EUROGRAPHICS 2017
The 38th annual conference of the
EUROPEAN ASSOCIATION FOR COMPUTER GRAPHICS

Topology Optimization for Computational Fabrication

Jun Wu, Niels Aage, Sylvain Lefebvre, Charlie Wang
https://topopt.weblog.tudelft.nl/

TU Delft
DTU Technical University of Denmark
Inria INVENTEURS DU MONDE NUMÉRIQUE

EUROGRAPHICS 2017
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TU Delft

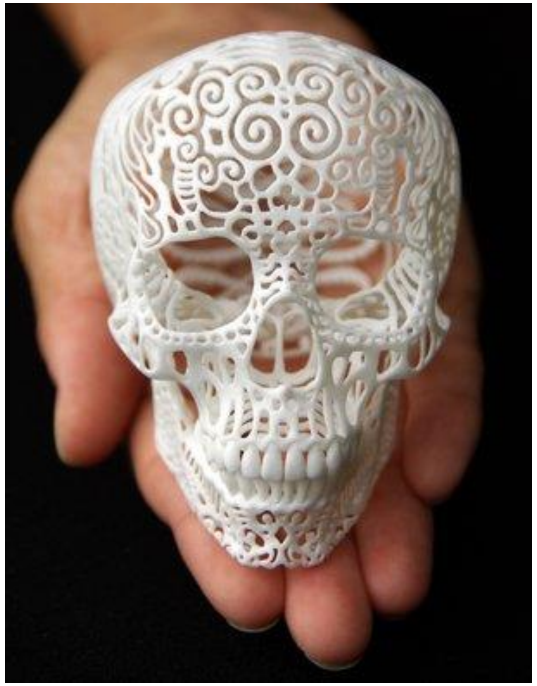
Topology Optimization for Computational Fabrication

Part 3: Topology Optimization with Controllable Geometric Features

Dr. Jun Wu
TU Delft

Additive Manufacturing: Complexity is free

TU Delft & MX3D, 2015



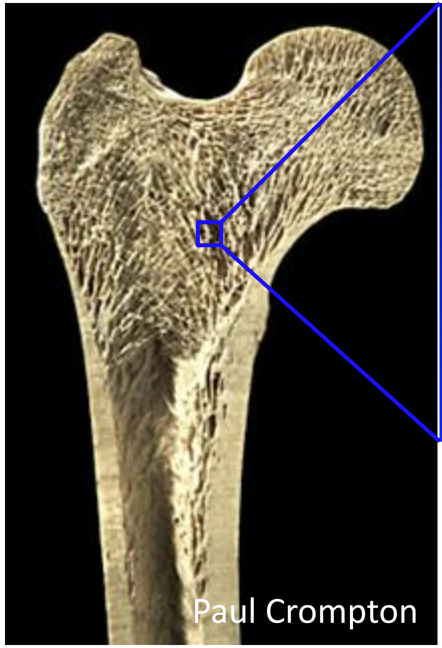
Joshua Harker

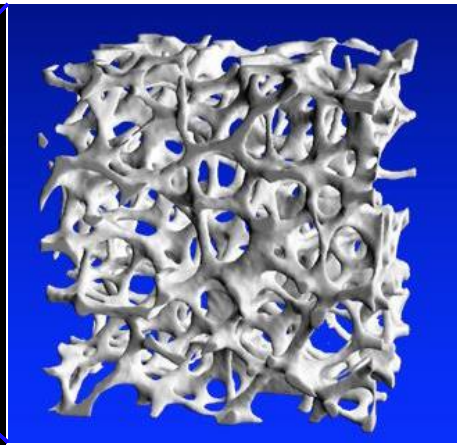
Scott Summit

Complexity is free? … Not really!

- Printer resolution: Minimum geometric feature size
- Layer-upon-layer: Supports for overhang region
- Shell-infill composite

Tiny details



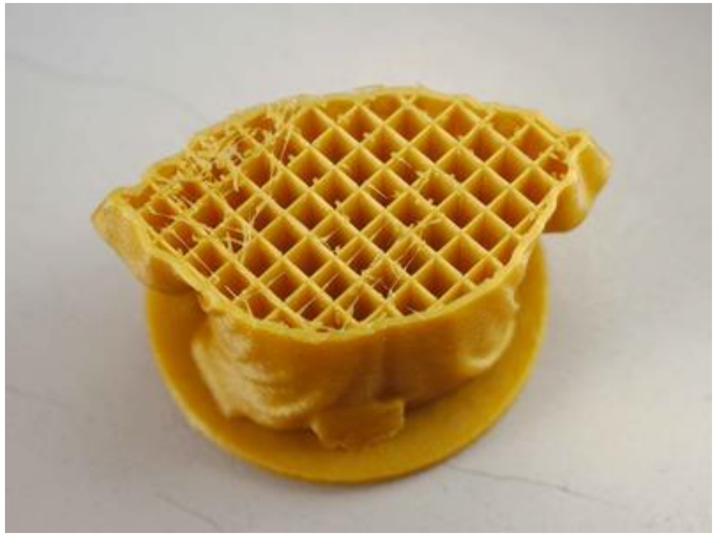


Ralph Müller

Supports

Concept Laser GmbH

Infill

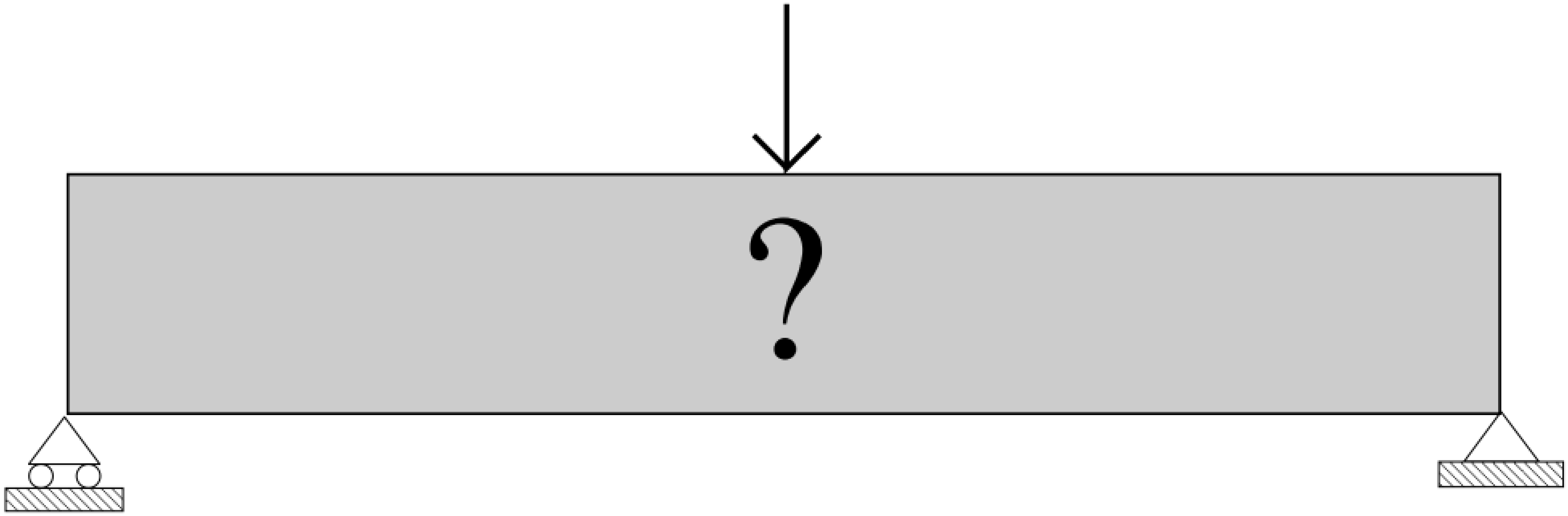


mpi.fs.tum.de

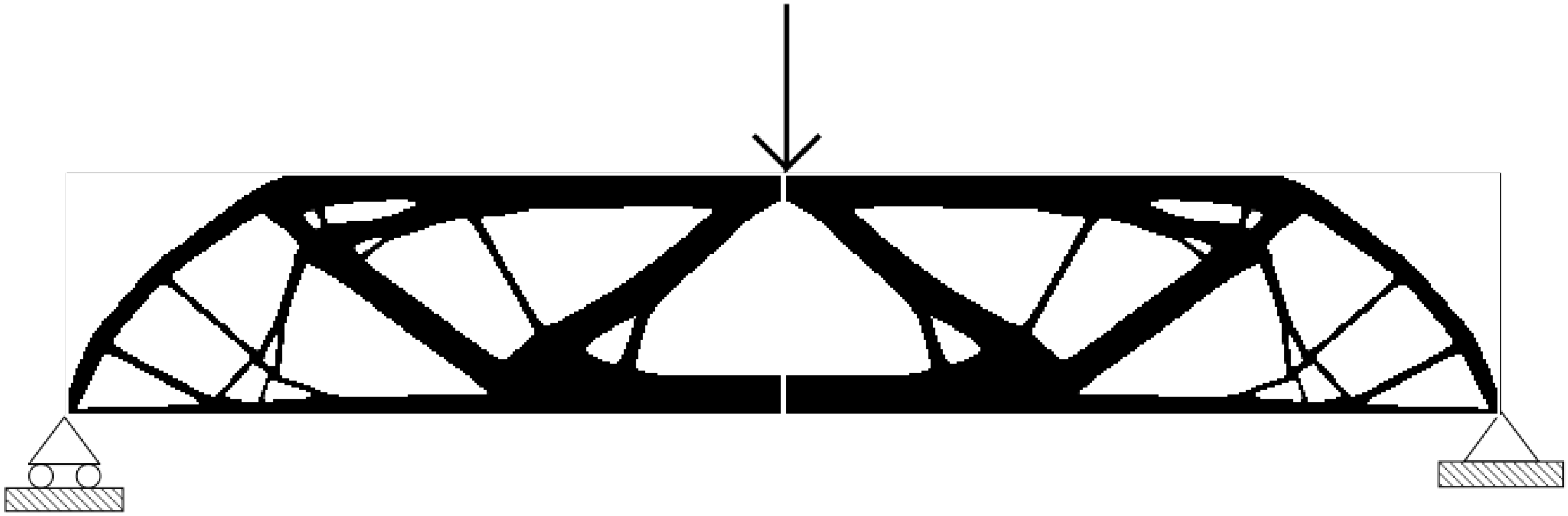
Outline

- Geometric feature control by **density filters**
- Geometric feature control by **alternative parameterizations**

Test case



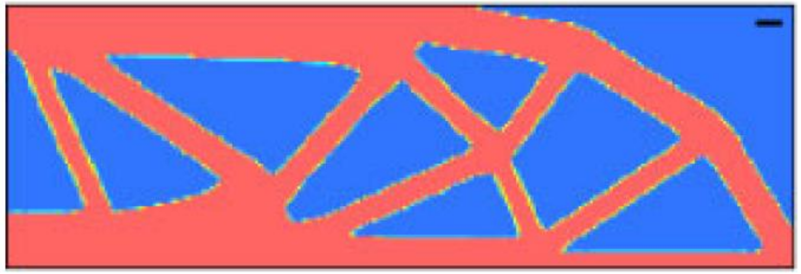
Test case



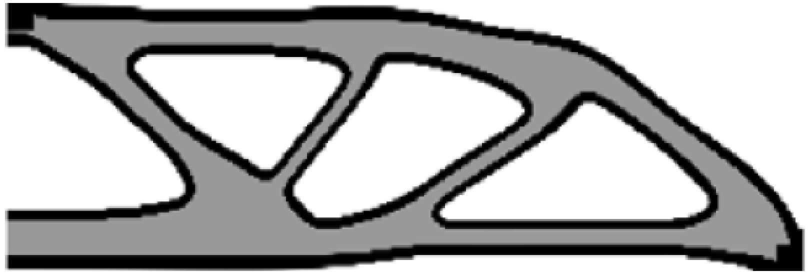
Geometric feature control by density filters (An incomplete list)

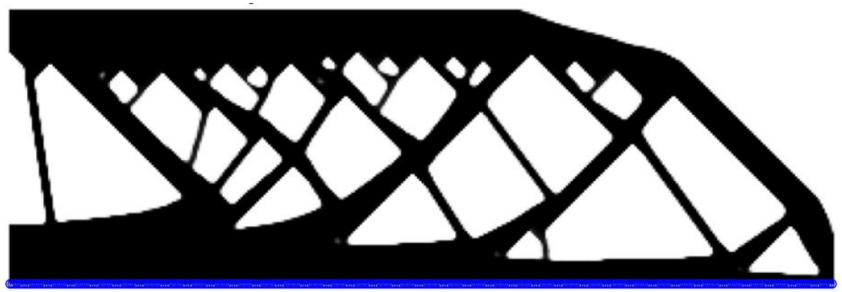
Reference

Minimum feature size, Guest’04

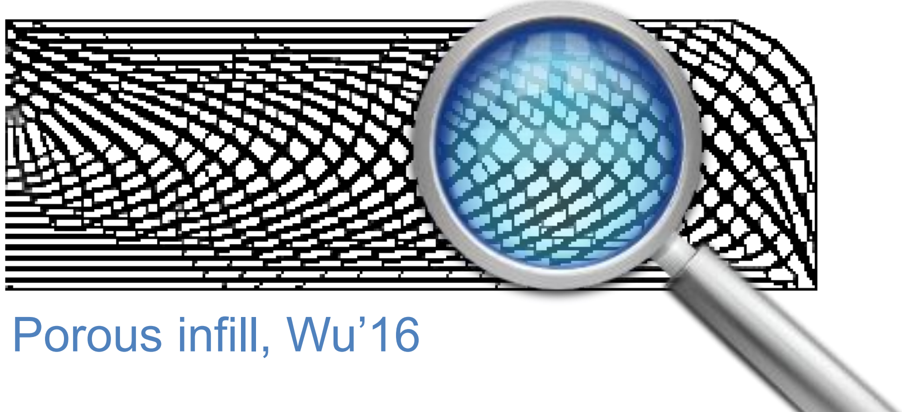


Coating structure, Clausen’15





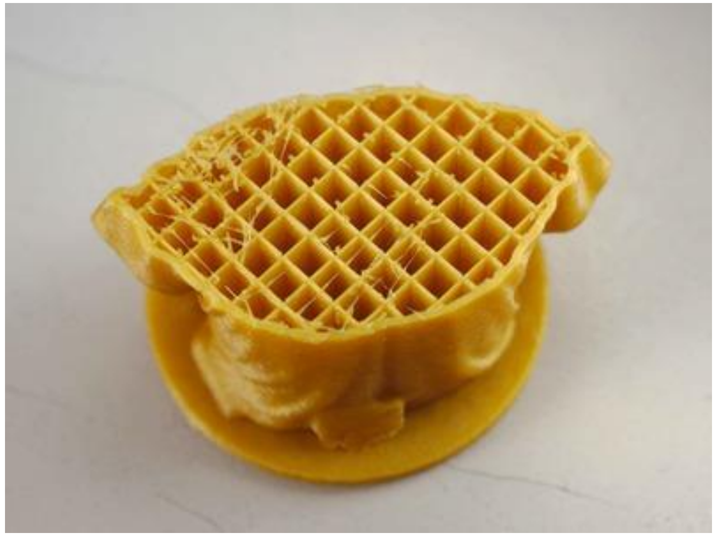
Self-supporting design, Langelaar’16



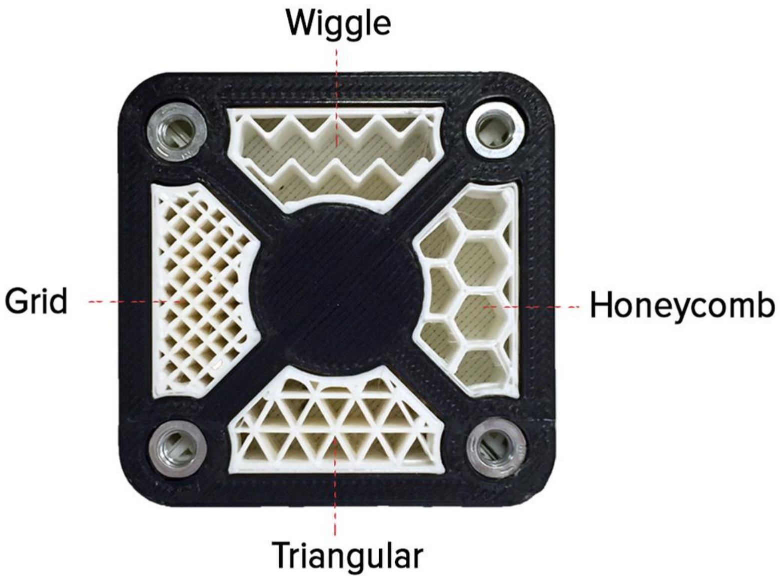
Porous infill, Wu’16

Infill in 3D Printing

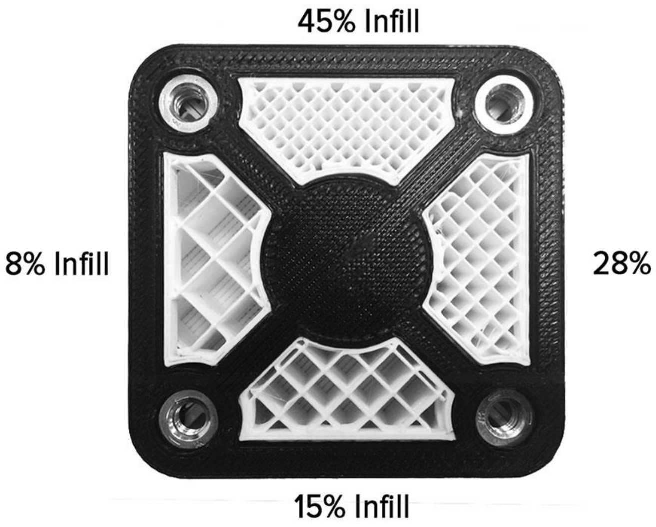
- A user-selected regular pattern, with a volume percentage
- A rough balance between
  - Physical properties (mass, strength), and
  - Cost (material usage, print time)



Infill



Different infill patterns

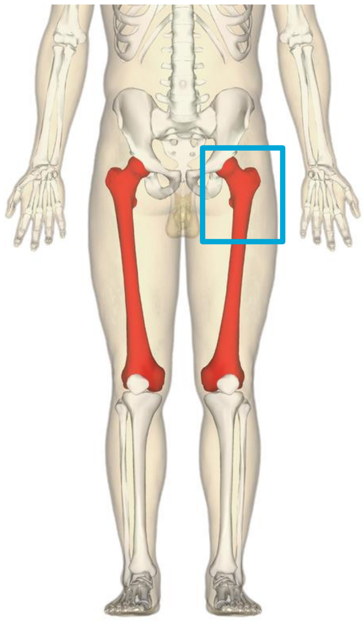


Different infill percentages

https://3dplatform.com/3d-printing-tips-infill-percentage-and-pattern-explained/

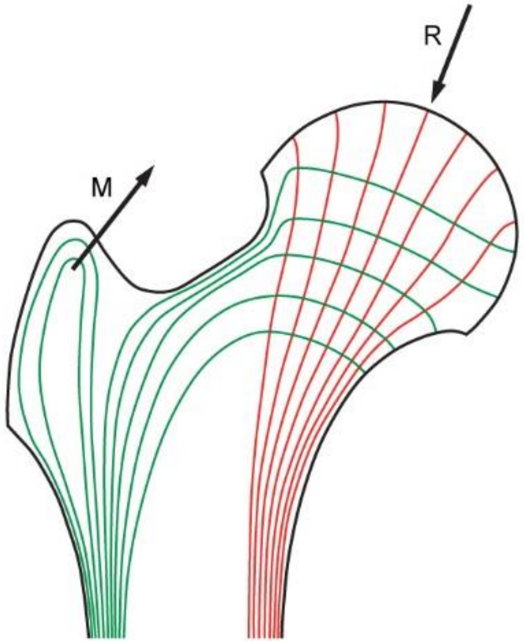
Infill in Nature

- Trabecular bone
  - Porous structures, oriented with the principle stress direction
  - Resulted from a natural optimization process
  - Light-weight-high-resistant



wikipedia.org

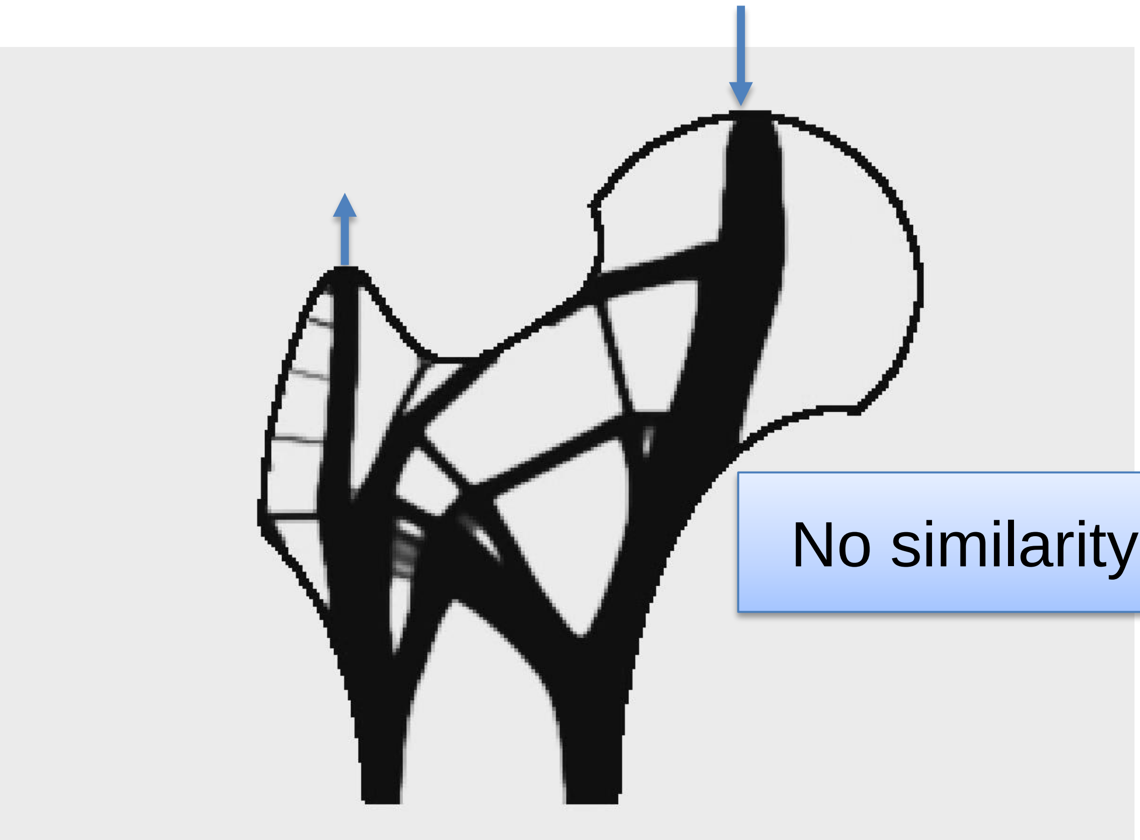
Cross-section of
a human femur



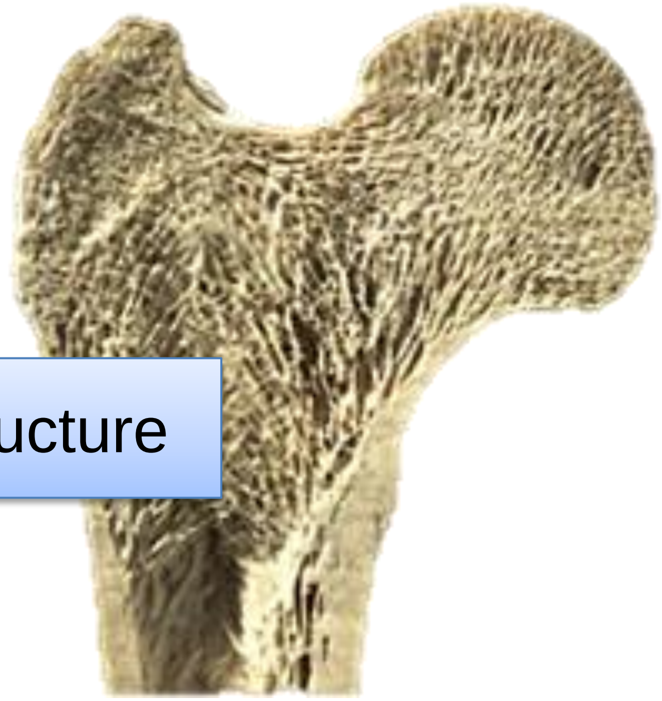
Principle stress directions

Optimize bone-like structures as infill for AM?

Topology Optimization Applied to Design Infill



Topology optimization

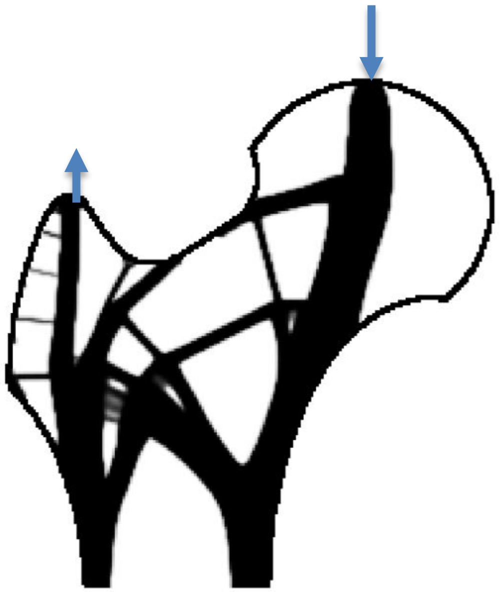


Infill in the bone

No similarity in structure

Topology Optimization Applied to Design Infill

- Materials accumulate to “important” regions
- The total volume $\sum_i \rho_i v_i \leq V_0$ does not restrict local material distribution



Infill by standard topology optimization

Infill in the bone

Approaching Bone-like Structures: The Idea

- Impose **local constraints** to avoid fully solid regions

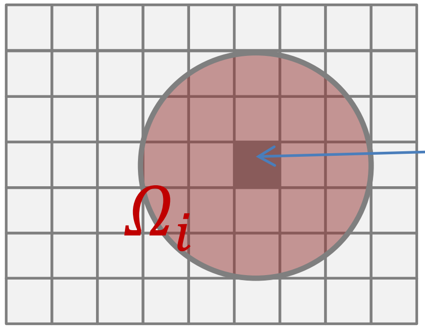
Min: $c = \frac{1}{2} U^T K U$

s.t. : $KU = F$

$\rho_i \in [0,1], \forall i$

~~$\sum_i \rho_i \leq V_0$~~

$\hat{\rho}_i \leq \alpha, \forall i$



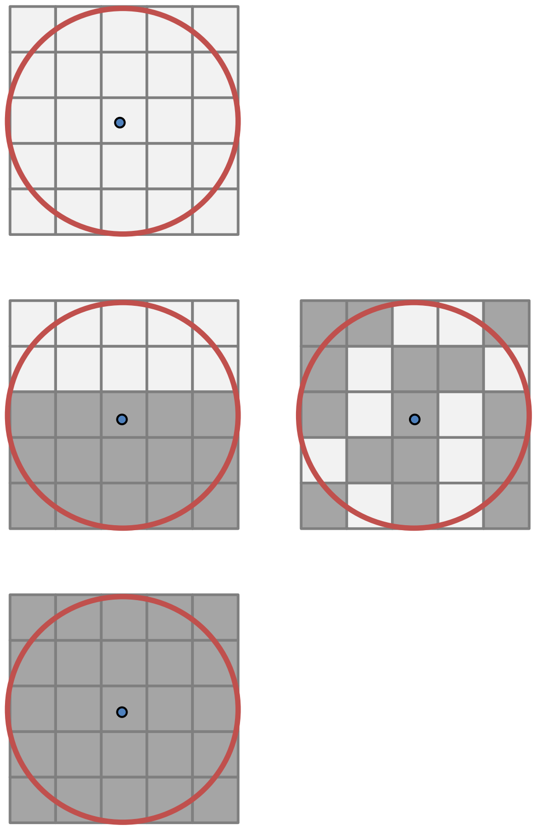
$$\hat{\rho}_i = \frac{\sum_{j \in \Omega_i} \rho_j}{\sum_{j \in \Omega_i} 1}$$

Local-volume measure

$\hat{\rho}_i = 0.0$

$\hat{\rho}_i = 0.6$

$\hat{\rho}_i = 1.0$



Constraints Aggregation (Reduce the Number of Constraints)

$\hat{\rho}_i \leq \alpha, \forall i$ ⟺ $\max_{i=1,\ldots,n} |\hat{\rho}_i| \leq \alpha$ ⟺ $\lim_{p\to\infty} \|\rho\|_p = \left(\sum_i (\hat{\rho}_i)^p\right)^{\frac{1}{p}} \leq \alpha$

Too many constraints!

A single constraint
But non-differentiable

A single constraint
and differentiable
Approximated with p =16

Optimization Process: The same as in the standard topopt

- Impose **local constraints** to avoid fully solid regions

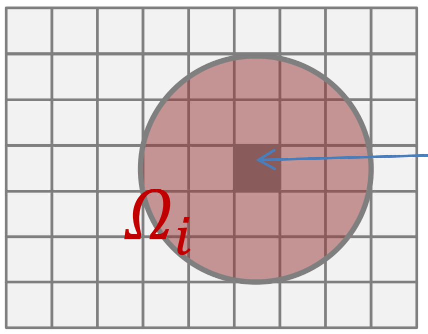
Min: $c = \frac{1}{2} U^T K U$

s.t. : $KU = F$

$\rho_i \in [0,1], \forall i$

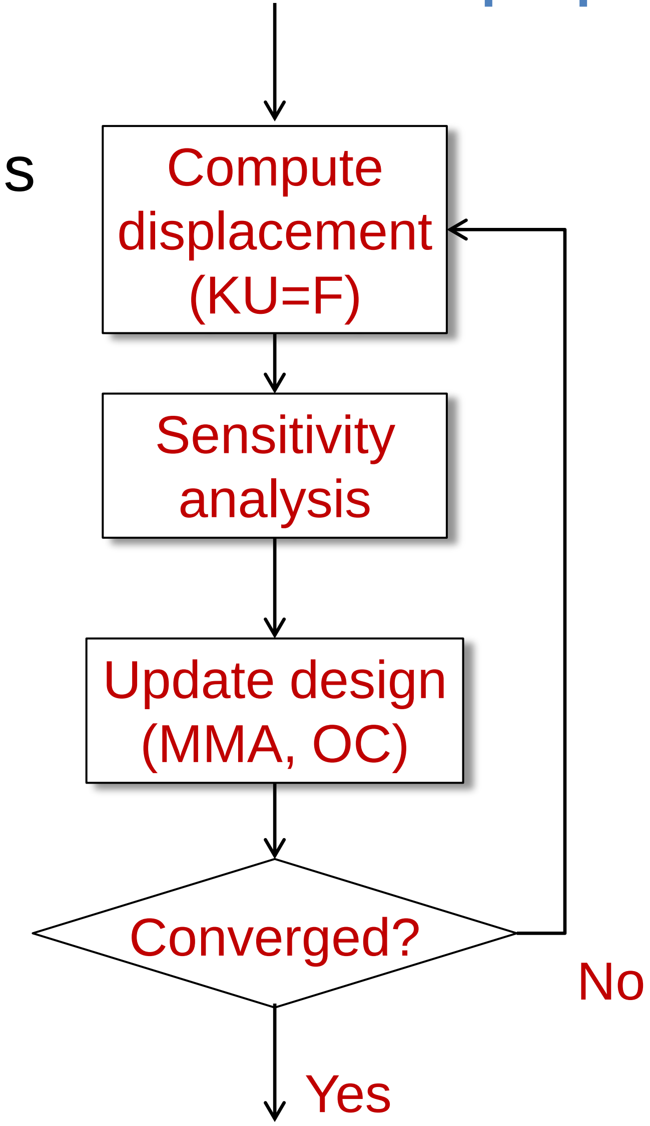
~~$\sum_i \rho_i \leq V_0$~~

$\hat{\rho}_i \leq \alpha, \forall i$



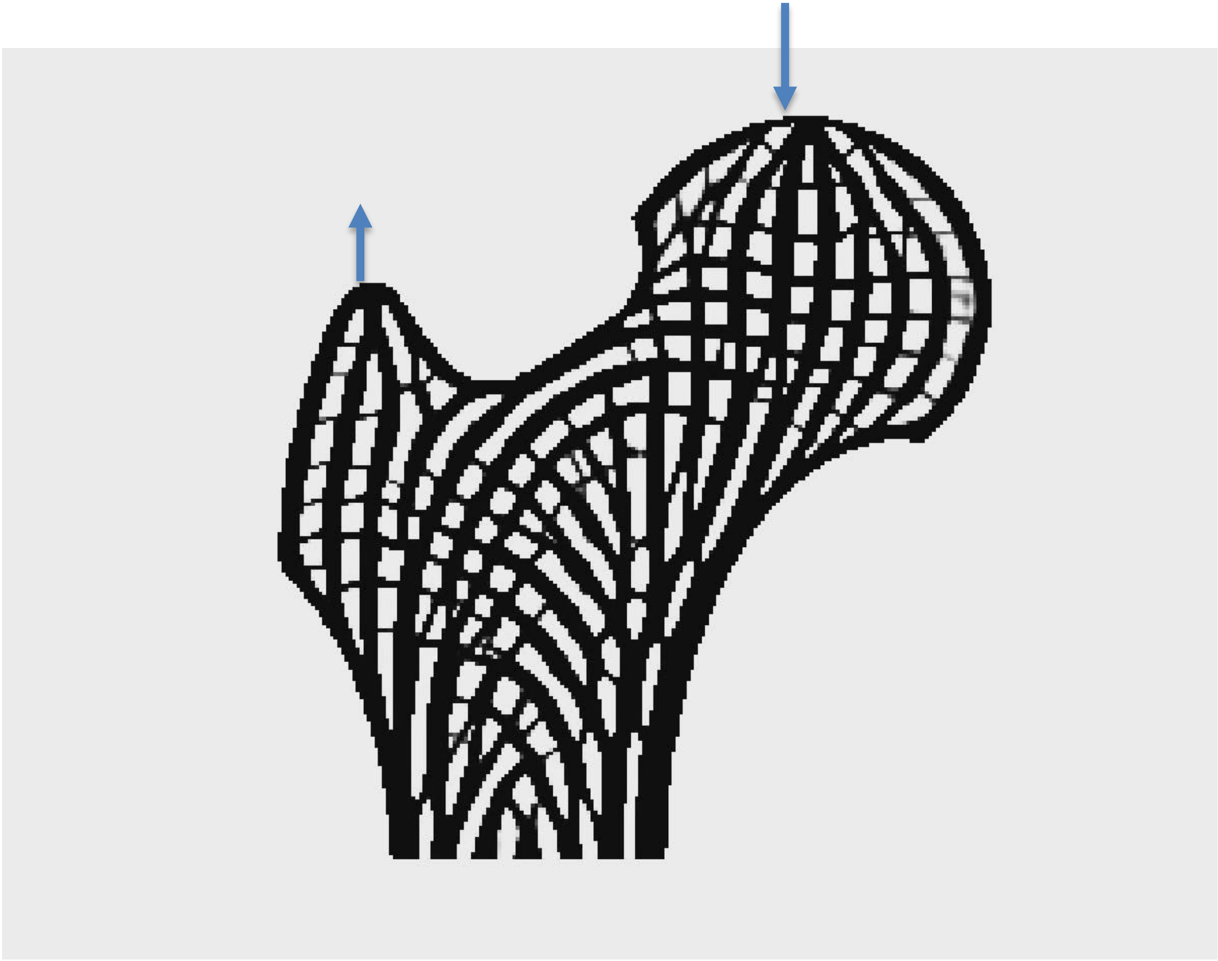
$$\hat{\rho}_i = \frac{\sum_{j \in \Omega_i} \rho_j}{\sum_{j \in \Omega_i} 1}$$

Local-volume measure

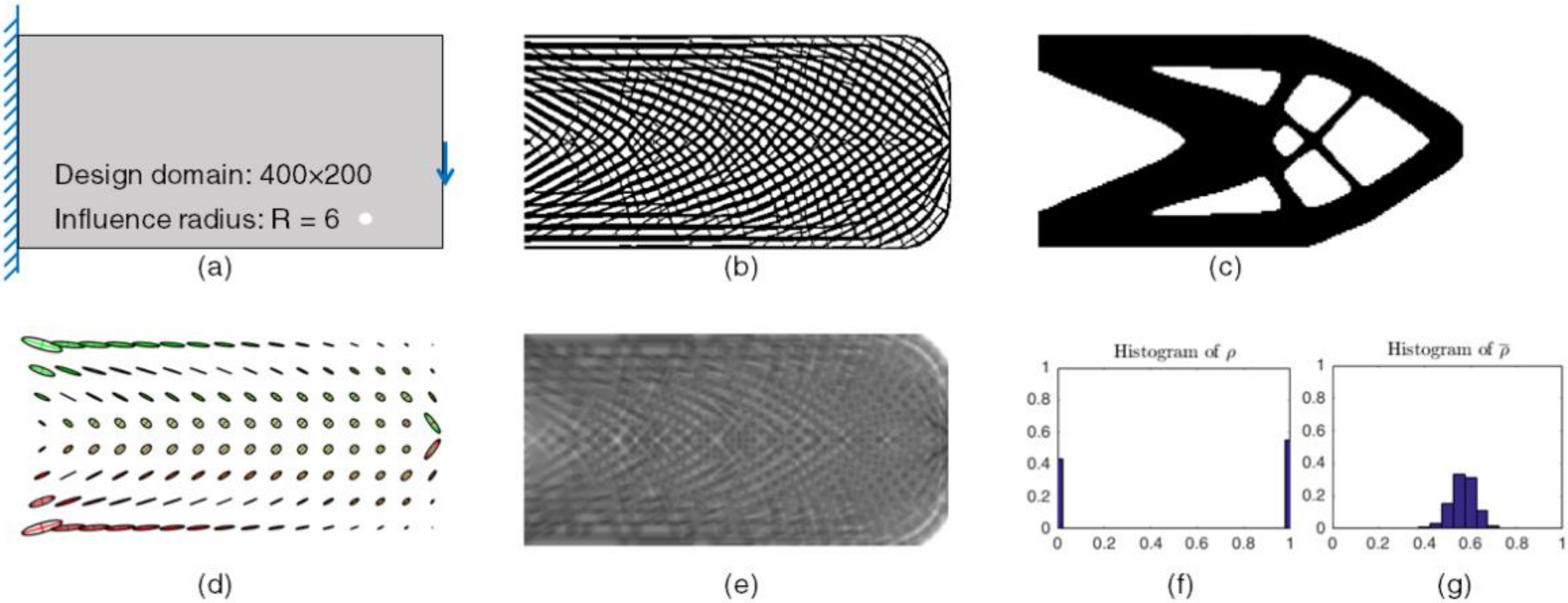


Bone-like Infill in 2D

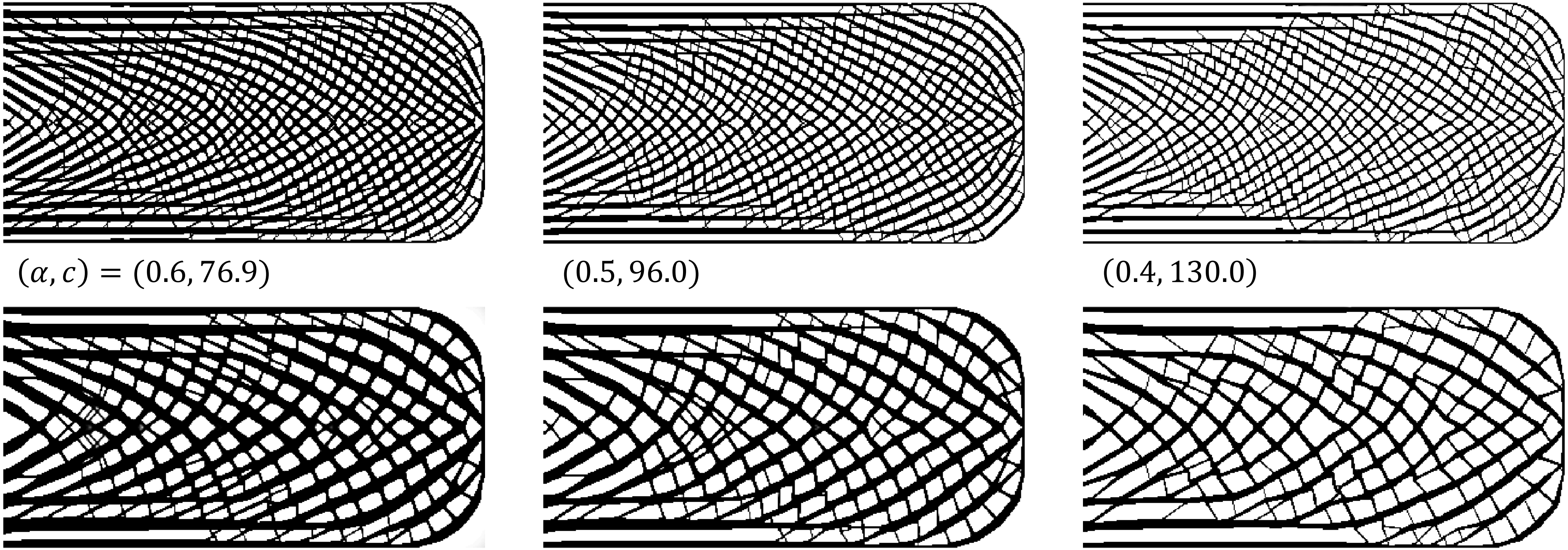
Cross-section of a human femur



A Test Example



Effects of Filter Radius and Local Volume Upper Bound



R=6

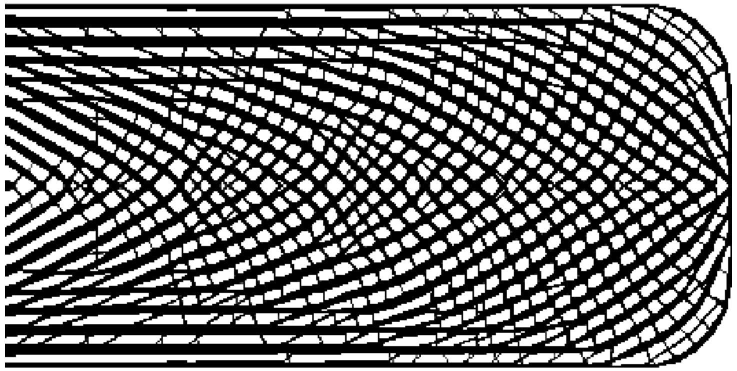
$(\alpha, c) = (0.6, 76.9)$ $(0.5, 96.0)$ $(0.4, 130.0)$

R=12

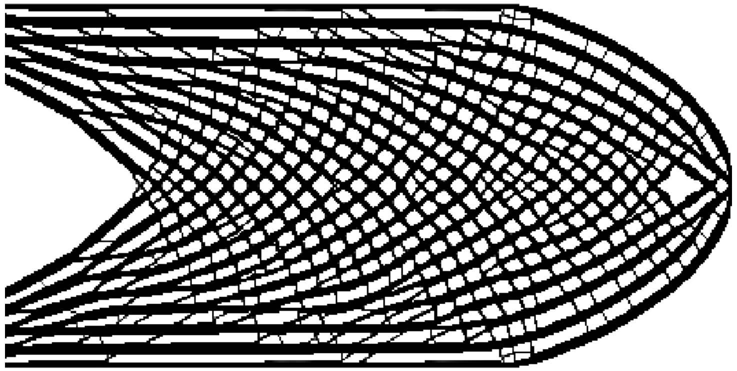
$(0.6, 73.9)$ $(0.5, 91.2)$ $(0.4, 119.8)$

Local and Global Volume Constraints

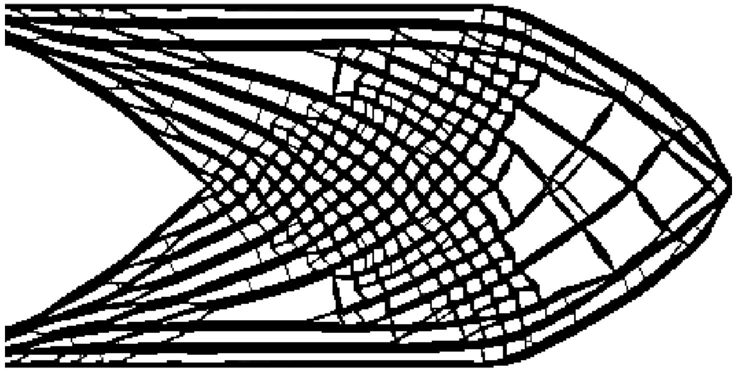
R=6



$(\alpha, \alpha_{total}, c) = (0.6, 0.56, 76.9)$

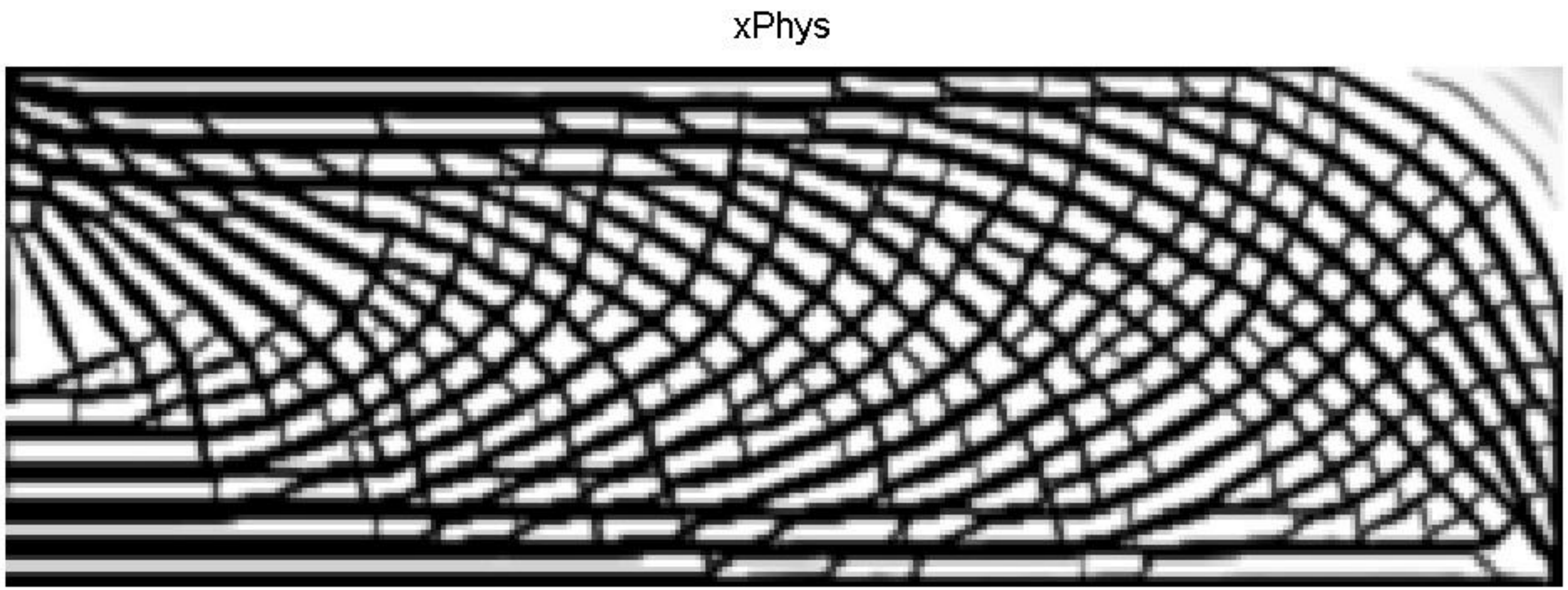


$(0.6, 0.50, 79.1)$

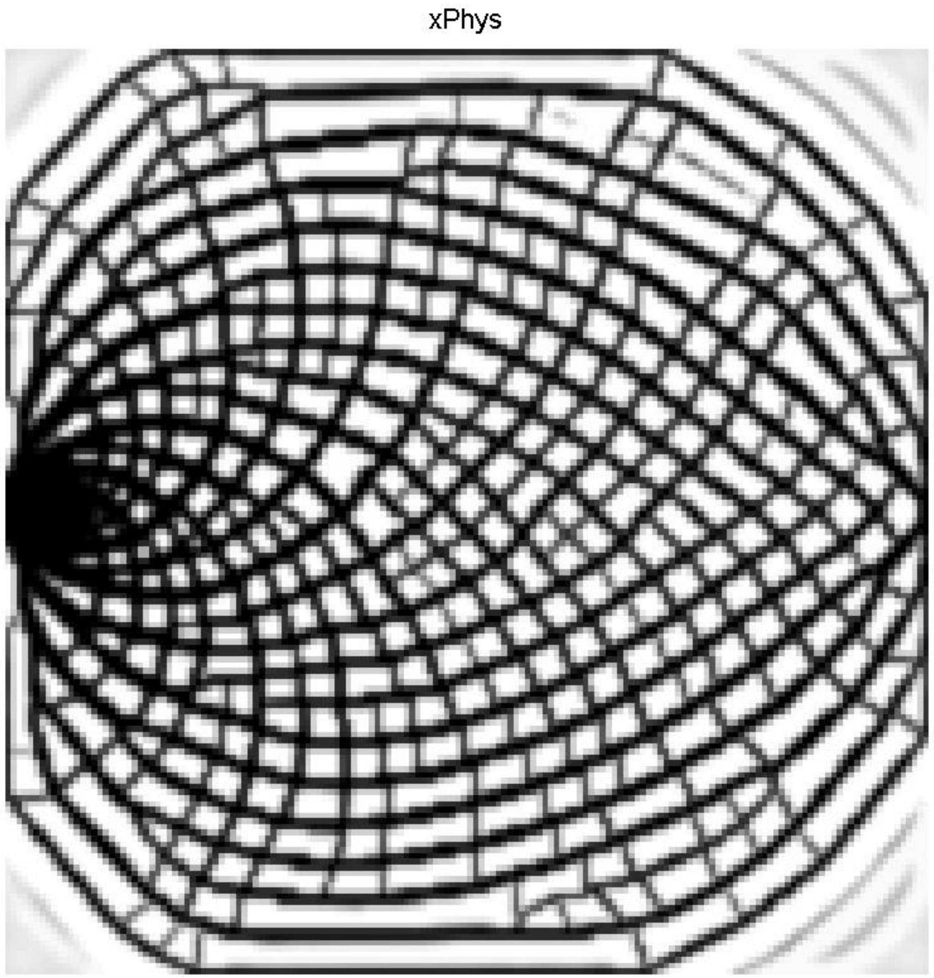


$(0.6, 0.40, 94.0)$

Result: 2D Animation



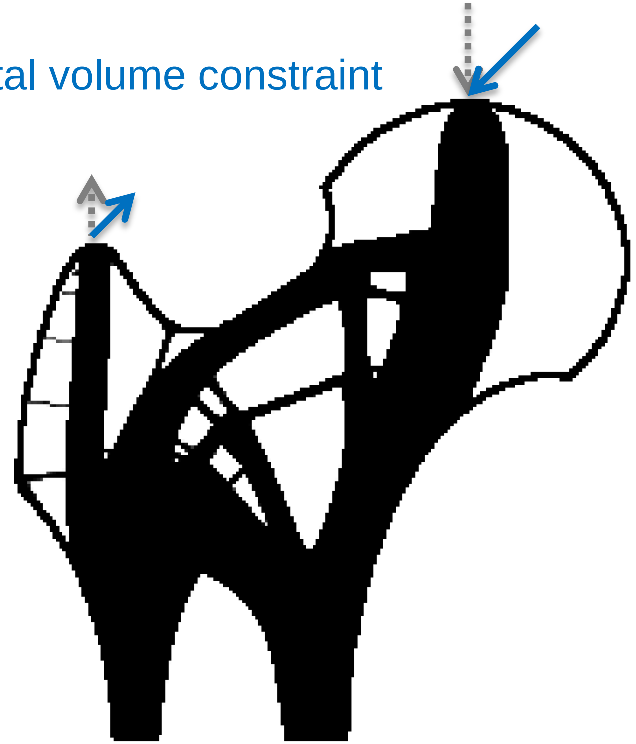
Result: 2D Animation



Robustness wrt. Force Variations

- Bone-like structures are significantly stiffer (126%) in case of force variations

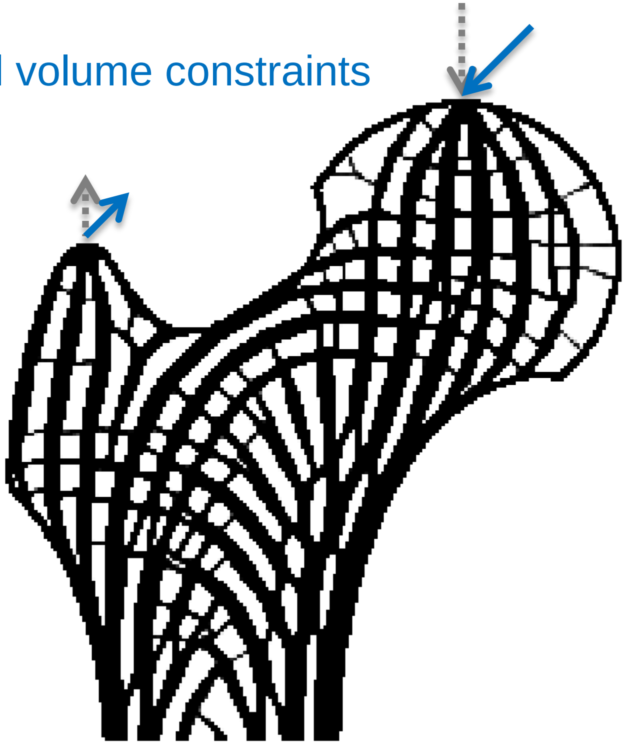
Total volume constraint



c = 30.54

c’= 45.83

Local volume constraints



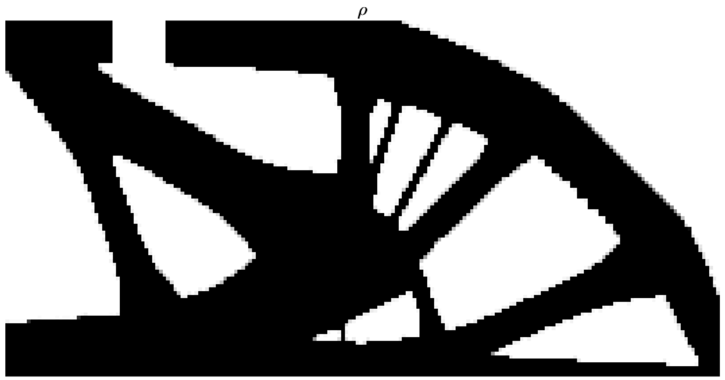
c = 36.72

c’ =36.23

Robustness wrt. Material Deficiency

- Bone-like structures are significantly stiffer (180%) in case of material deficiency

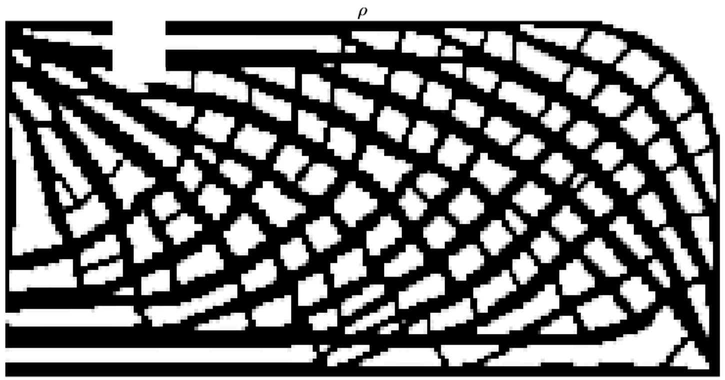
Total volume constraint



c = 76.83

c' =242.77

Local volume constraints

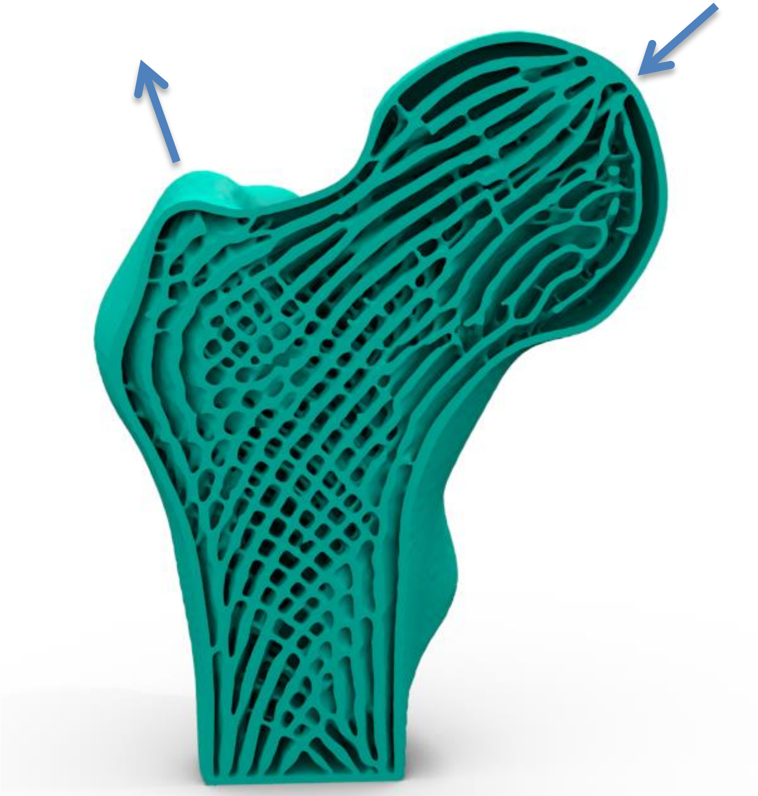


c = 93.48

c'= 134.84

Bone-like Infill in 3D

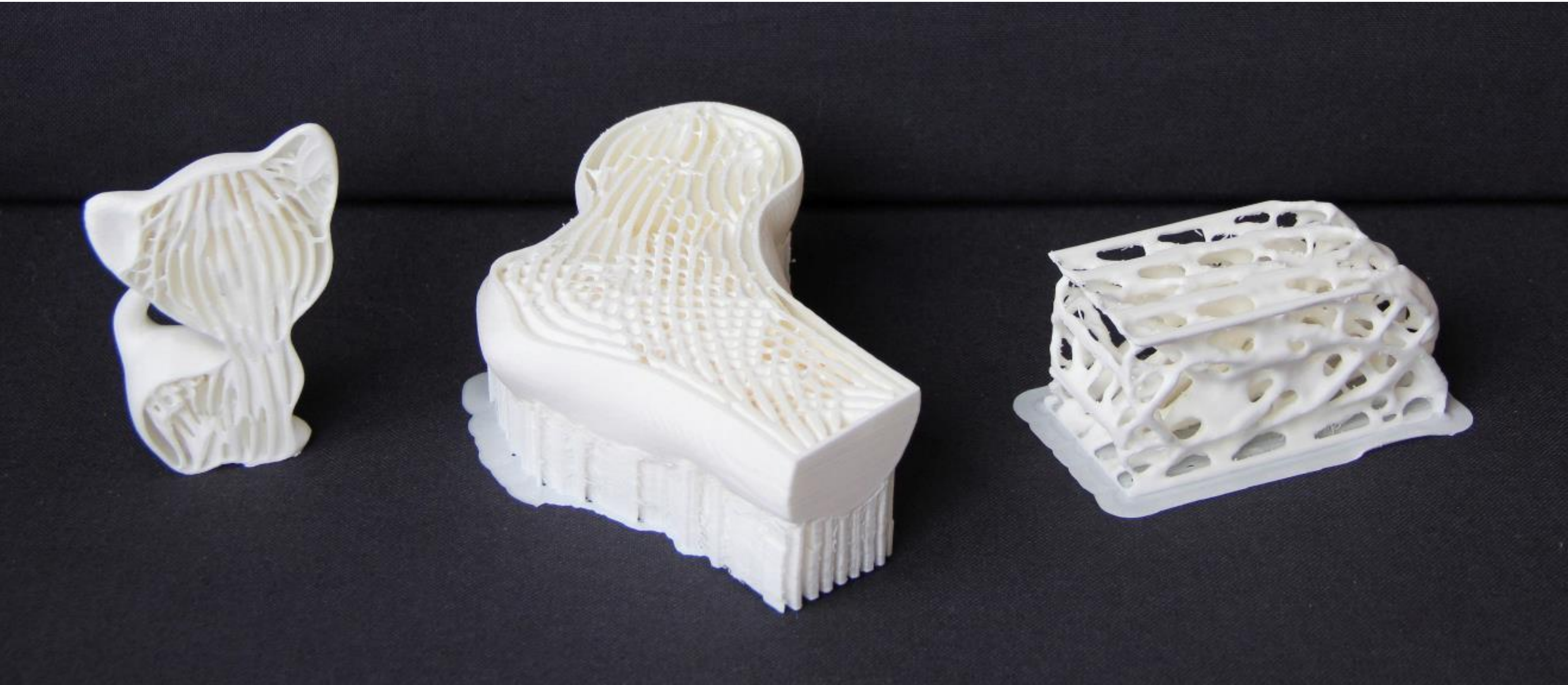
Infill in the bone



Optimized bone-like infill

Wu et al., TVCG'2017

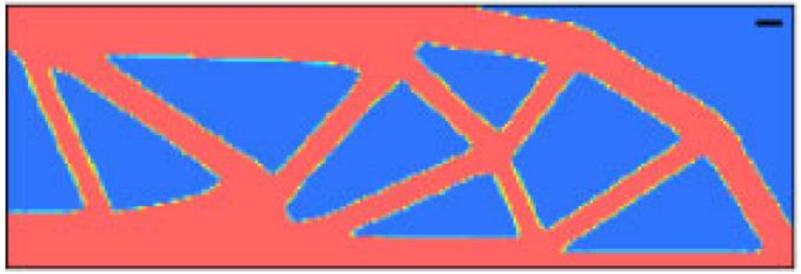
FDM Prints



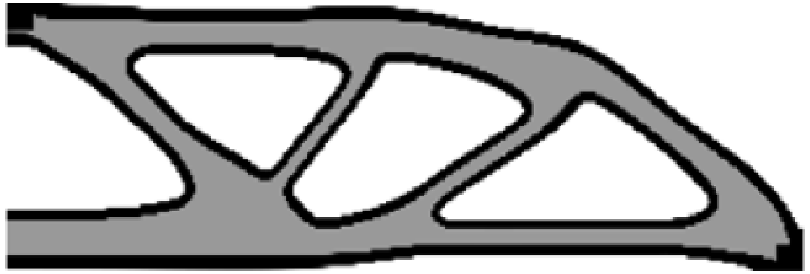
Geometric feature control by density filters
(An incomplete list)

Reference

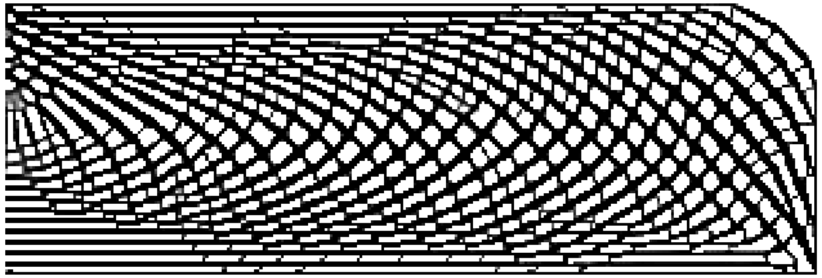
Minimum feature size, Guest'04



Coating structure, Clausen'15

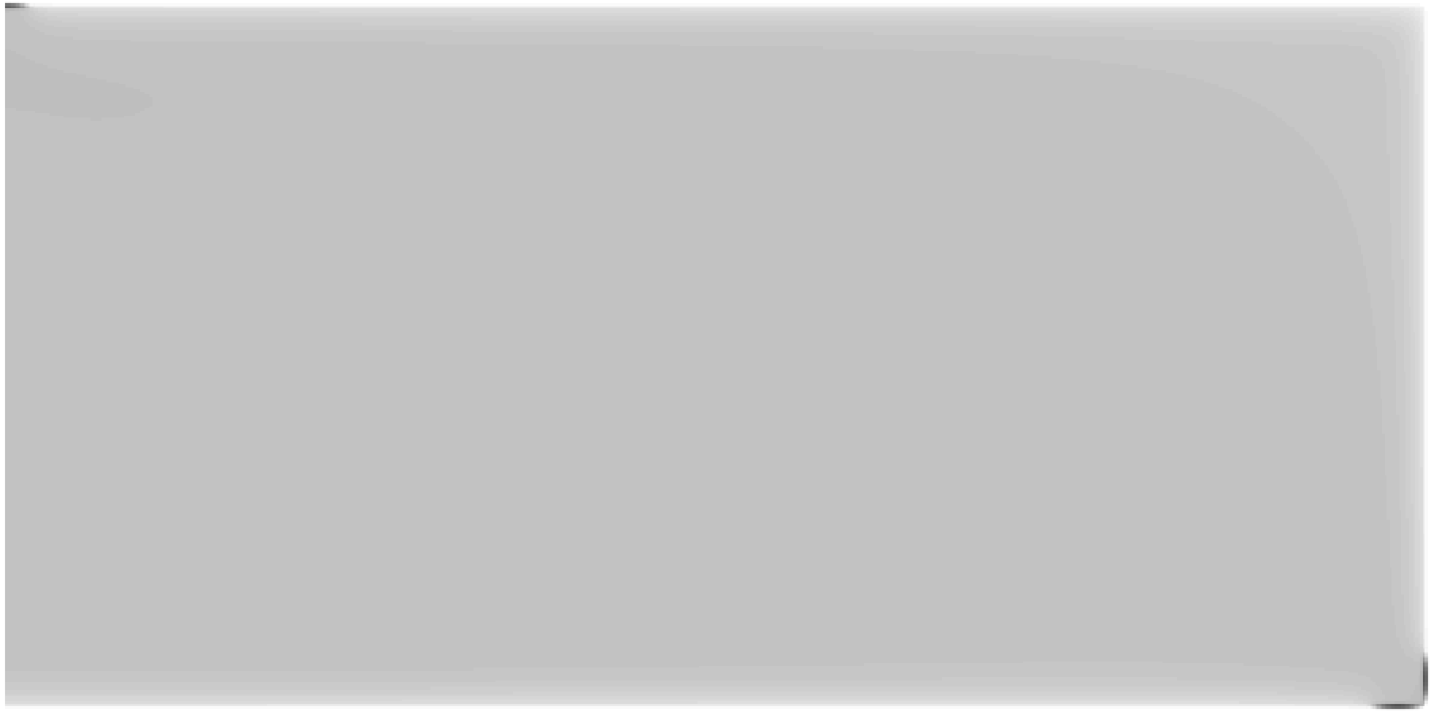


Self-supporting design, Langelaar'16



Porous infill, Wu'16

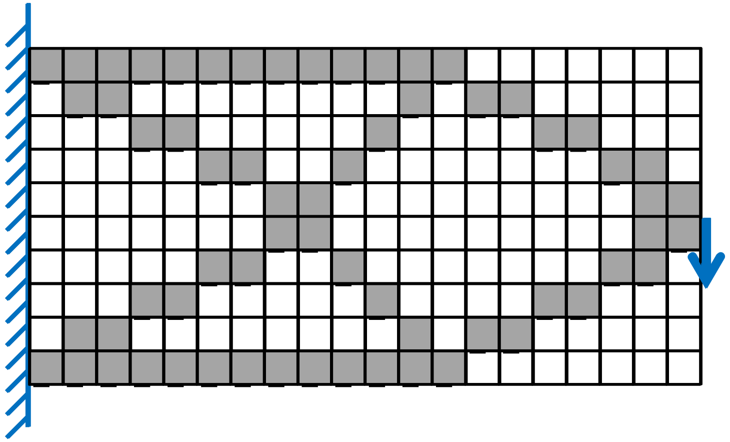
Concurrent Shell-Infill Optimization



Outline

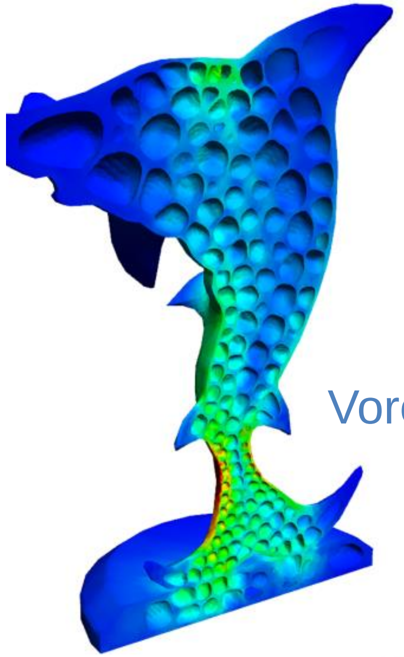
- Geometric feature control by **density filters**
- Geometric feature control by **alternative parameterizations**

Geometric feature control by alternative parameterizations (An incomplete list)

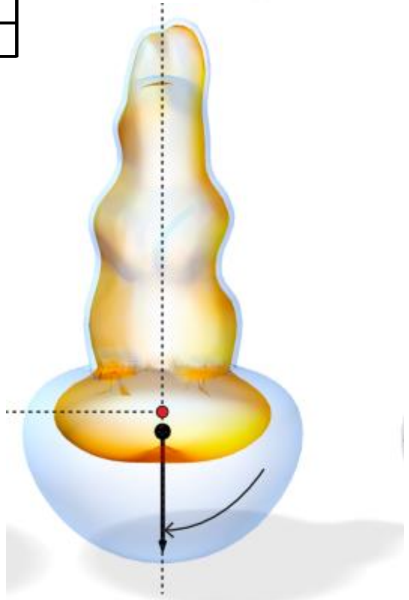


Reference: Voxel discretization

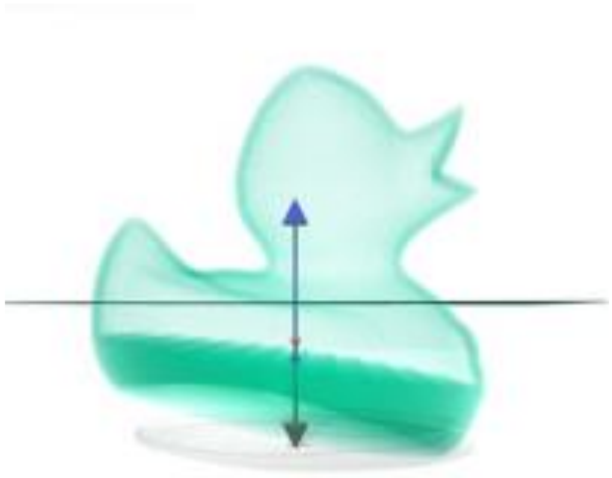
Skin-frame, Wang’13



Voronoi cells, Lu’14



Offset surfaces, Musialski’15

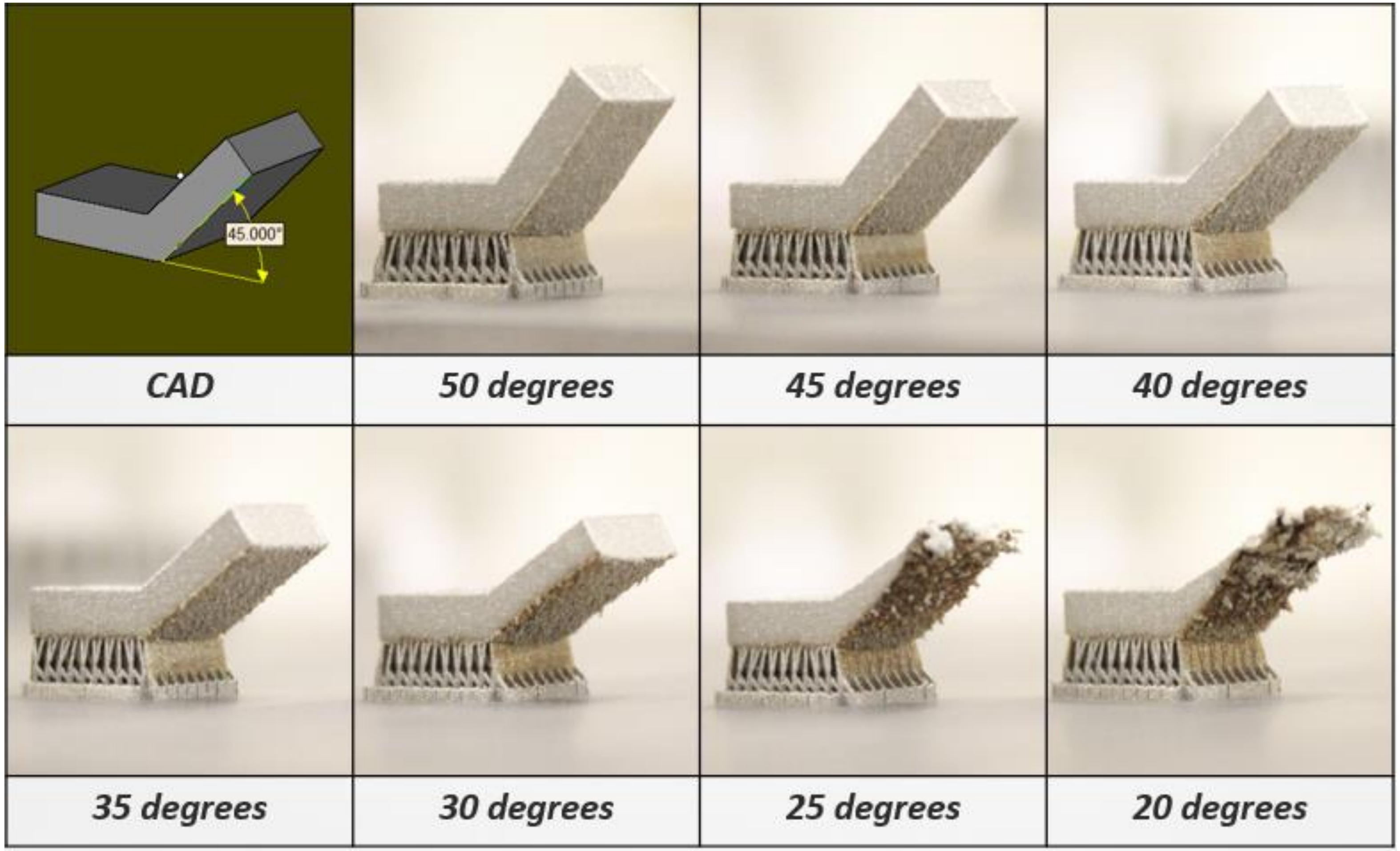


Ray representation, Wu’16

Adaptive rhombic, W[illegible]6

Overhang in Additive Manufacturing

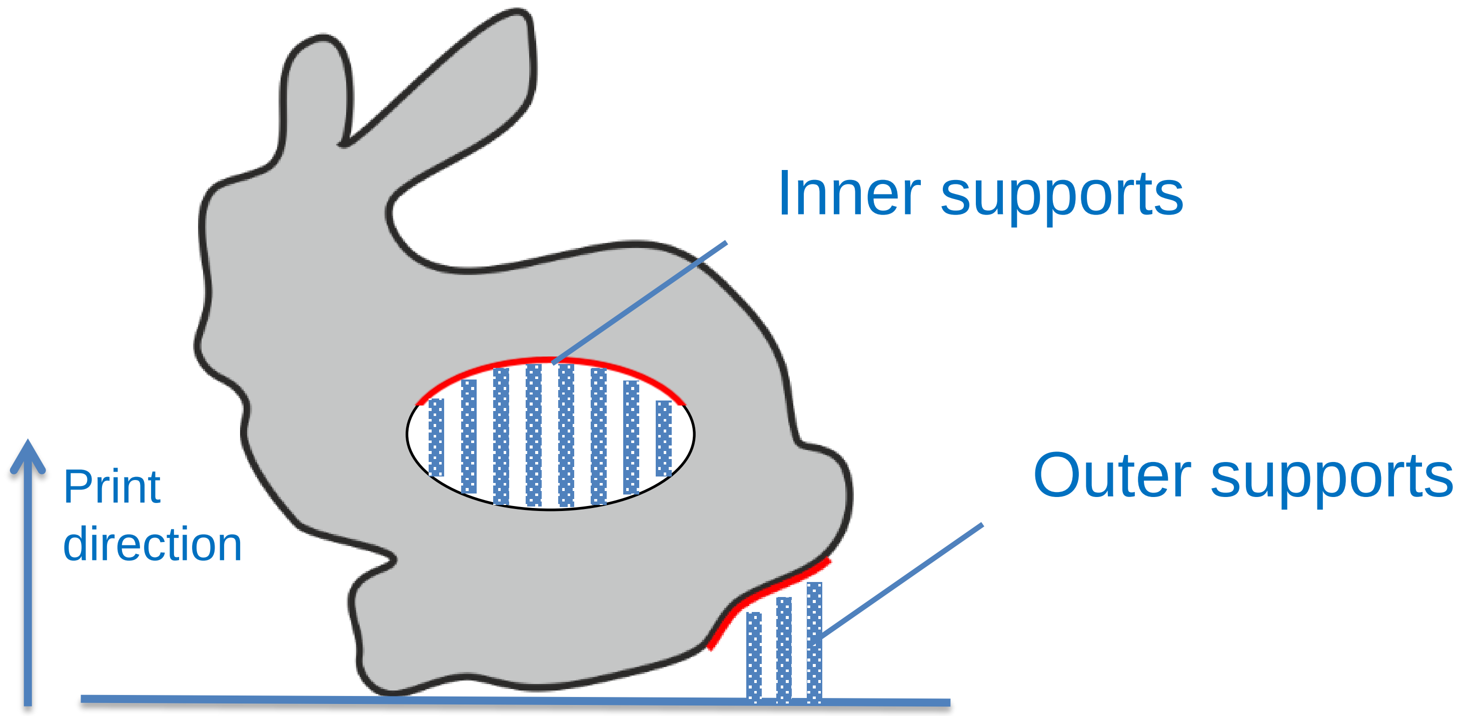
- Support structures are needed beneath overhang surfaces



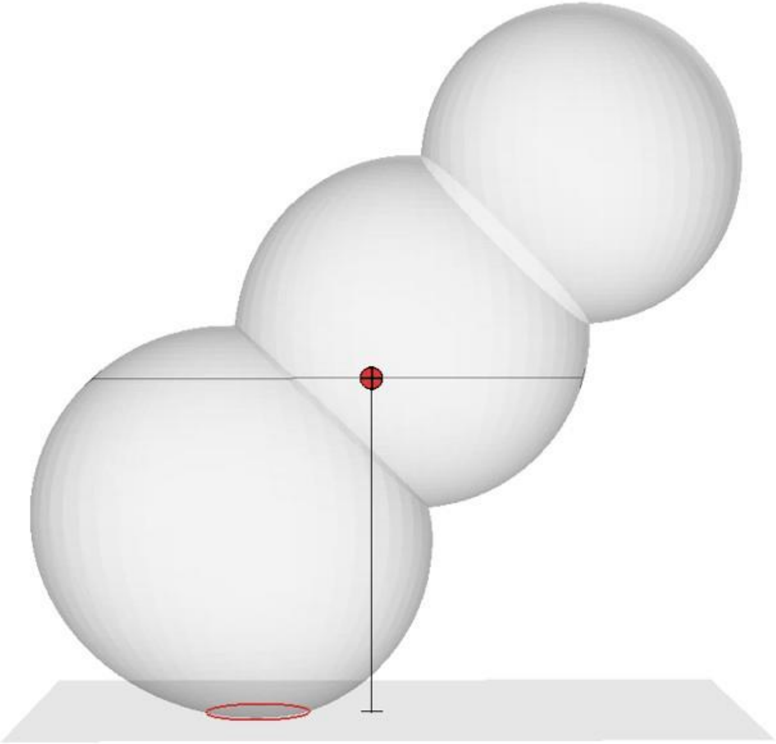
https://www.protolabs.com/blog/tag/direct-metal-laser-sintering/

Support Structures in Cavities

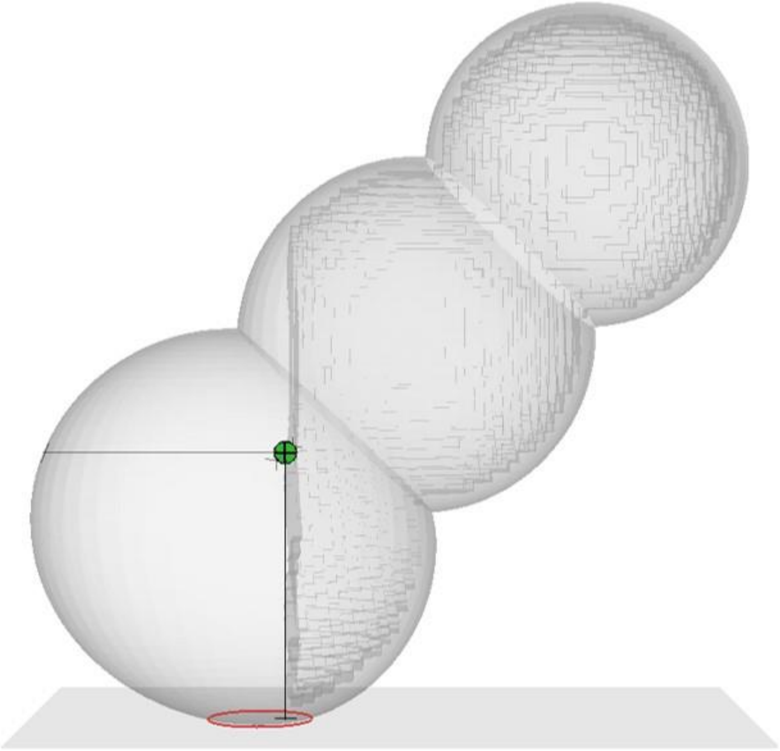
- Post-processing of inner supports is problematic



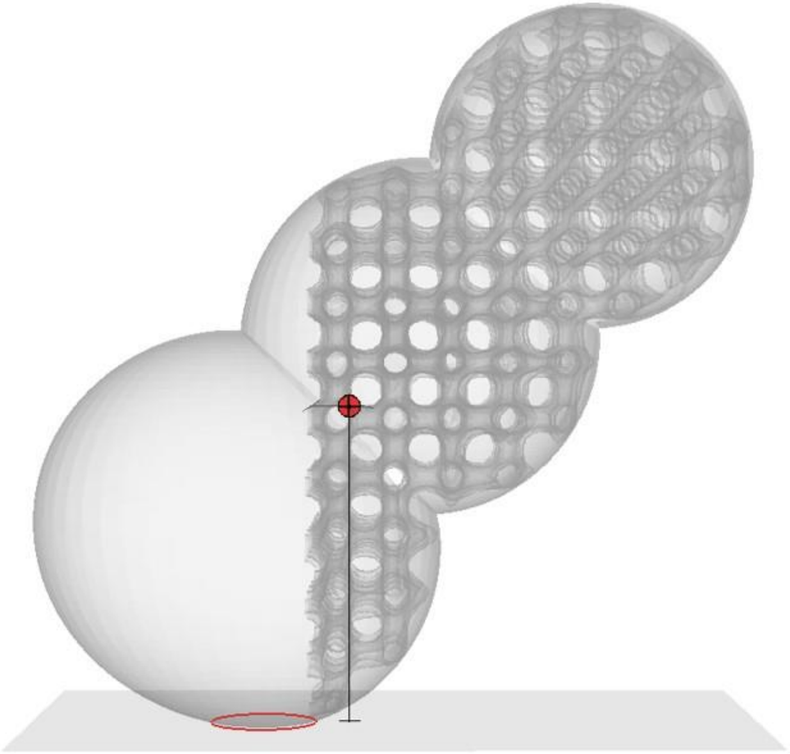
Infill & Optimization Shall Integrate



Solid,
Unbalanced



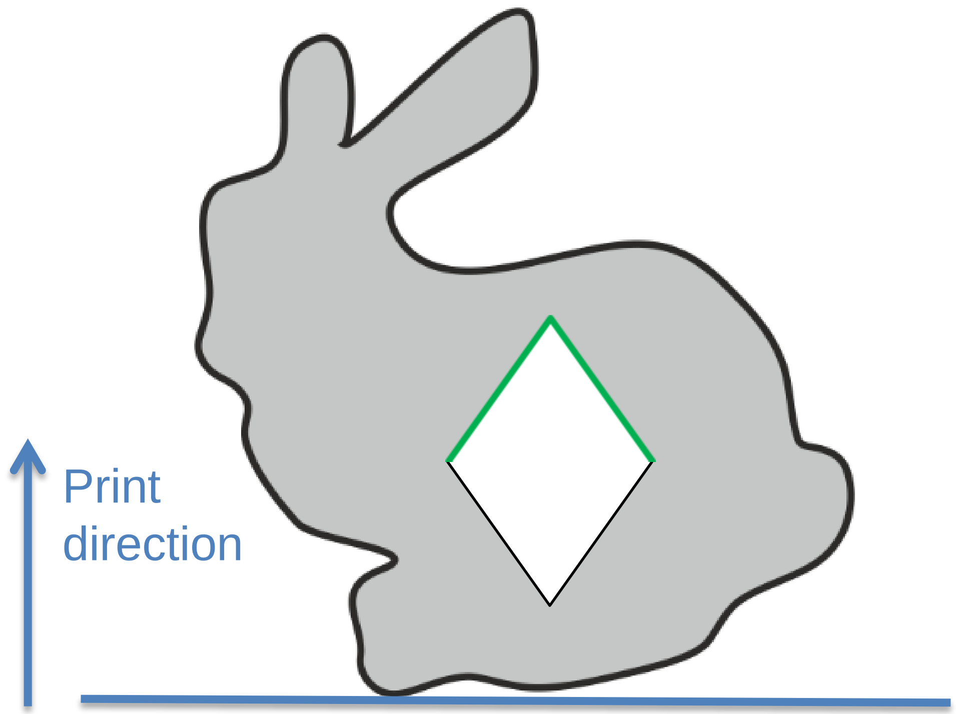
Optimized,
Balanced



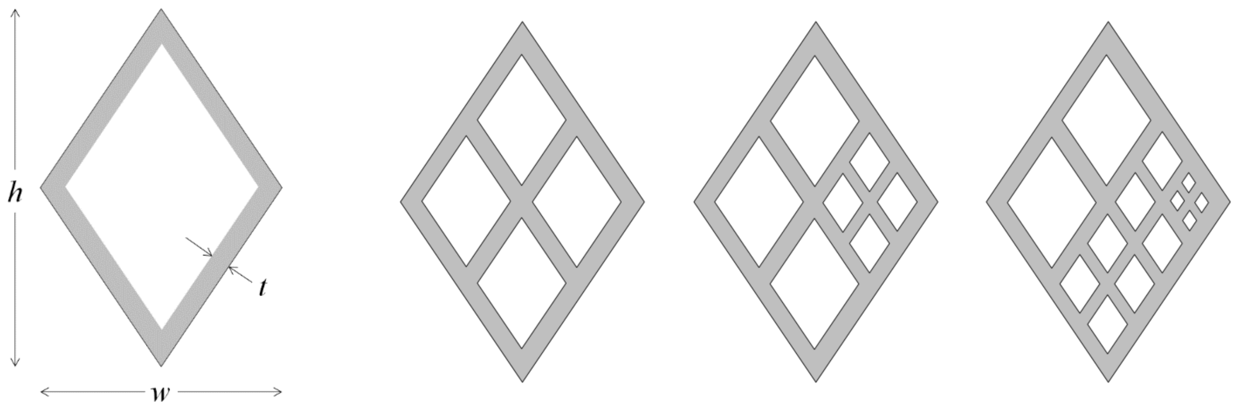
With infill,
Unbalanced

The Idea

- Rhombic cell: to ensure self-supporting
- Adaptive subdivision: as design variable in optimization

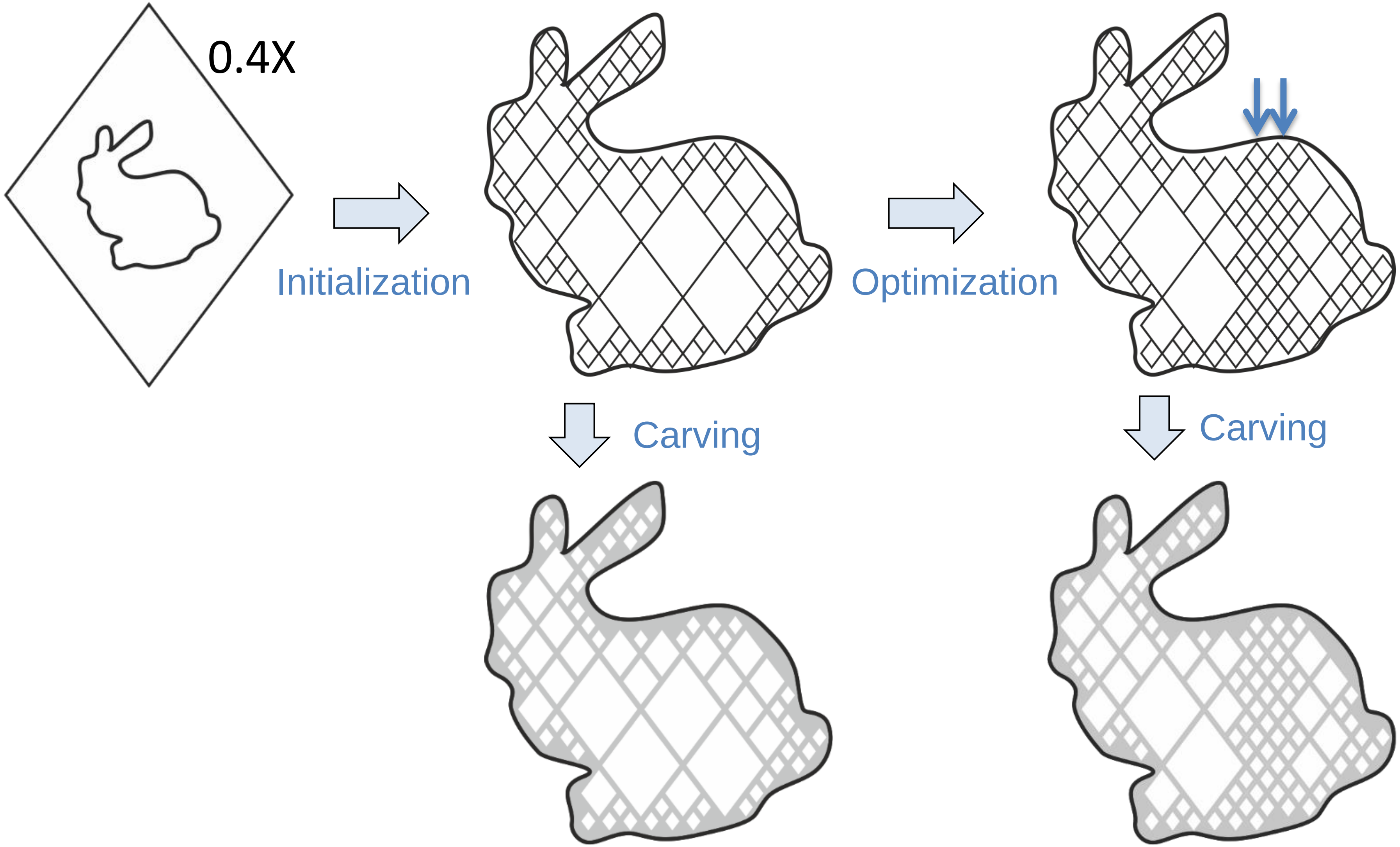


Rhombic cell



Adaptive subdivision

Self-Supporting Rhombic Infill: Workflow



Self-Supporting Rhombic Infill: Subdivision Criteria

- Min: $c = \frac{1}{2} U^T K U$ Subject to: $KU = F; V = \sum_i \rho_i \leq V_0$

Voxel-wise topology optimization

Per-voxel density as variable

$$\rho_i \in \{0.0, 1.0\}, \forall i$$

Per-voxel sensitivity: $G_i = -\frac{\partial c / \partial \rho_i}{\partial V / \partial \rho_i}$

Subdivision-based topology optimization

Per-subdivision as variable

$$\beta_c \in \{0, 1\}, \forall c$$

Per-voxel density assigned by subdivision

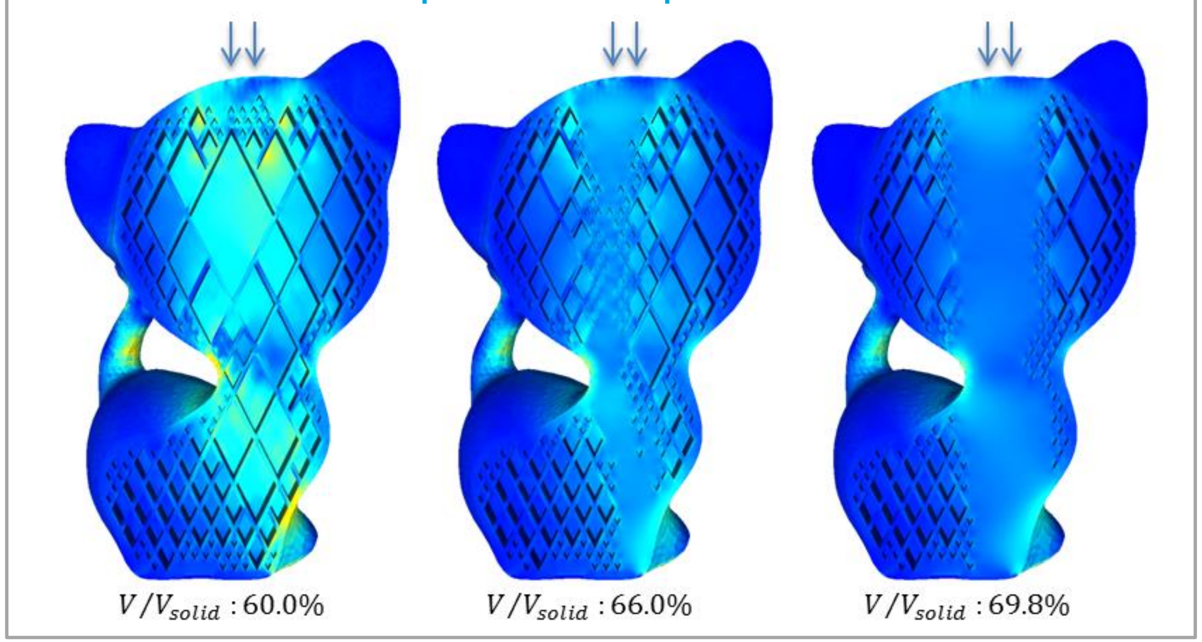
$$\rho_i(\beta) = \begin{cases} 1.0 & i \text{ covered by walls} \\ 0.0 & \text{otherwise} \end{cases}$$

Per-subdivision sensitivity: $G_c = -\frac{\partial c / \partial \beta_c}{\partial V / \partial \beta_c}$

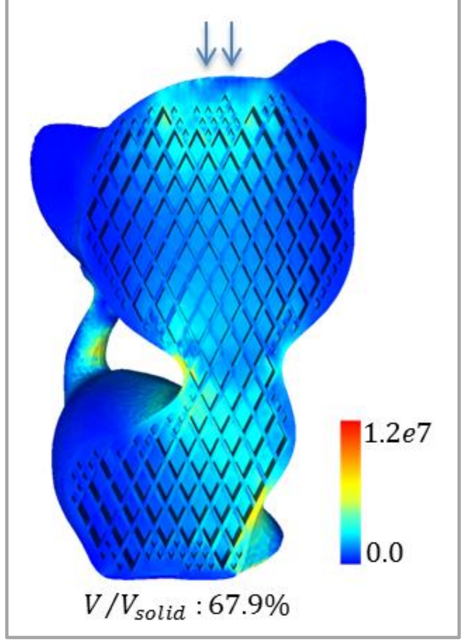
Self-Supporting Rhombic Infill: Results

- Optimized mechanical properties, compared to regular infill
- No additional inner supports needed

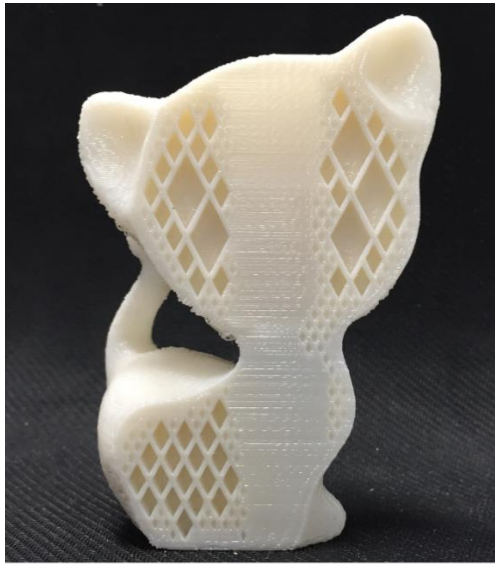
Optimization process



Reference

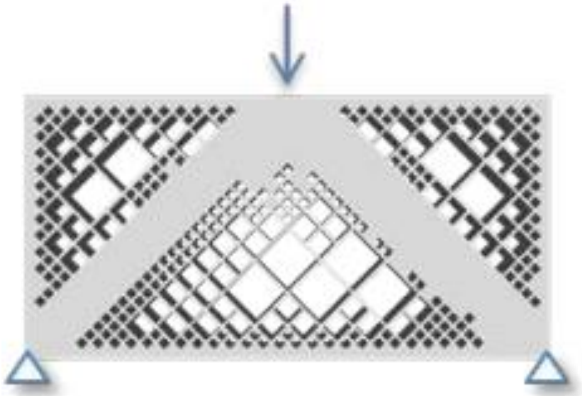


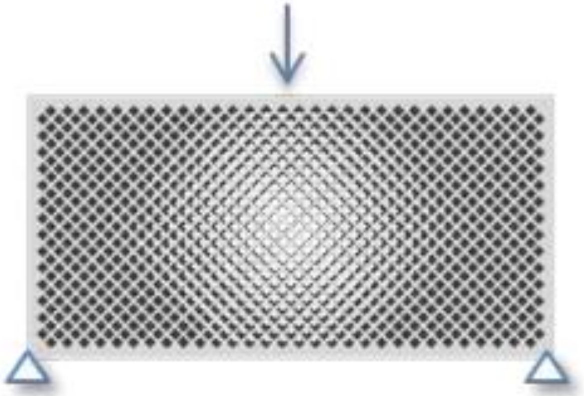
Print



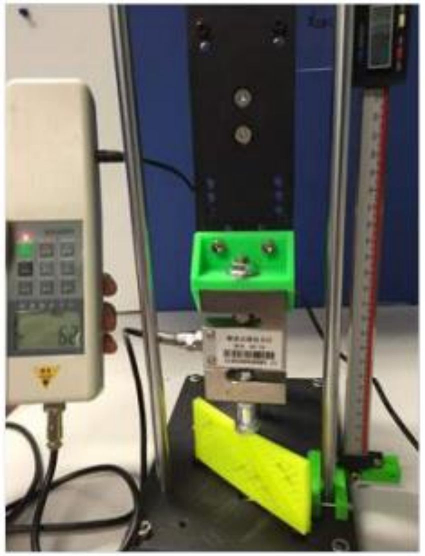
Wu et al., CAD’2016

Mechanical Tests





Under same force (62 N)



Dis.
2.11 mm

Dis.
4.08 mm

Under same displacement (3.0 mm)

Force
90 N

Force
58 N

Summary

- Geometric feature control by **density filters**
- Geometric feature control by **alternative parameterizations**

Thank you for your attention!

Questions?

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