CO_2 Footprint Minimisation for Additive Manufactured Bio-composite thin Structures

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December 9, 2022

Summary

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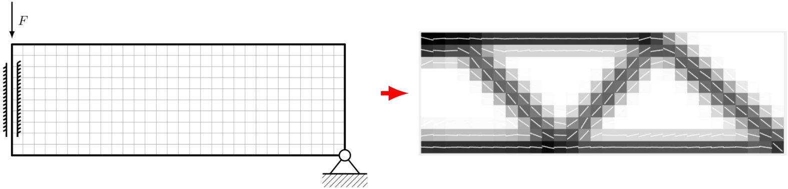
Introduction



- Aeronautical industry brings about demands such as the reduction of fuel consumption;
- New 3D printing technologies allow for new design methods;
- Sustainability plays an increasingly important role.

- SIMP Model [Andreassen 2011]

$$\text{minimize} : c(x) = \mathbf{U^T K U} = \sum_{e=1}^{N} u_e^T k_e u_e$$

$$\text{subject to} : \begin{cases} \frac{V(x)}{V_0} = f \\ \mathbf{KU} = \boldsymbol{F} \\ 0 < \rho_{min} \leq \rho \leq 1 \end{cases} \quad (1)$$

$$\boxed{k_e = (\rho_e)^p k_0}$$

- Problem Formulation [Jiang]

$$\text{minimize} : c(x) = \mathbf{U^T K U} = \sum_{e=1}^{N} u_e^T k_e u_e$$

$$\text{subject to} : \begin{cases} \frac{V(x)}{V_0} = f \\ \mathbf{KU} = \boldsymbol{F} \\ 0 < \rho_{min} \leq \rho \leq 1 \\ -1 \leq cos(\theta) \leq 1 \\ -1 \leq sin(\theta) \leq 1 \end{cases} \quad (2)$$

$$\boxed{k_e = k_e(\rho_e, \theta_e) = (\rho_e)^p k_e(\theta)}.$$

Geometry

- Several load cases considered:

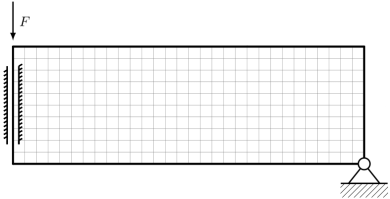


Figure: Half MBB Beam.

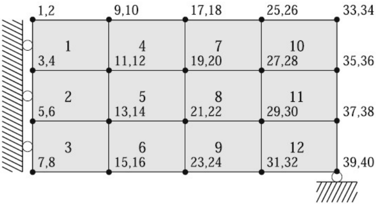


Figure: Mesh discretisation.

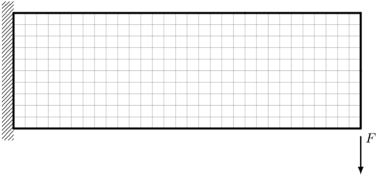


Figure: Cantilever Beam.

```
data.width = 30; % (mm) must be even because ...
    of load case
data.height = 15; % (mm) must be even ...
    because of load case
data.thickness = 1; % (mm)
data.elSize = 1; %square's side length (mm)
data.nelx = data.width/data.elSize;
data.nely = data.height/data.elSize;
data.elVol = ...
    data.elSize*data.elSize*data.thickness*1E-9;
    %m^3
```

FEM Analysis

```
%% FE-ANALYSIS
U     = zeros(2*(d.nely+1)*(d.nelx+1),1);
[KE, dKE] = lkod_multi(d, ang);
sK = reshape(KE.*repmat(volPhys'.^d.penal, ...
    64, 1), 64*d.nelx*d.nely,1);
K = sparse(d.iK,d.jK,sK); K = (K+K')/2;
% Cholesky factorization
[L,¬,s] = chol(K(d.freedofs,d.freedofs), ...
    'lower','vector');
% Forward/backward substitution
U(d.freedofs(s))=L'\(L\d.F(d.freedofs(s)));
%
KEe = reshape(KE, 8, 8, d.nelx*d.nely);
dKEe = reshape(dKE, 8, 8, d.nelx*d.nely);
Ue = reshape(U(d.edofMat)', 8, 1, ...
    d.nelx*d.nely);

%% COMPUTE OBJECTIVE FUNCTION (compliance)
c = U'* K * U; %same as line above
```

```
%% INITIAL DESIGN
ang0 = linspace(-pi/2,pi/2,data.N)';
rho0 = data.volfrac*ones(length(ang0), ...
    data.nely*data.nelx);
cos0 = 0.5*cos(ang0)*ones(1, ...
    data.nely*data.nelx);
sin0 = 0.5*sin(ang0)*ones(1, ...
    data.nely*data.nelx);
x0 = [rho0(:,:) cos0(:,:) sin0(:,:)];
X0 = CustomStartPointSet(x0);
```

```
problem = ...
     createOptimProblem('fmincon','objective',...
    @(x) fato_fmincon_multi(x, data), ...
    ... % initial gues s:
    'x0',ones(1,3*data.nely*data.nelx),...
    ... % linear inequality constraints: none
    ... % linear equality constraints:
    'Aeq', Aeq, 'beq', beq, ...
    ... % lower/upper bounds
    'lb', lb, 'ub', ub, ...
    ... % non-linear constraints: none
    'options', options); %optimization options
```

```
ms = MultiStart('UseParallel',true, ...
    'StartPointsToRun','all');
    ...
[data.x,data.fval,exitflag,output,solutionset] .
    = run(ms,problem,X0);
```

- **Density Filtering**

$$\tilde{x_e} = \frac{1}{\sum_{i \epsilon N_e} H_{ei}} \sum_{i \epsilon N_e} H_{ei} x_i \qquad (3)$$

where H_{ei} is the weight factor given by:

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

- **Gaussian Filtering on Fiber Orientation**

$$f(x, y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{(x-\mu)+(y-\mu)}{\sigma}\right)^2} \qquad (5)$$

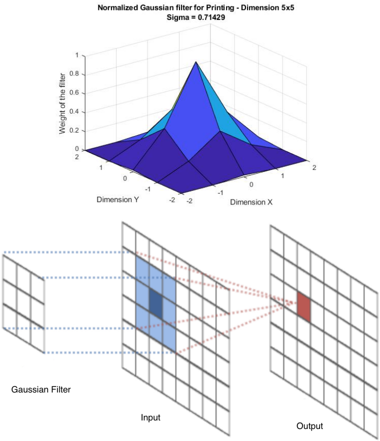


Figure: Gaussian Convolution.
[Stragiotti 2020]

- Taking into account its production phase and use on a vehicle. [Duriez 2022]

$$CO_2^{tot} = CO_2^{mat} + LD \times CO_2^{veh} \tag{6}$$

$$CO_2^{mat} = V^i \times f^i \times (\%^{Matrix} \times \rho^{Matrix} \times CO_2^{Matrix} + \%^{Fiber} \times \rho^{Fiber} \times CO_2^{Fiber}) \tag{7}$$

$$CO_2^{veh} = CO_2^{vehPerMass} \times Total\ Mass \tag{8}$$

$$CO_2^{vehPerMass} = FRC \times Vehicle\ Life \times CO_2^{Fuel} \times LDE \tag{9}$$

```
data.LD = 100000000; %Lifetime Distance (km)
data.VehLife = 25; % Vehicle life years
data.FRC = 1030; %kg Fuel /kg Transported ...
    Mass /year
data.CO2Fuel = 3.83E3;% kg CO2/Kg Fuel
data.CO2vehPerMass = ...
    data.FRC*data.VehLife*data.CO2Fuel/data.LD; ...
    %kgCO2 /km /Kg of Material
```

Considered Materials

Table: Material properties of available fibers and resins.

Type	Material	ρ Kg/m^3	E GPa	ν	CO^2_{mat} Kg/Kg
Fibers	Bamboo	700	17.5	0.04	1.0565
	Flax	1470	53.5	0.355	0.44
	Hemp	1490	62.5	0.275	1.6
	Carbon High Modulus	2105	760	0.105	68.1
	Carbon Low Modulus	1820	242.5	0.105	20.3
	S-Glass	2495	89.5	0.22	2.905
	E-Glass	2575	78.5	0.22	2.45
Resins	Cellulose	990	3.25	0.355	3.8
	PLA	1290	5.19	0.39	2.115
	PETG (abs)	1270	2.06	0.403	4.375
	Epoxy	1255	2.41	0.399	5.94
	Polyester	1385	4.55	0.35	4.5

- Composite characteristics obtained by the Rule of Mixtures. [Alger 2017]

$$E_{\text{Longitudinal Composite}} = E_{\text{Fiber}} \times V_{\text{Fiber}} + E_{\text{Matrix}} \times V_{\text{Matrix}} \tag{10}$$

$$E_{\text{Transverse Composite}} = (E_{\text{Fiber}} \times E_{\text{Matrix}})/(E_{\text{Fiber}} \times (1 - V_{\text{Fiber}})) + E_{\text{Matrix}} \times V_{\text{Fiber}} \tag{11}$$

Summary

Different Init. Conditions or Materials

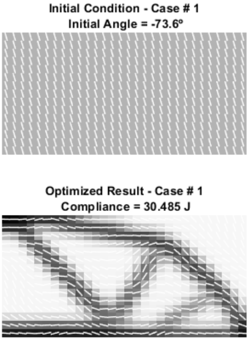
- Half MBB Beam (30 x 15 elements)

⇒ volfrac = 0.3

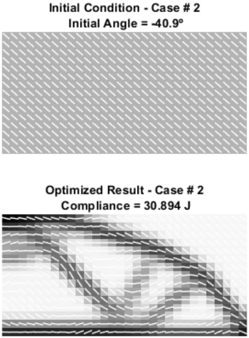
⇒ penal = 3

⇒ rmin = 1.5

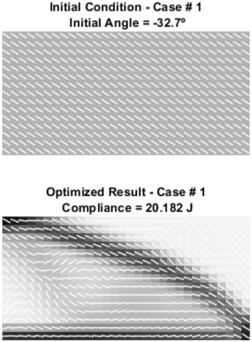
⇒ N = 23



Cellulose and 0.5 of Bamboo



Cellulose and 0.5 of Bamboo



Epoxy and 0.25 of E-Glass

Different Mesh Sizes

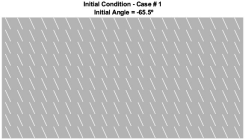
- Half MBB Beam - Cellulose and 0.5 of Bamboo

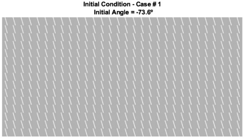
⇒ volfrac = 0.3

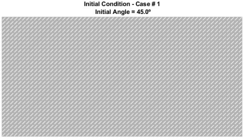
⇒ penal = 3

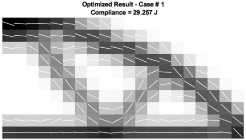
⇒ rmin = 1.5

⇒ N = 23

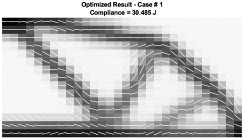




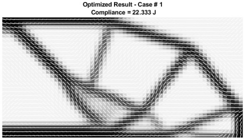




40 x 20



60 x 30



120 x 60

Different Mesh Sizes

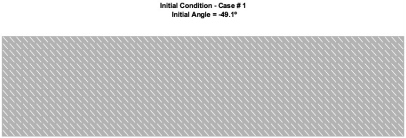
- Half MBB Beam - Cellulose and 0.5 of Bamboo

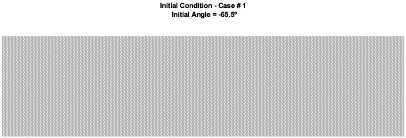
⇒ volfrac = 0.3

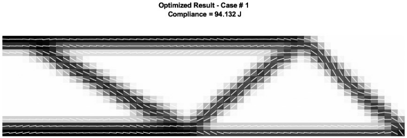
⇒ penal = 3

⇒ rmin = 1.5

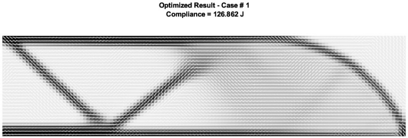
⇒ N = 23







120 x 30



240 x 60

CO_2 Footprint

RESULTS

CO2 IMPACT (KG OF CO2)	TOTAL MASS (KG)	SET
48863	0.00049545	Cellulose & 0.25 of Bamboo
45001	0.0004563	Cellulose & 0.5 of Bamboo
59114	0.0005994	Cellulose & 0.25 of Flax
65505	0.0006642	Cellulose & 0.5 of Flax
59381	0.0006021	Cellulose & 0.25 of Hemp
66038	0.0006696	Cellulose & 0.5 of Hemp

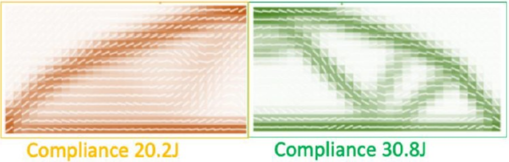


Figure: Info included in CO_2 results file.

Computation Time

Table: Execution time of optimisation of different cases.

Load Case & Domain Dimension	Material	Time (s)
HALF-MBB-BEAM	Cellulose & 0.5 Bamboo	10.990
60x30	Epoxy & 0.25 Flax	15.289
data.N = 23	Epoxy & 0.5 Flax	6.332
CANT	Cellulose & 0.5 Bamboo	16.930
60x30	Epoxy & 0.25 Flax	12.174
data.N = 23	Epoxy & 0.5 Flax	4.496
HALF-MBB-BEAM	Cellulose & 0.5 Bamboo	72.512
240x60	Epoxy & 0.25 Flax	43.575
data.N = 23	Epoxy & 0.5 Flax	53.078
CANT	Cellulose & 0.5 Bamboo	114.016
240x60	Epoxy & 0.25 Flax	86.849
data.N = 23	Epoxy & 0.5 Flax	40.068

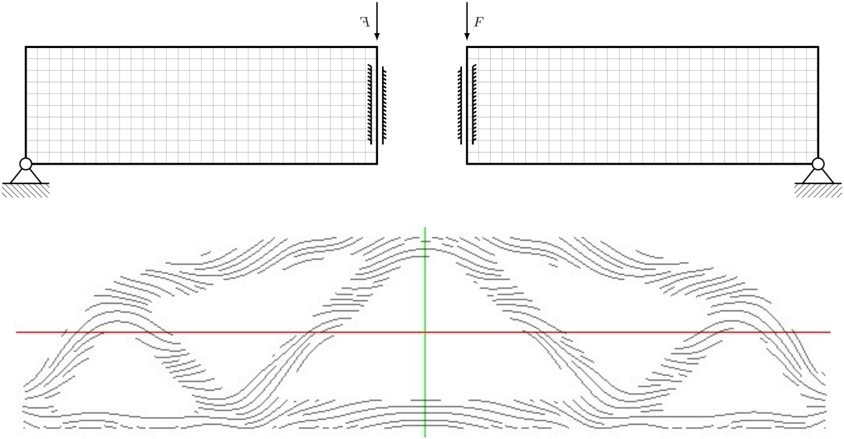


Figure: G-code output.

- It is possible to study environmental impact of structures in the earliest stages of a designing process;
- Topology optimisation and fibre path optimisation have many more applications than just mass reduction;
- Regardless of the impact on the production phase, the footprint of the use phase of the structure is much more important.

Future Work

- Validate obtained data;
- Print a sample;
- Perform 3 point bending test.

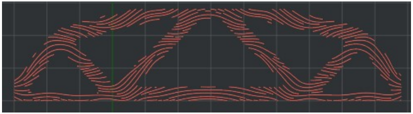


Figure: GCode output.

- Extend to out of plane 3D TopOptim (fiber's spatial orientation);
- Apply to other fields: Cost, ...

Thank you for your attention!
Do you have any questions?

Developed MATLAB code available on GitHub:

https://github.com/mid2SUPAERO/Fiber-Angle-and-Topology-Optimization

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