Un cadre de conception pour l'impression des structures minces multi-échelles, incluant une analyse de flambement non intrusive

How to check local buckling in multiscale topology optimization ?

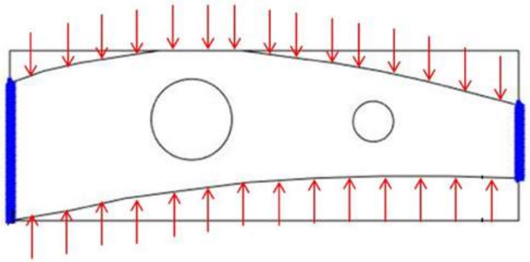
Edouard Duriez 1, @ , Frederic Lachaud 2, *, @ , Catherine Azzaro-Pantel 3, @ , Joseph Morlier 2, *, @ , Miguel Charlotte 4, *, @

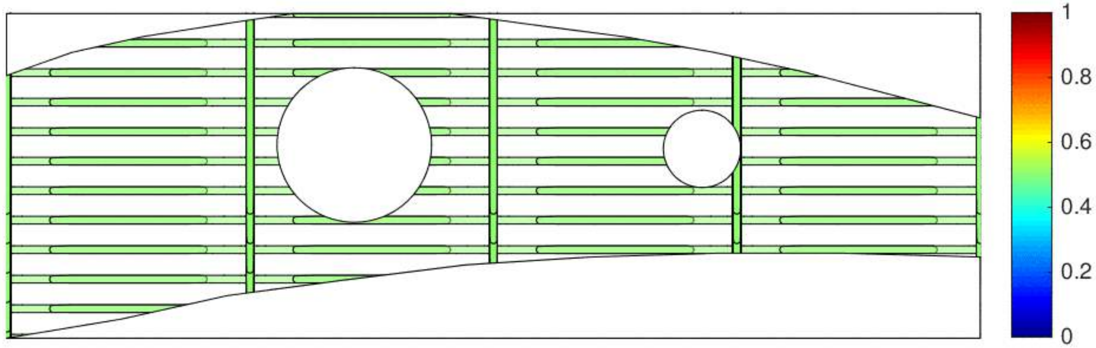
joseph.morlier@isae-supaero.fr

ICA cnrs dépasser les frontières isae Institut Supérieur de l'Aéronautique et de l'Espace SUPAERO

About Me? https://ica.cnrs.fr/en/author/jmorlier/

- Prof in Structural and Multidisciplinary Optimization





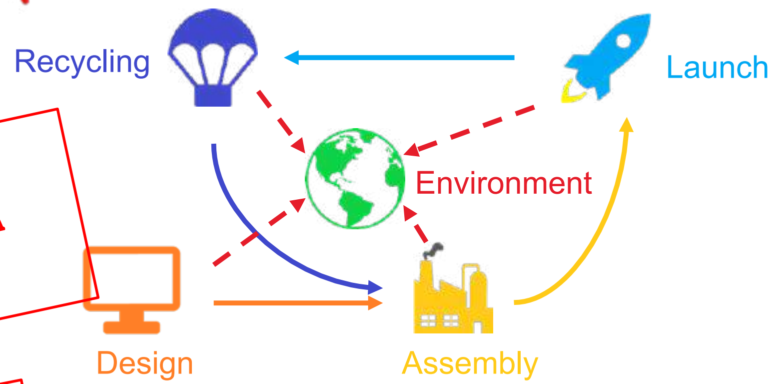
About Me?

https://ica.cnrs.fr/en/author/jmorlier/

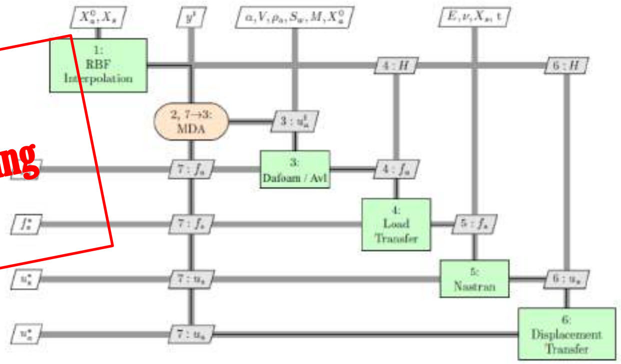
ICA

- 6 PhDs, 3 MsCs

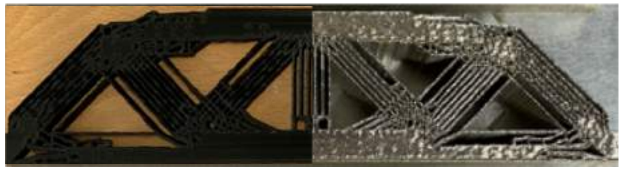
MDO for Aerospace systems Including LCA := EcoOptimization



MDO for Aeroelastic Wing design

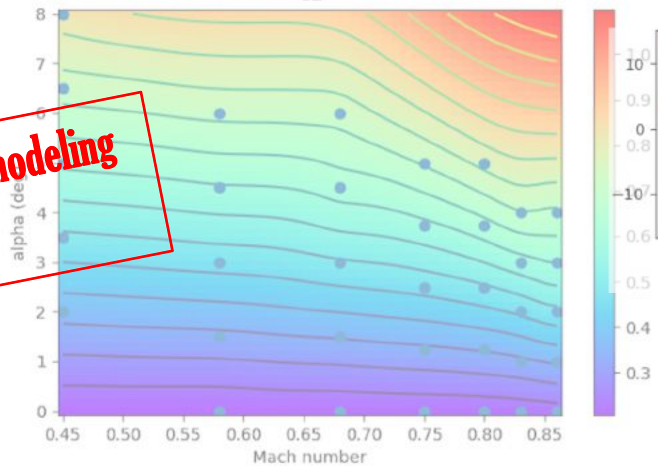


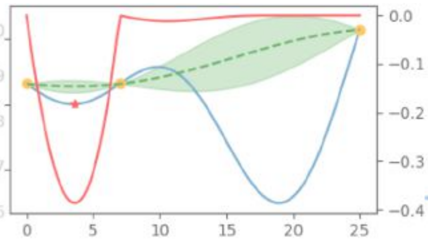
Digital fabrication



https://github.com/SMTorg/SMT

Surrogate modeling AI4E





SMT

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RMIT UNIVERSITY

TU Delft

UNIVERSITY OF MICHIGAN

Au programme

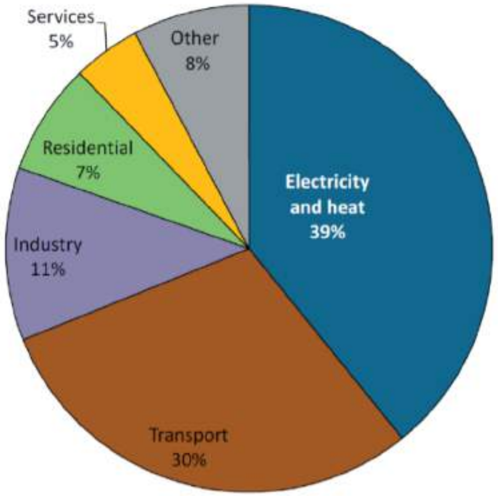
- **Part1: EMTO**
- **Part2: Buckling mitigation**
- **Conclusions**

Au programme

Thanks to Edouard Duriez

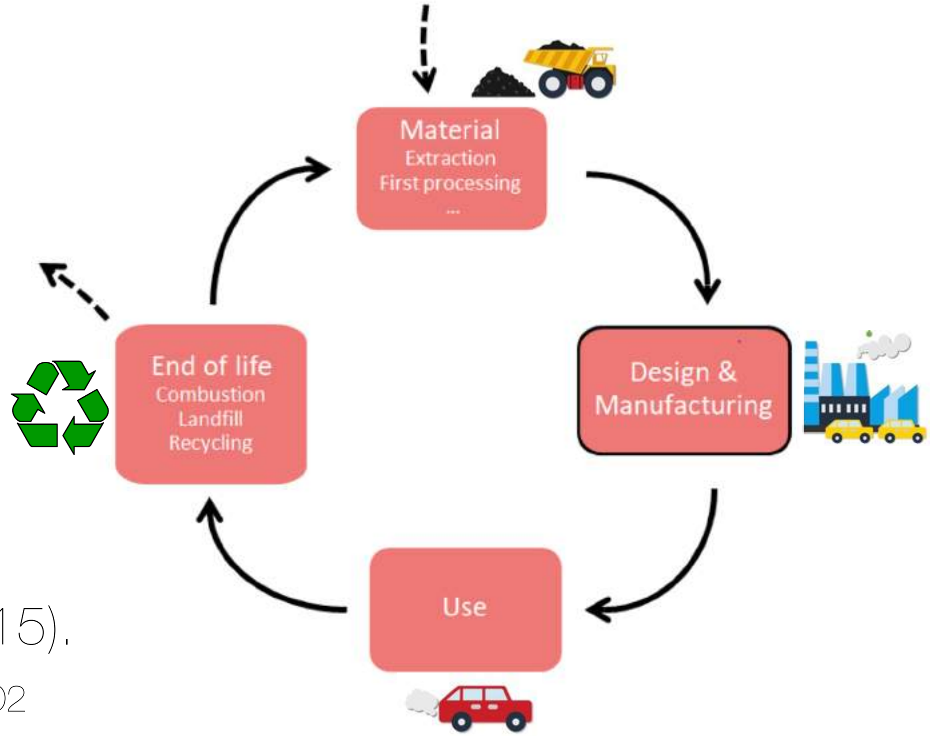
- **Part1: EMTO**
- **Part2: Buckling mitigation**
- **Conclusions**

Overview



CO_2 emissions of the OECD (2015).

International Energy Agency IEA. Energy and CO2 emissions in the OECD. 2017



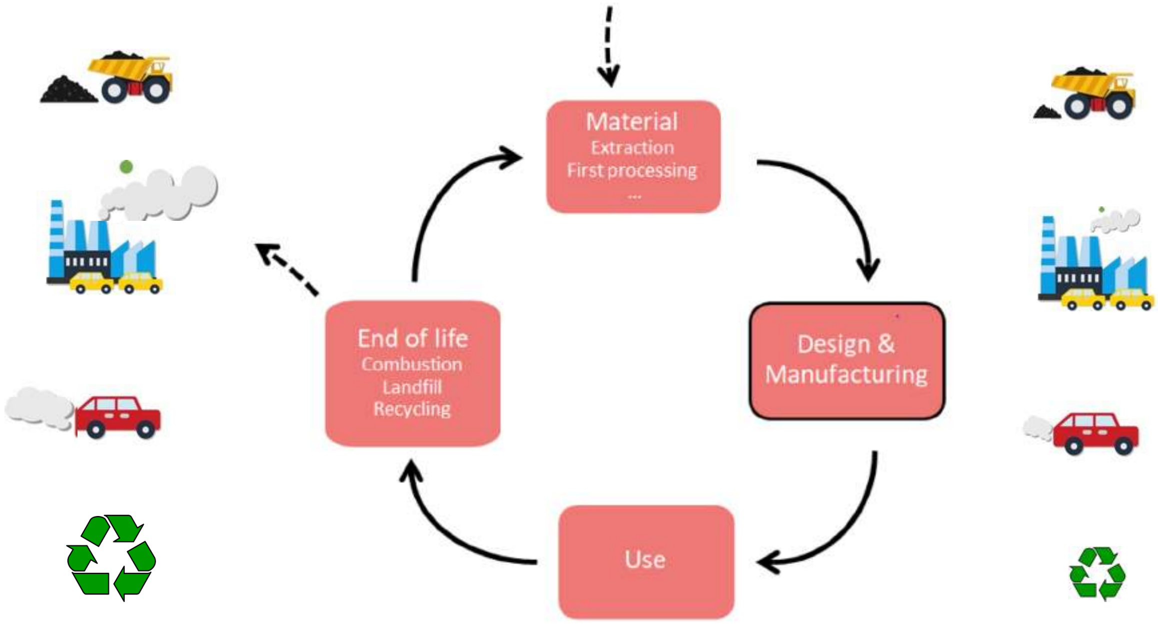
Vehicle life cycle

Q : How to find structural designs, materials and additive manufacturing processes with the lowest life-cycle CO_2 footprint**?**

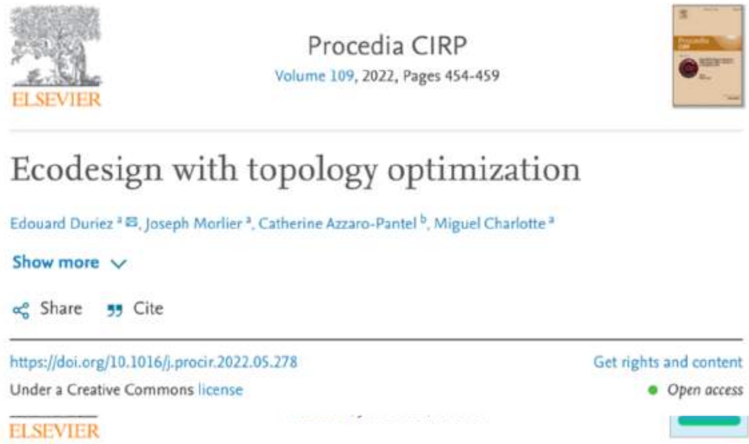
Hypothesis 1

- CO_2 emissions minimization of parts
  - If material choice is **imposed** => mass minimization

If not… more complicated



Vehicle life cycle



ELSEVIER

Procedia CIRP
Volume 109, 2022, Pages 454-459

Ecodesign with topology optimization

Edouard Duriez [a], Joseph Morlier [a], Catherine Azzaro-Pantel [b], Miguel Charlotte [a]

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ELSEVIER

A fast method of material, design and process eco-selection via topology optimization, for additive manufactured structures

Edouard Duriez [a], Catherine Azzaro-Pantel [b], Joseph Morlier [a], Miguel Charlotte [a]

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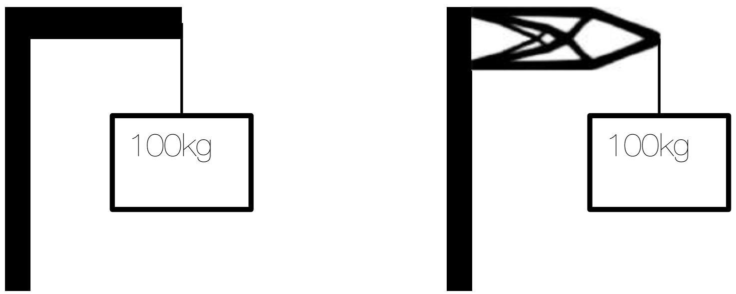
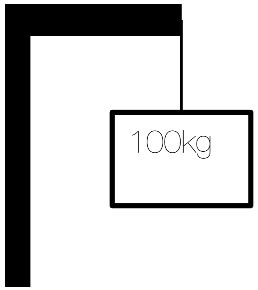
Mass minimization of parts

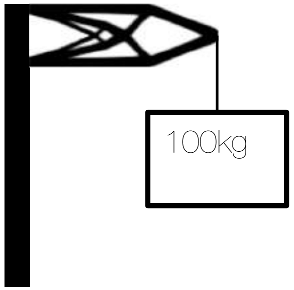
- Redesign through topology optimization
  => same performance



Mass minimization of parts

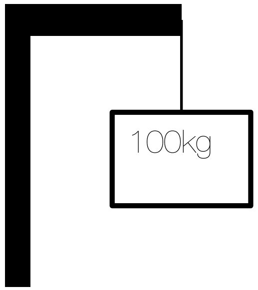
- Redesign through topology optimization
  => same performance but lower mass

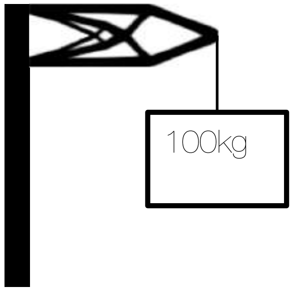




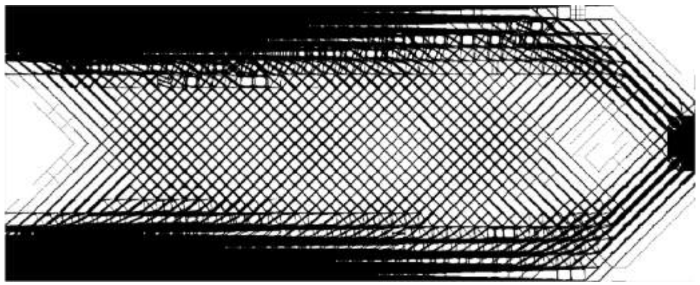
Mass minimization of parts

- Redesign through topology optimization
  => same performance but lower mass





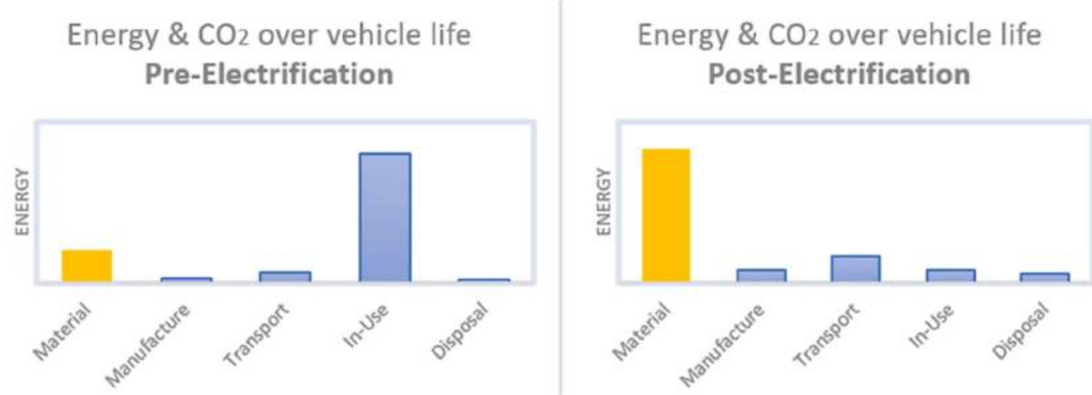
  - One step further : multiscale topology optimization



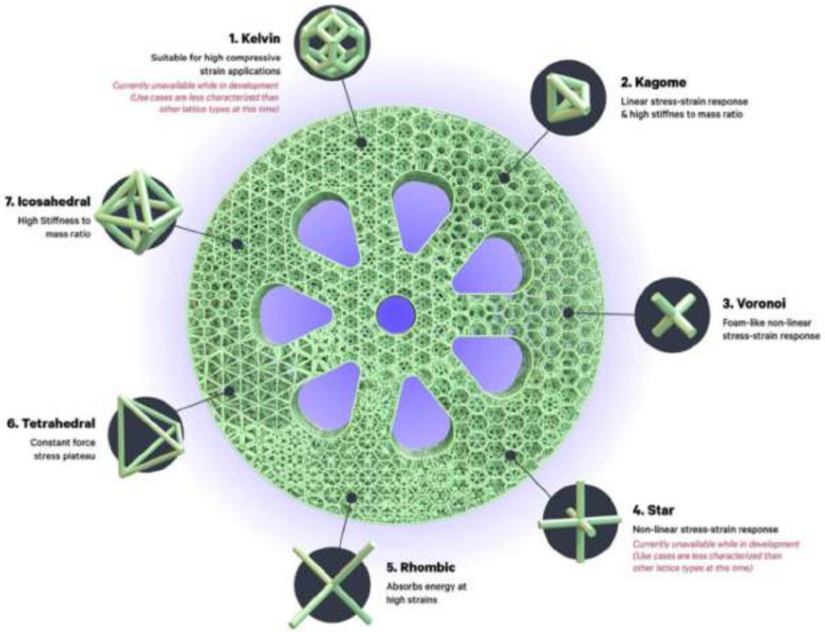
Unit cell/material/process

as new design variables in Structural and Multidisciplinary Optimization

Eco Material selection
Eco Process selection



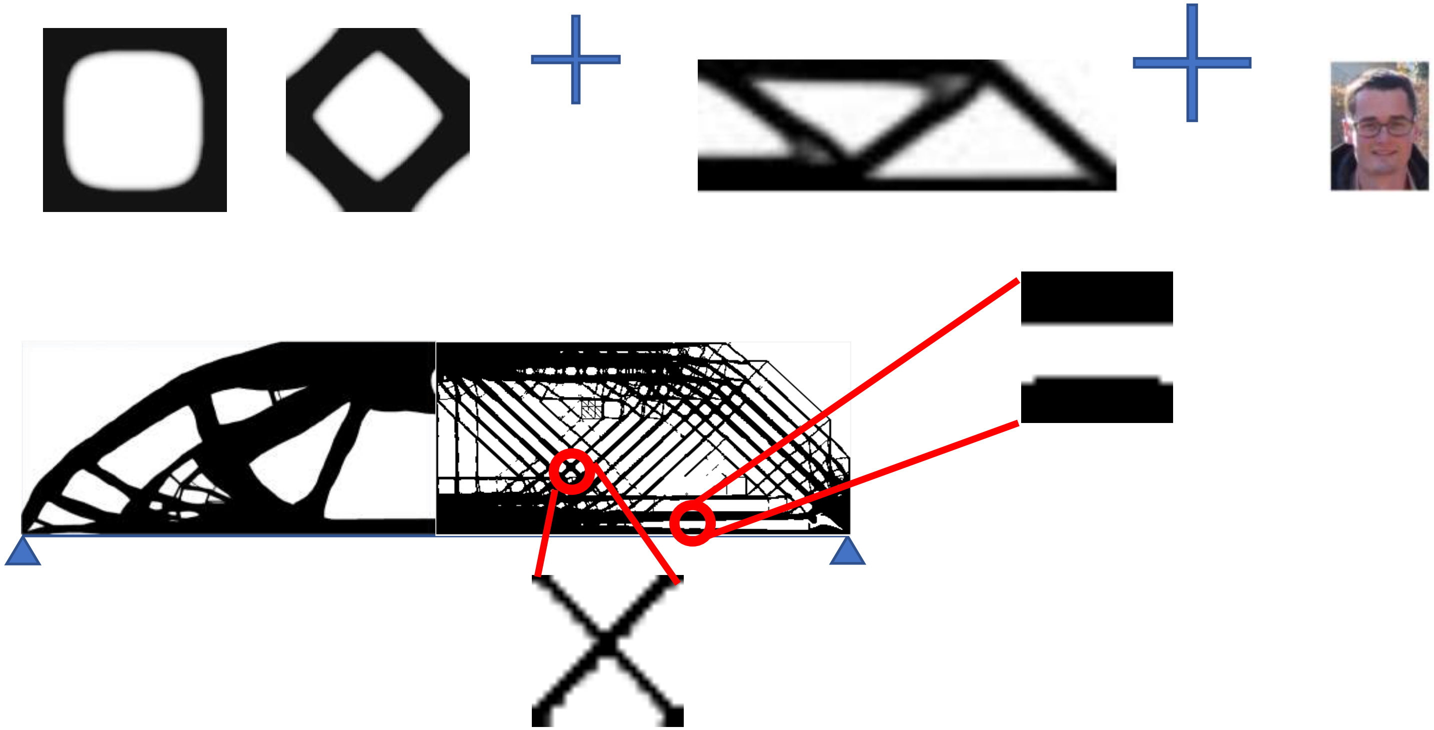
https://www.ansys.com/blog/the-impact-of-materials-on-sustainability-part-2



Unit cell design (anisotropy)
Digital materials

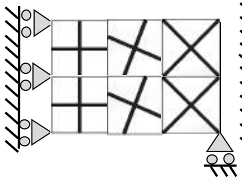
Multi-scale TO (well connected+ locally-oriented)

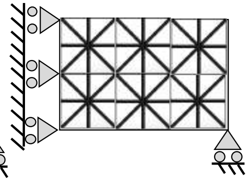
A two level optimization that combines Unit cell design & Topology Optimization



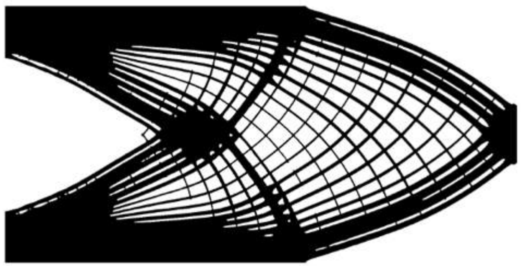
Xia L, Breitkopf P (2015) Design of materials using topology optimization and energy-based homogenization approach in Matlab. Struct Multidisc Optim 52(6):1229–1241.
Wu, Jun, Ole Sigmund, and Jeroen P. Groen. "Topology optimization of multi-scale structures: a review." Structural and Multidisciplinary Optimization 63.3 (2021): 1455-1480.

Main MTO methods

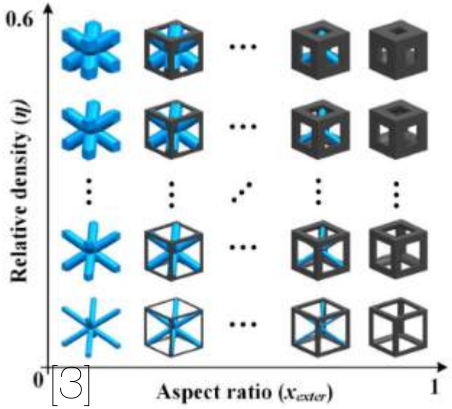




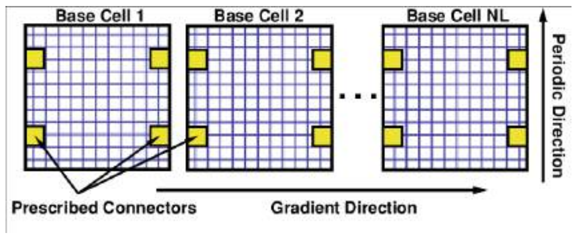
Approach	Examples	Connectivity	Locally adapted	Speed	Manufacturability
De-homogenization	[1],[2]				
Parametrized lattice	[3]				
Connectors	[4]				



[2]



[3]



[4]

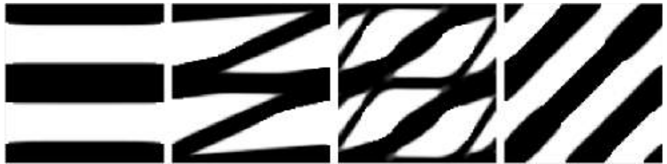
[1] Grégoire Allaire, Perle Geoffroy-Donders et Olivier Pantz. « Topology optimization of modulated and oriented periodic microstructures by the homogenization method ». en. In : *Computers & Mathematics with Applications*.
[2] Groen, Jeroen P., and Ole Sigmund. "Homogenization-Based Topology Optimization for High-Resolution Manufacturable Microstructures." *International Journal for Numerical Methods in Engineering*
[3] Wang, Chuang, et al. "Concurrent Design of Hierarchical Structures with Three-Dimensional Parameterized Lattice Microstructures for Additive Manufacturing." *Structural and Multidisciplinary Optimization*
[4] Zhou S, Li Q (2008) Design of graded two-phase microstructures for tailored elasticity gradients. Journal of Materials Science
[5] Wu, Jun, et al. "Topology Optimization of Multi-Scale Structures: A Review." *Structural and Multidisciplinary Optimization*

Scale-bridging variables

- Density : ρ

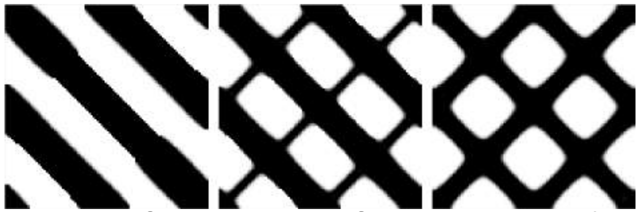
ρ=0.2 ρ=0.5 ρ=0.8

- Orientation : α



α = 0° α = 22.5° α = 33° α = 45°

Cubicity : x_{cub}



x_{cub} = 0 x_{cub} = 0.5 x_{cub} = 1

→ relative importance of the two principal directions. A value of 1 means the two principal directions are equivalent, while a value of 0 means the first principal direction alone is considered.

Microscale Problem

Since the objective is to create micro-structure with optimal properties towards specific directions, the objective function is a weighted function of the two components $E\alpha$ 1111 and $E\alpha$ 2222

the problem being solved at the micro-scale to obtain the i^{th} i^{th}-macrocell.

$$\begin{aligned} \underset{\rho_{i,j}}{\text{minimize}} \quad & c_i = E^{i\alpha}_{1111} * (1 - \frac{x^i_{\text{cub}}}{2}) + E^{i\alpha}_{2222} * \frac{x^i_{\text{cub}}}{2} \\ \text{subject to} \quad & K_i u_i^{A(pq)} = f_i^{(pq)} \\ & \sum_{j=1}^{m} \rho_{i,j} \leq m * x^i_{\text{dens}} \\ & \epsilon < \rho_{i,j} < 1 \end{aligned}$$

where K_i is the i^{th}-macrocell assembled stiffness matrix, $u_i^{A(pq)}$ and $f_i^{(pq)}$ are the global displacement vector and the external force vector of the i^{th}-macrocell for the case (pq) respectively, $\rho_{i,j}$ is the density of the j^{th} micro-element of the i^{th}-macrocell.

In all the results presented in Section 2.4, micro-structures of size 100*100 are used.

Rotated homogenized stiffness tensor

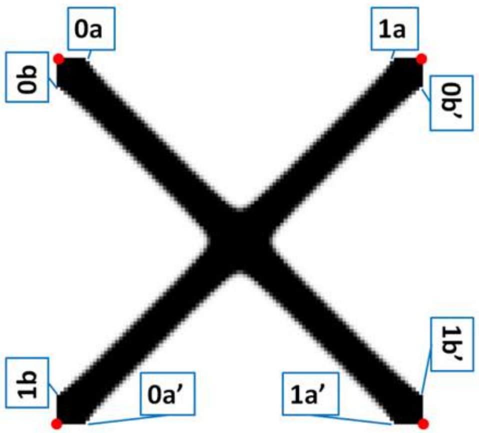
$$\boldsymbol{E}^{\alpha} = \boldsymbol{M}_{\alpha}^{T} * \mathbf{E} * \boldsymbol{M}_{\alpha} = (E^{\alpha}_{klmn})_{k,l,m,n\in\{1,2\}}$$

Transmission zones

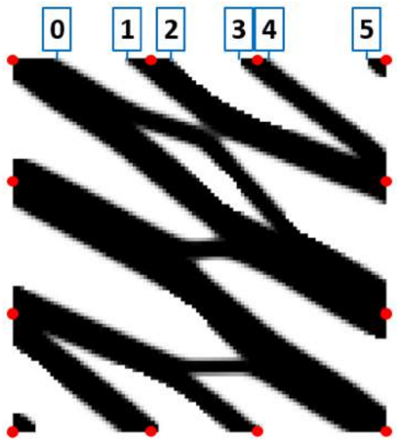
- To address connectivity issue
- Impose location of strain transmission from one cell to another

$\Rightarrow$ Periodic boundary conditions only in those locations

4 transmission Zones (TZ):



12TZ:



- Difference to Kinematical Connective constraints : absence of non-design zones

Zhou S, Li Q (2008) Design of graded two-phase microstructures for tailored elasticity gradients. Journal of Materials Science 43:5157–5167. https://doi.org/10.1007/s10853-008-2722-y

Multiscale Topology Optimization

Macroscale Problem

$$\underset{x^i_{\text{dens}}, x^i_a, x^i_b, \ldots}{\text{minimize}} \quad c = u^T K u$$

$$\text{subject } to \quad Ku = f$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \rho_{i,j} \leq n \times m \times v_f$$

$$\epsilon < \rho_{i,j} < 1$$

need to solve

Microscale Problem

$$\underset{\rho_{i,j}}{\text{minimize}} \quad c_i = E^{i\alpha}_{1111} \times \left(1 - \frac{x^i_{\text{cub}}}{2}\right) + E^{i\alpha}_{2222} \times \frac{x^i_{\text{cub}}}{2}$$

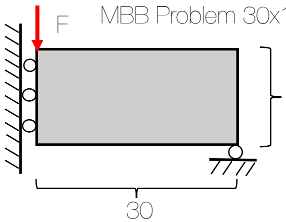
$$\text{subject to} \quad K_i u_i^{A(pq)} = f_i^{(pq)}$$

$$\sum_{j=1}^{m} \rho_{i,j} \leq m \times x^i_{\text{dens}}$$

$$x^i = [x^i_{\text{dens}}, x^i_{\text{or}}, x^i_{\text{cub}}]$$

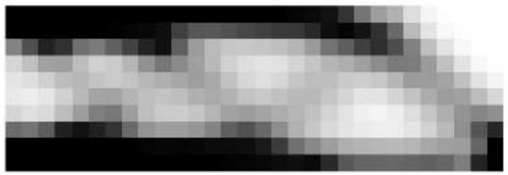
best unit cell per quad

MBB Problem 30x10 macro elements

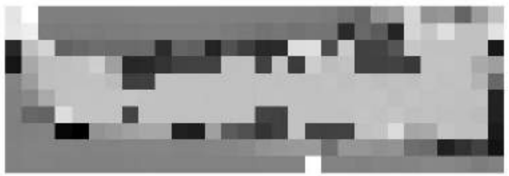


Theoretical compliance 192.7

Density of the cells

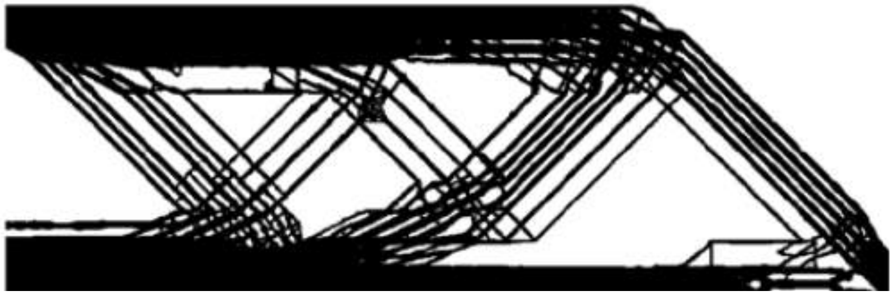


Orientation of the cells



Cubicity of the cells

Since the objective is to create micro-structure with optimal properties towards specific directions, the objective function is a weighted function of the two components $E\alpha$ 1111 and $E\alpha$ 2222

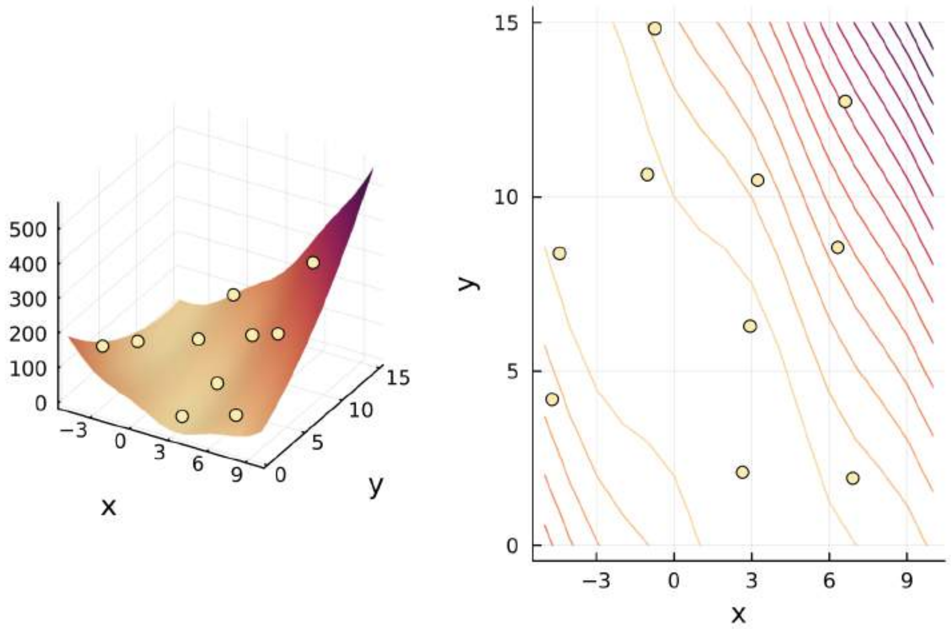


Comparison

- Top88 versus EMTO

How to speed up?

- To address speed issue ($t_{tot} = t_{cell} * n_{cell} * n_{it};\ t_{cell} = 10'$)



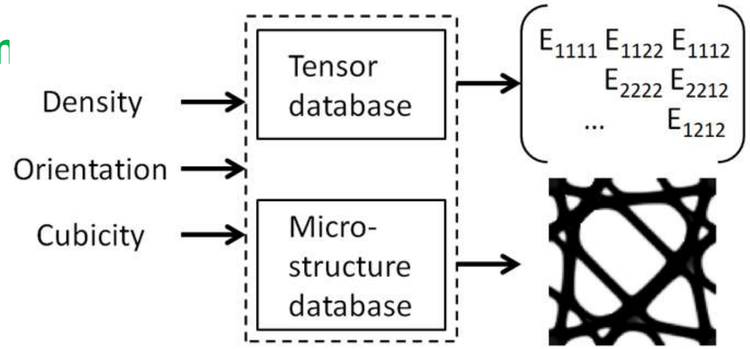
https://github.com/SMTorg/SMT

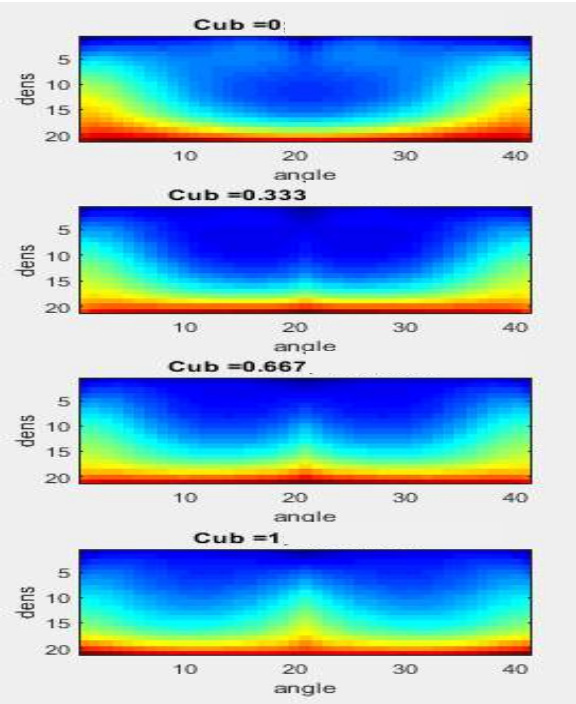
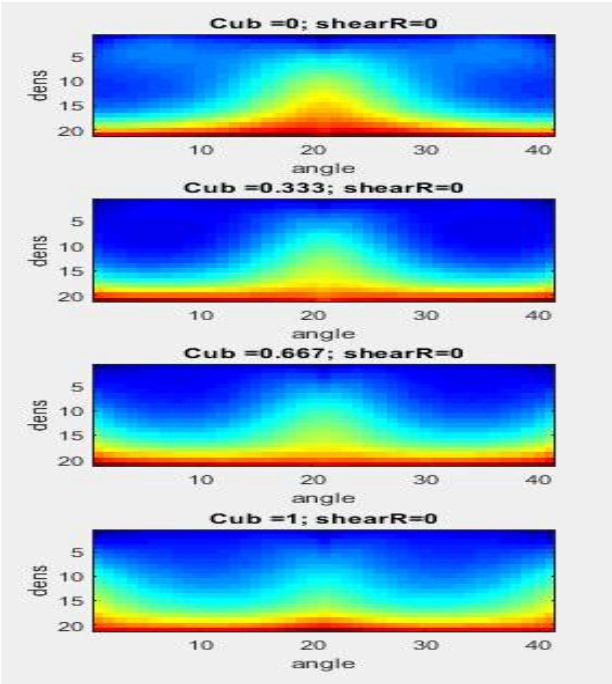
database:
https://data.mendeley.com/datasets/b5hyzxg7fv/1
DOI: 10.17632/b5hyzxg7fv.1

- t_{tot} =10’’ on 200-300 macro-element design

Elastic tensor's surrogate

to Avoid Nelement*cellOptimization at each macroOptim step



- 3 inputs : macro-density, angle, cubicity
- 6 outputs : elastic tensor values
- Gaussian interpolation : capture local effects but mitigate noise
- E1111  E2222: 

Efficient Multiscale Topology Optimization

Macroscale Problem

$$\underset{x^i_{dens}, x^i_a, x^i_b, \dots}{\text{minimize}} \quad c = u^T K u$$

$$\text{subject } to \quad Ku = f$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \rho_{i,j} \leq n \times m \times v_f$$

$$\epsilon < \rho_{i,j} < 1$$

$$x^i = [x^i_{\text{dens}}, x^i_{\text{or}}, x^i_{\text{cub}}]$$

Gaussian Process Regression

$$\mathbf{E}_{\text{pred}}(x^i) = \frac{\sum_{l=1}^{k} G(x^i, x_l)\mathbf{E}_{\text{db}}(x_l)}{\sum_{l=1}^{k} G(x^i, x_l)}$$

$$G(x^i, x_l) = \exp\left(\frac{-d_{\text{eucl}}(x^i, x_l)^2}{2b^2}\right)$$

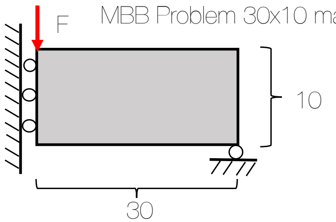
$$x^{i\prime} = [x^i_{\text{dens}} + \Delta, x^i_{\text{or}}, x^i_{\text{cub}}] \qquad \Delta = 0.01$$

$$\frac{\partial \mathbf{E}_{\text{pred}}}{\partial x_{\text{dens}}}(x^i) \approx \frac{\mathbf{E}_{\text{pred}}(x^{i\prime}) - \mathbf{E}_{\text{pred}}(x^i)}{\Delta}$$

Nearest Optimal

$$\boxed{x^i = [x^i_{\text{dens}}, x^i_{\text{or}}, x^i_{\text{cub}}]}$$

MBB Problem 30x10 macro elements



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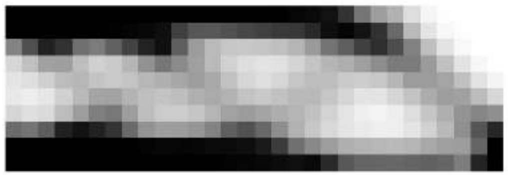
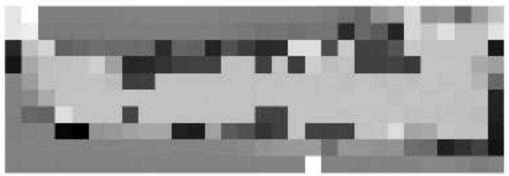
Density of the cells



Orientation of the cells

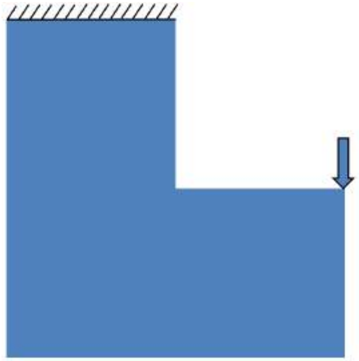


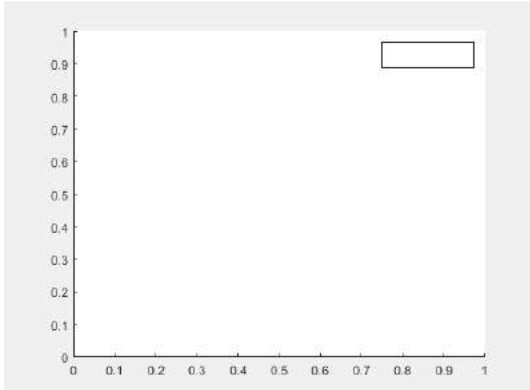
Cubicity of the cells

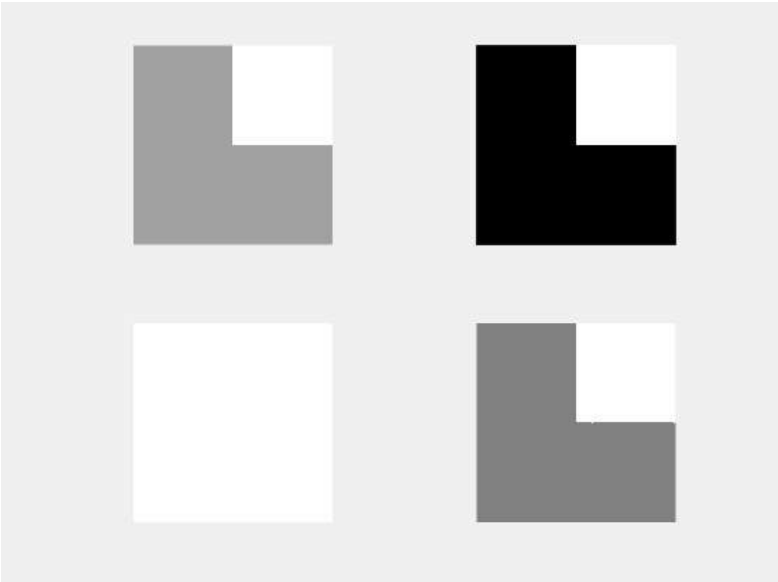
Result on classical test cases

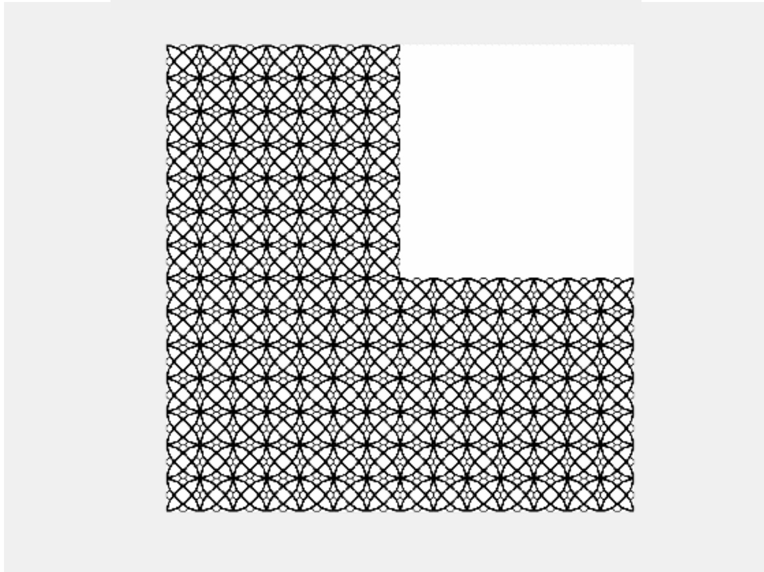
- Validation on
  small grid

$\Rightarrow$ Evaluate
full-scale design









- 4x14*14 design variables; stopping criteria : tolfun< 10^{-3}

More info

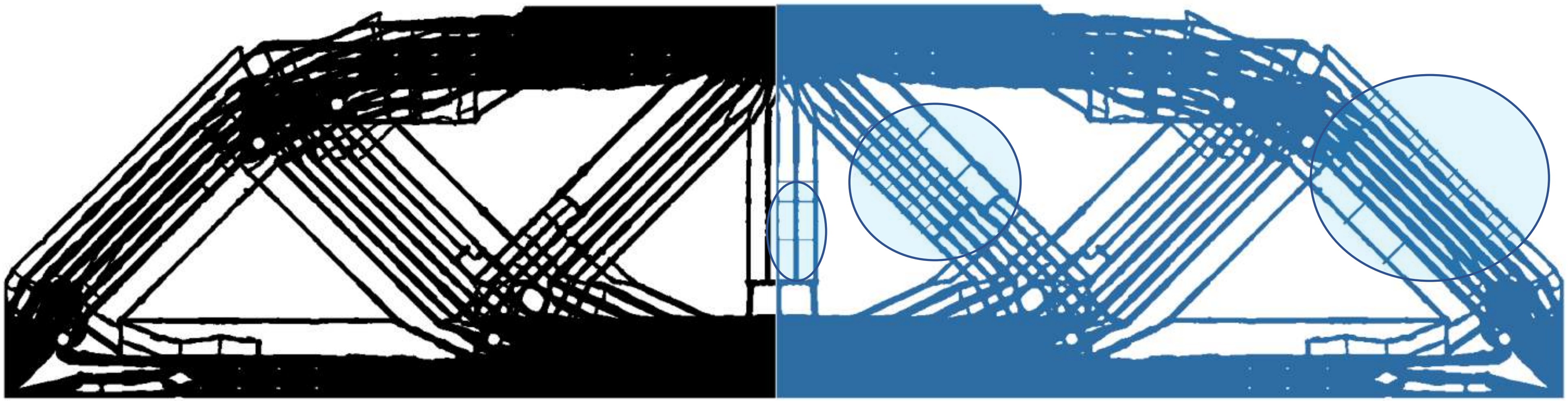
Duriez, E., Morlier, J., Charlotte, M., & Azzaro-Pantel, C. (2021). A well connected, locally-oriented and efficient multi-scale topology optimization (EMTO) strategy. Structural and Multidisciplinary Optimization, 1-24.

Au programme

Thanks to Edouard Duriez

- Part1: EMTO
- **Part2: Buckling mitigation**
- Conclusions

Do you see a difference (Left2Right)?



Avoid buckling constraint in the TopOpt loop

- Is there a « cheap »post treatment capable of detecting micro-structures responsible for the buckling ??

- We start by diminishing the size of the design to be studied by regrouping elements 4 by 4.
- We then retrieve the buckling load factors (BLF) and the associated eigen vectors of this design for the first 12 modes, using part of the code from

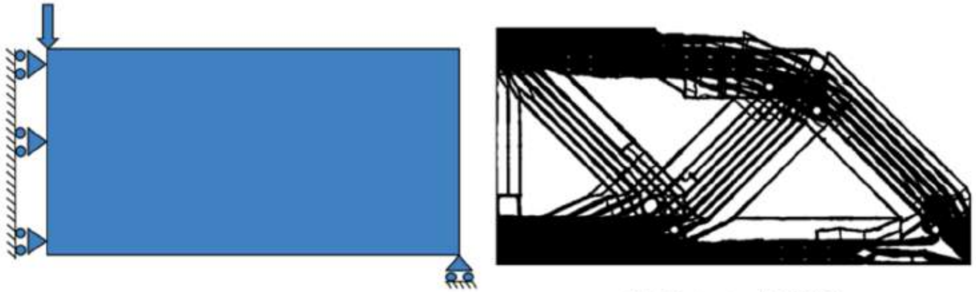
Ferrari, F., Sigmund, O. & Guest, J.K. Topology optimization with linearized buckling criteria in 250 lines of Matlab. Struct Multidisc Optim (2021).

```
>>topBuck250(480,240,3,4,2,'N',0.5,2,[0.1,0.7,1.2],300,2,0,0,0,{['V','C'],2.5})).
```

Need a score

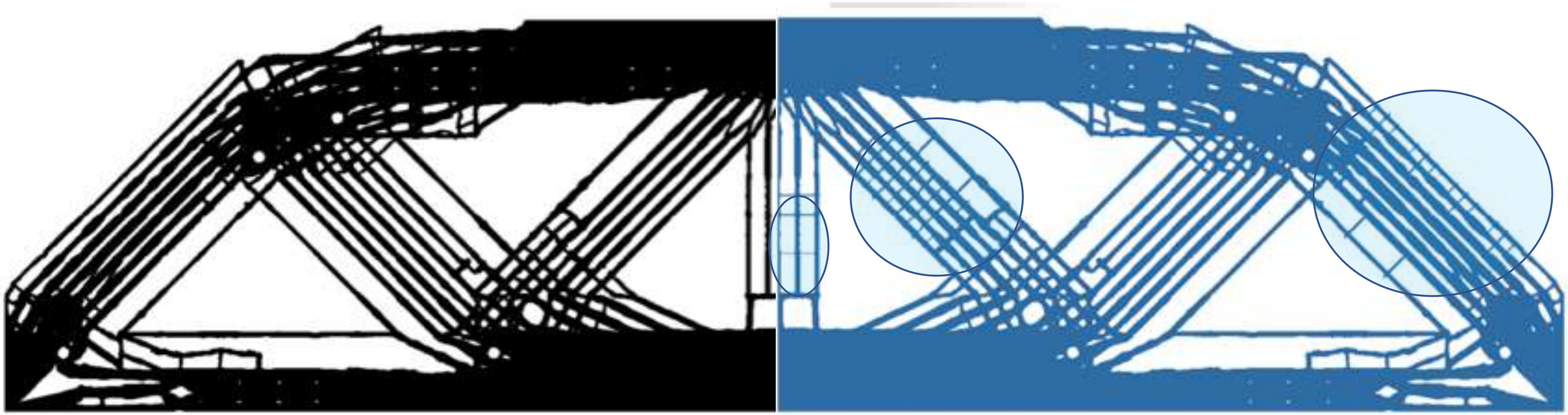
$$b_j = \sum_{i=1}^{12} \lambda_i \times \frac{d_{ij}}{\max_j (d_{ij})}$$

"buckling score" (b_j) for each cell, capturing how its elements are affected by buckling
The mean of this weighted displacement over each cell (j) is noted d_{ij}.



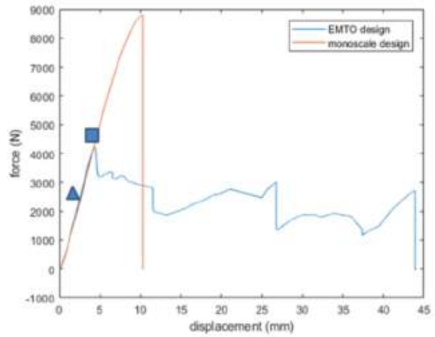
(a) The MBB beam problem.

(b) Output of EMTO.

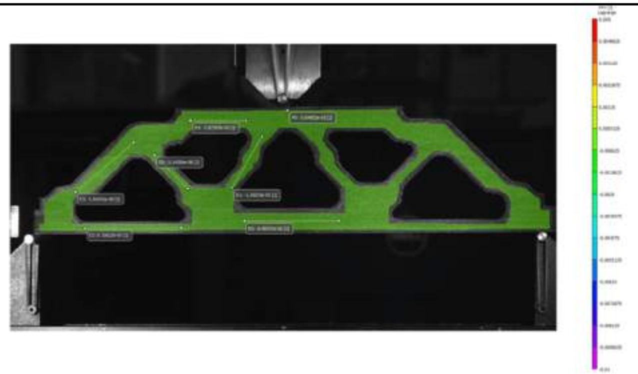


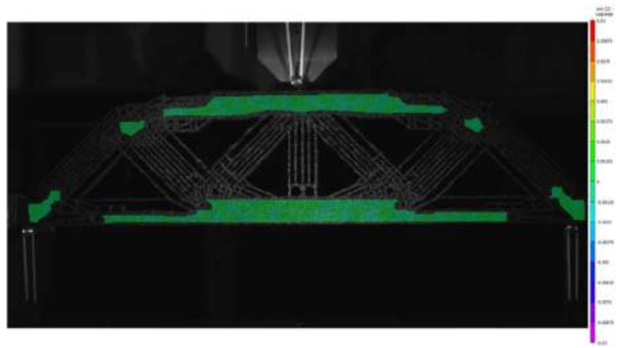
Experimental validation

- Comparison to top88 (smoothed) on same grid and same total volume fraction.
- Planar stiffness ($N/m2$) : S=$\frac{F}{\delta\, e}$



Method	planar stiffness $(\mathrm{N/m^2})$	F_{lim} /t(N/m)
EMTO + BMPT	$6.48{\times}10^7$	2.67e5
EMTO	$6.48{\times}10^7$	1.44e5
top88 smoothed	$6.17{\times}10^7$	2.67e5





- => EMTO takes advantage of printing anisotropy

Au programme

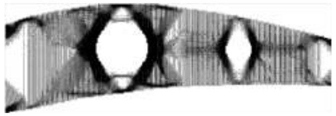
- **Part1: EMTO**
- **Part2: Buckling mitigation**
- **Conclusions**

Conclusions

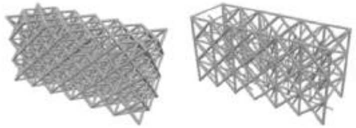
- VS monoscale:
  - Lower compliance
  - Lower maximum load
  - Higher energy absorption
- Design acceleration through SMT
- Framework enabling to easily mitigate local buckling
  - Keep stiffness advantage while having buckling limit load similar to monoscale
- Directional properties similar to composites (CFRP), but using only one material (and void) => easier recyclability?

Opensource initiatives

https://github.com/topggp/blog — **CSMA** 2017 et 2019



https://github.com/mid2SUPAERO/EMTO — **CSMA** 2022



https://github.com/mid2SUPAERO/TTO — **CSMA** 2022

https://github.com/mid2SUPAERO/SOMP_Ansys — **CSMA** 2024

https://github.com/mid2SUPAERO/EMTO/tree/main/buckling — **CSMA** 2024

https://github.com/SMTorg/SMT

Advances in Engineering Software
Volume 135, September 2019, 102662

A Python surrogate modeling framework with derivatives

Mohamed Amine Bouhlel [a], John T. Hwang [b], Nathalie Bartoli [c], Rémi Lafage [c], Joseph Morlier [d], Joaquim R.R.A. Martins [a]

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Research paper

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Paul Saves [a b 1], Rémi Lafage [a 1], Nathalie Bartoli [a 1], Youssef Diouane [c 1], Jasper Bussemaker [d 1], Thierry Lefebvre [a 1], John T. Hwang [e 1], Joseph Morlier [f 1], Joaquim R.R.A. Martins [g 1]

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joseph morlier
Professor in Structural and Multidisciplinary Design Optimization, ... any idea?

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