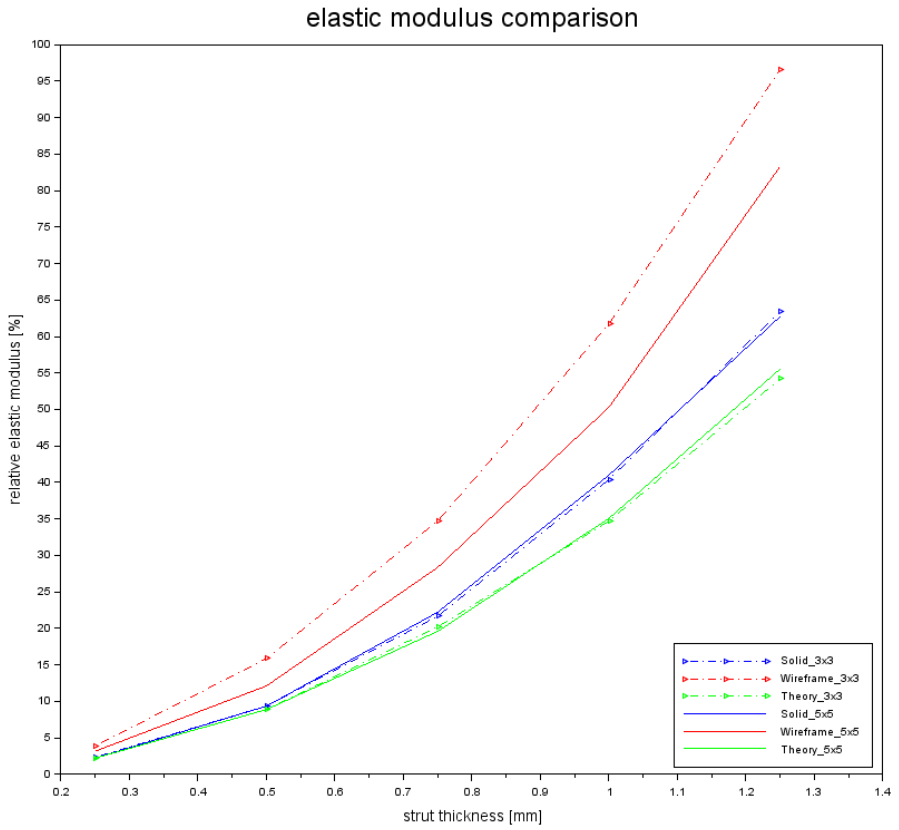


Discussion

Validity

- Sensitivity analysis

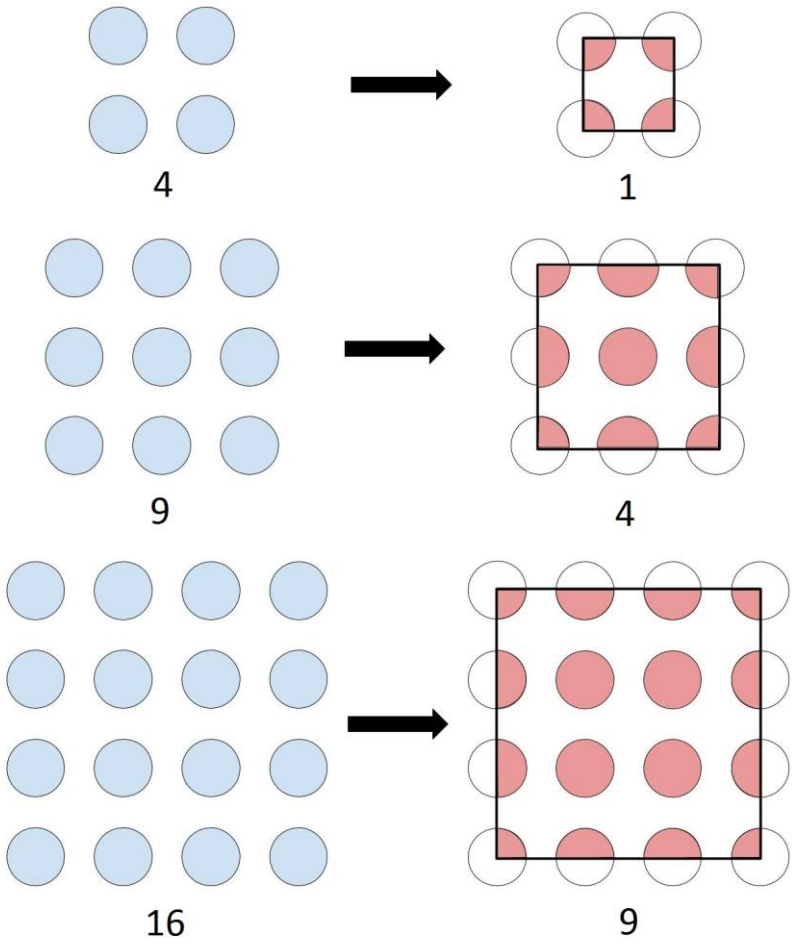




Discussion

Validity

- Sensitivity analysis
- Cutoff error



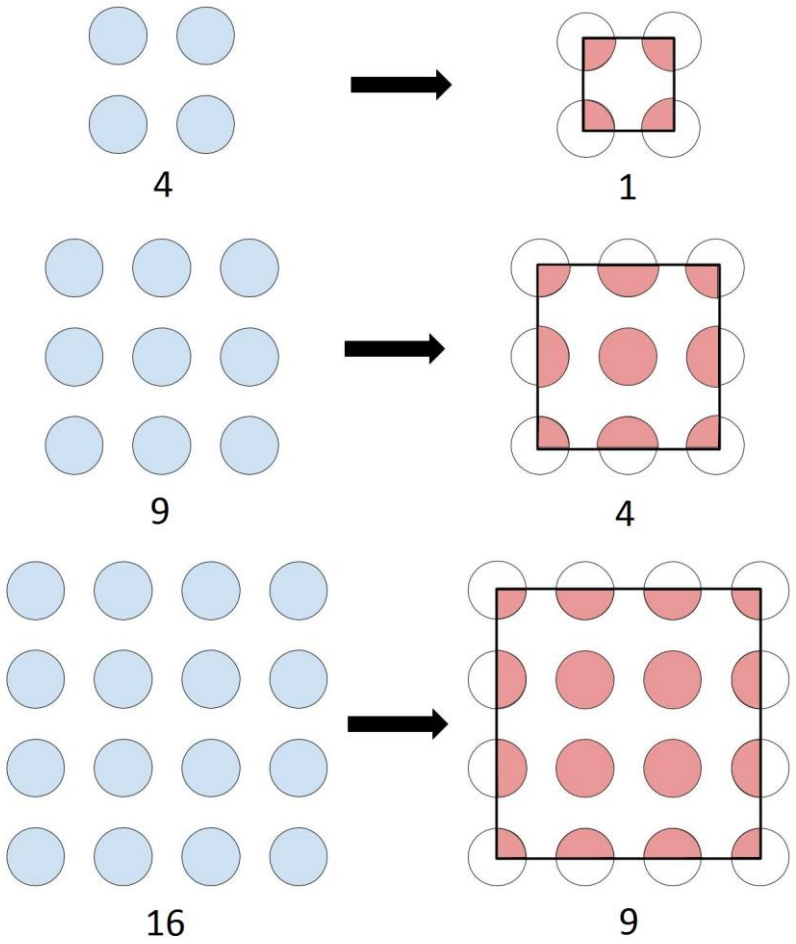
Discussion

Validity

- Sensitivity analysis
- Cutoff error

$$A_{true} = \frac{i^2}{(i+1)^2} A_{sim}$$

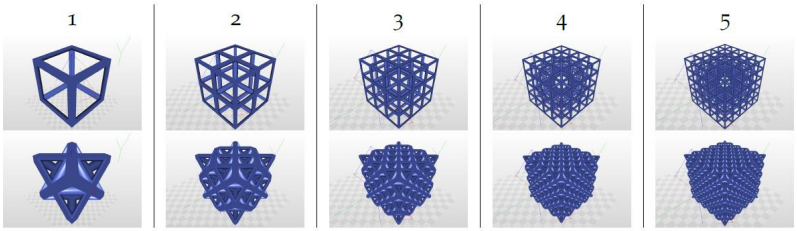
$$i: \quad Number\ of\ Cells$$

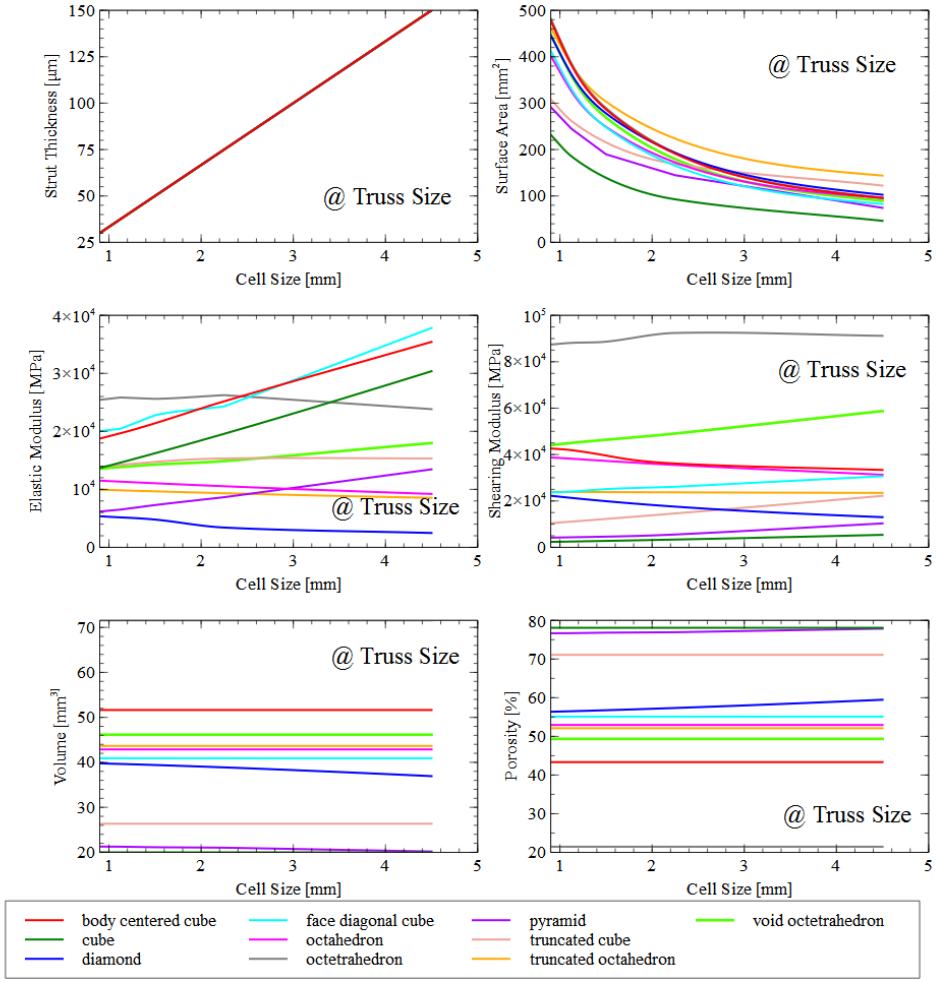


Results

Validity

- Sensitivity analysis
- Cutoff error





Discussion

Validity

- Sensitivity analysis
- Cutoff error

Further Work

- Experimental comparison

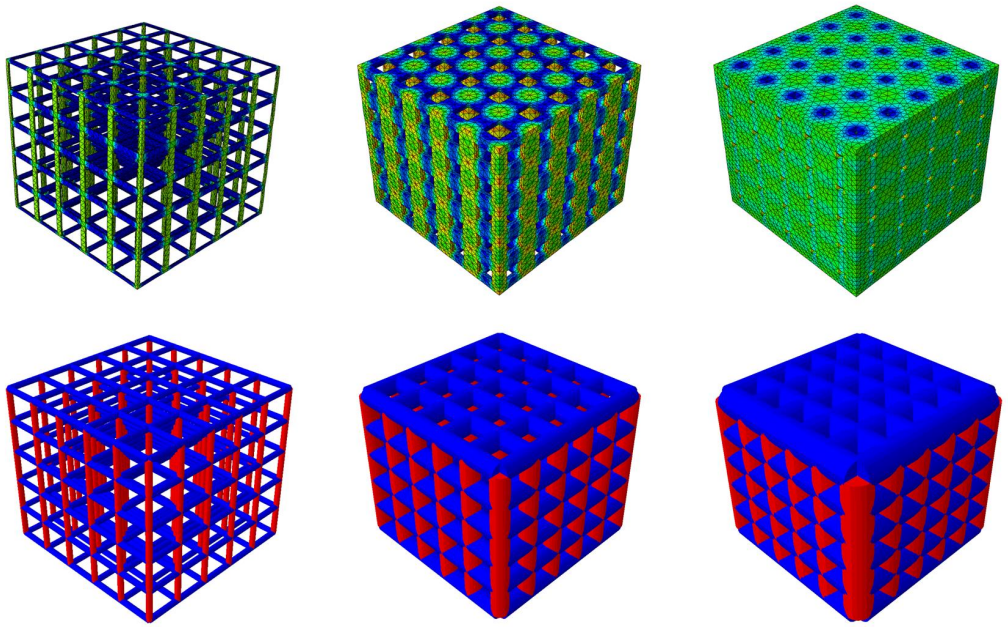
Discussion

Validity

- Sensitivity analysis
- Cutoff error

Further Work

- Experimental comparison
- Vary method
  - Solid elements



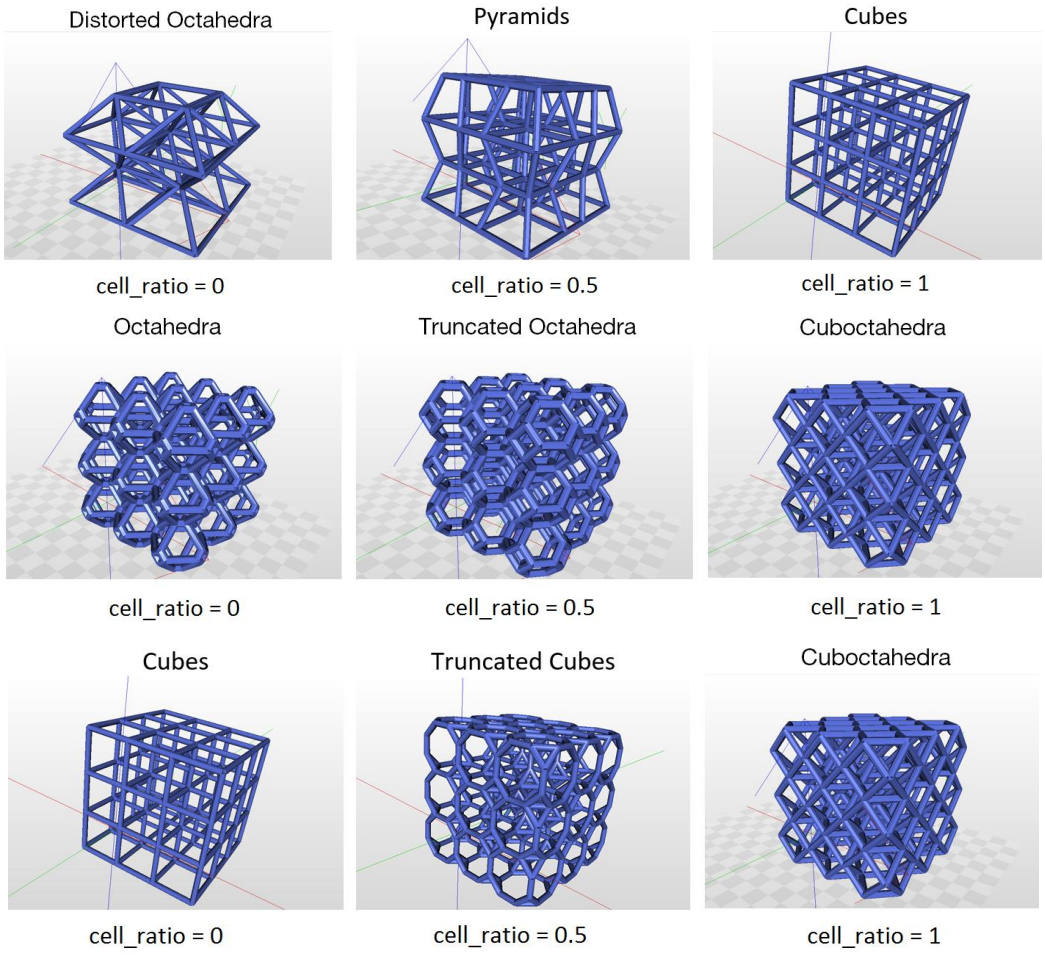
Discussion

Validity

- Sensitivity analysis
- Cutoff error

Further Work

- Experimental comparison
- Vary method
  - Solid elements
  - Other parameters



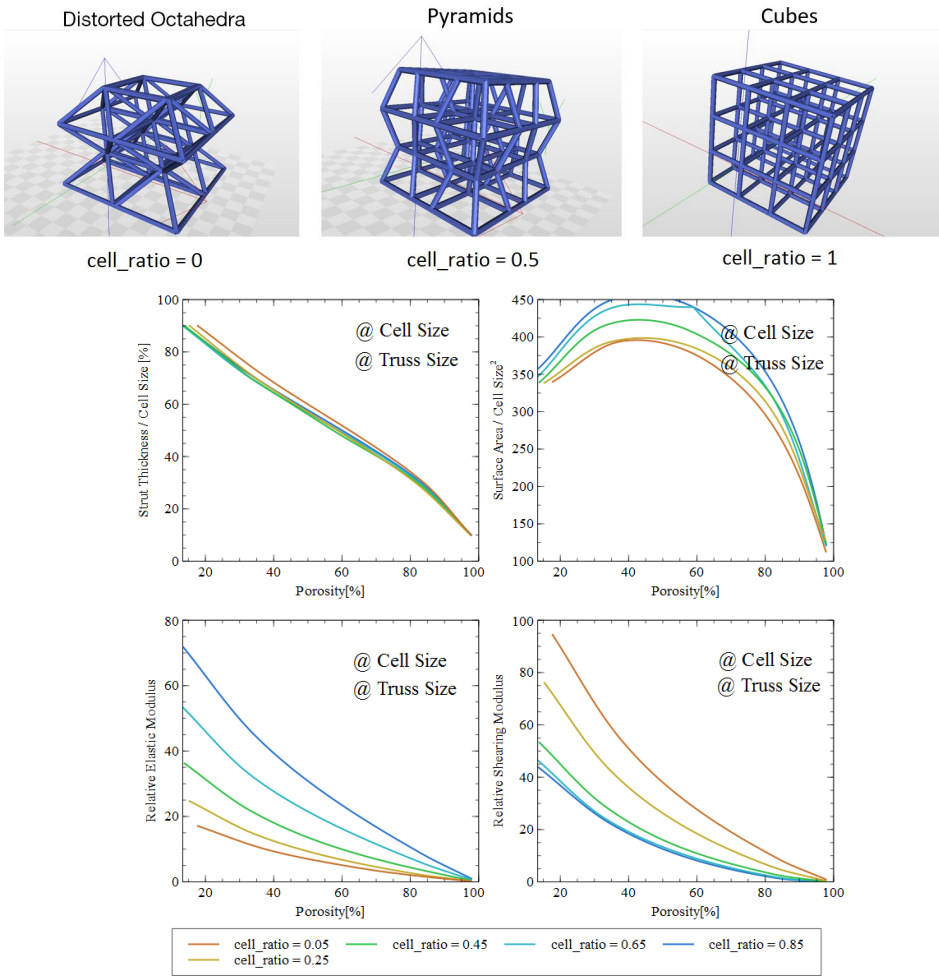
Discussion

Validity

- Sensitivity analysis
- Cutoff error

Further Work

- Experimental comparison
- Vary method
  - Solid elements
  - Other parameters



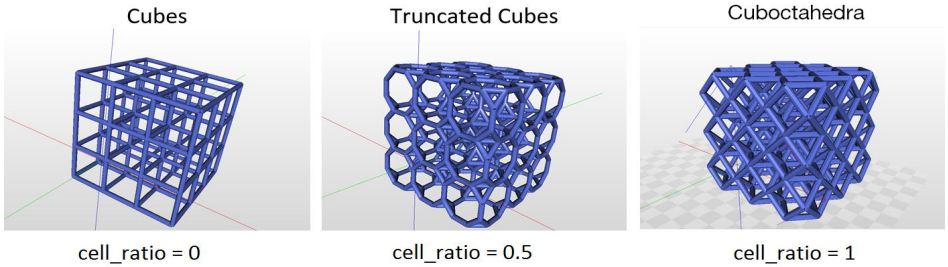
Discussion

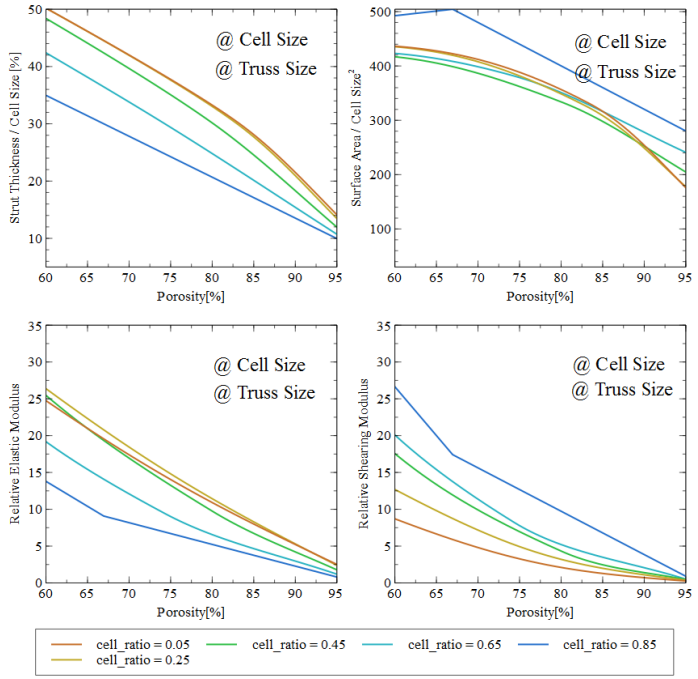
Validity

- Sensitivity analysis
- Cutoff error

Further Work

- Experimental comparison
- Vary method
  - Solid elements
  - Other parameters





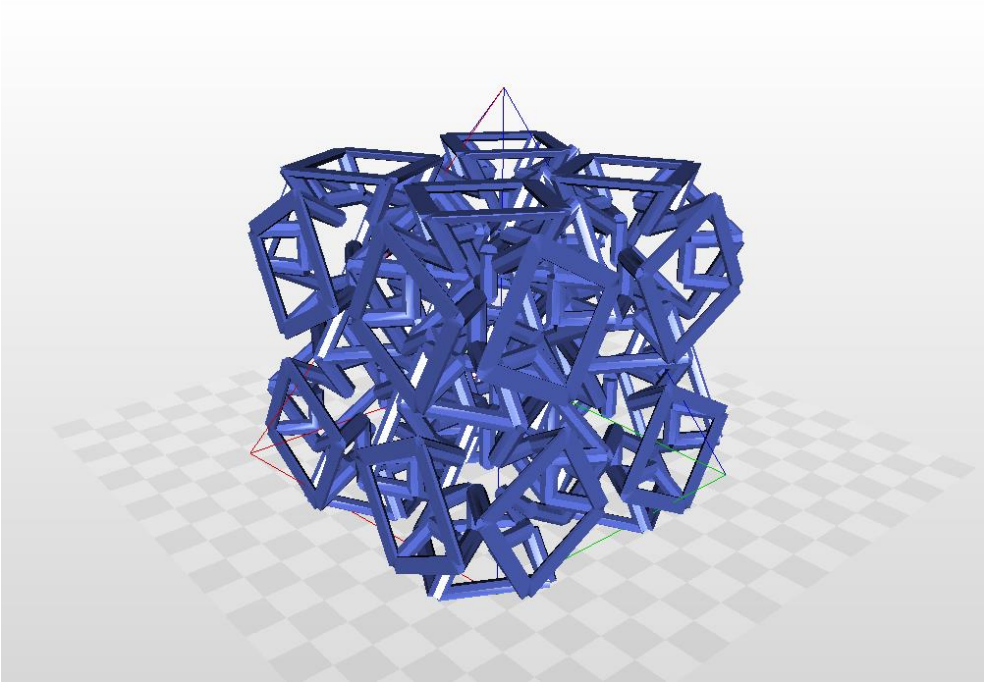
Discussion

Validity

- Sensitivity analysis
- Cutoff error

Further Work

- Experimental comparison
- Vary method
  - Solid elements
  - Other parameters
- Other topics
  - Auxetics



Conclusion

- A Method to evaluate and optimize BTE-scaffolds for mechanical properties and form properties has been introduced
- Fast evaluation with beam elements, but cutoff error needs to be adressed