3D Topology Optimization for Composite Sandwich Structures by the Coating Approach

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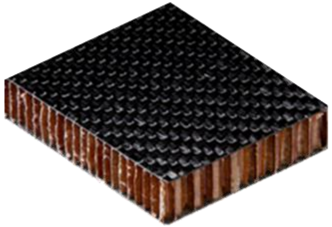
Background

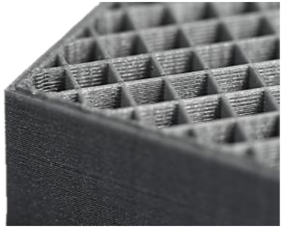
Traditional composite structures

Source: NLR-TP-2016-201



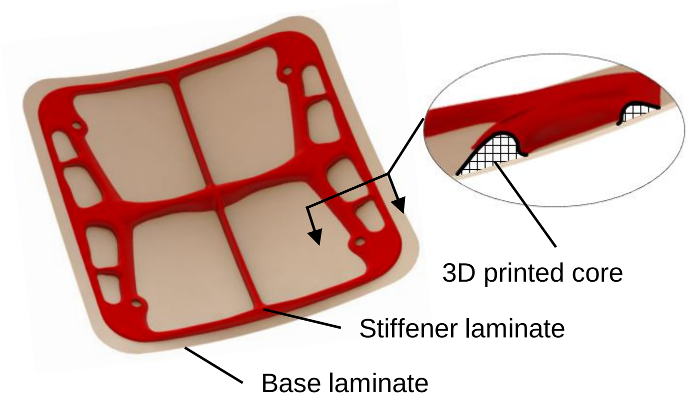
Source: custom-composite.com

Additive manufacturing



3dhubs.com

Complex self-stiffened structures



Lehnert, Master's thesis, McGill (2019)

stratasys.com

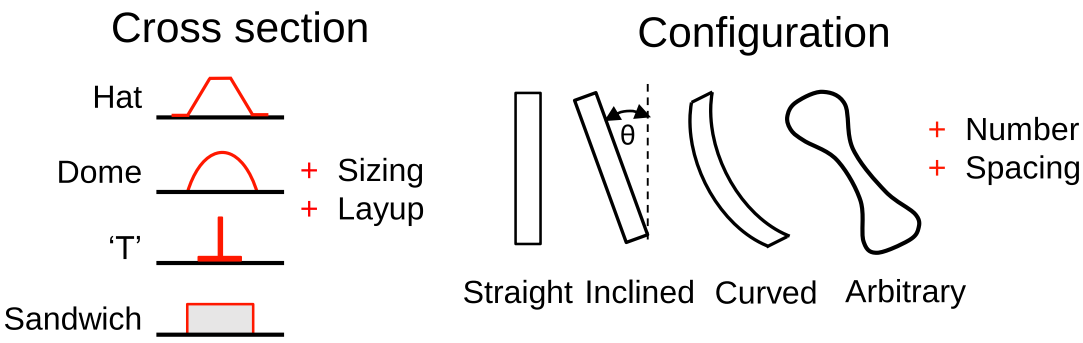
Problematic

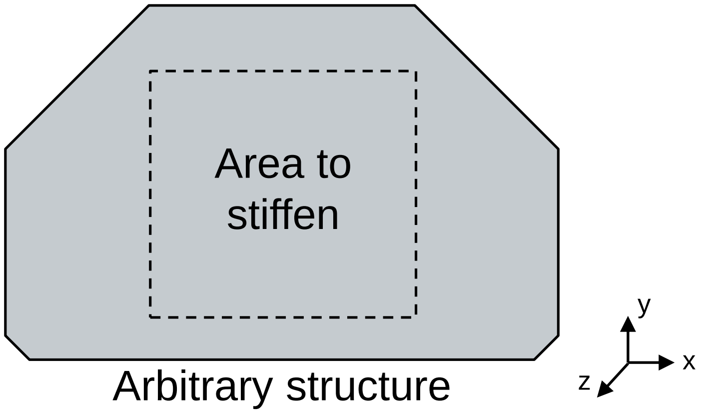
Design of non-standard stiffened structures

- Highly complex task
- Limitations of existing design tools
  - Sizing optimization
  - Shape optimization
  - Topology optimization

Solution:

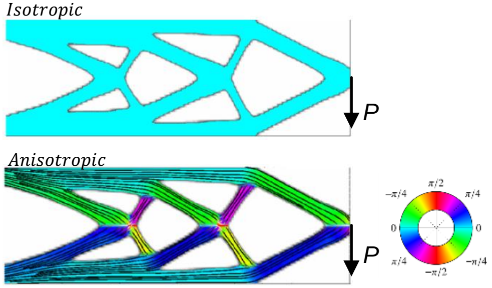
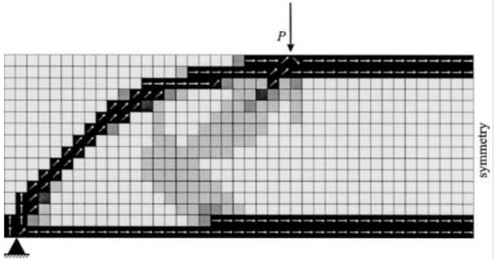
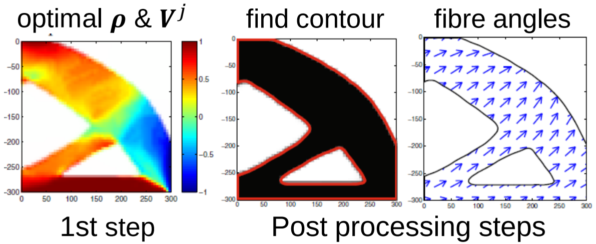
- Develop topology optimization for composite materials





Arbitrary structure

Overview of topology optimization for composite structures

Approach	**Continuous fibre angle**	**Multi-material**	**Lamination parameters**
Design variables	ρ_i & θ_i, $\forall i \in \Omega$	ρ_i^j, $j = 1..n_c$ & $\forall i \in \Omega$	ρ_i & V_i^j, $\forall i \in \Omega$ & $j = 1..12$
Optimization scheme	*Simultaneous or sequential*	*Simultaneous*	*Sequential*
Example			
	Nomura et al. (2015)	*Stegmann & Lund (2005)*	*Peeters et al. (2015)*

- Limited to 2D problems
- Handles material orientations through additional design variables
- Poor control on manufacturability of the solution, no experimental demonstration/evaluation

Project objectives

1. Develop a 3D topology optimization approach for sandwich structures with anisotropic shells
   - Assume laminate properties are known a priori (constant stiffness and thickness)
   - Core has constant relative density
2. Develop an approach to approximate local material orientations based on the manufacturing process
   - Fabric draping
   - Material extrusion additive manufacturing
3. Conduct an experimental benchmark for AM structures optimized for minimum compliance
   - Isotropic vs the developed anisotropic approach

Methodology

Formulation of the topology optimization problem

Minimize compliance :

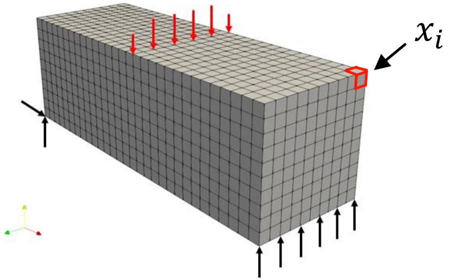
$$C = \boldsymbol{U}^T \boldsymbol{K}(\boldsymbol{x})\boldsymbol{U}$$

Subject to :

$$\boldsymbol{K}(\boldsymbol{x})\boldsymbol{U} = \boldsymbol{F}$$

$$g(\boldsymbol{x}) = V(\boldsymbol{x}) - v_f V_{tot} \leq 0$$

$$0 \leq x_{min} \leq x_i \leq 1, \quad i = 1, \dots, Ne$$

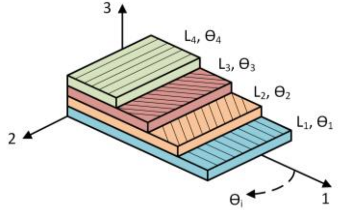


Finite element stiffnesses:

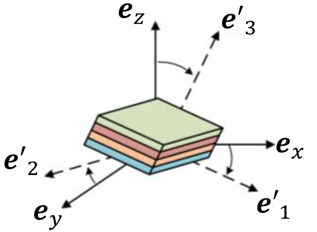
$$\boldsymbol{k}_{lam,i} = \int \boldsymbol{B}^T \boldsymbol{D}_{\mathrm{i}}(x_i, \boldsymbol{D}_{lam}, \{\boldsymbol{e'}_1, \boldsymbol{e'}_2, \boldsymbol{e'}_3\}_i)\boldsymbol{B}\, d\Omega$$

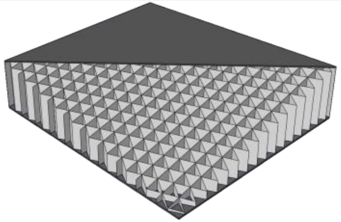
$$\boldsymbol{k}_{core,i} = \int \boldsymbol{B}^T \boldsymbol{D}_{\mathrm{i}}(x_i, \boldsymbol{D}_{core})\boldsymbol{B}\, d\Omega$$

Local csys

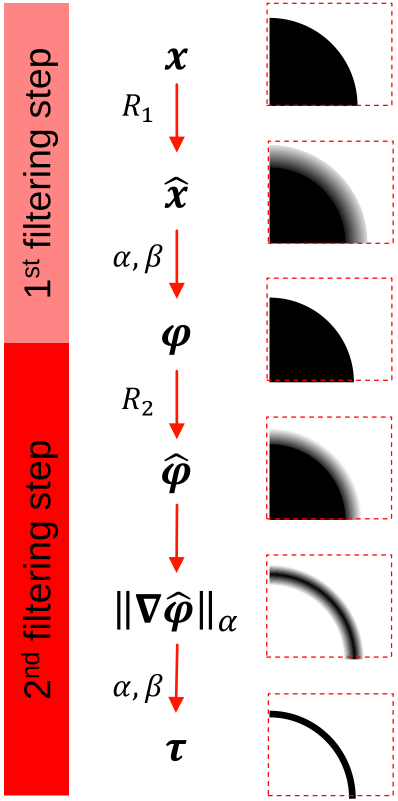


Global csys





Two-step filtering approach with local material orientations



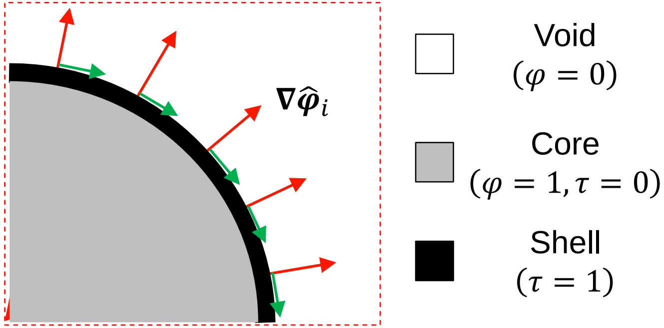
$$-r_1^2\nabla^2\hat{x} + \hat{x} = x$$

$$\boldsymbol{\varphi} = \frac{\tanh\beta_1\eta_1 + \tanh\beta_1(\hat{\boldsymbol{x}} - \eta_1)}{\tanh\beta_1\eta_1 + \tanh\beta_1(1 - \eta_1)}$$

$$-r_2^2\nabla^2\hat{\varphi} + \hat{\varphi} = \varphi$$

$$\|\nabla\hat{\boldsymbol{\varphi}}\|_\alpha = \frac{1}{\alpha}\sqrt{\frac{\partial\hat{\boldsymbol{\varphi}}}{\partial x}^2 + \frac{\partial\hat{\boldsymbol{\varphi}}}{\partial y}^2 + \frac{\partial\hat{\boldsymbol{\varphi}}}{\partial z}^2}$$

$$\boldsymbol{\tau} = \frac{\tanh\beta_2\eta_2 + \tanh\beta_2(\|\nabla\hat{\boldsymbol{\varphi}}\|_\alpha - \eta_2)}{\tanh\beta_2\eta_2 + \tanh\beta_2(1 - \eta_2)}$$



Density interpolation:

$$\boldsymbol{\rho}_{phys} = \rho_c\boldsymbol{\varphi} + (\rho_s - \rho_c\boldsymbol{\varphi})\boldsymbol{\tau}$$

Local orientations in shell:

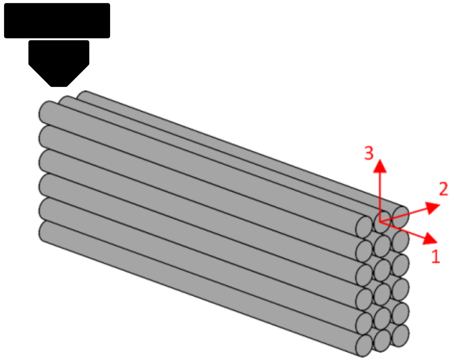
$\|\nabla\hat{\boldsymbol{\varphi}}\|_\alpha \neq 0$ → $\nabla\hat{\boldsymbol{\varphi}} \perp$ shell → $\boldsymbol{\theta}(\nabla\hat{\boldsymbol{\varphi}})$

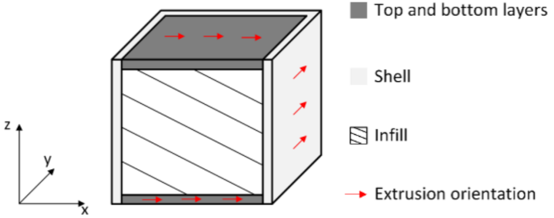
$$\boldsymbol{D}_{phys} = \boldsymbol{D}_c\boldsymbol{\varphi}^p + (\boldsymbol{D}_s(\boldsymbol{\theta}) - \boldsymbol{D}_c\boldsymbol{\varphi}^p)\boldsymbol{\tau}^p$$

Ref.: Clausen A., Aage N., and Sigmund O. (2015)

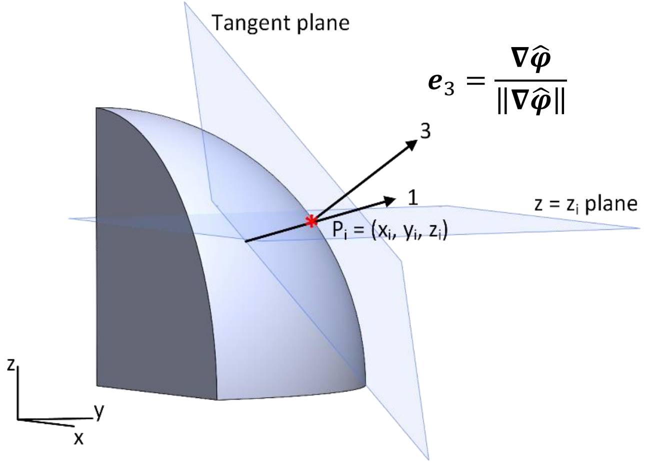
Approximation approach for local material orientations in 3D problems

Extrusion AM process:



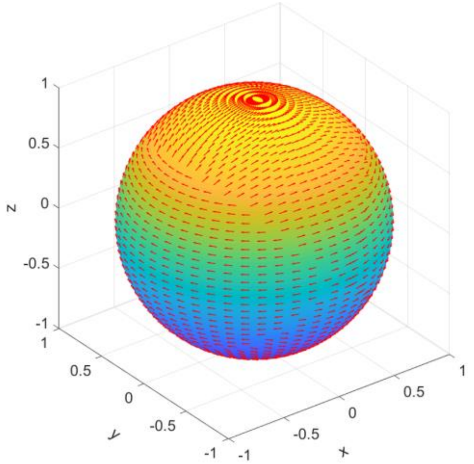


Approximation approach of the local extrusion orientations:



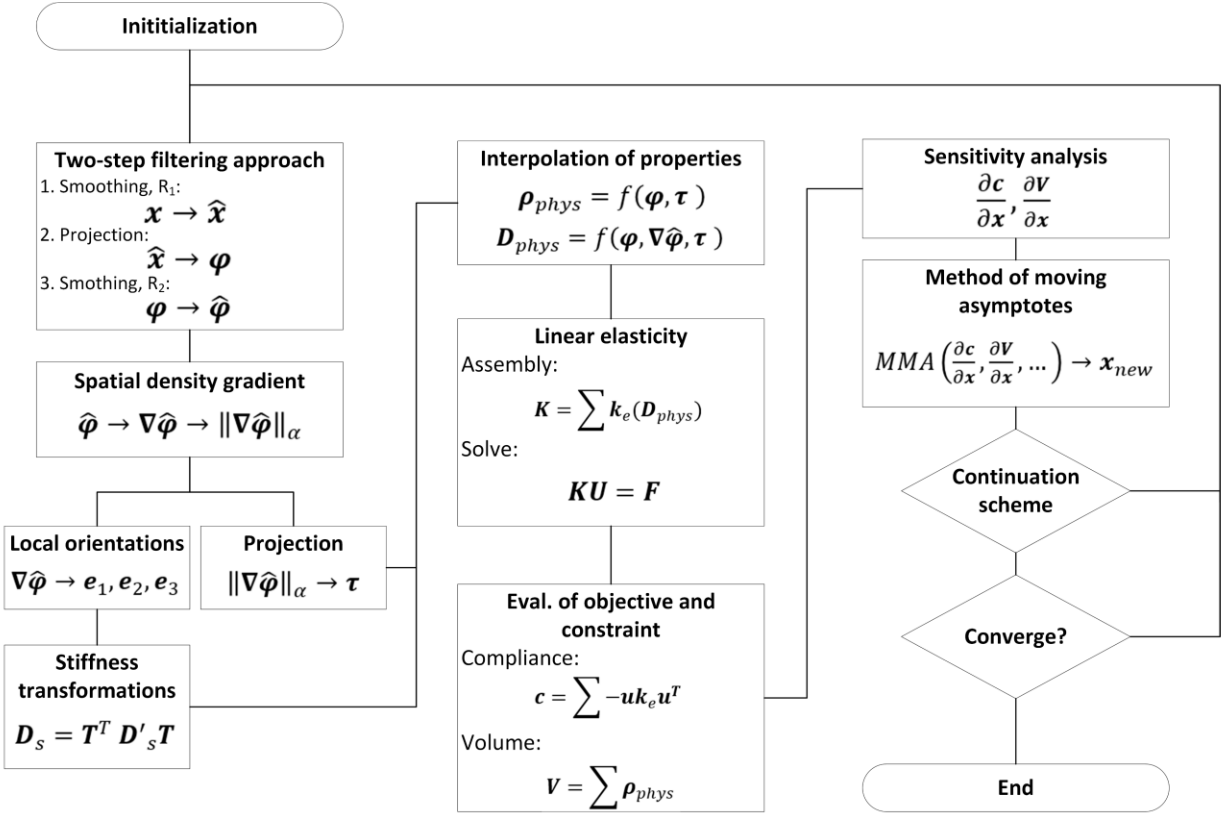
Local routine:

1. Find tangent plane from $\boldsymbol{e}_3$
2. Select intersecting plane
3. Calculate $\boldsymbol{e}_1, \boldsymbol{e}_2 = f(\boldsymbol{\nabla}\hat{\boldsymbol{\varphi}})$
4. Transform stiffness tensor



Resulting distribution of local extrusion orientations

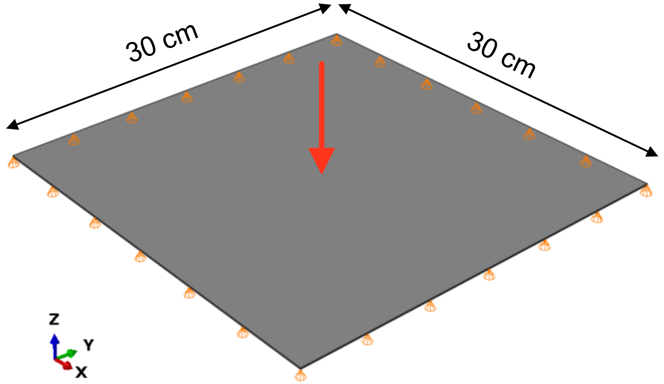
Optimization flow chart

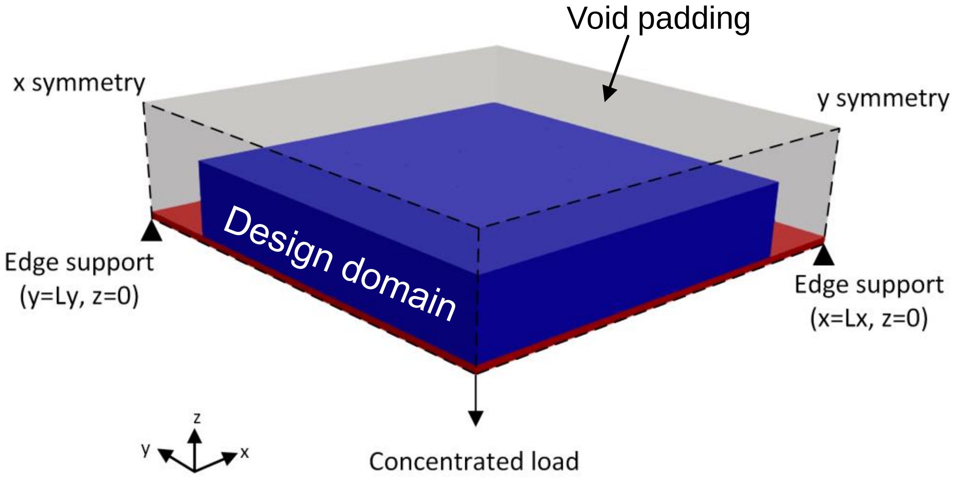


Results

- Design of a composite stiffened panel
- Experimental benchmark using extrusion additive manufactured MBB beams

Composite stiffened panel problem





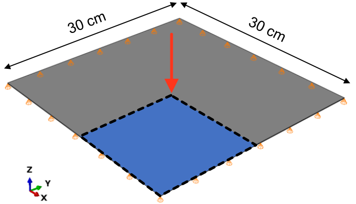
Load = -10 N
Max sandwich thickness = 20 mm
Shell laminate = 1 mm, Cross-ply $[0°/90°]_s$
Base laminate = 2 mm, Quasi-iso $[0°/45°/-45°/90°]_s$
Mesh : 600 x 600 x 80 (28.8 M hex elements)

E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
10 GPa	5 GPa	5 GPa	0.25	0.25	0.4	2.5 GPa	2.5 GPa	2 GPa

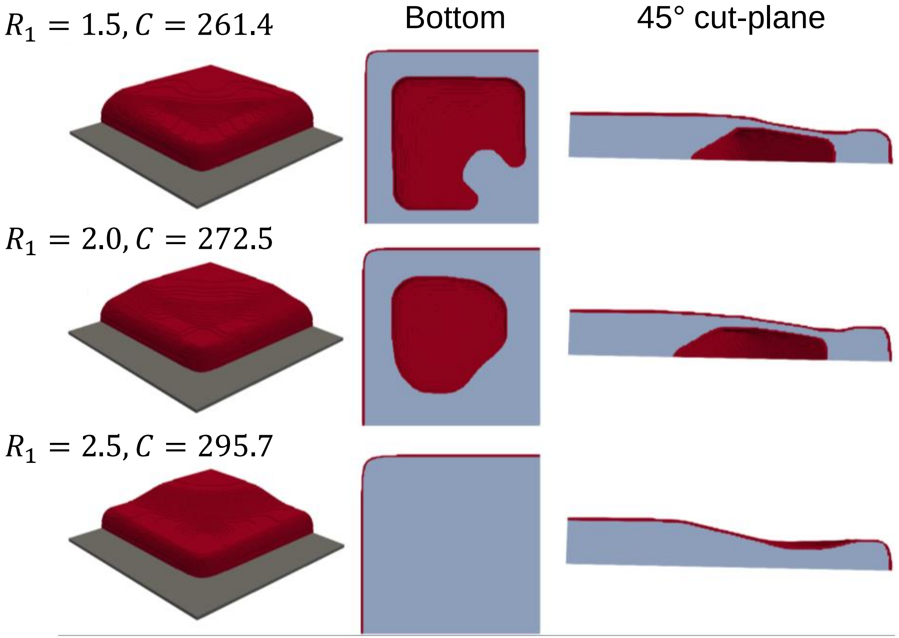
Specific gravity: 1.2

Triangular honeycomb core $(SG = 1.44,\ E_{core,s} = 10\ \text{GPa},\ \nu = 0.25)$

Effect of base structure filter radius size

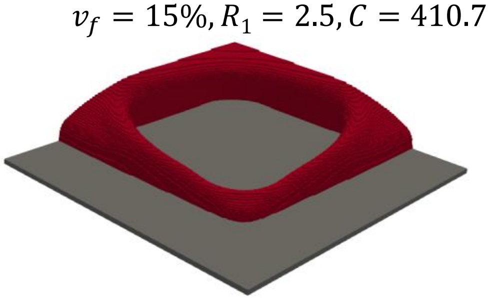


Volume fraction = 30%, Core rel. Density = 30%



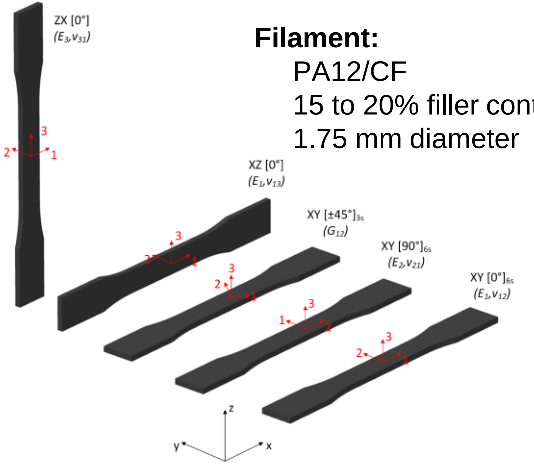
- Manufacturability controlled by proper selection of R_1 and v_f
- Trade-off between performance & manufacturability

Low v_f solution



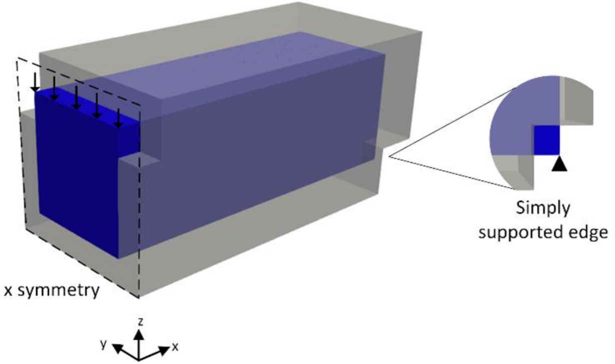
Experimental benchmark using extrusion additive manufactured MBB beams

Material characterization



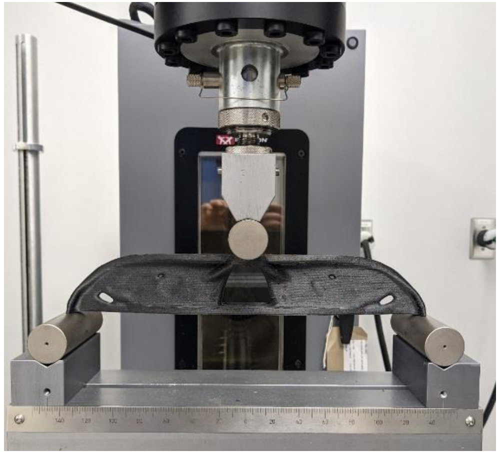
Filament:
PA12/CF
15 to 20% filler content
1.75 mm diameter

Topology optimization



Isotropic vs orthotropic solutions

Fabrication & testing



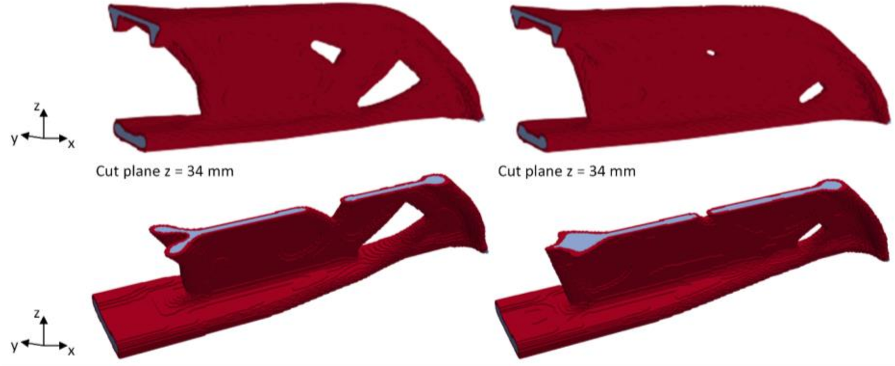
Topology optimization solutions to the MBB problem

Benchmark study

Case	Volume fraction (v_f)	First filter radius (R_1)	Shell thickness ($t_s = 0.4R_2$)
1	15%	10 mm	1.5 mm
2	30%	10 mm	1.5 mm
3	15%	20 mm	1.5 mm
4	30%	20 mm	1.5 mm
5	15%	10 mm	1.0 mm
6	30%	10 mm	1.0 mm

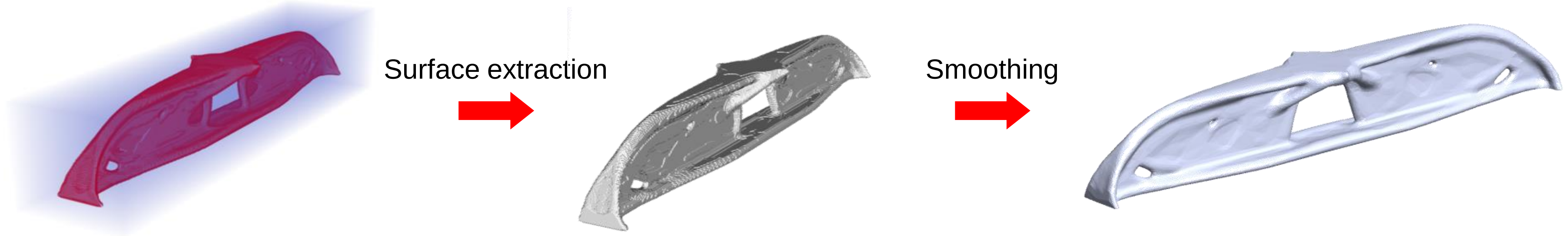
Numerical results

Case 1

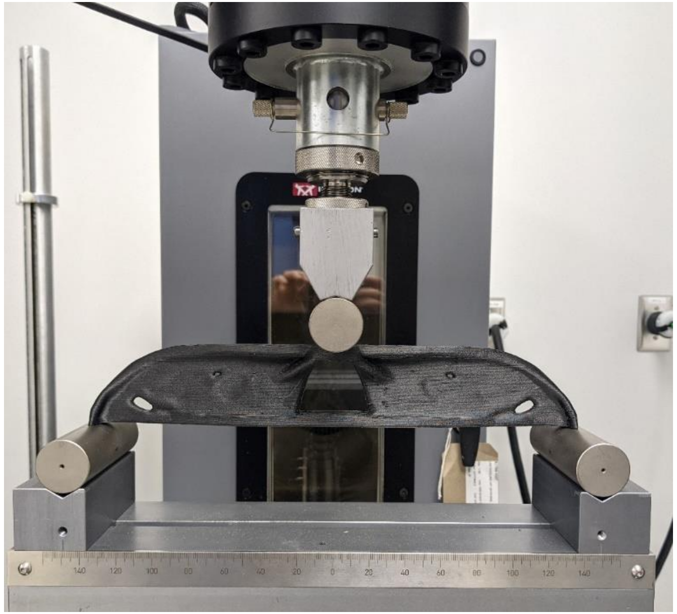


Isotropic (c = 1441)   Orthotropic (c = 1639)

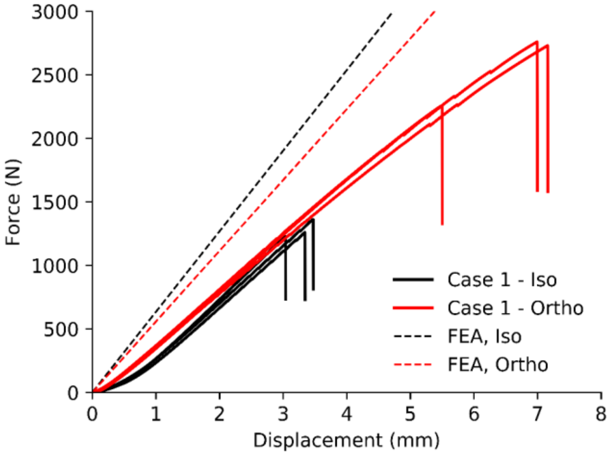
Post-treatment



Load deflection curves for case 1 solutions



v_f = 15%
R_1 = 10 mm
t_{shell} = 1.5 mm



Case 1 - Isotropic

Case 1 - Orthotropic

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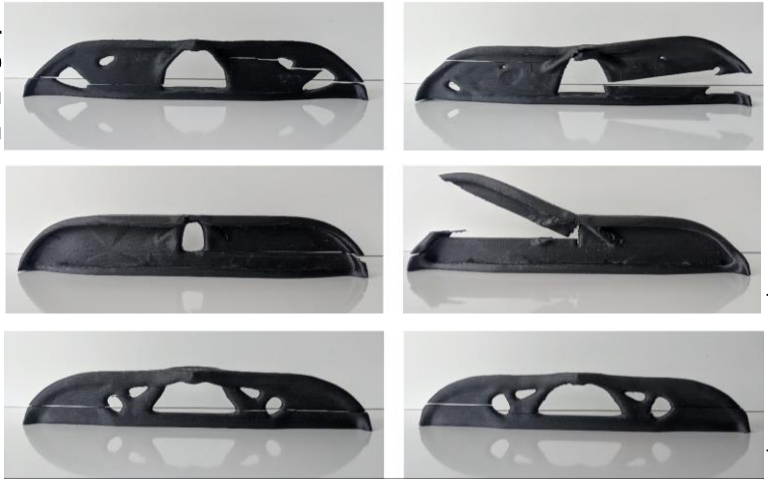
Experimental benchmark – Summarized results

Isotropic | Orthotropic

Case 1
v_f = 15%
R_1 = 10 mm
t_{shell} = 1.5 mm

Case 2
v_f = 30%
R_1 = 10 mm
t_{shell} = 1.5 mm

Case 3
v_f = 15%
R_1 = 20 mm
t_{shell} = 1.5 mm

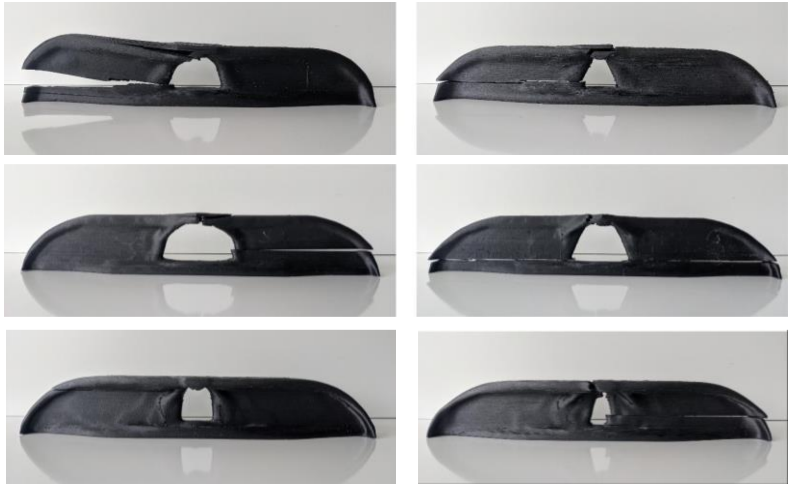


Isotropic | Orthotropic

Case 4
v_f = 30%
R_1 = 20 mm
t_{shell} = 1.5 mm

Case 5
v_f = 15%
R_1 = 10 mm
t_{shell} = 1.0 mm

Case 6
v_f = 30%
R_1 = 10 mm
t_{shell} = 1.0 mm



Case	Bending stiffness [N/mm]			Maximum load [N]			Maximum displacement [mm]		
	Iso	Orth	Difference	Iso	Orth	Difference	Iso	Orth	Difference
1	457	437	4.4%	1282	2580	50.3%	3.3	6.6	49.8%
2	679	623	8.2%	4006	3781	5.6%	7.1	6.6	6.5%
3	316	294	7.0%	1226	1122	8.4%	4.1	4.0	3.2%

Case	Bending stiffness [N/mm]			Maximum load [N]			Maximum displacement [mm]		
	Iso	Orth	Difference	Iso	Orth	Difference	Iso	Orth	Difference
4	512	526	2.7%	3741	4486	16.6%	9.1	11.9	23.5%
5	291	391	25.6%	1779	2586	31.2%	7.7	7.7	0.2%
6	436	442	1.4%	1836	3368	45.5%	4.9	10.0	50.7%

Conclusions

- The new parameterization opens new design opportunities for composite sandwich structures using topology optimization.
- Manufacturability of the solution requires proper selection of the topology optimization parameters.
- Accounting for material anisotropy improved load bearing capacity of the optimized designs.

Future work

- Apply method to broader sets of problems (buckling stability, combined loads, etc.)
- Include modeling approaches to improve local material orientation approximations.
- Improve modelling of the laminate.
- Concurrent optimization of material orientations.

Acknowledgments

- McGill Structures & Composite Materials Laboratory

CRIAQ COMP 1601 Project: