Ecodesign and 3D topology optimization

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Summary

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Topology optimization
- Problem formulation
- Filtering
- Extension to 3D

3D printing
- Manufacturing constraints
- Printing path

Results
- Implementation
- Reference problem
- Initial angle dependence
- Mesh independence
- Filter radius dependence
- Fiber volume fraction change
- Material change

Remarks

Problem formulation - 2D optimization

- Variables: density and angle [Jiang 2017]

$$\min_{\boldsymbol{\rho},\boldsymbol{\theta}} c(\boldsymbol{\rho},\boldsymbol{\theta}) = \sum_e \rho_e^p \boldsymbol{u_e^T} \boldsymbol{k_0}(\theta_e) \boldsymbol{u_e^T}$$

$$\text{s.t.} \begin{cases} \frac{V(\boldsymbol{\rho})}{V_0} \leq f \\ \boldsymbol{KU} = \boldsymbol{F} \\ 0 < \rho_{min} \leq \boldsymbol{\rho} \leq 1 \\ -2\pi \leq \boldsymbol{\theta} \leq 2\pi \end{cases} \tag{1}$$

- Orientation given by coordinates [Nomura 2015]

$$\min_{\boldsymbol{\rho},\boldsymbol{\theta}=(\boldsymbol{\xi},\boldsymbol{\eta})} c(\boldsymbol{\rho},\boldsymbol{\theta}) = \sum_e \rho_e^p \boldsymbol{u_e^T} \boldsymbol{k_0}(\theta_e) \boldsymbol{u_e^T}$$

$$\text{s.t.} \begin{cases} \frac{V(\boldsymbol{\rho})}{V_0} \leq f \\ \boldsymbol{KU} = \boldsymbol{F} \\ 0 < \rho_{min} \leq \boldsymbol{\rho} \leq 1 \\ -1 \leq \boldsymbol{\xi} \leq 1 \\ -1 \leq \boldsymbol{\eta} \leq 1 \end{cases} \tag{2}$$

Filtering - Density

Convolution filter applied on the sensitivities to ensure mesh independence

$$\rho_e \widetilde{\frac{\partial c}{\partial \rho_e}} = \frac{\sum_i H_{ei}\, \rho_e\, \frac{\partial c}{\partial \rho_e}}{\sum_i H_{ei}}, \tag{3}$$

$$H_{ei} = \max(0, r_{min} - \Delta(e, i)) \tag{4}$$

Filtering - Fiber orientation

Ensure mesh independence and smooth fiber curvatures

- Convolution filter on sensitivities, analogous to density
- Convolution filter on the material tensor [Jantos 2020]

$$\widetilde{\mathbb{E}_6}|_e = \frac{\sum_i H_{ei}\, \mathbb{E}_6|_i}{\sum_i H_{ei}} \tag{5}$$

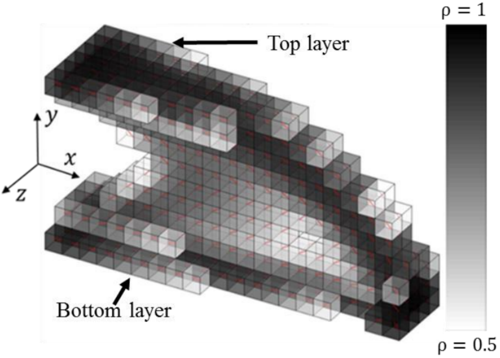
- Gaussian filter on angles (final design) [Stragiotti 2020]
- Convolution filter on angles (every iteration) [Schmidt 2020]

$$\tilde{\theta}_e = \frac{\sum_i H_{ei}\, \hat{\theta}_i}{\sum_i H_{ei}}, \tag{6}$$

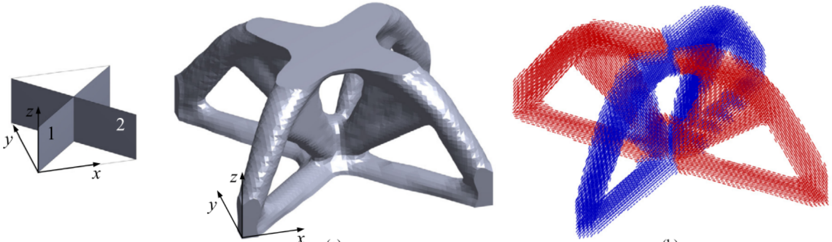
$$\hat{\theta}_i = \begin{cases} -\theta_i & \text{if } \theta_e \cdot \theta_i \leq 0 \\ \theta_i & \text{otherwise} \end{cases} \tag{7}$$

Extension to 3D

- Choose printing direction and divide the domain in layers [Jiang 2017]



- Define allowable printing planes [Qiu 2022]

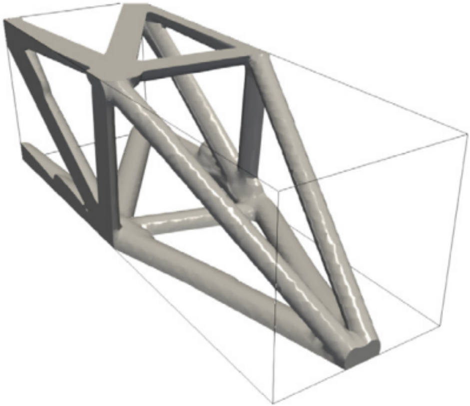


(a)

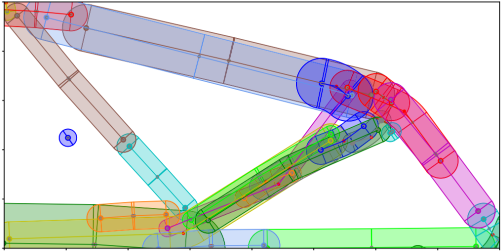
(b)

Extension to 3D

- Use discrete components, straight bars [Smith 2021]

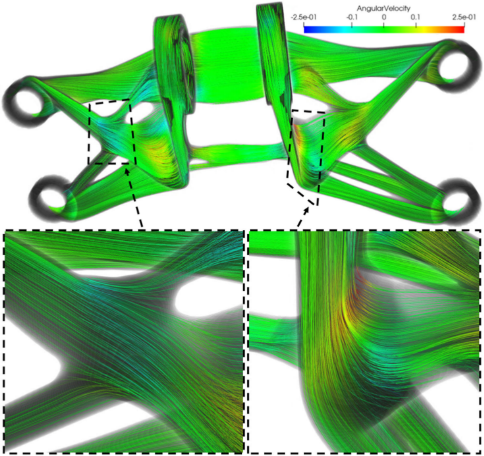


- Use discrete curved components, 2D - to be extended to 3D [Greifenstein 2023]



Extension to 3D

- Free 3D orientations defined by elevation and azimuth, not suitable for current manufacturing methods [Schmidt 2020]



Summary

Manufacturing constraints

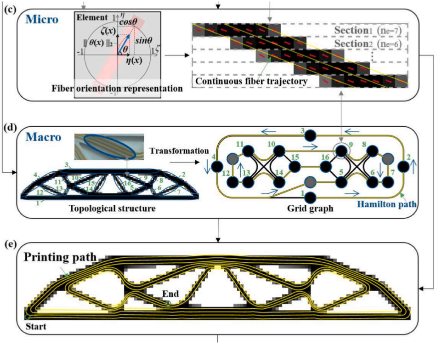
- Hatch spacing and printed radius [Huang 2022]
  - Constraints added during printing path planning
- Minimum self-supporting angle [Gaynor 2016]
  - Implicitly adds overhang constraint by modifying the design variables
  - Computational difficulties due to nonlinearities introduced by projecting the design variables into the actual design
  - Removes necessity of supports with a low cost in compliance

Printing path

Infill methods: how to convert the optimized orientations into continuous fiber paths [Papapetrou 2020]

- EQS method
  - Equally spaced fibers parallel to the boundary of the optimized structure
  - Good for relatively simpler cases but limited for complex cases
- Streamline method
  - Streamlines from the optimized orientation vector field
  - Computationally expensive but more robust and straightforward
- Offset method
  - Fiber paths are obtained parallel to the optimized lay-out
  - Very robust even for relatively complex design domains, but may not follow the optimized orientation in some regions

Printing path planning



[Huang 2022]

Divide optimized structure in finite sections and find Hamilton path on the graph to obtain a single continuous path

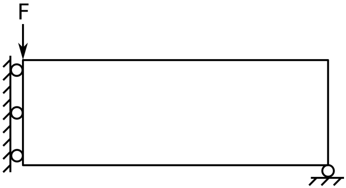
Summary

- Optimization code: Python
- FEA solver: Ansys

- Design variables: $\boldsymbol{\rho}, \boldsymbol{\theta}$
- Variable updating algorithm: MMA
- Fiber orientation filter: $\tilde{\theta}_e = \frac{\sum_i H_{ei}\,\hat{\theta}_i}{\sum_i H_{ei}}$

Reference problem

- Half MBB beam, 30 mm x 15 mm
- 10 N force



Variations of the problem were compared to base case to verify the solution properties:

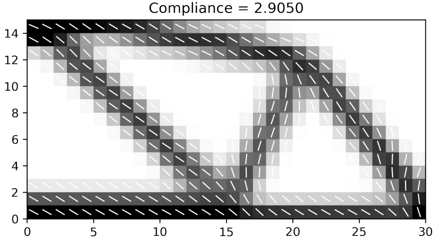
- Mesh: 30 x 15 elements
- Material: Cellulose and 0.5 bamboo
- Volume fraction constraint: 0.3
- Filter radius: 1.5 mm
- Initial orientation: -73.6°

30 x 15 elements

Cellulose and 0.5 bamboo

$r_{min} = 1.5$ mm

$\theta_0 =$ -73.6°

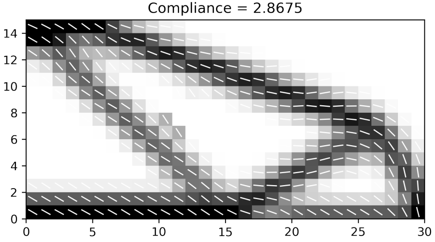


30 x 15 elements

Cellulose and 0.5 bamboo

$r_{min} = 1.5$ mm

$\theta_0 =$ -40.9°

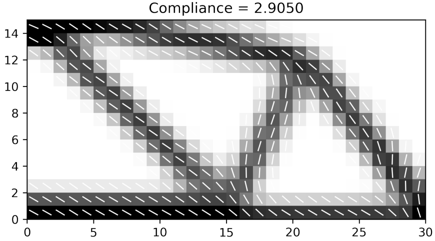


30 x 15 elements

Cellulose and 0.5 bamboo

$r_{min} = 1.5$ mm

$\theta_0 =$ -73.6°

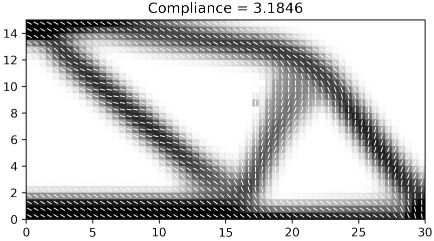


60 x 30 elements

Cellulose and 0.5 bamboo

$r_{min} = 1.5$ mm

$\theta_0 =$ -73.6°

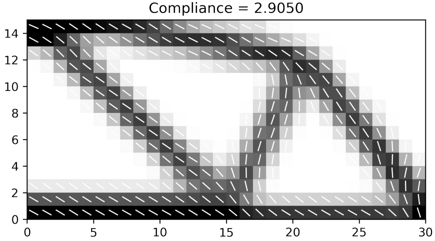


30 x 15 elements

Cellulose and 0.5 bamboo

$r_{min} = 1.5$ mm

$\theta_0 =$ -73.6°

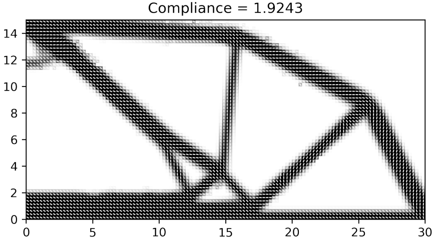


120 x 60 elements

Cellulose and 0.5 bamboo

$r_{min} = 0.5$ mm

$\theta_0 =$ -73.6°



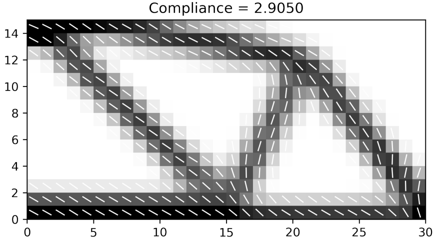
Fiber volume fraction change

30 x 15 elements

Cellulose and 0.5 bamboo

$r_{min} = 1.5$ mm

$\theta_0 =$ -73.6°

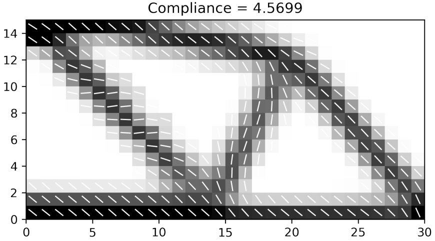


30 x 15 elements

Cellulose and 0.25 bamboo

$r_{min} = 1.5$ mm

$\theta_0 =$ -73.6°

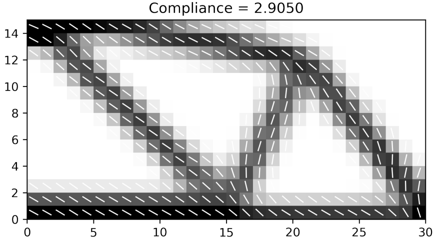


30 x 15 elements

Cellulose and 0.5 bamboo

$r_{min} = 1.5$ mm

$\theta_0 =$ -73.6°

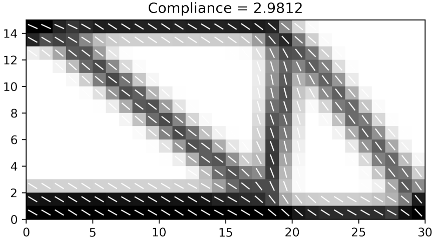


30 x 15 elements

Epoxy and 0.25 E-glass

$r_{min} = 1.5$ mm

$\theta_0 =$ -73.6°



Summary

Remarks

- Algorithm sometimes finds local minima with orientations rotated 90° to the expected (more often with the Gaussian filter than with the convolution filter)
- Sensitivities $\partial c / \partial \boldsymbol{\theta}$ hard-coded with analytical expressions for the 2D stiffness matrix

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