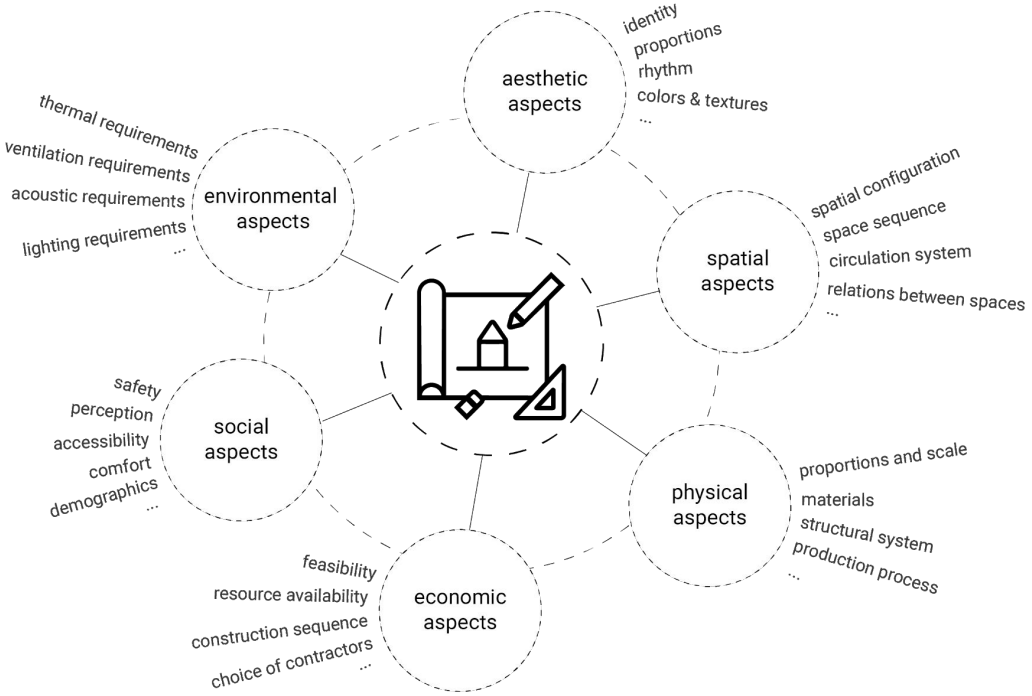
P5

BIO-INSPIRED APPROACH TO EARLY-STAGE STRUCTURAL FORM FINDING

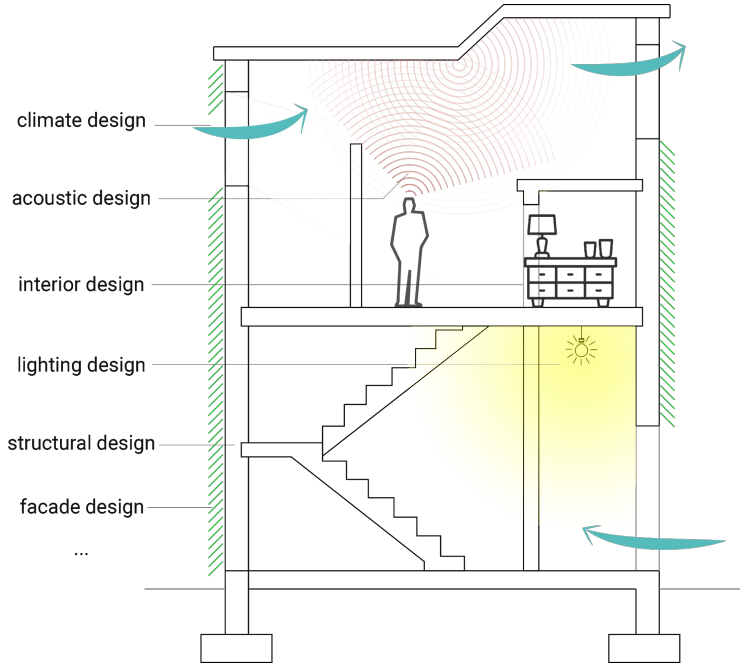
Ivan Avdić | 4749472

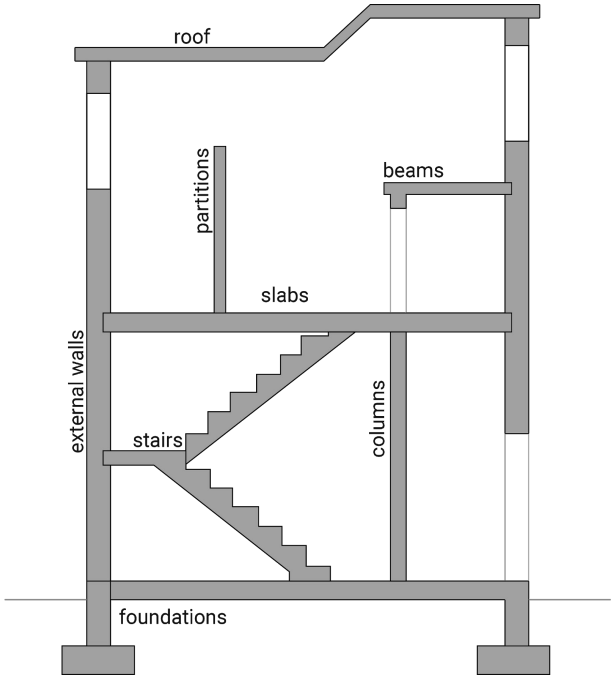
dr. ir. Pirouz Nourian | Architectural Engineering + Technology, Design Informatics
dr. ir. Matthijs Langelaar | Faculty 3mE, Precision and Microsystems Engineering (PME)

> “[...] the construction sector contributes to 23% of air pollution, 50% of CO2 emissions, 40% of drinking water pollution, and 50% of landfill wastes. [...] accounts for 40% of worldwide energy usage, with estimations that by 2030 emissions from commercial buildings will grow by 1.8%.”
>
> *USGBC*

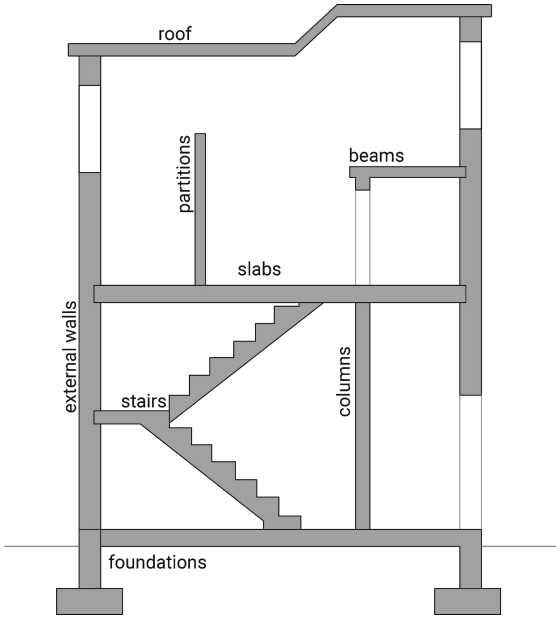


- Architectural design is a multidimensional problem (dimension = degree of freedom)
- Human designers are incapable of holistically tackling such problems

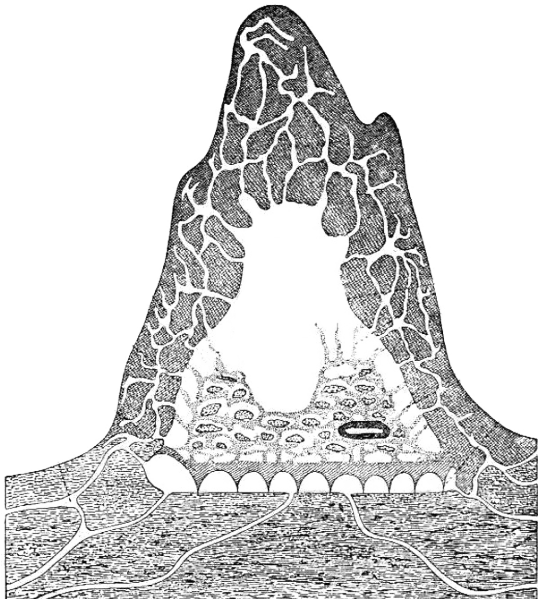


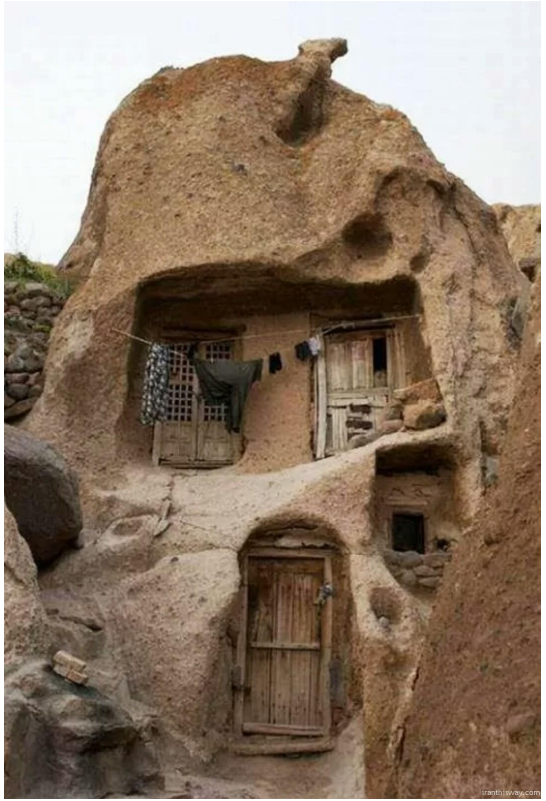


- Reducing the dimensionality to a comprehensible one by discretization (building as sum of its parts)
- problem of design linearity



VS





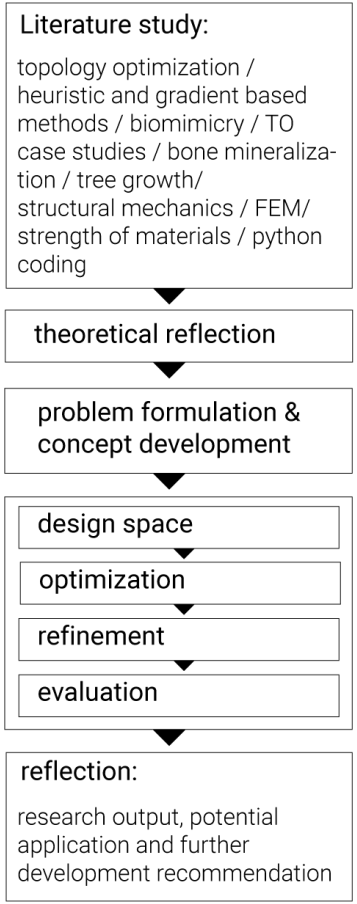
Kandovan house, Iran

- In nature “form and structure come into being by way of a common developmental process, depending on physical and chemical laws” (Frei Otto, 1985)
- “Material is expensive, but form is cheap” (Vincent, 1997)

Q: What if we as human designers were able to design structures in the same way nature does: by perfectly fitting form to function, using only the materials and energy we need? Rather than designing a building, can we discover its design?

A: Topology Optimization as an approach for the joint morphogenesis of form and structure
-used at end stage of design for building elements
-lack of application to large scale problems

O: Creation of a bio-inspired approach towards designing the topological layout of a building's structural system, while considering its spatial configuration?

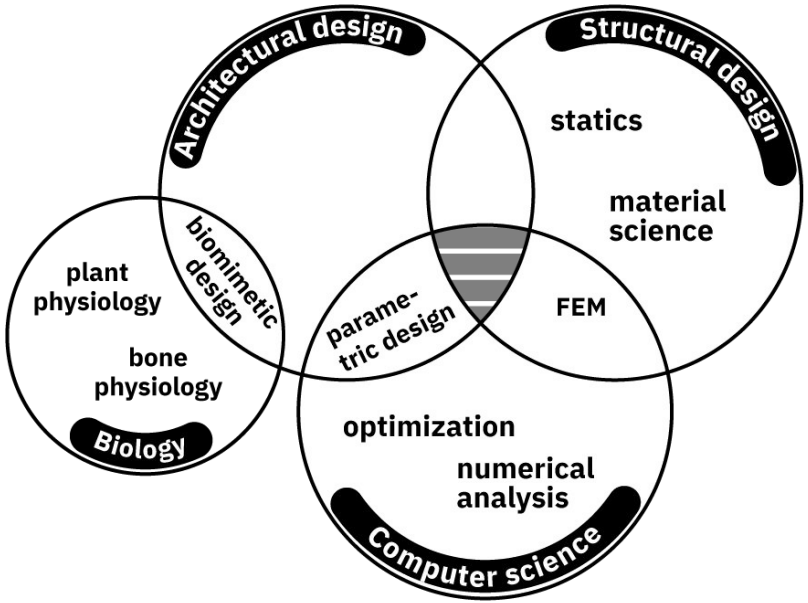


- understanding of main concepts
- mathematical and theoretical underpinnings
- successful case studies

- reflection on the conducted research
- choosing the right model phenomenon
- deciding on the method
- developing the methodology

- creating the environment
- testing
- solving a design problem

- result discussion
- possibilities and limitations
- further improvements


Architectural design
Structural design
statics
material science
plant physiology
biomimetic design
bone physiology
Biology
parame-tric design
FEM
optimization
numerical analysis
Computer science

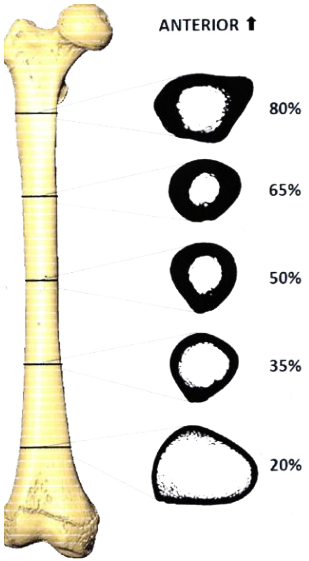
maxim: “In nature materials are expensive but form is cheap”
Julian Vincent (1997). Stealing ideas from nature

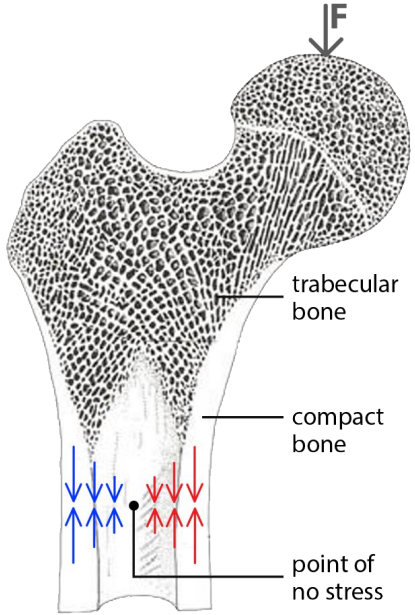
paradigm: “Less material and more design”
Michael Pawlyn (2016). Biomimicry in Architecture

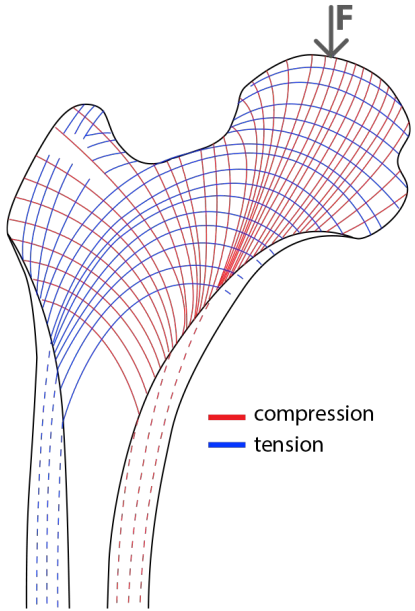
axiom: “uniform stress”
D’Arcy Wentworth Thompson (1942). On Growth and Form
Claus Mattheck (1992). Design in Nature- Learning from Trees

macro scale

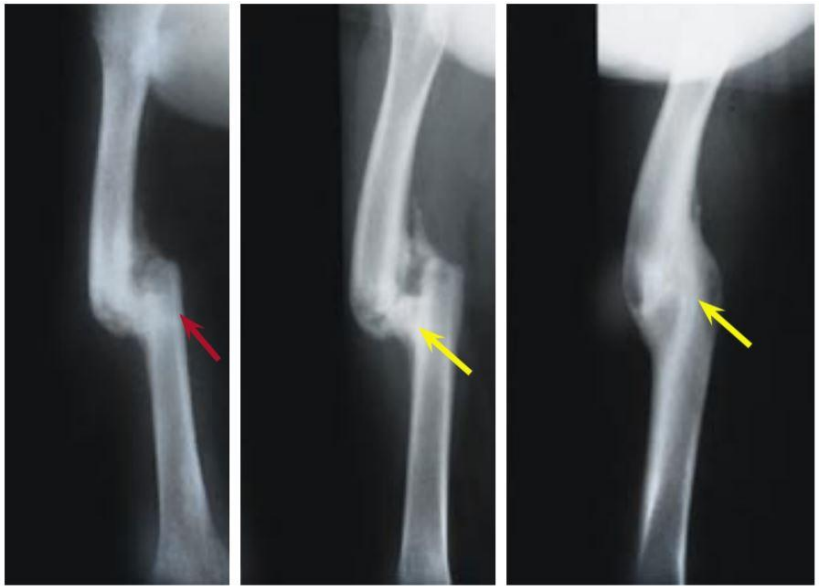
micro scale







1.Differentiation of Young's modulus based on stress - **SKO**



2.reduction of notch stresses through active mineralization - **CAO**

SKO CAO

DESIGN SPACE

creation of the design domain based on user input on spaces, boundary conditions and materials

- voxel size (resolution)
- spaces (voids)
- loads: position, type, magnitude
- supports: position, type
- material: yield strength, poisson, cross section, coef. of T exp., $E_{modulus}$

OPTIMIZATION

achieving a rough voxelized design in an itterative fashion.

- FEM analysis
- calculating resultant forces N, V, M
- calculating reference stress (principal, Von Mises, Utilization)
- conversion of stress to new E values
- termination condition
- removing unnecessary material

REFINEMENT

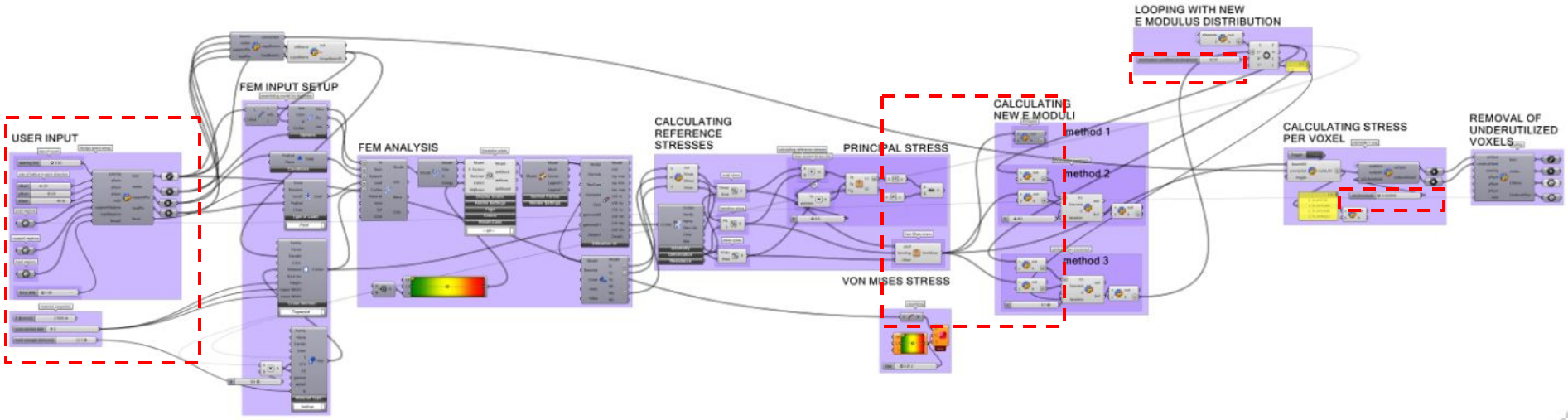
resolving notch stresses and smoothening the voxelized design.

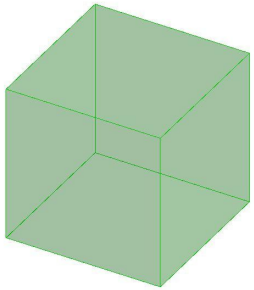
- FEM analysis w/ initial constant E
- calculating reference stress (principal, Von Mises, Utilization)
- $\sigma_{ref} = T(x,y,z)$, temp.
- FEM run with thermal loading. E/400, alphaT≠0
- addition of thermal displacements to nodal point coordinates

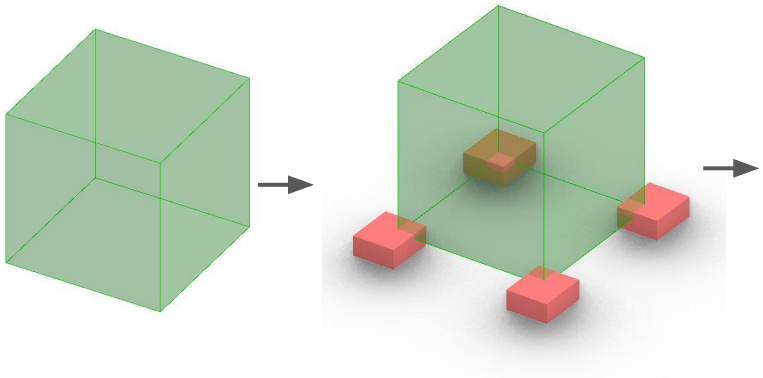
EVALUATION

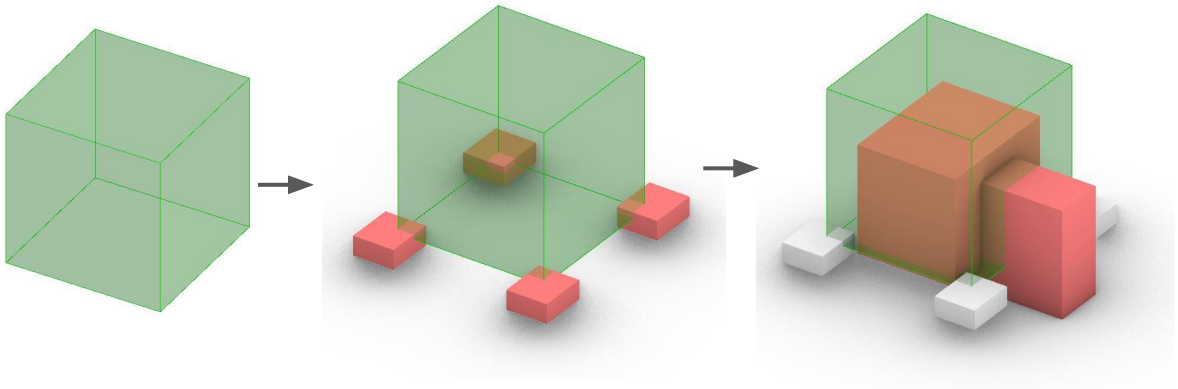
evaluating the proposed design against comercially available software

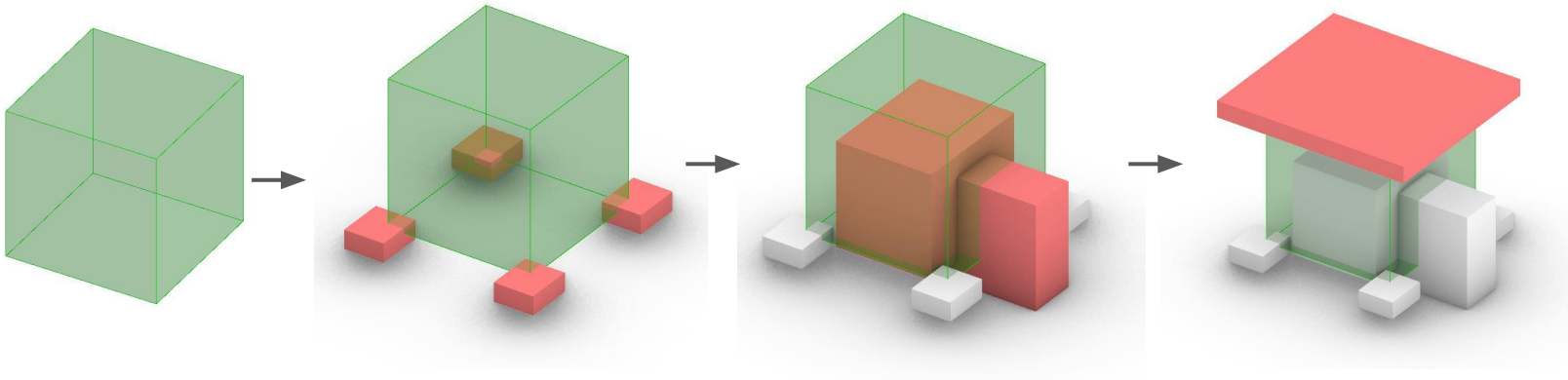
- FEM analysis w/ initial constant E
- comparison with commecial software

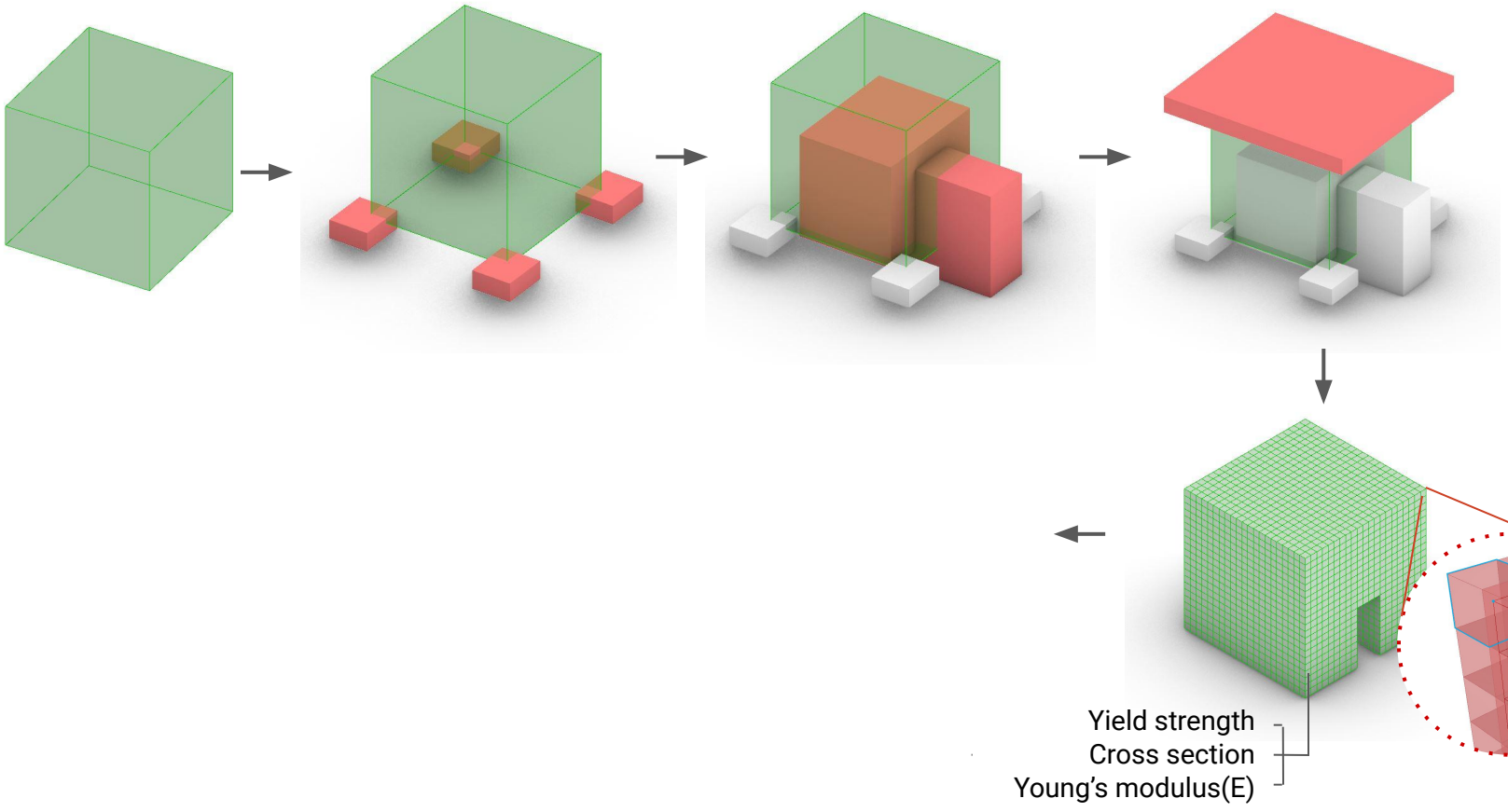

USER INPUT
FEM INPUT SETUP
FEM ANALYSIS
CALCULATING REFERENCE STRESSES
PRINCIPAL STRESS
VON MISES STRESS
CALCULATING NEW E MODULI
method 1
method 2
method 3
LOOPING WITH NEW E MODULUS DISTRIBUTION
CALCULATING STRESS PER VOXEL
REMOVAL OF UNDERUTILIZED VOXELS

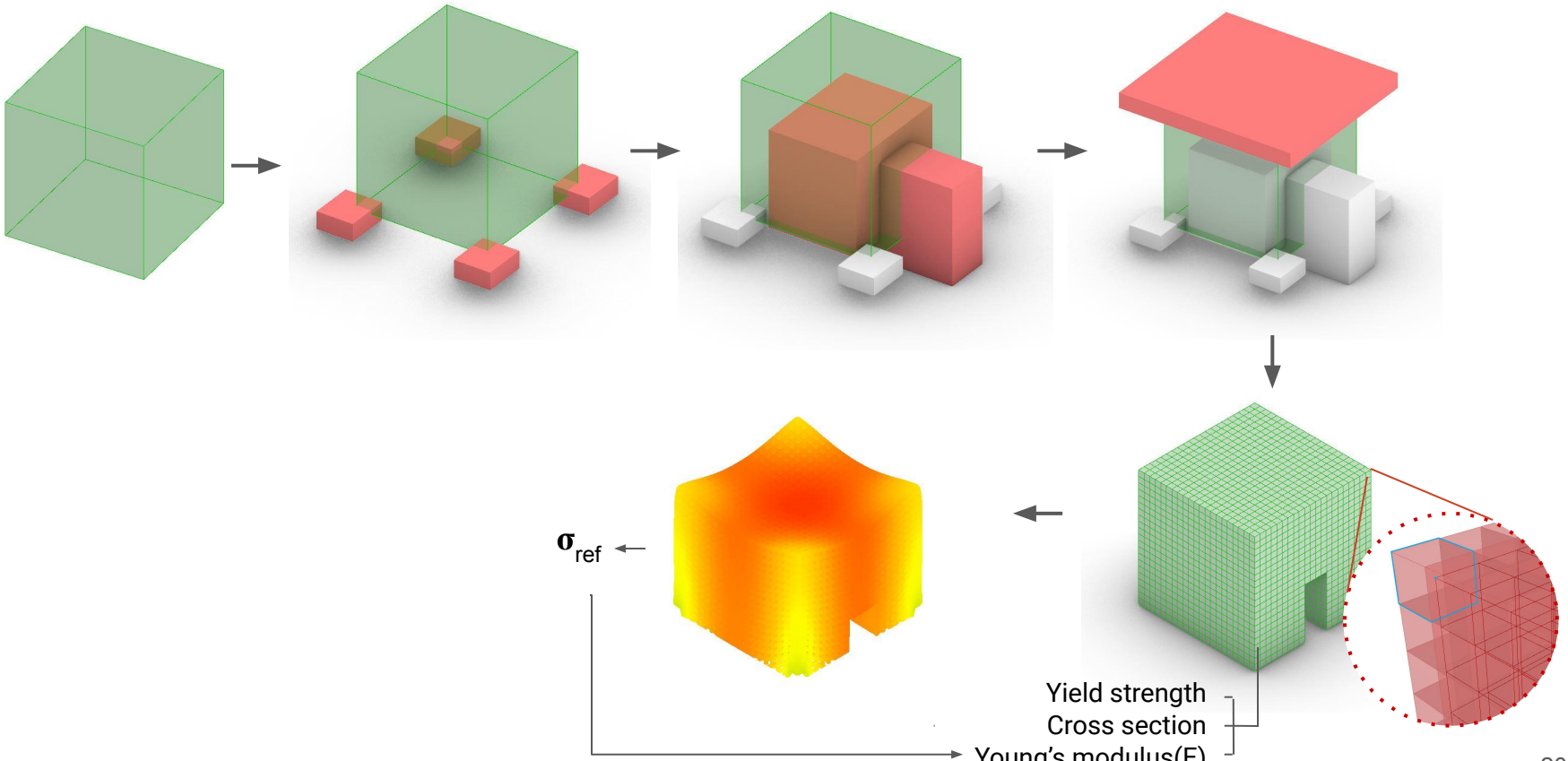


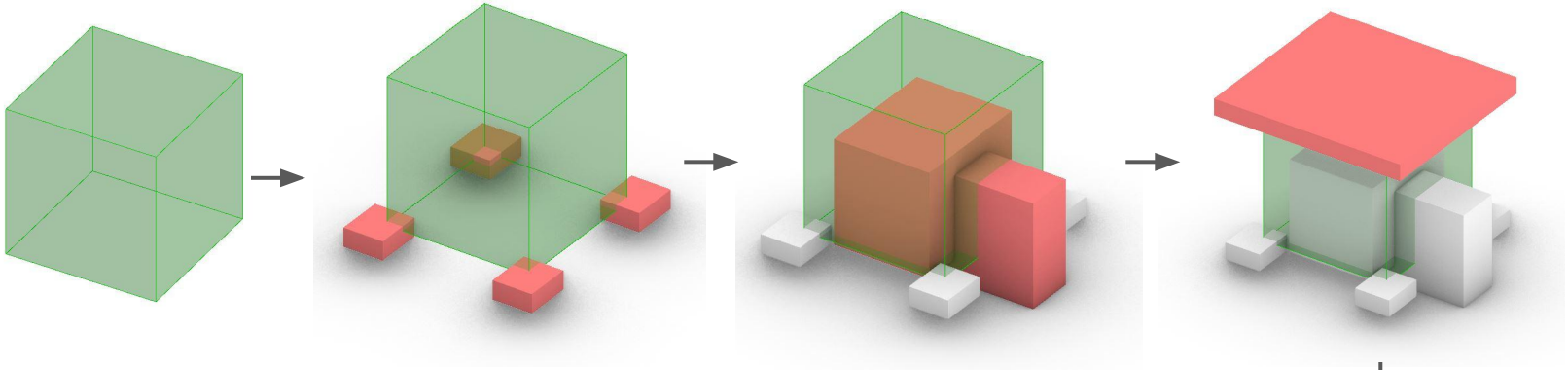







Yield strength
Cross section
Young's modulus(E)

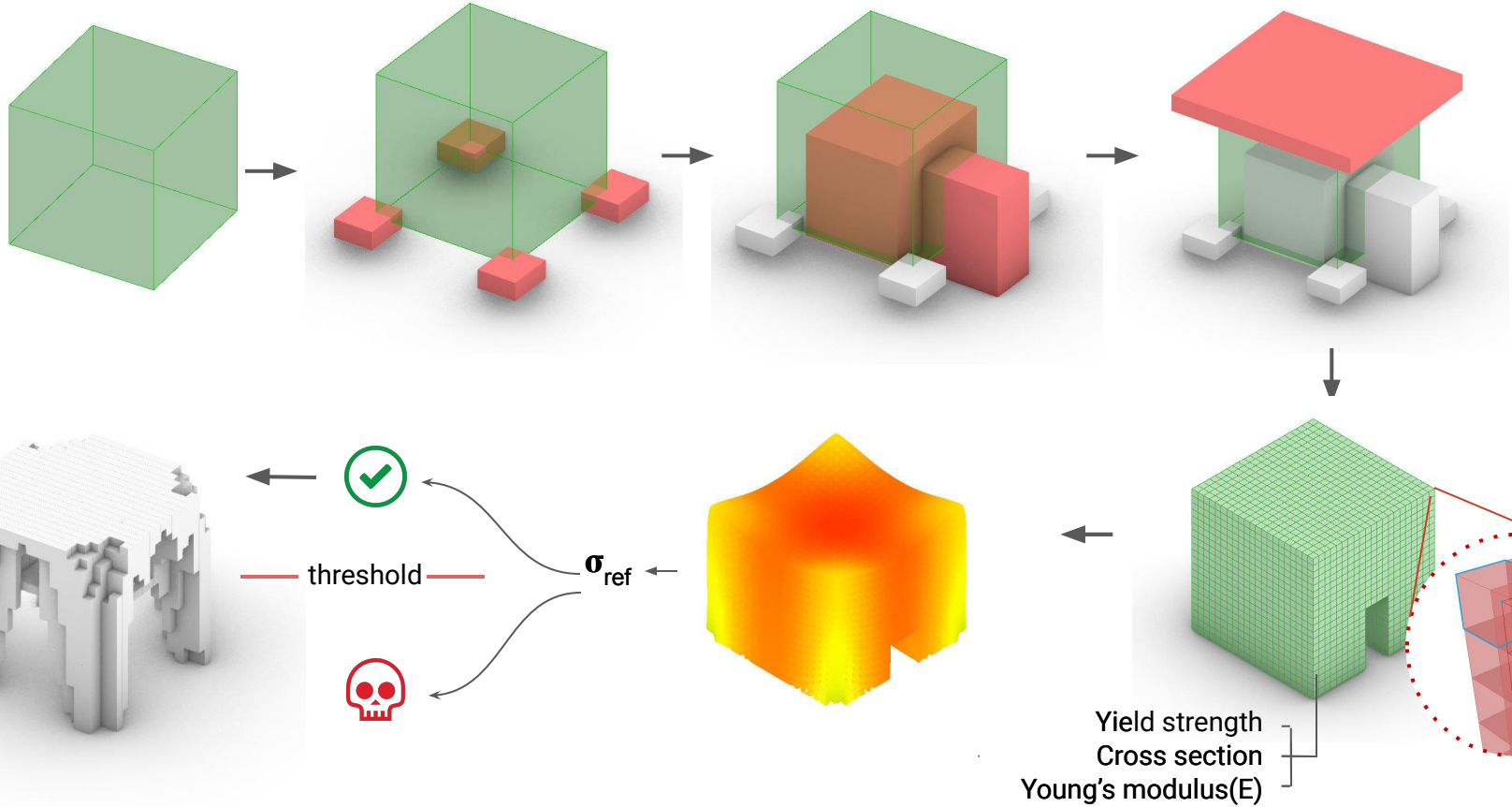

σ_{ref}
Yield strength
Cross section
Young's modulus(E)

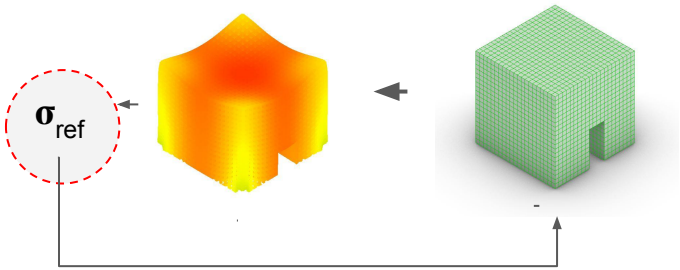


x200

σ_{ref}

Yield strength
Cross section
Young's modulus(E)


threshold
σ_{ref}
Yield strength
Cross section
Young's modulus(E)

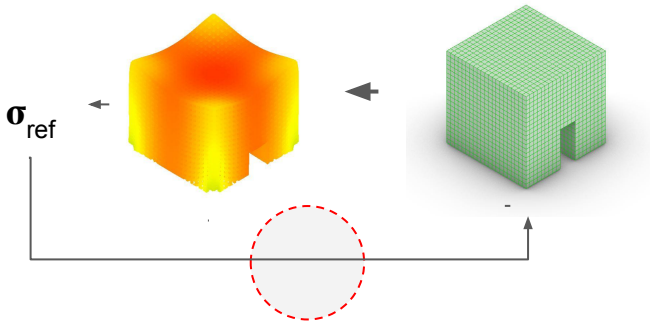


Option1: von Mises reference stress

$$\sigma_{vm} = \sqrt{(\sigma_{axial} + \sigma_{bending})^2 + 3\tau_{sh}^2}$$

Option2: principal reference stress

$$\sigma_{pr} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\frac{(\sigma_x - \sigma_y)^2}{2} + \tau_{xy}^2}$$



Option1: von Mises reference stress

$$\sigma_{vm} = \sqrt{(\sigma_{axial} + \sigma_{bending})^2 + 3\tau_{sh}^2}$$

Option2: principal reference stress

$$\sigma_{pr} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\frac{(\sigma_x - \sigma_y)^2}{2} + \tau_{xy}^2}$$

Option1: stress method

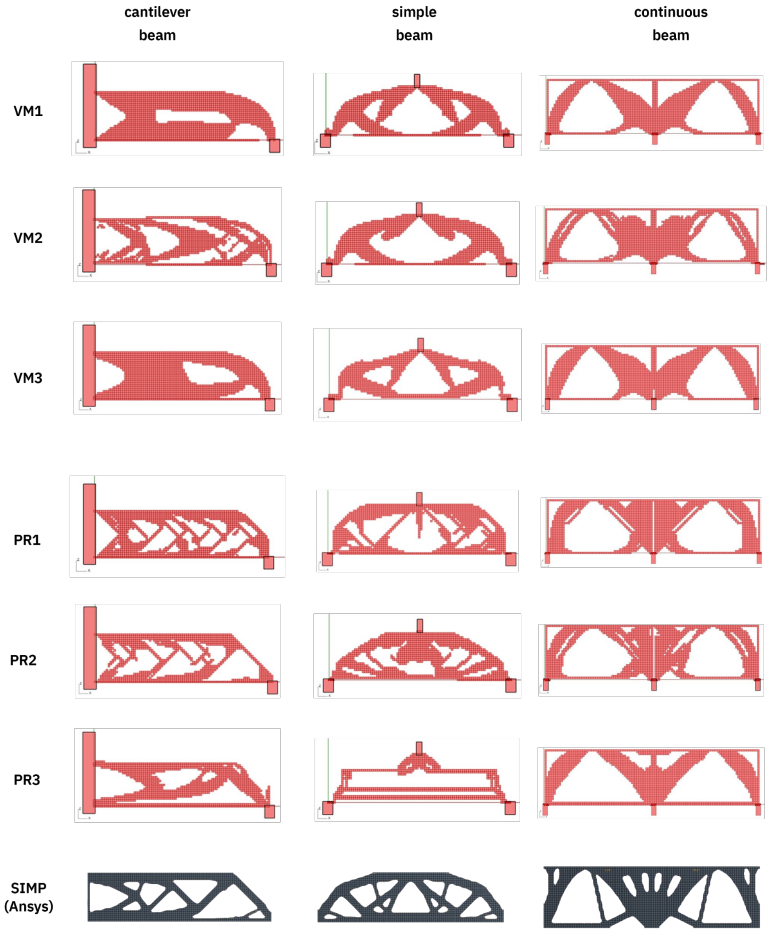
$$E_{n+1} = k\sigma_n$$

Option2: local stress-increment method

$$E_{n+1} = E_n + k(\sigma_n - \sigma_{n-1})$$

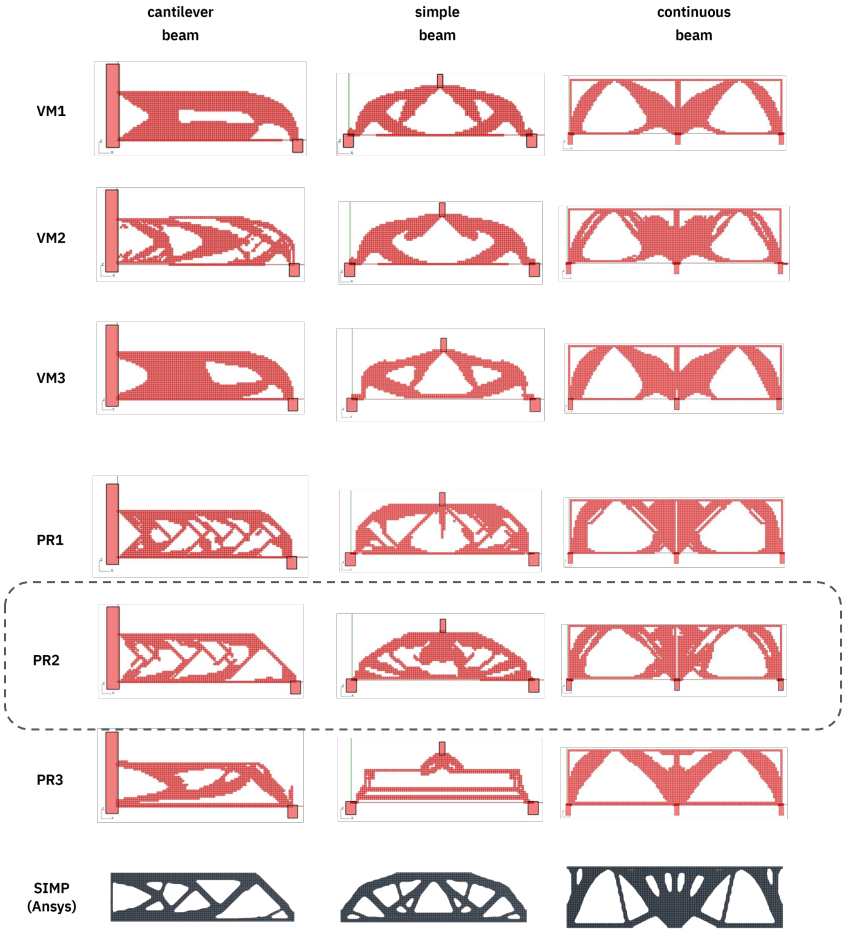
Option3: global stress-increment method

$$E_{n+1} = E_n + k(\sigma_n - \sigma_{allowable})$$



	Reference stress	method	original displacement [cm]	Displacement after SKO [cm]	% mass remaining	% above allowable stress	number of iterations	score
Cantilever beam	Von mises	$E=\sigma$	0.031	0.13	70 %	0%	200	24
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.16	51%	0%	200	23.9
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.126	71%	0%	200	24
	principal	$E=\sigma$		0.151	55.3%	0%	200	24.6
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.18	47%	0%	200	29.6
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.186	50%	0%	200	24.8
Simple beam	Von mises	$E=\sigma$	0.004	0.042	45%	0%	200	34.2
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.05	45%	0%	200	32.2
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.03	42%	0%	200	33.7
	principal	$E=\sigma$		0.04	46%	0%	200	31.3
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.04	48.5%	0%	50	32.5
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.34	30%	0%	200	20.7
Continuous beam	Von mises	$E=\sigma$	0.02	0.45	44%	0.8%	80	19.2
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.4	47%	0.6%	100	18.8
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.38	50%	0.6%	100	21.2
	principal	$E=\sigma$		0.1	49%	0%	200	26
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.1	47%	0%	100	25.8
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.11	43%	0.02%	100	24

Table 2: overview of the best obtained results for the TOY problems with all setups

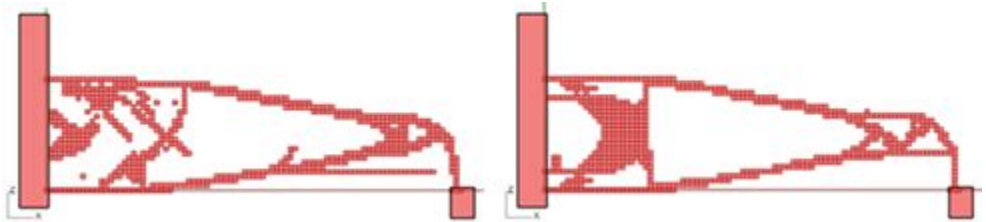


	Reference stress	method	original displacement [cm]	Displacement after SKO [cm]	% mass remaining	% above allowable stress	number of iterations	score
Cantilever beam	Von mises	$E=\sigma$	0.031	0.13	70 %	0%	200	24
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.16	51%	0%	200	23.9
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.126	71%	0%	200	24
	principal	$E=\sigma$		0.151	55.3%	0%	200	24.6
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.18	47%	0%	200	29.6
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.186	50%	0%	200	24.8
Simple beam	Von mises	$E=\sigma$	0.004	0.042	45%	0%	200	34.2
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.05	45%	0%	200	32.2
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.03	42%	0%	200	33.7
	principal	$E=\sigma$		0.04	46%	0%	200	31.3
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.04	48.5%	0%	50	32.5
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.34	30%	0%	200	20.7
Continuous beam	Von mises	$E=\sigma$	0.02	0.45	44%	0.8%	80	19.2
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.4	47%	0.6%	100	18.8
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.38	50%	0.6%	100	21.2
	principal	$E=\sigma$		0.1	49%	0%	200	26
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{principal\,n-1})$		0.1	47%	0%	100	25.8
		$E_{n+1}= E_0 + k(\sigma_{principal\,n} - \sigma_{ref})$		0.11	43%	0.02%	100	24

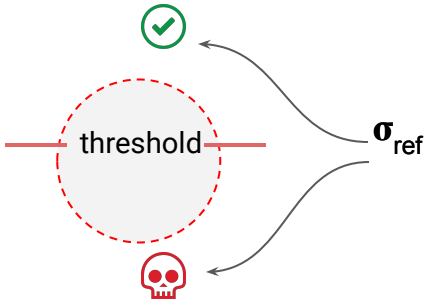
Table 2: overview of the best obtained results for the TOY problems with all setups

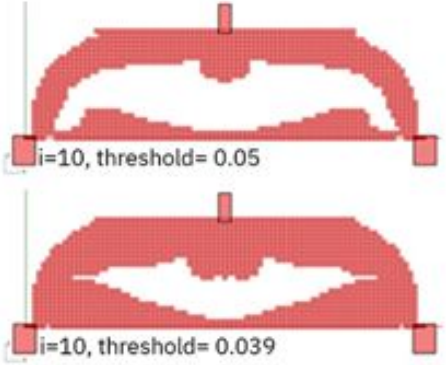
Option2: local stress-increment method

$$E_{n+1} = E_n + k(\sigma_n - \sigma_{n-1})$$

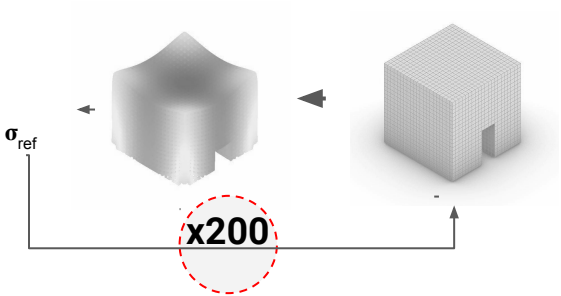


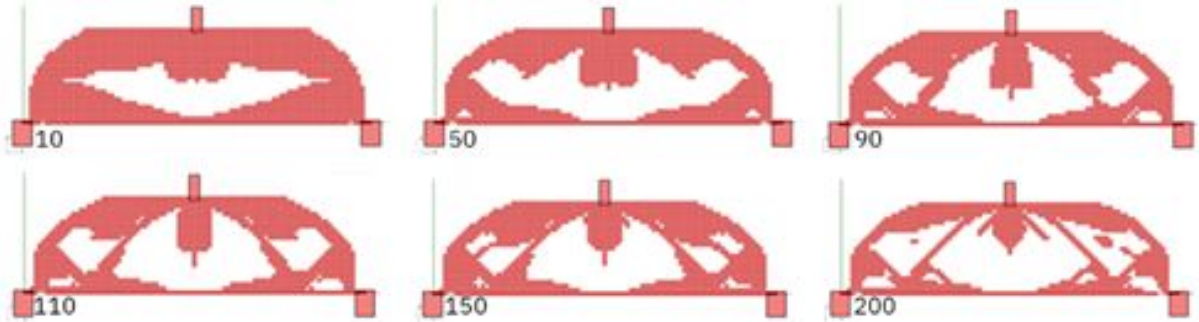
k=100/$\sigma_{allowable}$ gives best results





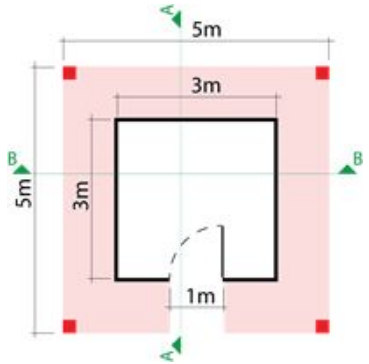
Threshold = maintaining between 50-70% material shows to be viable.



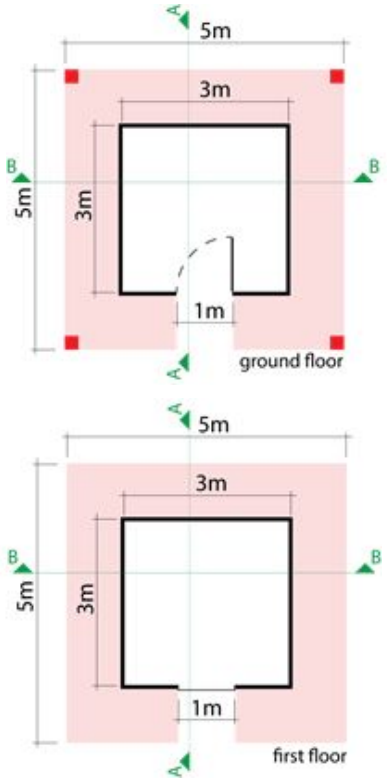


Stress method - **200** iterations
local stress-increment method - **100** iterations
Global stress increment method - **25-50** iterations

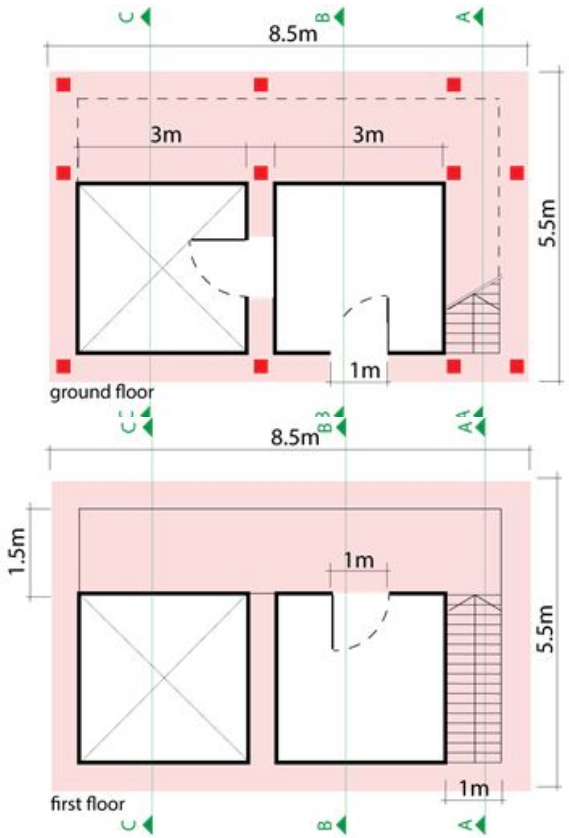
3D



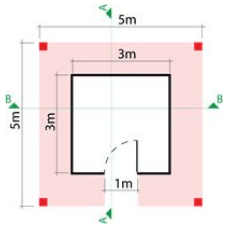
Case1:
ground floor house



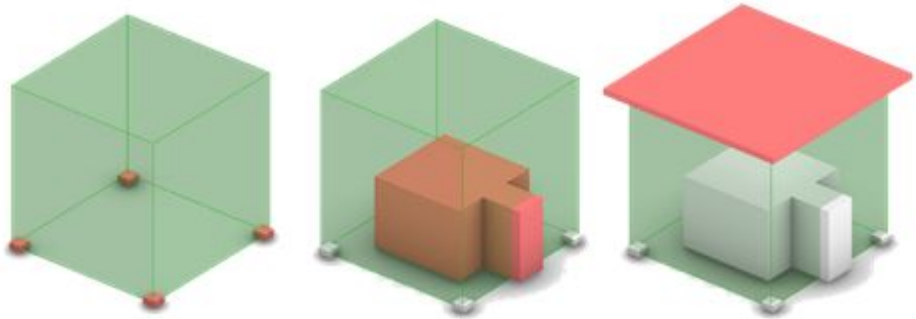
Case2:
Single story house



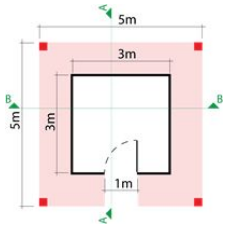
Case3:
Complex house



Case1:
ground floor house



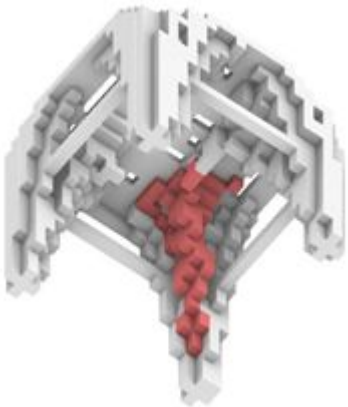
Design space setup



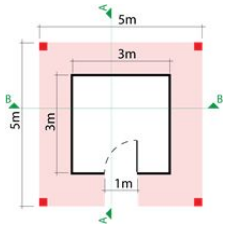
Case1:
ground floor house

Result: 47% material remaining

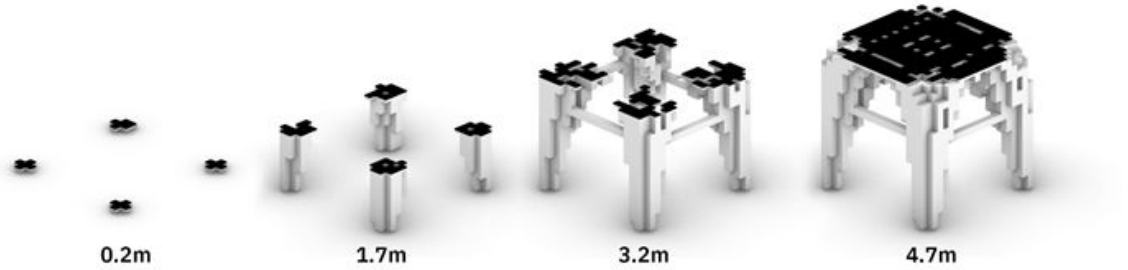
Tension ties?



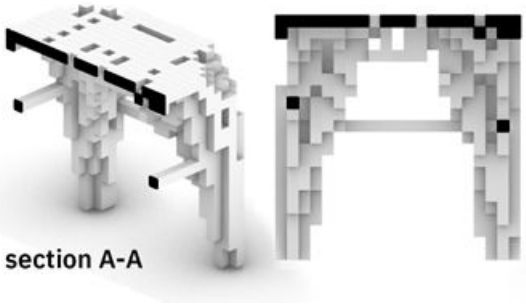
Fan vault?

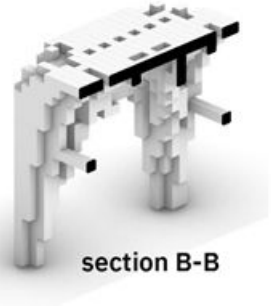


Case1:
ground floor house

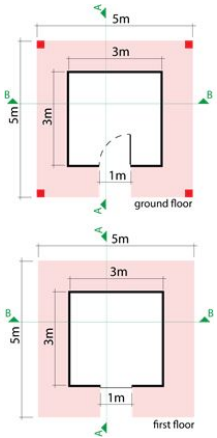


Horizontal sections

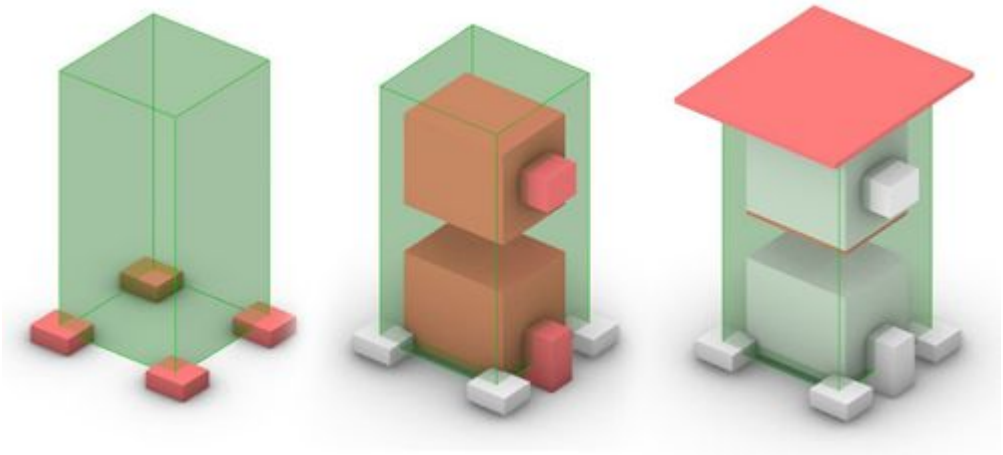




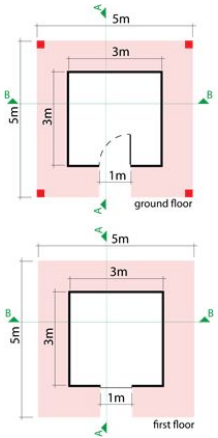
Vertical sections



Case2:
Single story house



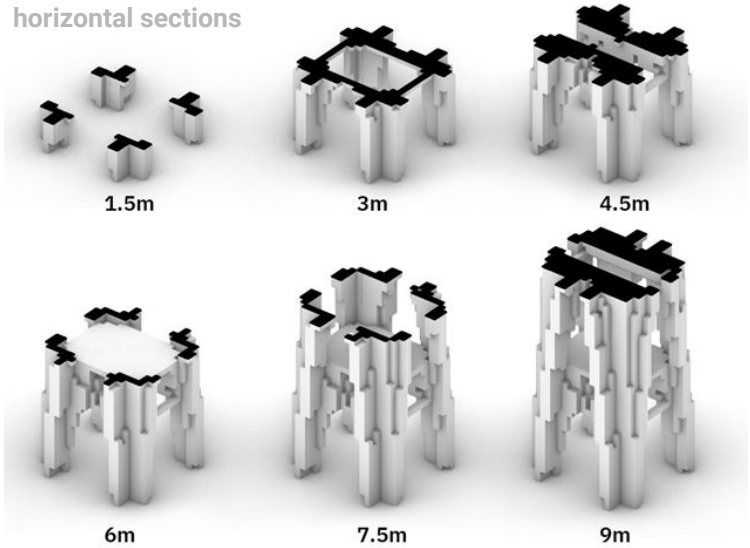
Design space setup



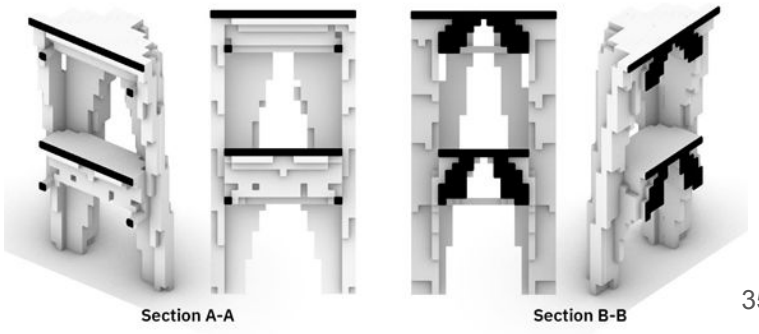
Case2:
Single story house

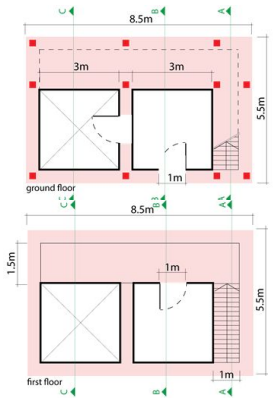
Result: 50% material remaining

horizontal sections

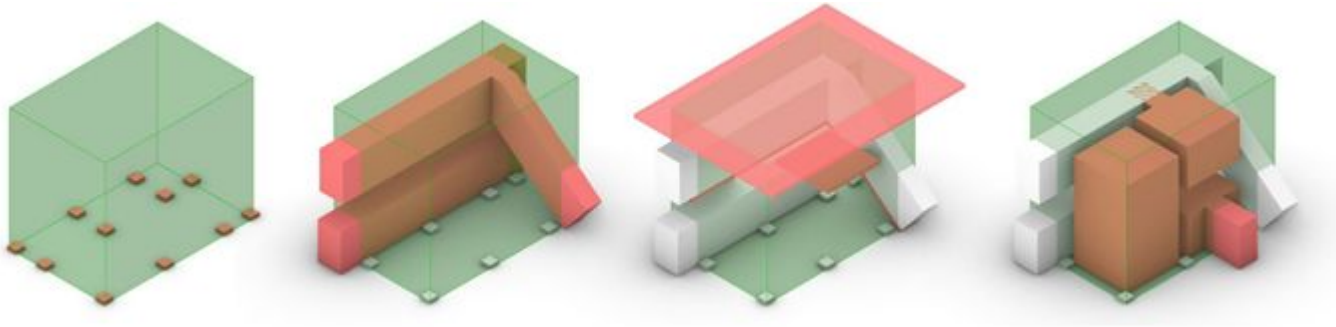


vertical sections

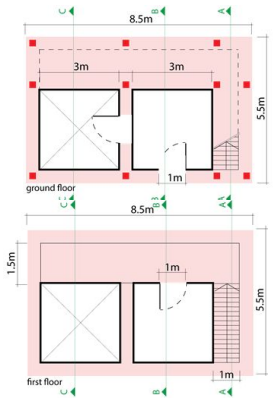




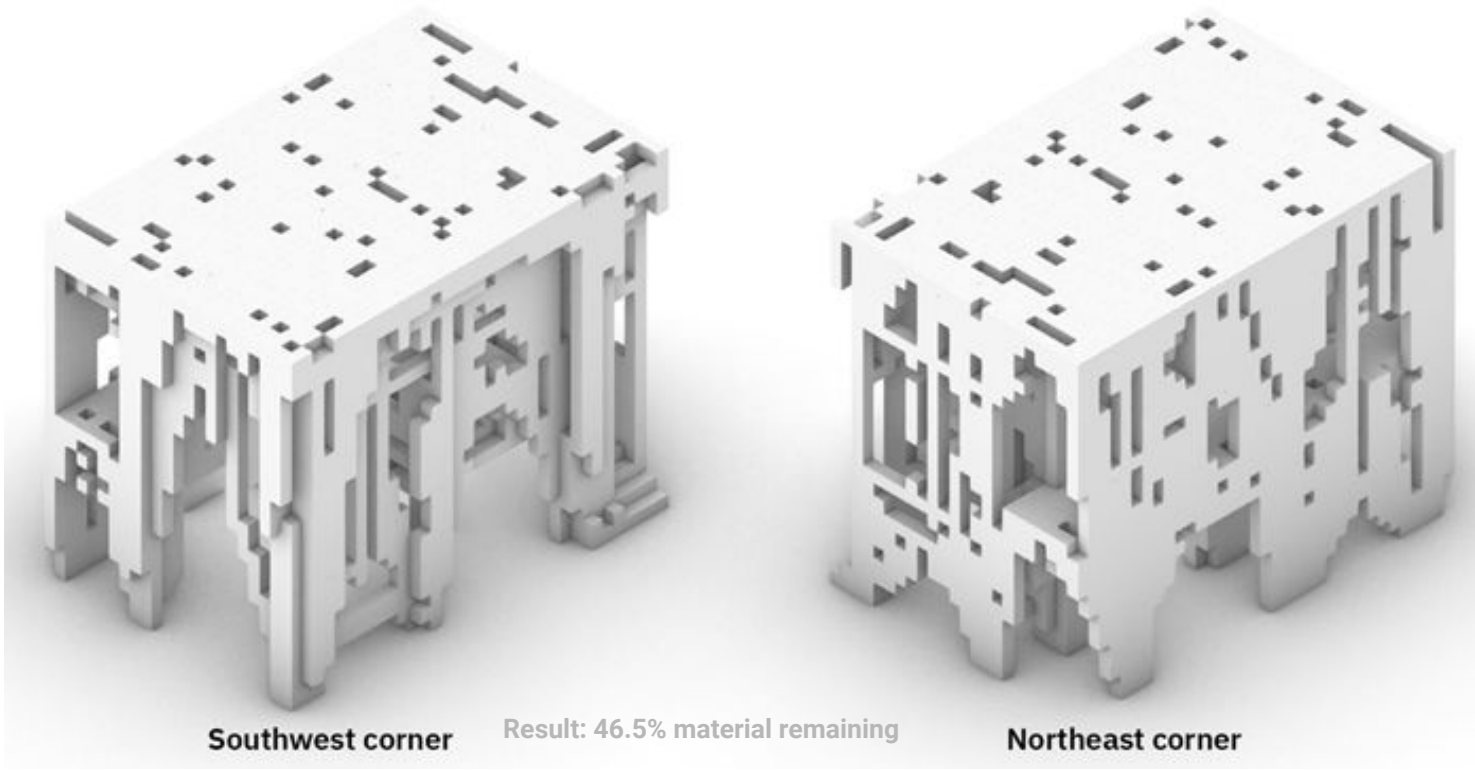
Case3:
complex house

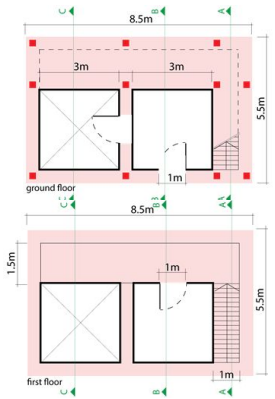


Design space setup

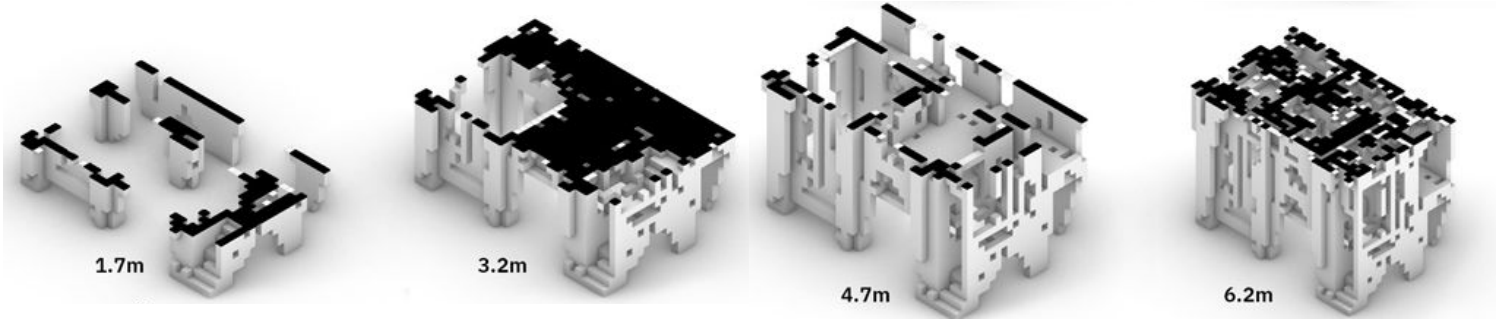


Case3:
complex house

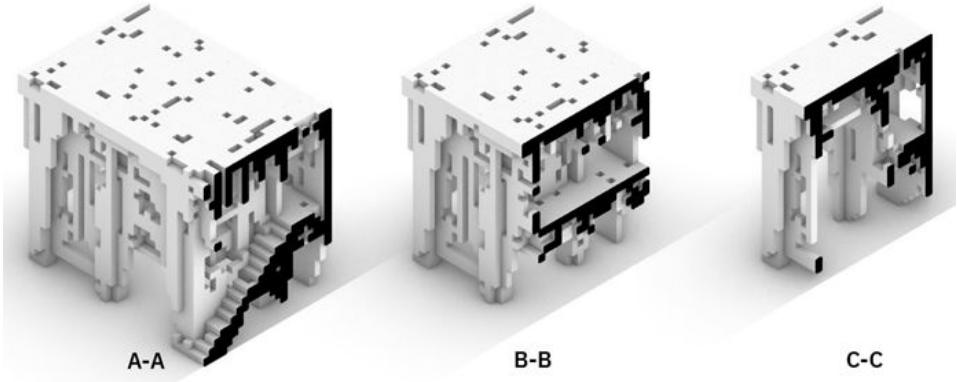




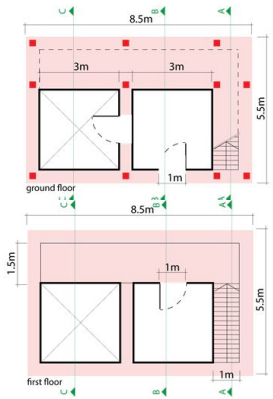
Case3:
complex house



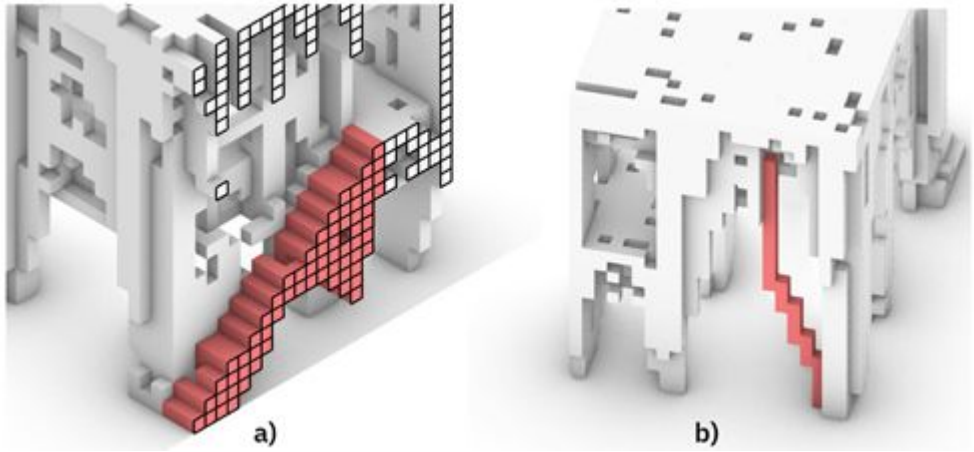
Horizontal sections



Vertical sections

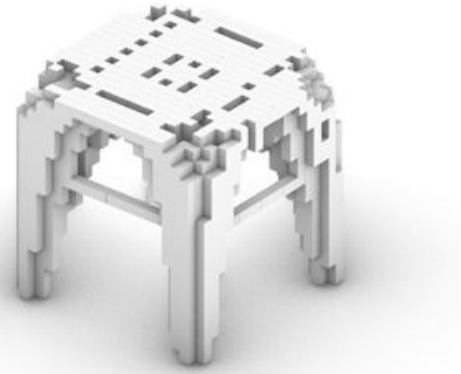


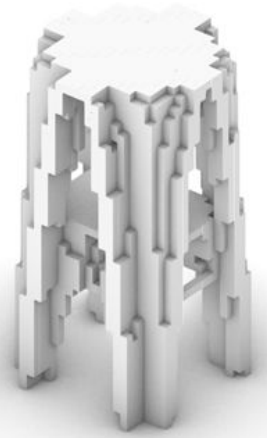
Case3:
complex house

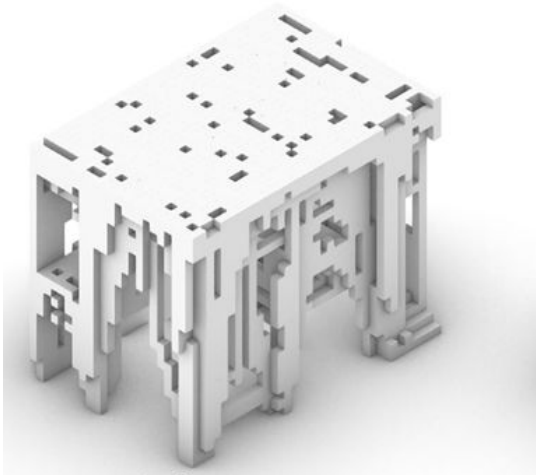


Interesting occurrences

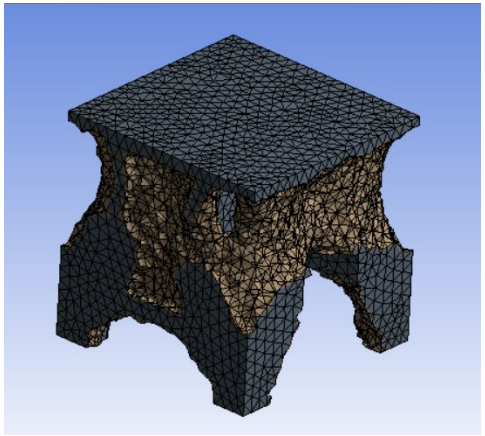
SKO

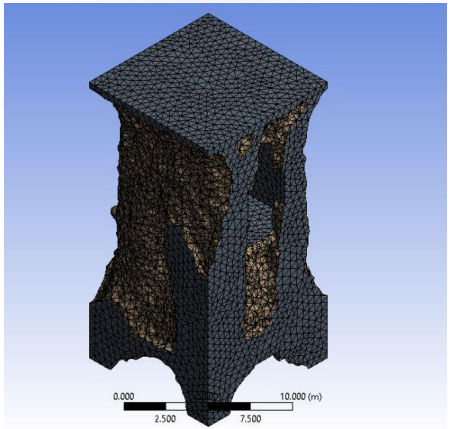


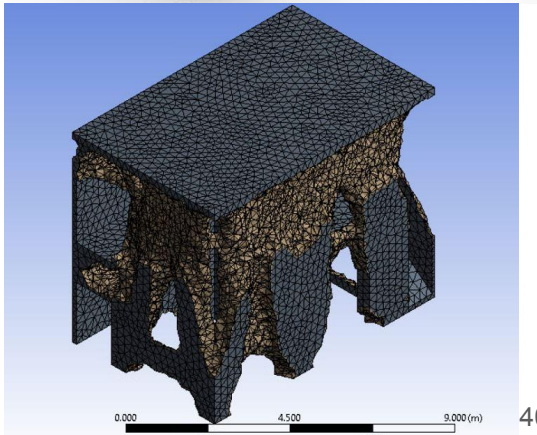




SIMP by Ansys

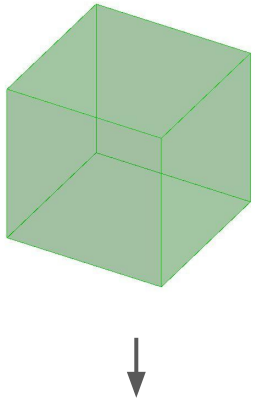






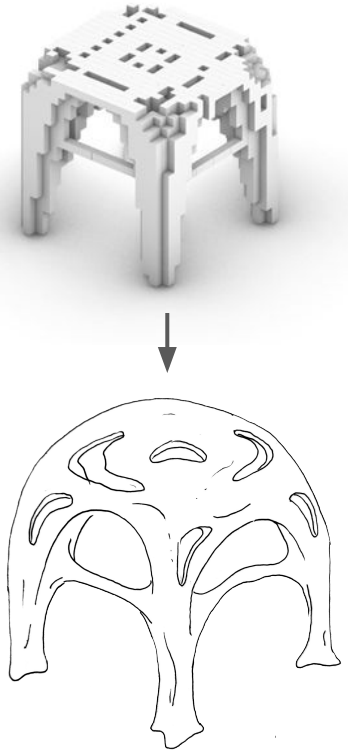
General conclusions

- Bio-inspired computational tool for early stage design of building structures created
- Method integrated in the standard workflow of designers within RH/GH with Python and FEM analysis through Karamba
- Different parameters and their influence on the final output are explored, PR2 method chosen as best performing
- Method functions in 2D and 3D to a certain extent
- Final geometry can indicate a more optimal structure with respect to material usage

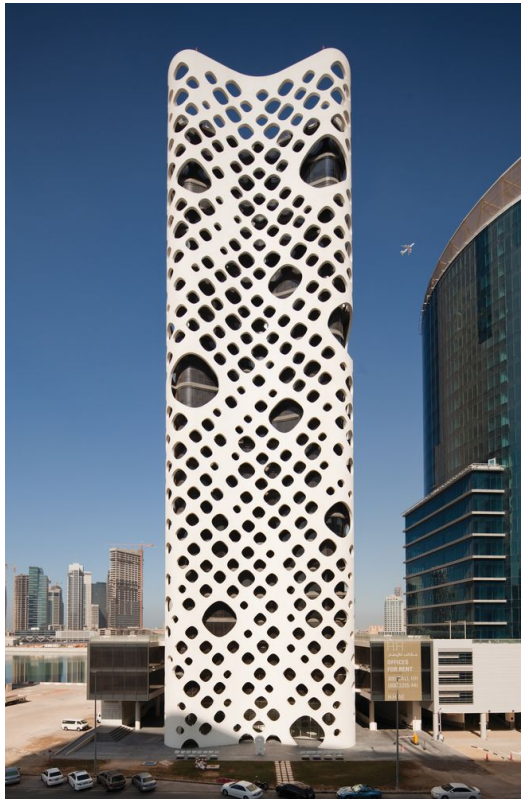


recommendations

- Developing a more deterministic way of deriving the appropriate variable values for k, σ_{ref} , threshold...
- Introducing a logic for removal of checkerboard patterns
- Improvements in the code which could lead to shorter simulation times, or allowing for increased resolution for same amount of time.
- Writing a custom volumetric FEM solver in python - avoid the need for abstraction into beam lattice and for use of Karamba
- Developing the CAO method for reducing notch stresses could lead to better performing results



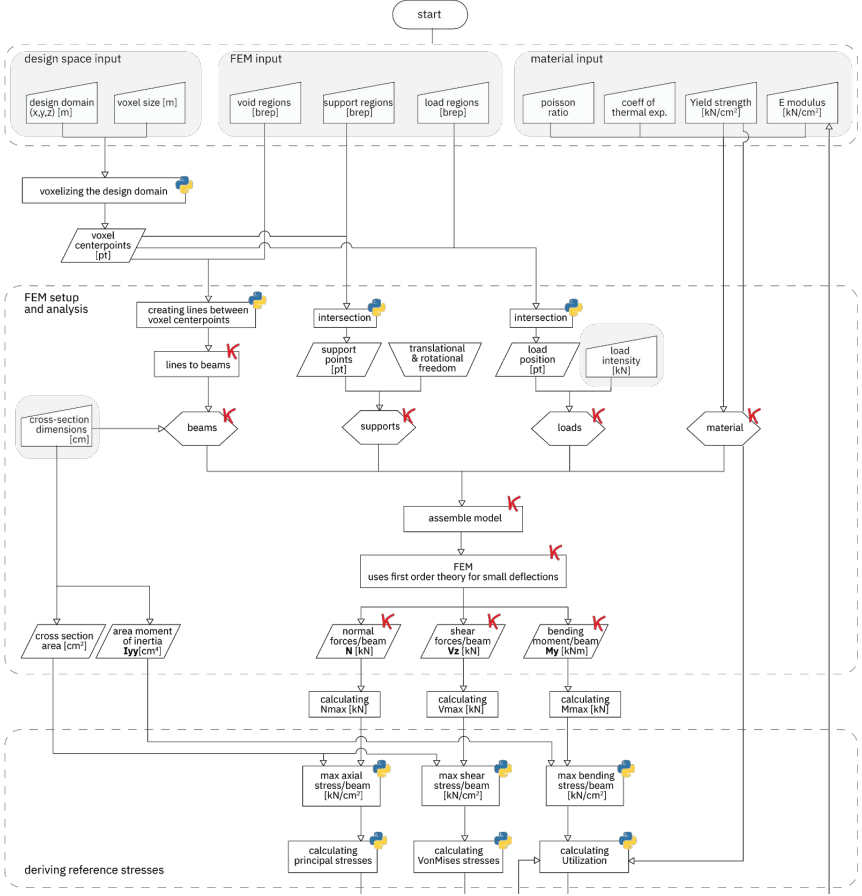
Applicability 2D

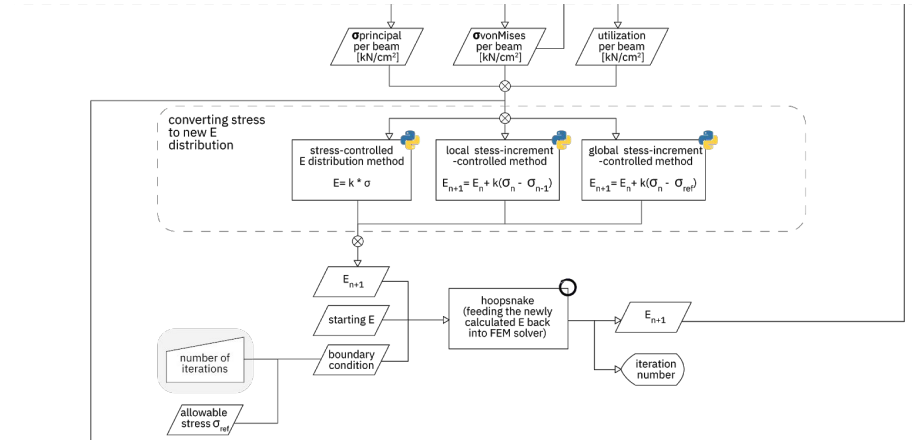


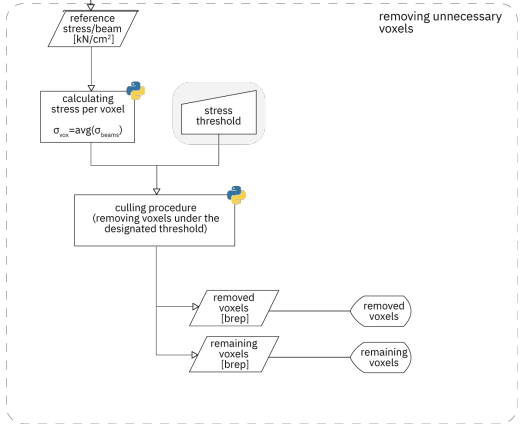
Applicability 3D

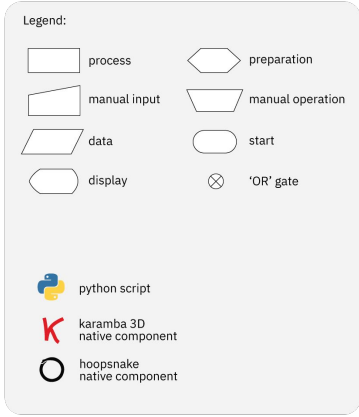
THANK YOU

ХВАЛА


start
design space input
design domain (x,y,z) [m]
voxel size [m]
FEM input
void regions [brep]
support regions [brep]
load regions [brep]
material input
poisson ratio
coeff of thermal exp.
Yield strength [kN/cm²]
E modulus [kN/cm²]
voxelizing the design domain
voxel centerpoints [pt]
FEM setup and analysis
creating lines between voxel centerpoints
intersection
intersection
lines to beams
support points [pt]
translational & rotational freedom
load position [pt]
load intensity [kN]
cross-section dimensions [cm]
beams
supports
loads
material
assemble model
FEM uses first order theory for small deflections
cross section area [cm²]
area moment of inertia Iyy[cm⁴]
normal forces/beam N [kN]
shear forces/beam Vz [kN]
bending moment/beam My [kNm]
calculating Nmax [kN]
calculating Vmax [kN]
calculating Mmax [kN]
max axial stress/beam [kN/cm²]
max shear stress/beam [kN/cm²]
max bending stress/beam [kN/cm²]
calculating principal stresses
calculating VonMises stresses
calculating Utilization
deriving reference stresses


σprincipal per beam [kN/cm²]
σvonMises per beam [kN/cm²]
utilization per beam [kN/cm²]
converting stress to new E distribution
stress-controlled E distribution method
E= k * σ
local stess-increment -controlled method
E_n+1 = E_n + k(σ_n - σ_n-1)
global stess-increment -controlled method
E_n+1 = E_n + k(σ_n - σ_ref)
E_n+1
starting E
boundary condition
hoopsnake (feeding the newly calculated E back into FEM solver)
E_n+1
iteration number
number of iterations
allowable stress σ_ref


reference stress/beam [kN/cm²]
removing unnecessary voxels
calculating stress per voxel
σ_vox =avg(σ_beams)
stress threshold
culling procedure (removing voxels under the designated threshold)
removed voxels [brep]
removed voxels
remaining voxels [brep]
remaining voxels


Legend:
process
preparation
manual input
manual operation
data
start
display
'OR' gate
python script
karamba 3D native component
hoopsnake native component