Topology optimization for staged construction with applications to additive manufacturing

Oded Amir and Yoram Mass
structopt.net.technion.ac.il

Technion - Israel Institute of Technology
Faculty of Civil & Environmental Engineering

EUCCO 2016, September 12 2016, Leuven, BELGIUM

Context – AATiD consortium

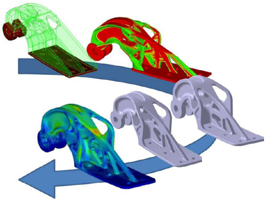
Develop advanced technologies for design and 3-D printing of optimized complex aero-structures made of Titanium alloys, Ti-6Al-4V

Detailed goals:

- Identify cost-effective parts, material qualification, optimize process, simulate process, welding of printed parts, ...
- Use **topology optimization** to achieve superior aero-structures design compared with traditional design, in terms of weight, cost and performance;
- **Embed printing technologies' limitations in the structural design process**.

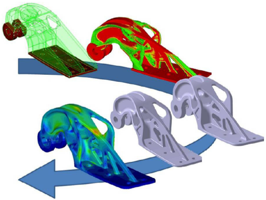
Coupling TopOpt and Titanium AM

Airbus A320 nacelle hinge bracket [Tomlin and Meyer, 2011]:

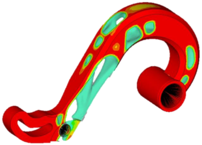


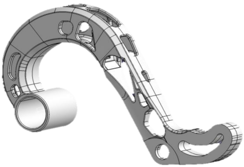
Coupling TopOpt and Titanium AM

Airbus A320 nacelle hinge bracket [Tomlin and Meyer, 2011]:



IAI Gulfstream G250 gooseneck hinge [Muir, 2013]:





Challenges in AM

Additive manufacturing typically requires **extensive support material** to prevent curling and distortion:

- Support overhang / inclination angle;
- Support horizontal bridging distances;
- Improve heat transfer.

Support material **counter-balances achievements of optimal design**:

- Longer build time, more material usage;
- Extensive rework required for removing supports;
- Difficulties in clearing supports in internal holes;
- Compromise on stiffness-to-weight.

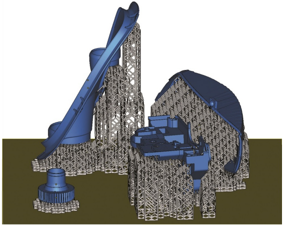
Challenges in AM

Additive manufacturing typically requires **extensive support material** to prevent curling and distortion:

- Support overhang / inclination angle;
- Support horizontal bridging distances;
- Improve heat transfer.

Support material **counter-balances achievements of optimal design**:

- Longer build time, more material usage;
- Extensive rework required for removing supports;
- Difficulties in clearing supports in internal holes;
- Compromise on stiffness-to-weight.



Support structure (Materialise)

Dealing with overhang limitations

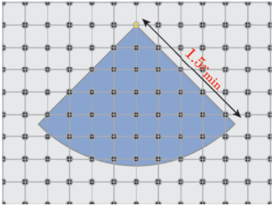
Necessary to embed the support requirement into the optimization

- Post-process an optimized design?
- Optimize for no-support?
- Optimize for minimum support?
- Optimize the build direction?

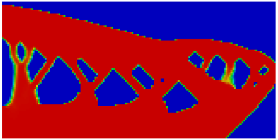
Dealing with overhang limitations

Necessary to embed the support requirement into the optimization

- Post-process an optimized design?
- Optimize for no-support?
- Optimize for minimum support?
- Optimize the build direction?



Use projection method to require support in specified angle [Gaynor, 2015] →



Dealing with overhang limitations

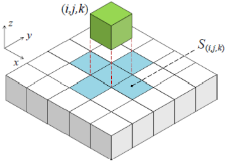
Necessary to embed the support requirement into the optimization

- Post-process an optimized design?
- Optimize for no-support?
- Optimize for minimum support?
- Optimize the build direction?

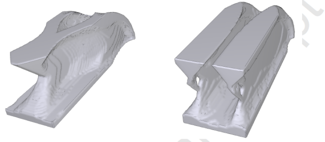
Dealing with overhang limitations

Necessary to embed the support requirement into the optimization

- Post-process an optimized design?
- Optimize for no-support?
- Optimize for minimum support?
- Optimize the build direction?



Use AM-filter to ensure that material is supported [Langelaar, 2016] →



a) Printable part of reference design b) AM-optimized design for $z_{\min}$ baseplate

Current research

Goal: Derive a procedure that can account for a given overhang limitation

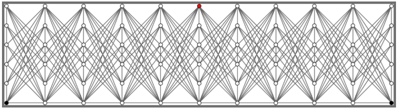
Desired features:

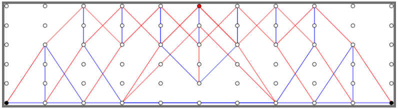
- Can generate designs with no support;
- Can generate designs with limited support;
- To be investigated in 2-D but extendable to 3-D;
- Minimal compromise on performance $\equiv$ stiffness-to-weight trade-off.

Virtual skeleton approach – briefly

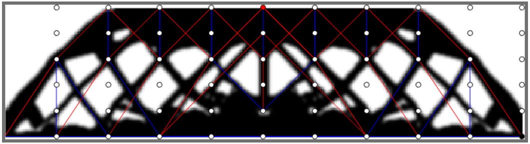
Main idea: allowable directions defined on a discrete line model (truss...) $\rightarrow$ virtual scaffold for continuum topology optimization

AM-oriented truss optimization



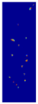
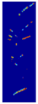
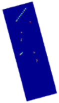
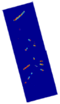


Topology optimization prioritized on virtual skeleton

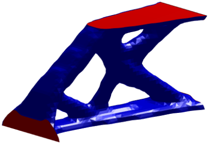


Virtual skeleton approach – briefly

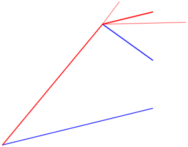
Table 4: Half MBB beam results

Case	Results	Layout	Gradient	Ref. gradient
Baseline	$c = 166.49$ UP = 6.09% for 90° UP = 4.74% for −75°		N/A	N/A
Print at 90°	$c = 169.63$ PD = 0.32% UP = 2.5%			
Print at −75°	$c = 170.17$ PD = 2.21% UP = 2.26%			

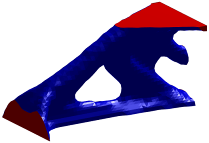
Standard



Truss



Suggested

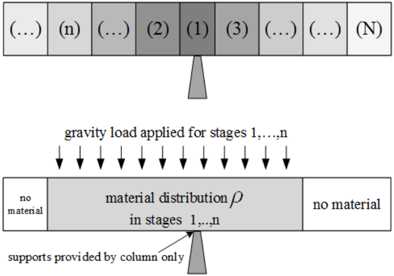


Staged construction – balanced cantilever

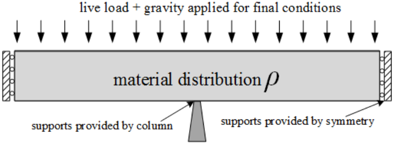
Topology optimization for staged construction

Looking at the design of a balanced cantilever bridge:

During construction



Final conditions



Topology optimization for staged construction

$$\min_{\boldsymbol{\rho}} \qquad f(\overline{\boldsymbol{\rho}}) = \mathbf{f}_f^T \mathbf{u}_f + \sum_{n=1}^{N_{STG}} \theta_n \mathbf{f}_n^T \mathbf{u}_n$$

$$\text{s.t.:} \qquad g(\overline{\boldsymbol{\rho}}) = \sum_{e=1}^{N_E} \overline{\rho}_e v_e - V^\star \leq 0$$

$$0 < \rho_{min} \leq \rho_e \leq 1, \qquad e = 1, ..., N_E$$

$$\text{with:} \qquad \mathbf{K}_f \mathbf{u}_f = \mathbf{f}_f$$

$$\mathbf{K}_n \mathbf{u}_n = \mathbf{f}_n \qquad n = 1, ..., N_{STG}$$

Remarks:

- We have N_{STG} construction stages, with unique stiffness matrices, boundary conditions and loads
- We use **standard** topology optimization “ingredients”: SIMP, density filter, MMA, Heaviside projection (if necessary)

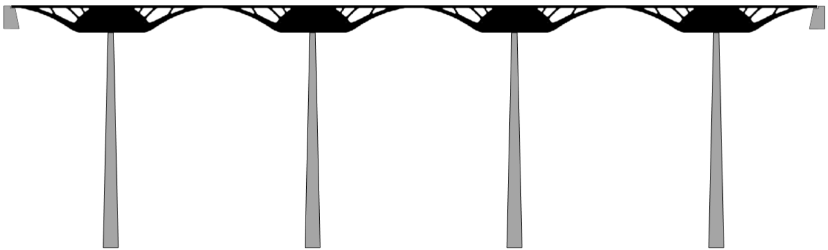
Topology optimization for staged construction

Results of the staged construction approach, balanced cantilever bridge:

stages	optimized layout	comments
N/A		baseline design
		low θ, volume active
		high θ, volume inactive
		low θ, volume active
		high θ, volume inactive

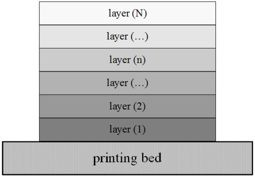
Topology optimization for staged construction

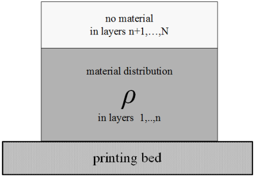
Results of the staged construction approach, balanced cantilever bridge:

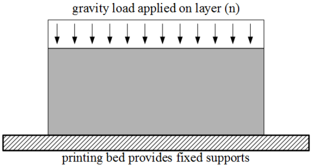


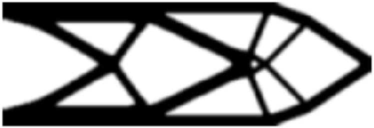
Additive manufacturing as "staged construction"

We see AM as a "layered" or "sliced" construction process:

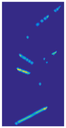
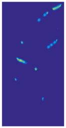
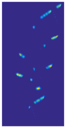




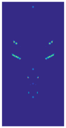
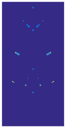




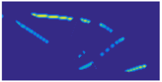
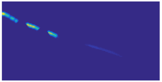
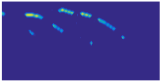
Preliminary results – half MBB

slicing fractions	$\mathbf{f}_f^T \mathbf{u}_f$	*NSVF*	optimized layout	non-supported regions
N/A	72.8921	0.0061		
$[80, 120]\,/160$	80.7397	0.0028		
$[50, \ldots, 150@20]\,/160$	76.4435	0.0044		

Preliminary results – cantilever

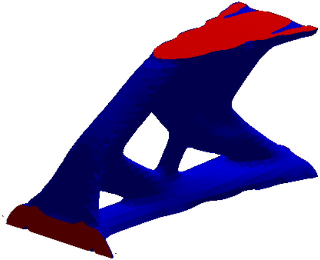
slicing fractions	$\mathbf{f}_f^T \mathbf{u}_f$	$NSVF$	optimized layout	non-supported regions
N/A	56.4807	0.0046		
$[80, 100, 120]/160$	60.8694	0.0021		
$[80, 90, 100, 110]/160$	59.4172	0.0018		

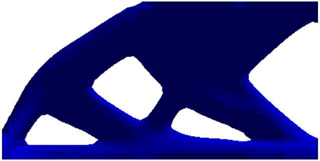
Preliminary results – half MBB

slicing fractions	$\mathbf{f}_f^T \mathbf{u}_f$	*NSVF*	optimized layout	non-supported regions
N/A	72.8921	0.0112		
$70/80$	85.0811	0.0027		
$[70, 80]/80$	81.0217	0.0061		

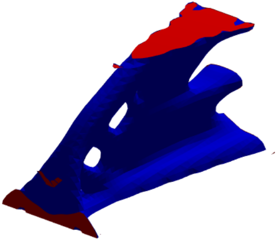
Preliminary results – 3-D cantilever

Standard





Sliced approach at $Z_{max}/2$



Conclusions and outlook

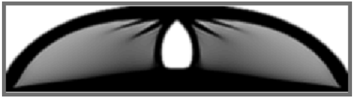
- Simple approach, uses standard top-opt procedures
- Possibility for control: slicing pattern, penalties θ_n
- Straightforward implementation in pixel/voxel based top-opt, can extend to account for actual manufacturing process
- Buildability not 100% guaranteed, some post-processing may be required
- Compromise on optimized performance
- Cost of multiple simulations per design cycle
- No need for black-and-white convergence??? revival of gray material???

Conclusions and outlook

- Simple approach, uses standard top-opt procedures
- Possibility for control: slicing pattern, penalties θ_n
- Straightforward implementation in pixel/voxel based top-opt, can extend to account for actual manufacturing process
- Buildability not 100% guaranteed, some post-processing may be required
- Compromise on optimized performance
- Cost of multiple simulations per design cycle
- No need for black-and-white convergence??? revival of gray material???

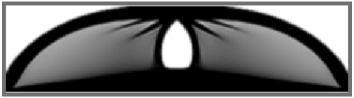
Conclusions and outlook

- Simple approach, uses standard top-opt procedures
- Possibility for control: slicing pattern, penalties θ_n
- Straightforward implementation in pixel/voxel based top-opt, can extend to account for actual manufacturing process
- Buildability not 100% guaranteed, some post-processing may be required
- Compromise on optimized performance
- Cost of multiple simulations per design cycle
- No need for black-and-white convergence??? revival of gray material???



Conclusions and outlook

- Simple approach, uses standard top-opt procedures
- Possibility for control: slicing pattern, penalties θ_n
- Straightforward implementation in pixel/voxel based top-opt, can extend to account for actual manufacturing process
- Buildability not 100% guaranteed, some post-processing may be required
- Compromise on optimized performance
- Cost of multiple simulations per design cycle
- No need for black-and-white convergence??? revival of gray material???



Thank you for listening

References I

Gaynor, A. T. (2015).
Topology Optimization Algorithms for Additive Manufacturing.
PhD thesis, The Johns Hopkins University.

Langelaar, M. (2016).
Topology optimization of 3d self-supporting structures for additive manufacturing.
Additive Manufacturing.

Muir, M. (2013).
Multidisciplinary optimisation of a business jet main exit door hinge for production by additive manufacturing.
In *The 8th Altair Technology Conference. Altair Engineering*.

Tomlin, M. and Meyer, J. (2011).
Topology optimization of an additive layer manufactured (ALM) aerospace part.
In *Proceeding of the 7th Altair CAE technology conference*, pages 1–9.