Topology optimization with discrete geometric components made of composite materials

Hollis Smith & Julián Norato

University of Connecticut

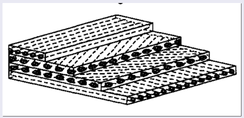
April 29, 2021

Presentation Overview

Motivation

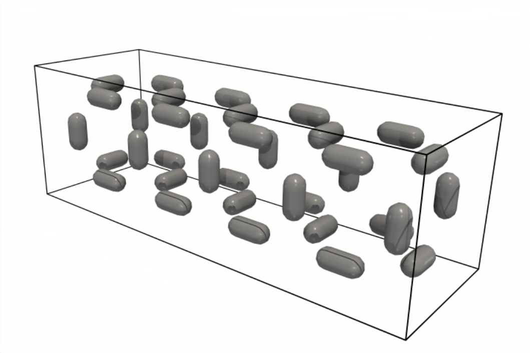
- Want to design with *continuous-fiber* reinforced components:

www.rockwestcomposites.com

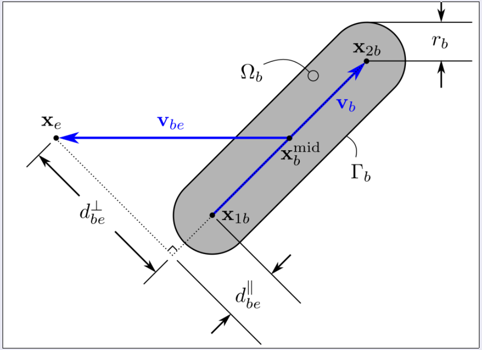


Daniel & Ishai, 2nd ed.

- superior mechanical properties
- manufacturing lends itself to geometric primitives (e.g., bars and plates)

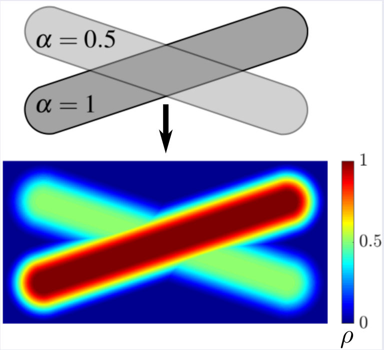


Geometry Projection



- Primitive definition
  - bars defined as offset segments
  - Ω_b : points within r_b of the medial segment are solid
  - Segment parameterized by two endpoints.
- Primitives mapped to density field
  - A density field ρ_b computed for each bar
  - ρ_b : smooth Heaviside of signed-distance to boundary Γ_b

Combining primitives



size variable α_b for each bar

- Boolean union is a smooth-maximum $\rho = \widetilde{\max}_b(\rho_b \cdot \alpha_b)$
- p-norm and KS-function used previously for a single or multiple isotropic materials, but not compatible with *anisotropic* materials.
- Here, we use the softmax:

$$\mathrm{softmax}(\mathbf{x}; p) = \sum_i w_i(\mathbf{x}; p) x_i$$

where

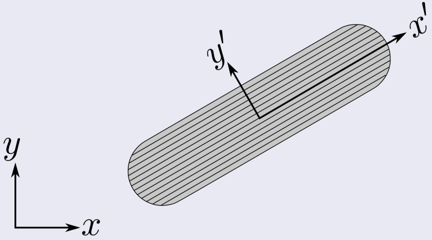
$$w_i = \underset{i}{\mathrm{softargmax}}(\mathbf{x}; p) = \frac{e^{px_i}}{\sum_j e^{px_j}}$$

Bar material properties

- reinforcement is aligned with the axis of each bar
- material properties rotate with components:

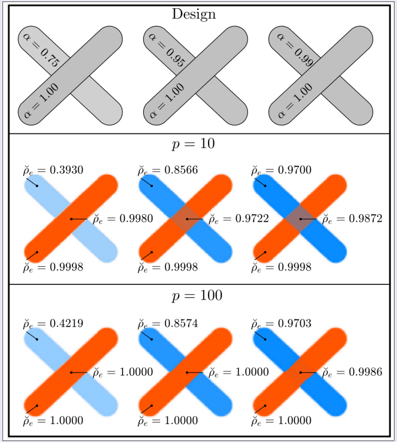
$$R^b_{ii'} = \hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_{i'b}$$

$$(\mathbf{C}_b)_{ijkl} = \sum_{i',j',k',l'} R^b_{ii'} R^b_{jj'} R^b_{kk'} R^b_{ll'} (\mathbf{C}_b)_{i'j'k'l'}$$



- design-dependent material properties

Material interpolation



$\breve{\rho}_e$ is the penalized element density

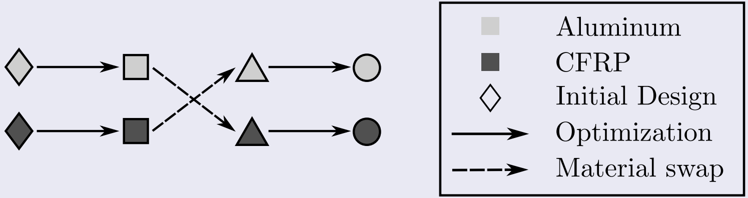
- softmax weights w_i used to interpolate material properties of each component
- weights form a convex combination: $\sum_i w_i = 1; w_i > 0$.
- large softmax parameter p renders a one-hot vector of w_i
- size variable α controls which component dominates intersections
- elasticity tensor:

$$\boxed{\mathbf{C} = \mathbf{C}_{\text{void}} + \sum_b w_b \breve{\rho}_b (\mathbf{C}_b - \mathbf{C}_{\text{void}})}$$

Examples

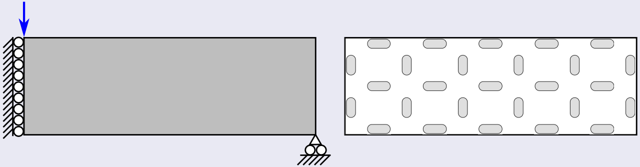
Material	E_1 [GPa]	E_2 [GPa]	ν_{12}	ν_{23}	G_{12} [GPa]
Carbon epoxy AS4/3501-6	113.6	9.650	0.334	0.540	6.0
Aluminum 6061-T6	68.9	–	0.33	–	–

Material properties used for all examples



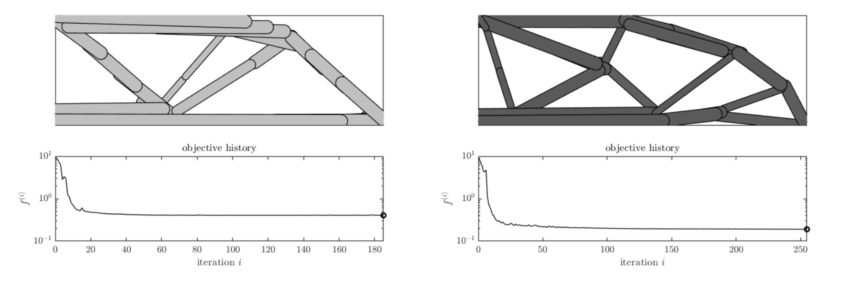
Flow diagram for design comparison

MBB beam

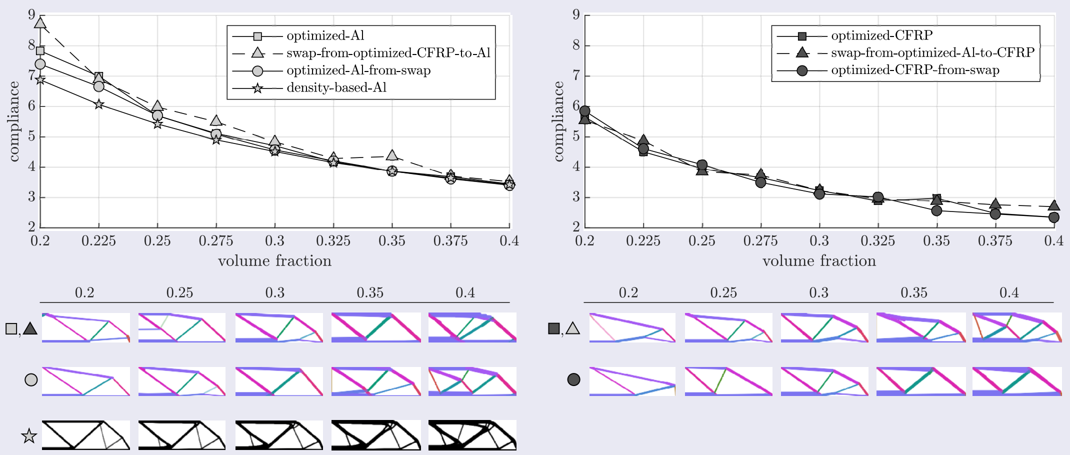


Aluminum

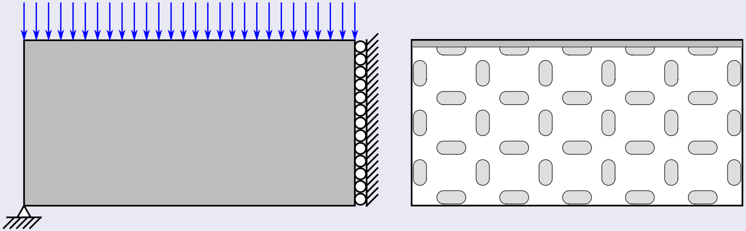
CFRP



MBB beam – volume sweep

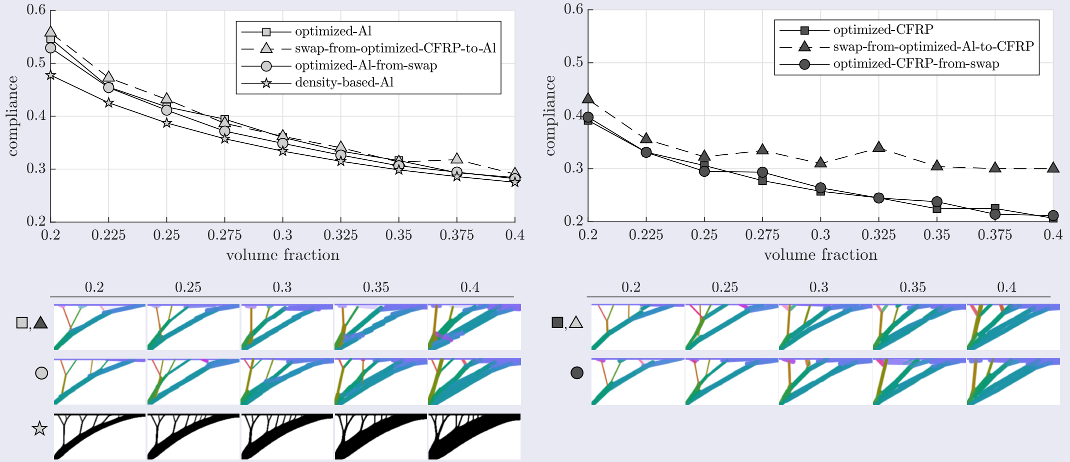


Bridge

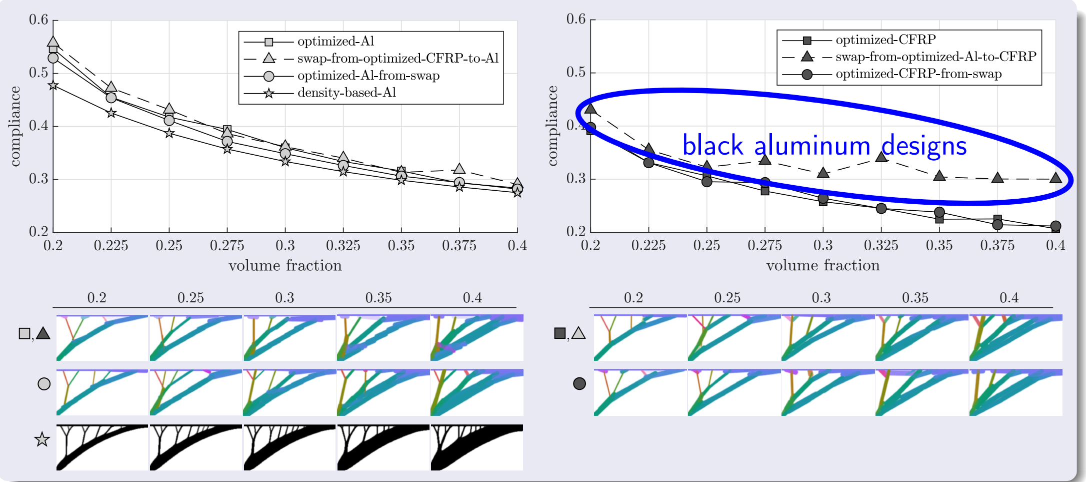


- distributed load to promote bending in some members
- expect optimized aluminum designs will perform poorly when swapped to CFRP

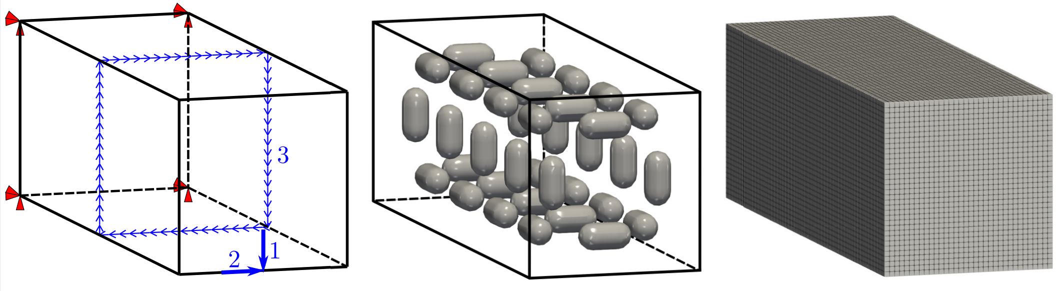
Bridge – volume sweep



Bridge – volume sweep

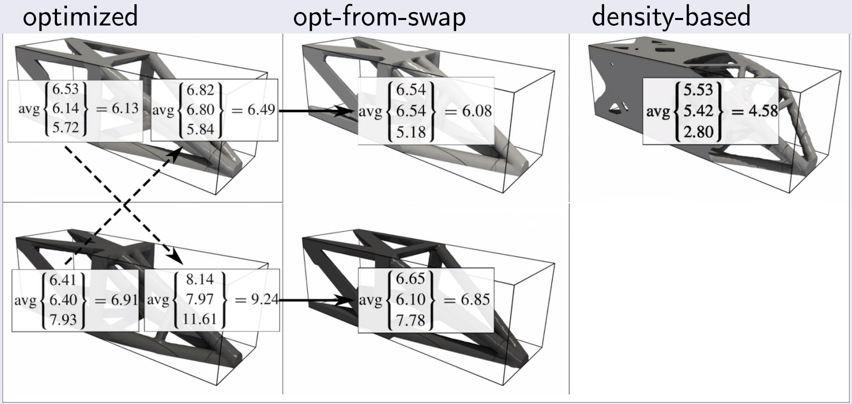


3D Cantilever

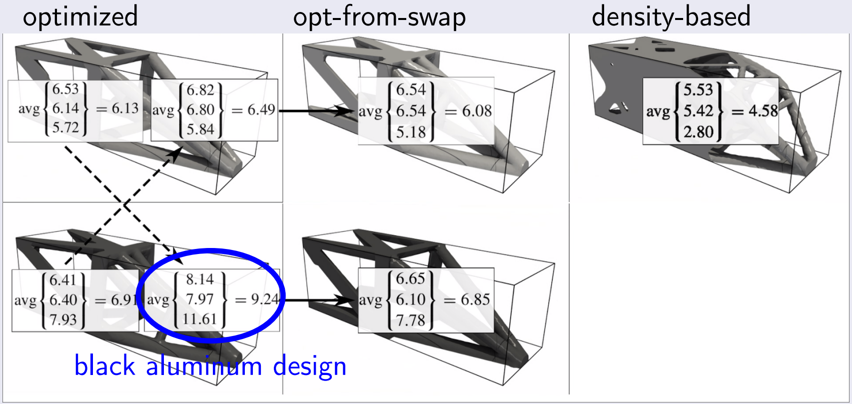


- three load cases
- $\sim 118,000$ elements

3D Cantilever – comparison



3D Cantilever – comparison



Conclusions

- First topology optimization method for composites made from geometric primitives
- Targeted toward long-fiber reinforced materials
- Black aluminum approach is sub-optimal

Thanks to the U.S. Office of Naval Research, Grant Number N00014-17-1-2505, for support to conduct this work.