Topology optimization with additive manufacturing constraints

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CIMNE INTERNATIONAL CENTRE FOR NUMERICAL METHODS IN ENGINEERING

UdG AMADE

AMADE Days
July 11th 2024

Background

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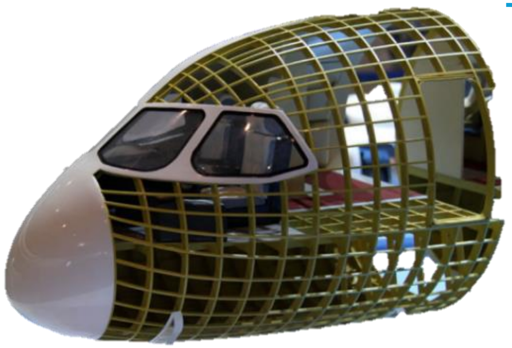
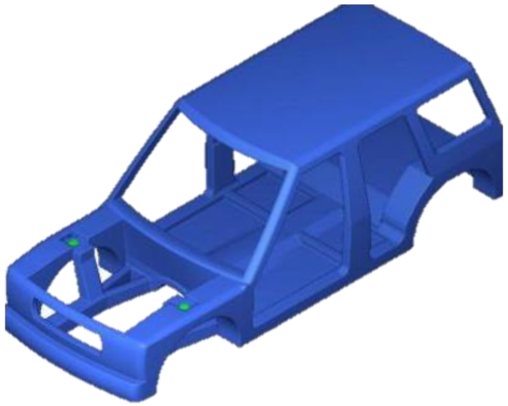
Need to reduce fuel consumption and environmental impact in the transport industry

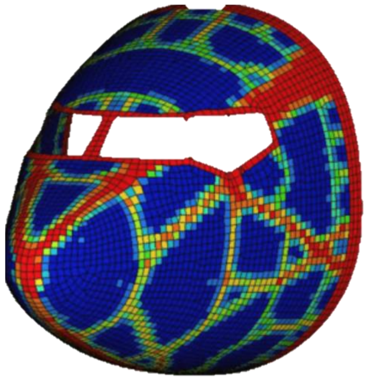
Aerospace industry

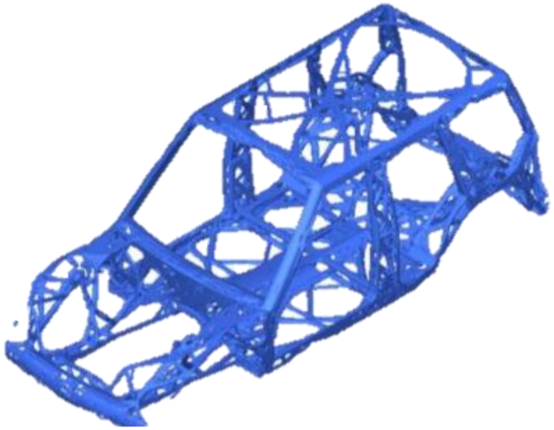


Automotive industry



Topology Optimization





Topology Optimization

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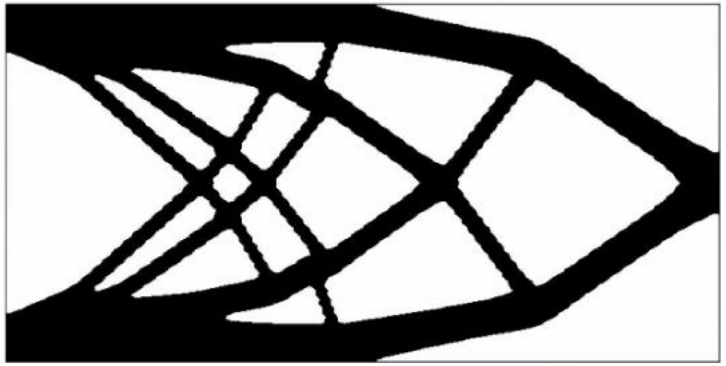
Problem formulation



$$\chi = \begin{cases} 1 & \text{if} \quad x \in \Omega \\ 0 & \text{if} \quad x \notin \Omega \end{cases}$$

$$\begin{cases} \min\limits_{\chi,u} & J(\chi,u) \\ \text{s.t} & a(\chi,u,v) = l(v) \\ & g_i(\chi) \leq 0 \end{cases}$$

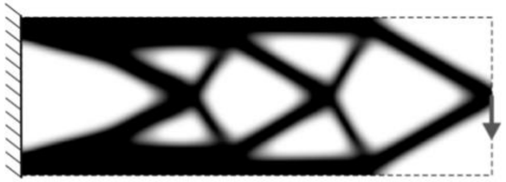
Common functionals:

$$J(\chi,u) = \int_D f u(\chi) dV \qquad g(\chi) = \int_D \chi dV - V^*$$

Design variables

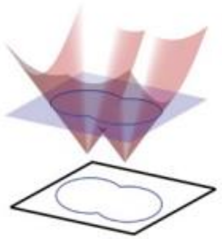
✗ The original design variable is discontinuous

✓ **Density** $\rho \in [0,1]$



$$C(\rho) = \rho^3 C^{(1)} + (1-\rho)^3 C^{(0)}$$

✓ **Level set** $\chi(\psi) = \begin{cases} 1 & \text{if} \quad \psi \leq 0 \\ 0 & \text{if} \quad \psi > 0 \end{cases}$



Additive manufacturing

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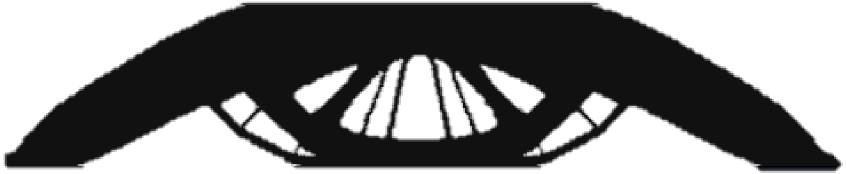
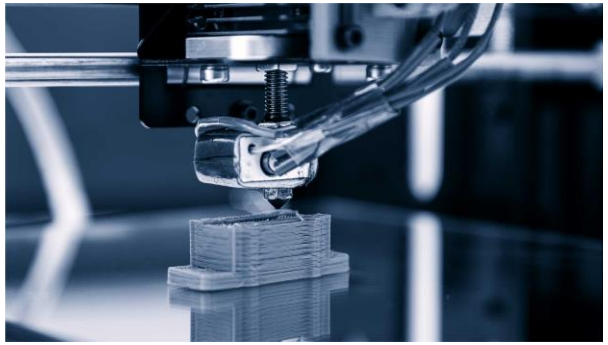
01
50%

Topology optimized design



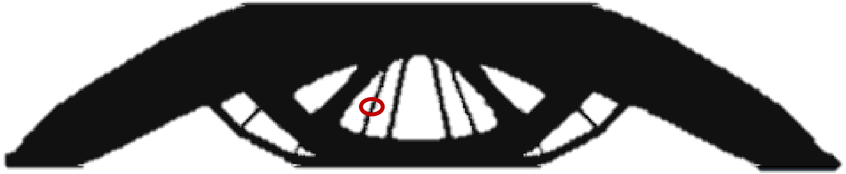


Use of additive manufacturing (3D CAD data printing)

02
75%

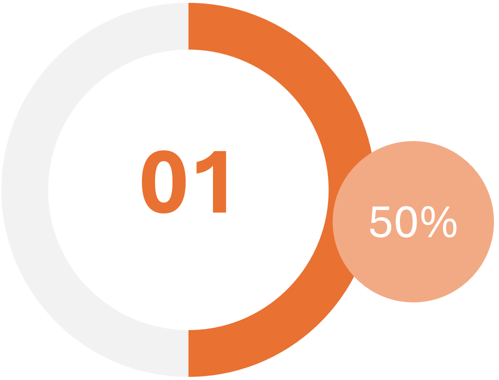
03
85%

3D printing process failed!
Not enough sensitivity of the machine

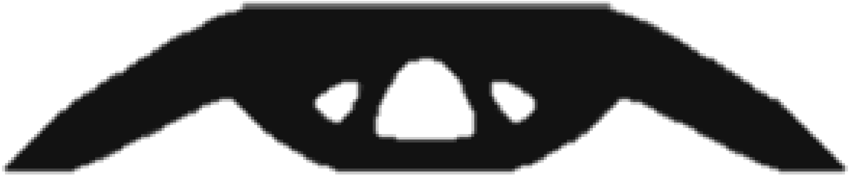


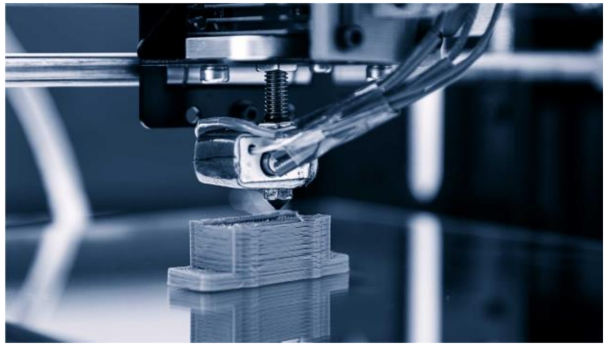
Minimum length scale constraint

Additive manufacturing

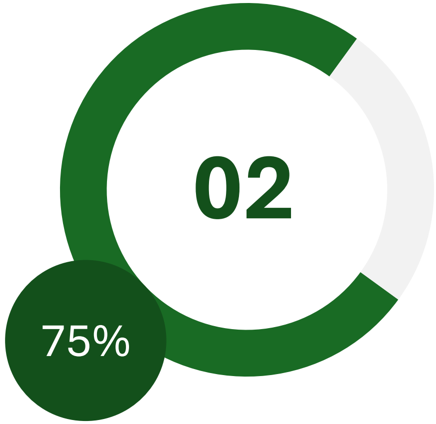


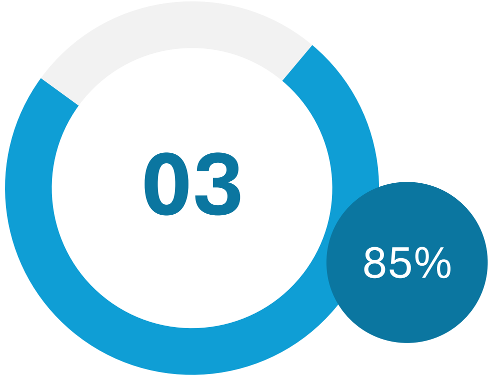
Topology optimized design



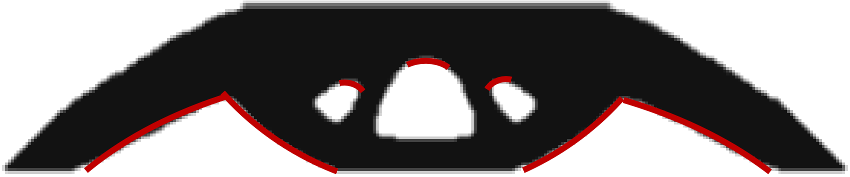


Use of additive manufacturing
(3D CAD data printing)





3D printing process failed!
Material fell during deposition process



Overhang constraint

Motivation for length scales and overhang

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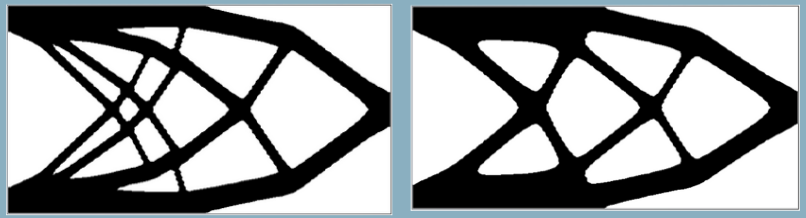
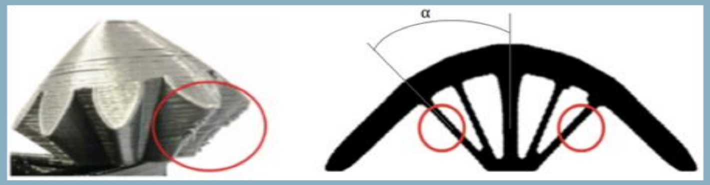
Length scales constraints

Thickness of bars must be monitored



Overhang constraints

Angle between the vertical axis and tangent vectors smaller than 45º



Bound formulation and three fields representation
(Lazarov, B.S., F. Wang & O. Sigmund, 2016)

← **Density** →

Overhang filtering through threshold projection
(Gaynor and Guest, 2016)

Isotropic Perimeter as penalty term
(S. Amstutz, C. Dapogny & A. Ferrer, 2022)

← **Level set** →

Mechanical constraints (intermediate shapes self weight compliance)
(G. Allaire et. al., 2017)

Motivation for length scales and overhang

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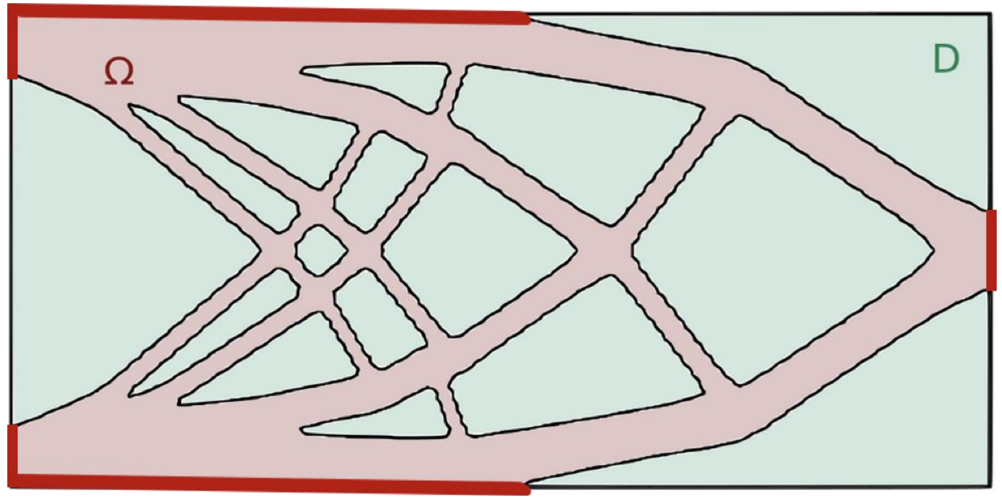
Current challenges: larger number of inequality & PDE constraints, layer-by-layer computation of the gradient and complex shape derivatives.

Length scales constraints		Overhang constraints
Bound formulation and three fields representation	← **Density** →	Overhang filtering through threshold projection
	↕	
Isotropic Perimeter as penalty term	← **Level set** →	Mechanical constraints (intermediate shapes self weight compliance)

Aim: propose a different method to decrease the shape complexity and control the overhang. Advantages: simplicity (perimeter), efficiency (no extra constraints) and useful for density and level set approaches.

Global isotropic and anisotropic perimeter
Definition

The **Perimeter** is a functional that computes the length of Ω boundaries.



Relative perimeter
INTERNAL BOUNDARIES

Total perimeter
INTERNAL + EXTERNAL BOUNDARIES

$$Per(\Omega) = \int_{\partial\Omega} 1 d\Gamma$$

- ✓ Shape derivative (level set)
- ✗ Gradient methods (density)

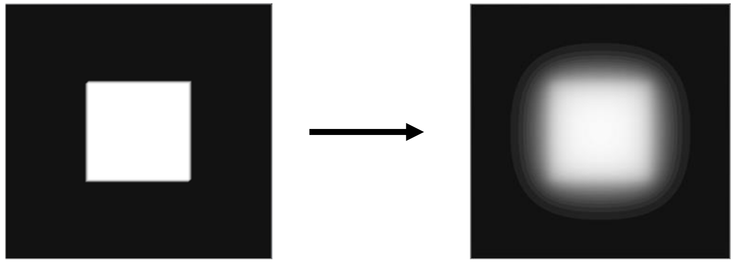
→ **1. Domain filtering**
2. Perimeter computation

Global isotropic and anisotropic perimeter
Definition

1. Domain filtering

Global isotropic relative perimeter: $H^1(D)$ projection with Neumann boundary conditions (smoothing).

$$\min_{\rho_\epsilon \in H^1} \frac{1}{2}\int_D \underbrace{(\rho_\epsilon - \chi)^2}_{\text{Similar}} dV + \frac{\epsilon^2}{2}\int_D \underbrace{(\nabla \rho_\epsilon)^2}_{\text{Finite gradient}} dV \equiv \min_{\rho_\epsilon \in H^1} J(\rho_\epsilon)$$

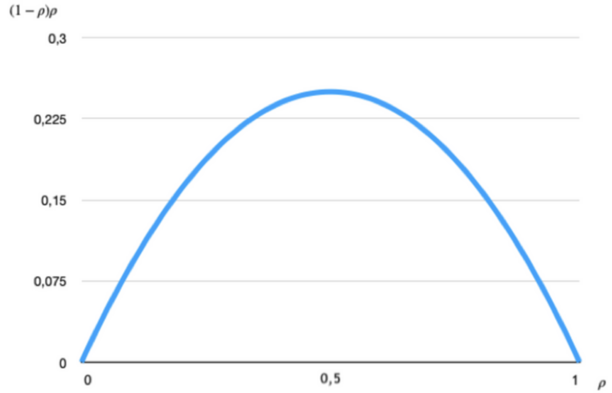


χ ρ_ϵ

2. Perimeter computation

$$P = \frac{1}{2\epsilon}\int_D (1-\rho_\epsilon)\chi \cdot dV$$

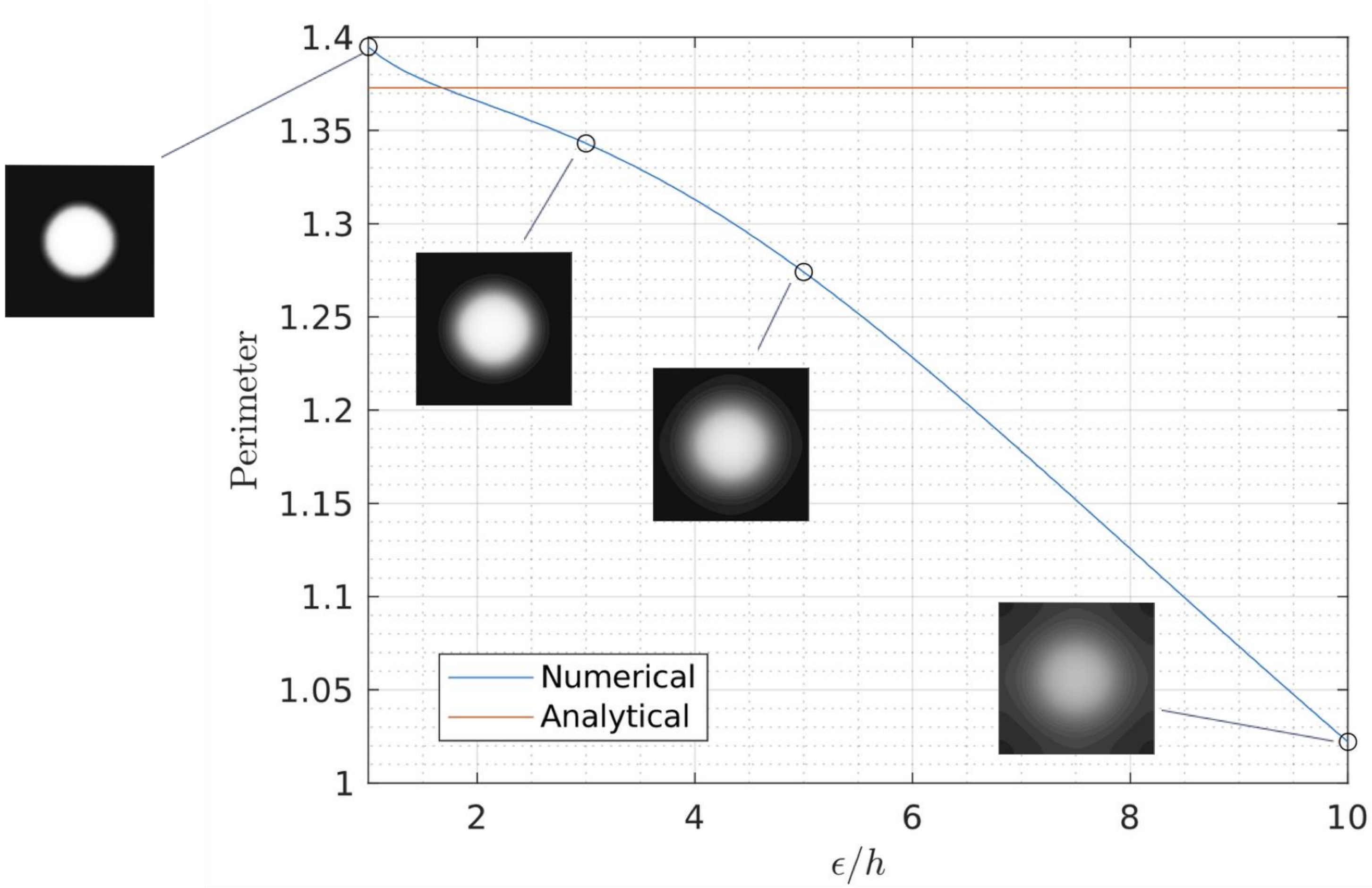
(S. Amstutz, C. Dapogny & A. Ferrer, 2022)



Density example

Global isotropic and anisotropic perimeter
Definition

Relative perimeter convergence

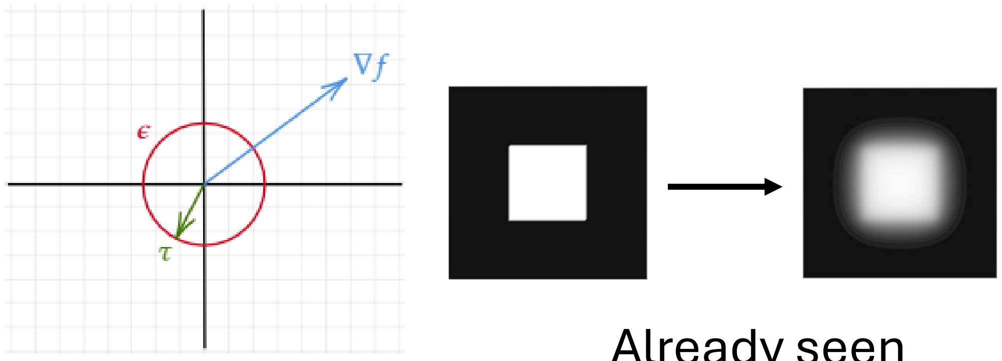


$$P = \frac{1}{2\epsilon}\int_D (1-\rho_\epsilon)\chi \cdot dV$$

Global isotropic and anisotropic perimeter
Definition

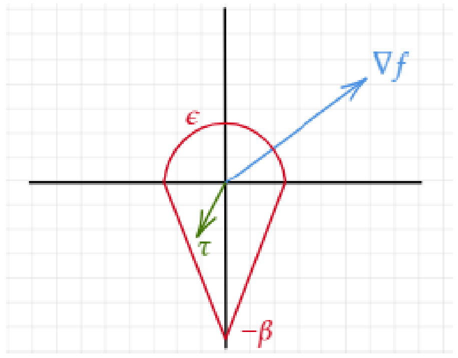
<u>Other domain filterings:</u>

1. Isotropic perimeter.



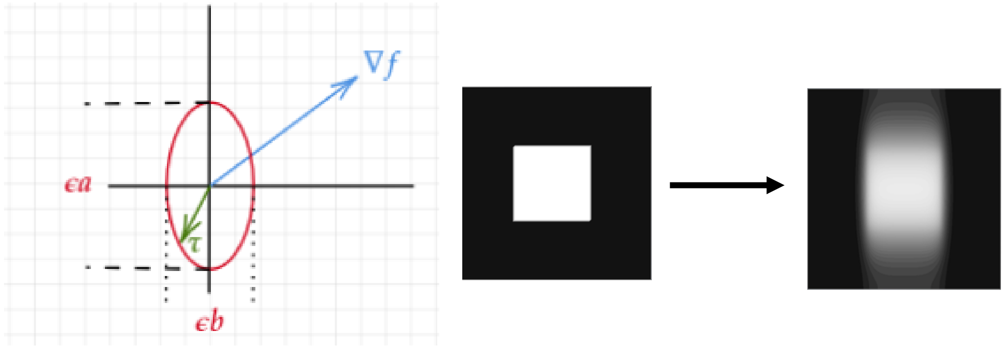
Already seen

3. Non-linear anisotropic perimeter.



Pending to implement

2. Anisotropic perimeter.



Implementation

$$\begin{cases} \min\limits_{\chi} & j(u_\chi) + \boxed{\gamma P(\chi)} \\ s.t & \int_D \chi \cdot dV - V^* = 0 \end{cases}$$

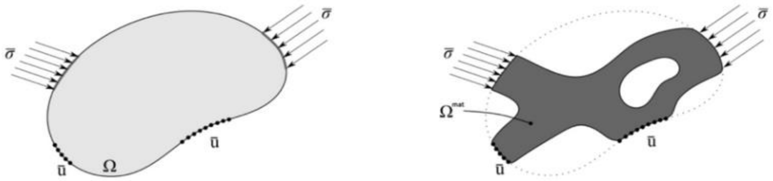
Application to topology optimization of structures and compliant mechanisms

Now, we will solve two optimization problems in the macroscopic scale:

$$\begin{cases} \min\limits_{\chi} & j(u_\chi) + \gamma P(\chi) \\ s.t & \int_D \chi \cdot dV - V^* = 0 \end{cases}$$

Minimum compliance $\quad j(u_\chi) = \int_D f u_\chi dV$

Compliant mechanisms $\quad j(u_\chi) = \int_{\partial D} k u_\chi dV$

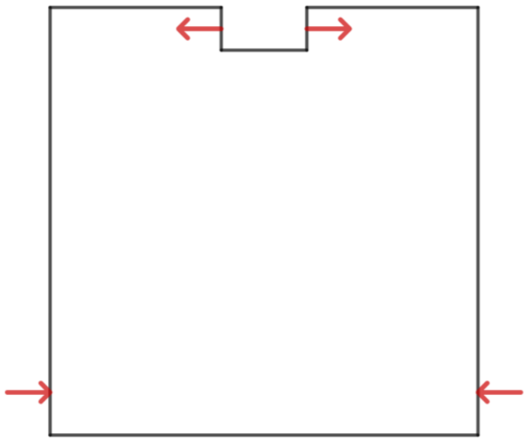


Design domain **Optimal design**

With u_χ solution of $a(\chi, u, v) = l(v)$

Several possibilities for the constitutive law

Cantilever beam



Gripper

Application to topology optimization of structures and compliant mechanisms

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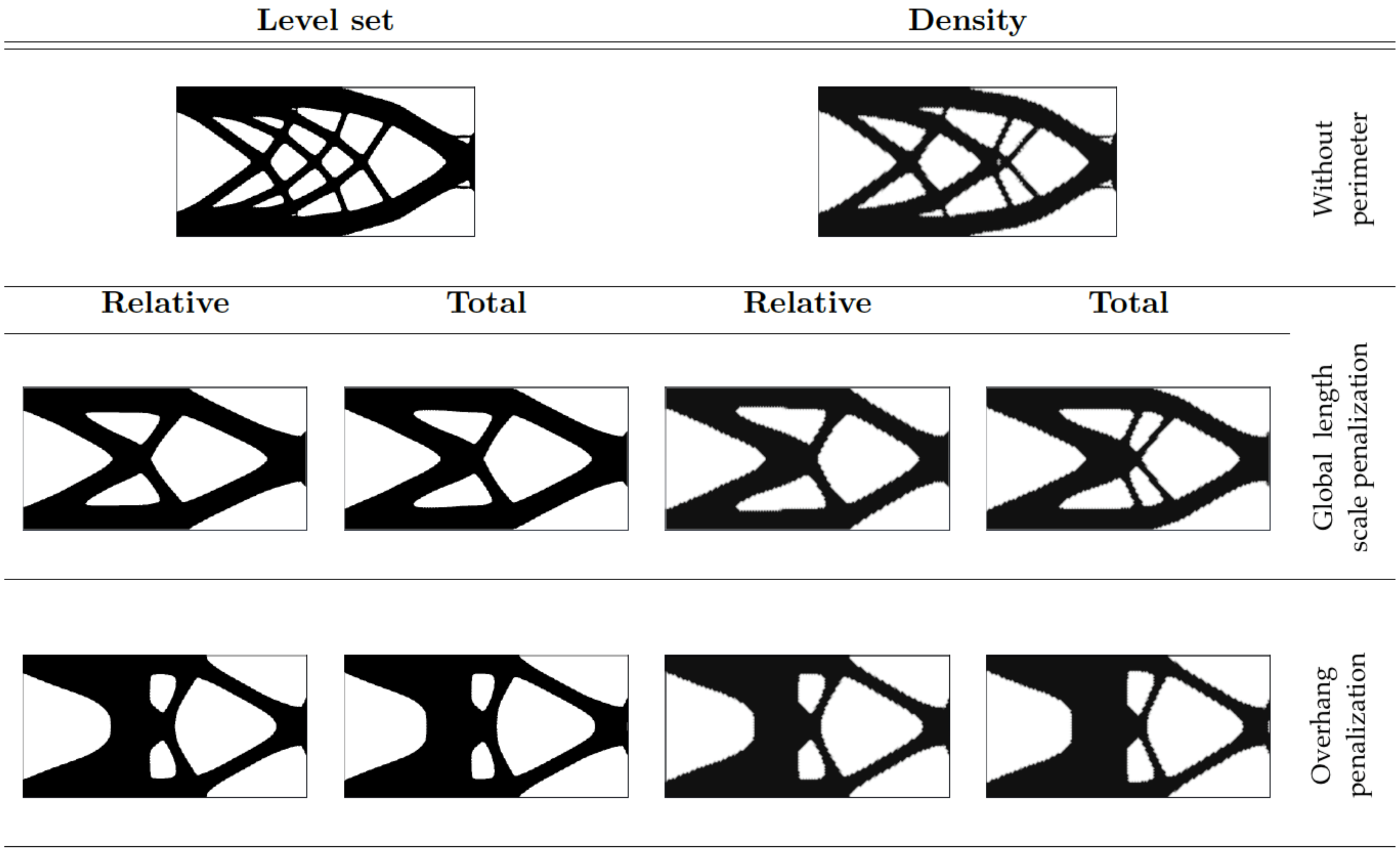


Cantilever beam

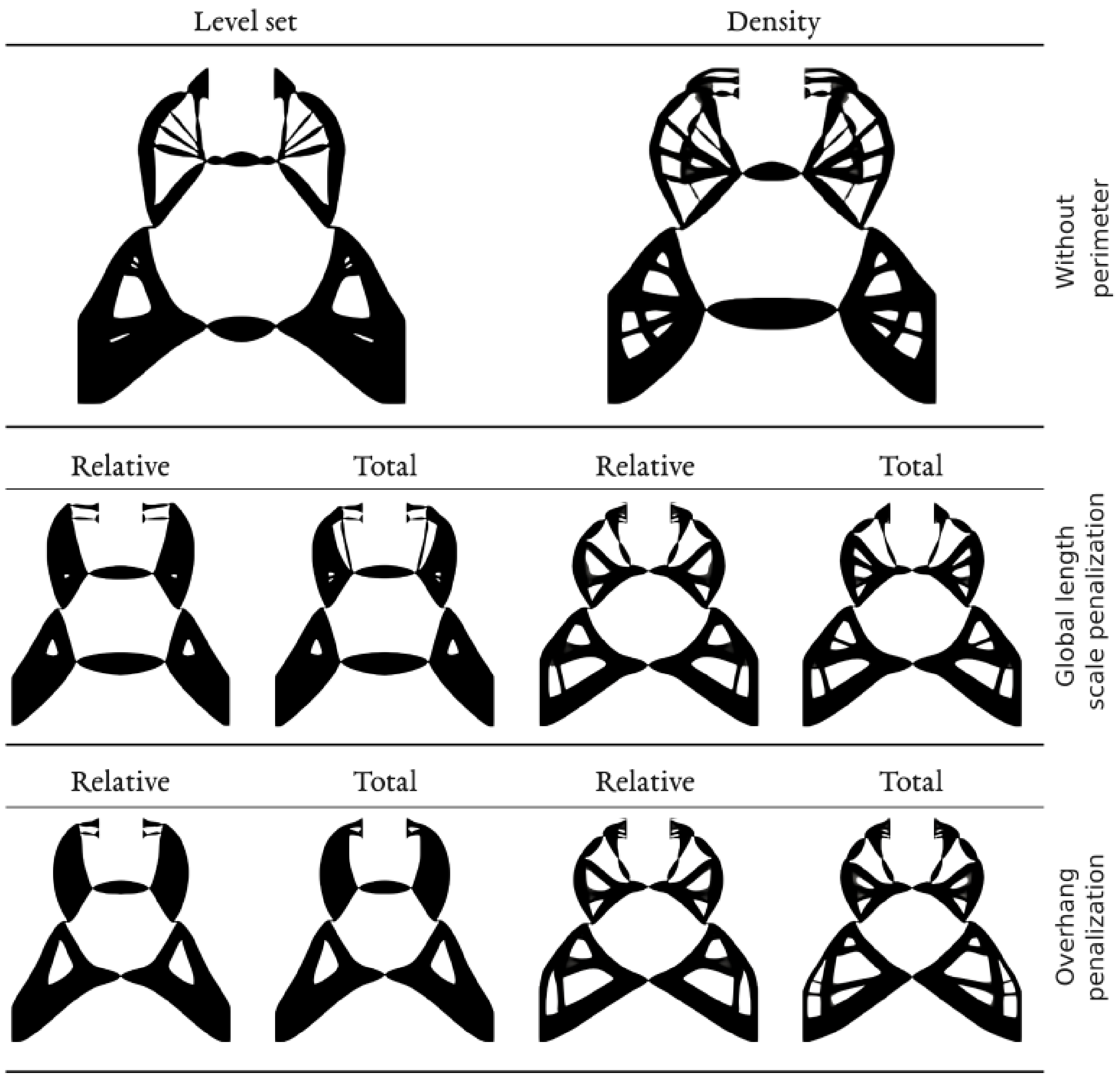
$\nu = 45^\circ$
$\alpha = 0^\circ$

ISOTROPIC PERIMETER

$\nu = 85^\circ$
$\alpha = 90^\circ$

ANISOTROPIC PERIMETER

Application to topology optimization of structures and compliant mechanisms



$\nu = 45^\circ$

$\alpha = 0^\circ$

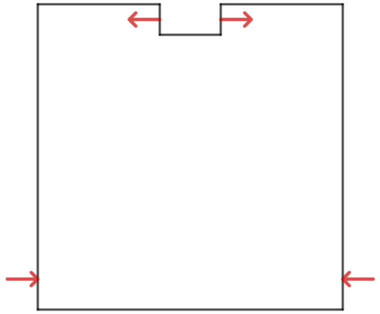
ISOTROPIC PERIMETER

$\nu = 85^\circ$

$\alpha = 90^\circ$

ANISOTROPIC PERIMETER

Gripper compliant mechanism



Extension to material design

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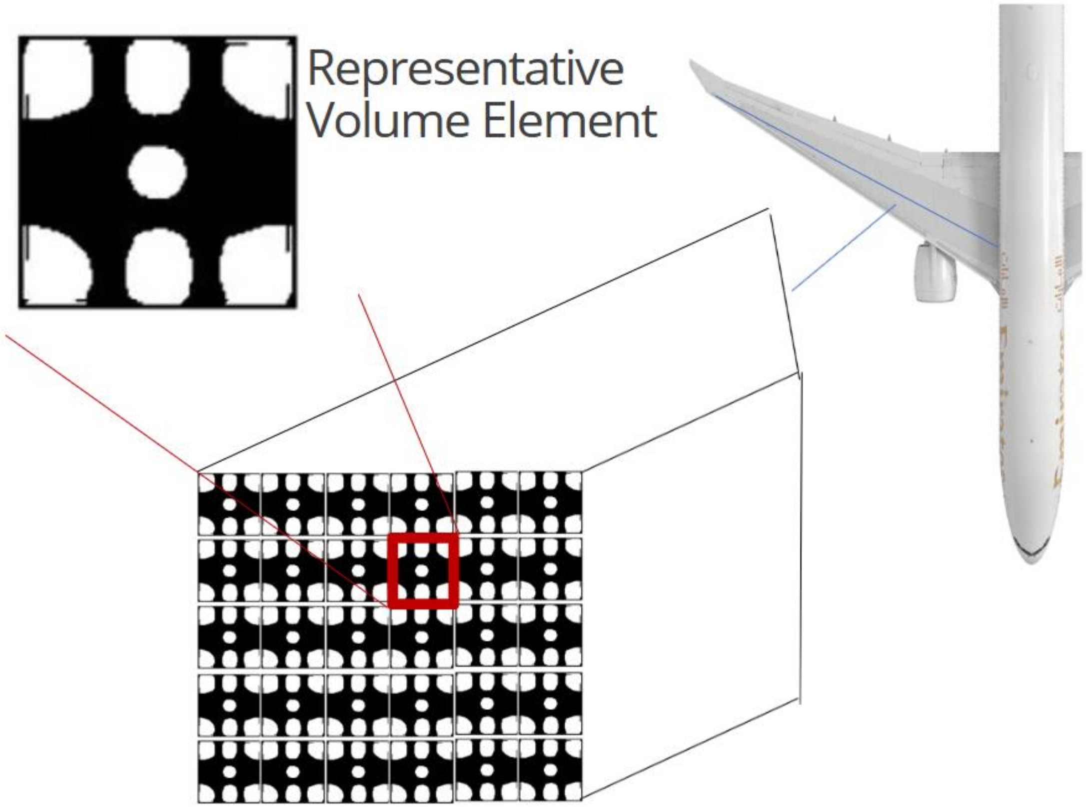
Consider the homogenized elasticity tensor satisfying:

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} = \mathbb{C} \cdot \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{xy} \end{bmatrix}$$

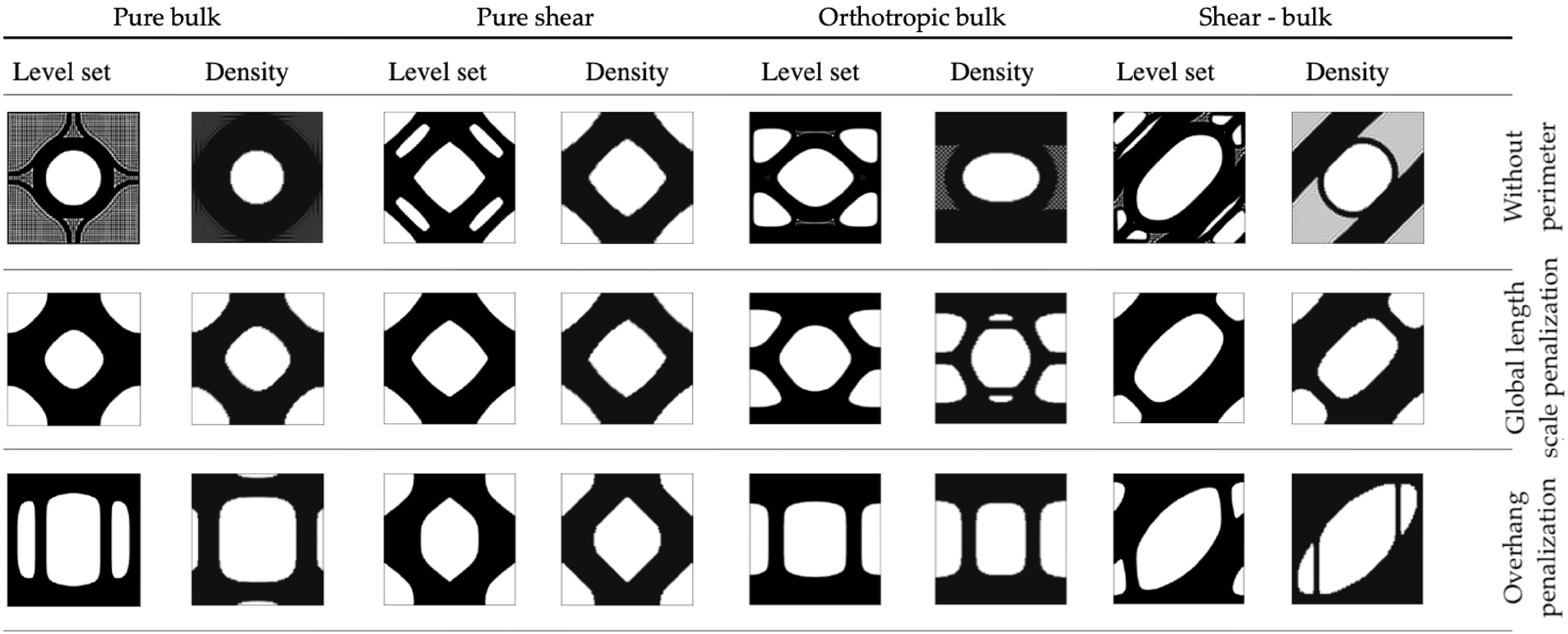


Optimization problem:

$$\begin{cases} \min\limits_{\chi} & \alpha_h^T \mathbb{C}^{-1} \beta_h + kP \\ \text{s.t} & \displaystyle\int_D \chi \cdot dV - V^* = 0 \end{cases}$$

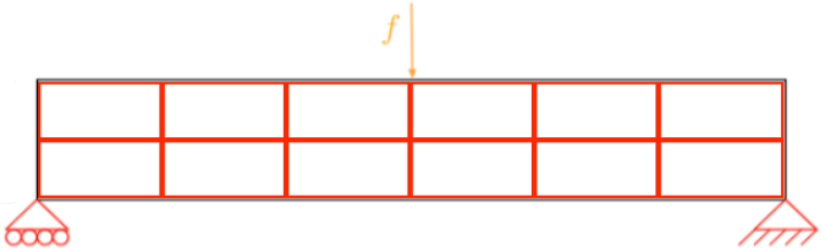
(E.A. de Souza Neto, S. Amstutz, S.M. Giusti, A.A. Novotny)

Extension to material design



Extension to local perimeter

<u>New motivation</u>: control the length of boundaries and overhang more locally.



One Lagrange multiplier per subdomain.

1

$$\begin{cases} \min\limits_{\chi} & \int_D f u_\chi dV + \gamma P(\chi) \\ s.t & \int_D \chi \cdot dV - V^* = 0 \end{cases}$$

2

$$\begin{cases} \min\limits_{\chi} & \int_D f u_\chi dV \\ s.t & \int_D \chi \cdot dV - V^* = 0 \\ & P(\chi) - P^* \leq 0 \; (\lambda_{Glob}) \end{cases}$$

3

$$\begin{cases} \min\limits_{\chi} & \int_D f u_\chi dV \\ s.t & \int_D \chi \cdot dV - V^* = 0 \\ & P_1(\chi) - P^* \leq 0 \; (\lambda_1) \\ & P_2(\chi) - P^* \leq 0 \; (\lambda_2) \\ & \dots \\ & P_{n_{subD}}(\chi) - P^* \leq 0 \; (\lambda_{n_{subD}}) \end{cases}$$

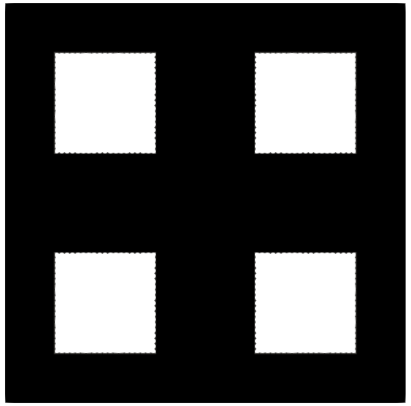
4

$$\begin{cases} \min\limits_{\chi} & \int_D f u_\chi dV \\ s.t & \int_D \chi \cdot dV - V^* = 0 \\ & \frac{1}{2\epsilon} \int_D \delta\lambda (1 - \rho_\epsilon(\chi)) \chi dV - P^* \leq 0 \end{cases}$$

Extension to local perimeter

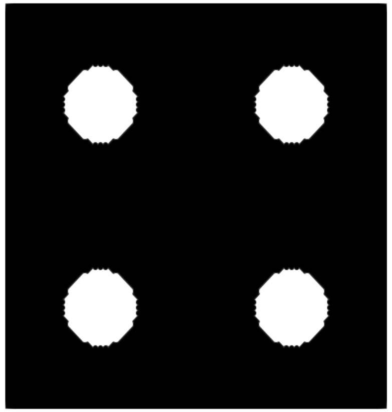
<u>First example</u>: global isotropic relative perimeter versus local isotropic perimeter.

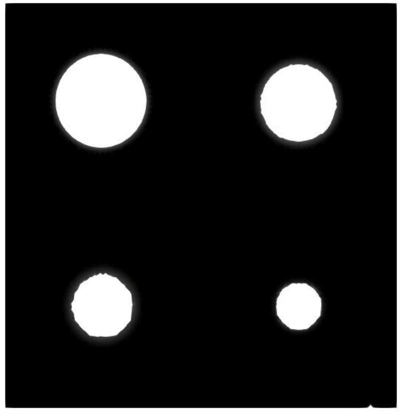
$$\begin{cases} \min\limits_{\chi} & V(\chi) = \int_D \chi \cdot dV \\ \text{s.t} & \dfrac{1}{2\epsilon}\int_D (1-\rho_\epsilon(\chi))\chi dV - P^* \leq 0 \end{cases}$$



Initial guess

$$\begin{cases} \min\limits_{\chi} & V(\chi) = \int_D \chi \cdot dV \\ \text{s.t} & \dfrac{1}{2\epsilon}\int_D \delta\lambda(1-\rho_\epsilon(\chi))\chi dV - P^* \leq 0 \end{cases}$$

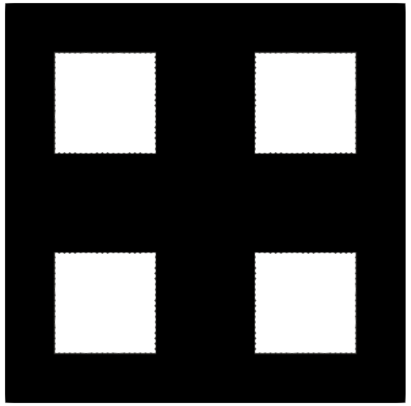




Extension to local perimeter

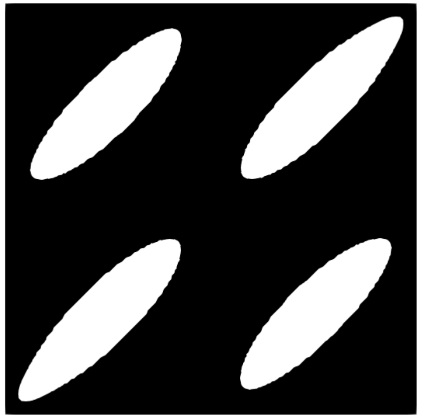
<u>Second example</u>: global anisotropic relative perimeter versus local anisotropic perimeter.

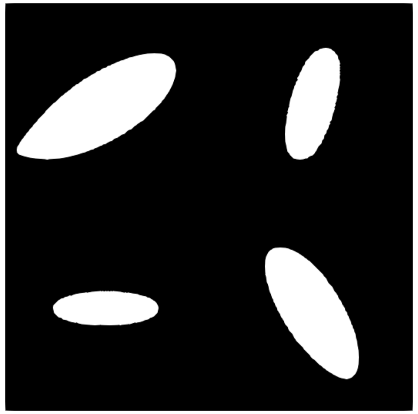
$$\begin{cases} \min\limits_{\chi} & V(\chi) = \displaystyle\int_D \chi \cdot dV \\ \text{s.t} & \dfrac{1}{2\epsilon}\displaystyle\int_D (1-\rho_\epsilon(\chi))\chi dV - P^* \leq 0 \end{cases}$$



Initial guess

$$\begin{cases} \min\limits_{\chi} & V(\chi) = \displaystyle\int_D \chi \cdot dV \\ \text{s.t} & \dfrac{1}{2\epsilon}\displaystyle\int_D \delta\lambda(1-\rho_\epsilon(\chi))\chi dV - P^* \leq 0 \end{cases}$$





Conclusions

Main idea: smooth the boundary & penalize gray areas

- Isotropic smoothing controls the global length
- Anisotropic smoothing may generally penalize also overhang regions

Avoiding bound formulation or extra mechanical constraints

Method useful for density and level set

Ongoing:

- Local perimeter as constraints
- Implementing the sense of the 3D printing
- **Topology optimization with composites**

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References

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GitHub

SwanLab/Swan

https://github.com/SwanLab/Swan/

WHAT

Features

Material design

Swan can perform analyses of microstructures: when combining it with its topology optimization capabilities, novel metamaterials can be designed in order to tackle complex challenges and further push the boundaries of engineering.

Structural design

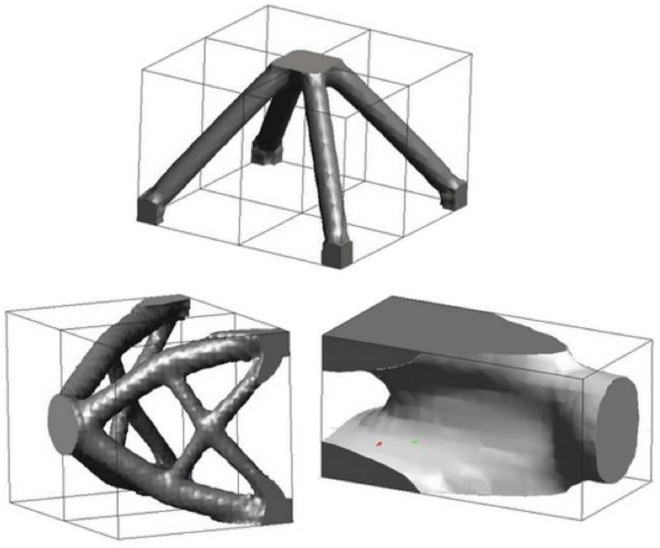
The modular design of Swan allows the combination of several functionals in order to define complex optimization problems. Among the functionals that can be used as constraints are compliance, volume, and perimeter. Swan also features density-based optimizers like Projected Gradient, MMA and IPOPT, as well as level-set methods such as SLERP, Projected SLERP and Hamilton-Jacobi.

Multi-scale

One of the key features that sets Swan apart from other topology optimization toolboxes is the ability to design optimal materials at the micro scale, and reuse the obtained results to perform analyses at the macro level.

Multiphysics, and much more

We are constantly looking ahead and recruiting new contributors in order to keep expanding Swan's capabilities. Among the planned upcoming features are multiphysics, 3D microstructural optimization, and many more.



Optimization of the 3D cantilever benchmark

References

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Global length and overhang control for level set and density approaches via perimeter minimization

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Article already submitted to a journal!

AjutsOró cultura científica en català

GitHub https://github.com/SwanLab/Swan/