Final Project 2.2:
2-D Topology Optimization

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Abstract

This project explores an already developed 99-line code by Sigmund [1] and was further condensed by Andreassen and Erik to 88 lines [2]. This code is useful in applying sensitivity or density filters in order to optimize a 2-D Beam structure depending on its loading and boundary conditions. Several simulations are conducted and compared for two common beam types. Among them include a simply balanced beam and a simple cantilever. Cases discussed include multiple load cases, and passive elements [2].

I. Introduction

The purpose of this project is to implement and customize an optimization algorithm in order to minimize "the compliance of a structure at its equilibrium state with respect to its topology" [3]. The fundamental essence of topology optimization is essentially to conduct some form of finite element analysis. In other words, a given geometry or design is deconstructed into n finite elements. Each respective element is assigned a density value (x_i) which in turn corresponds to a material's characteristics. For example, x_i could be represented mechanically via the slope of its stress-strain curve at 2% of its offset, also known as Young's Modulus. It can also be used to represent the amount of thermal or electrical resistance or conductivity a material contains. Optimizing this scenario is important, especially from an engineering perspective. Optimizing the amount of material distribution based on the forces and boundary conditions placed on a design ensures that the proper material is being used, money isn't being wasted from overdesigning, and the design is mechanically, thermally, or electrically sound. Specifically, compliance minimization refers to the seeking of "the stiffest structure within a certain volume limit to withhold a particular load" [3]. This can be written mathematically below in **Equation 1**.

$$\min_{x} f = u^T K(x) u$$

$$subject\ to: h = K(x)u = d,$$

$$g = V(x) \leq v,$$

$$x \in [0,1].$$

***Equation 1**: Topology Optimization Problem*

Where V(x) is the total volume, *v* is the maximum volume, *u* is the displacement of the structure under load *d*, n_d is the degrees of freedom, and *K(x)* is the global stiffness matrix of the structure [3].

II. Background

There are six major sections in this 88-lines of code including **Material Properties**, **Finite Elements**, **Loads and Boundary Conditions**, **Finite Elements**, **Filtering and Sensitivity Analysis**, and **Plotting**. All of these components are described below in great detail.

III. Material Properties

As shown below in **Figure 1**, the script initiates with defining the material properties Young's Modulus. As referenced previously, Young's Modulus is simply the slope of the stress-strain curve of a material.

```
%% MATERIAL PROPERTIES
%Youngs Modulus is E0
E0 = 1;
Emin = 1e-9;
%Let nu be Poisson's Ratio
nu = 0.3;
```

Figure 1: *Material Properties (see* ***Appendix****)*

Figure 2 below depicts a curve that is typical for ductile materials, in this case steel. Tensile testing per ASTM standard allows for this depiction of how any material behaves when an increasing load (or stress) is placed on it.

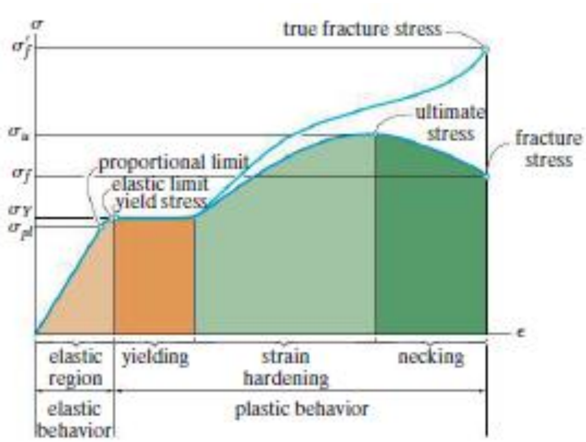

Figure 2*: Conventional and true stress-strain diagram for ductile materials (steel)[4]*

Per this standard, specimens are tested using a tensile tester as seen below in **Figure 3**.

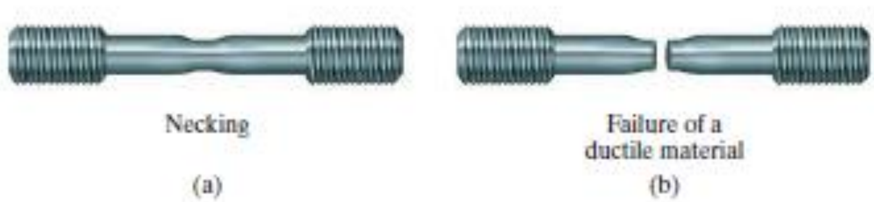

***Figure 3**: Typical Test Specimen for Ductile Material[4]*

Ductile materials react in several phases when a load is being applied to it. The four main regions include the elastic region, yielding, strain hardening, and necking. The elastic region is when the specimen begins to "stretch" such as a rubber band would when a force is applied to it. Once the specimen reaches its yield stress, it will begin to fail mechanically such that it can no longer return to its original state. Furthermore, the end of the yielding phase begins strain hardening. At this point, the material is plastically deforming until it reaches its ultimate (or maximum stress). Past the point of ultimate stress is when necking occurs, and the specimen finally fails and reaches its fracture stress. The MATLAB script also takes advantage of Poisson's ratio, as defined below in **Equation 2.** It is defined as the negative of the ratio between the latitudinal to longitudinal strain.

$$v = -\frac{\epsilon_{lat}}{\epsilon_{long}}$$

***Equation 2**: Poisson's ratio[4]*

Now that there's a general understanding of how to define material properties, we can discretely decompose our geometry mathematically into finite elements.

IV. Finite Elements

Separating your design geometry into finite elements allows there to be a mathematically discretized method of calculating how a material with react based on the forces and boundary conditions applied onto it.

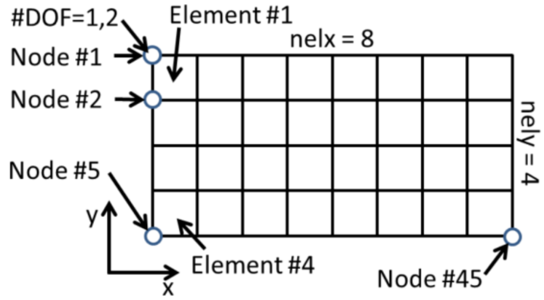

Figure 4: *Discretizing simple rectangular geometry into finite elements[3]*

As shown above in **Figure 4**, for this particular algorithm, a simple rectangular geometry is discretized into simplified square elements. In reality, many programs have the ability to discretize geometries into triangles, polygons, or any mixture of shapes that are able to conform seamlessly to the provided geometry. For this case, *nelx* and *nely* are used to specify the number of elements in the x and y direction respectively. DOF specifies the number of degrees of freedom that each node is able to move freely in.

```
%% PREPARE FINITE ELEMENT ANALYSIS
A11 = [12  3 -6 -3;  3 12  3  0; -6  3 12 -3; -3  0 -3 12];
A12 = [-6 -3  0  3; -3 -6 -3 -6;  0 -3 -6  3;  3 -6  3 -6];
B11 = [-4  3 -2  9;  3 -4 -9  4; -2 -9 -4 -3;  9  4 -3 -4];
B12 = [ 2 -3  4 -9; -3  2  9 -2;  4  9  2  3; -9 -2  3  2];
KE = 1/(1-nu^2)/24*([A11 A12;A12' A11]+nu*[B11 B12;B12' B11]);
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
edofVec = reshape(2*nodenrs(1:end-1,1:end-1)+1,nelx*nely,1);
edofMat = repmat(edofVec,1,8)+repmat([0 1 2*nely+[2 3 0 1] -2 -1],nelx*nely,1);
iK = reshape(kron(edofMat,ones(8,1))',64*nelx*nely,1);
jK = reshape(kron(edofMat,ones(1,8))',64*nelx*nely,1);
```

Figure 5: *Finite Element Analysis implemented within the MATLAB algorithm (see* ***Appendix****)*

As depicted above in **Figure 5**, the beginning A and B matrices are used to describe the beam's stiffness matrix in conjunction with Poisson's ratio. *Nodenrs* defines a matrix with *nelx* and *nely* respectively. *Nodenrs* is also utilized in the storage of *edofVec* which is used to determine the eight degrees of freedom indices for each finite element. *Edofmat* collects the results of *edofVec*. Finally, *iK* and *jK* reshape the *edofMat* matrix using a Kronecker matric product[2].

V. Loads and Boundary Conditions

Figure 6 below shows how the load *F* and boundary conditions *fixeddofs*, *alldofs*, and *freedofs* are all determined mathematically in order to accurately depict any given design scenario

```
% DEFINE LOADS AND SUPPORTS (HALF MBB-BEAM)
% F is a sparse column vector that specifies the loading on the beam
F = sparse(2,1,-1,2*(nely+1)*(nelx+1),1);
U = zeros(2*(nely+1)*(nelx+1),1);
%This section defines your boundary conditions/degrees of freedom
fixeddofs = union([1:2:2*(nely+1)],[2*(nelx+1)*(nely+1)]);
alldofs = [1:2*(nely+1)*(nelx+1)];
freedofs = setdiff(alldofs,fixeddofs);
```

***Figure 6**: Load and Boundary Conditions (see **Appendix**)*

For this particular project, several different loads and boundary conditions were placed on a beam and simple cantilever. All of these cases are described in greater detail in the subsequent sections.

i. MBB Beam

A MBB Beam is a classical engineering problem where a beam is supported by four rollers, three along its x-axis and one supporting its y-axis. A force is also placed on the beam perpendicular to the y-axis at x=0. All of the design domains, boundary conditions, and external loadings are depicted below in **Figure 7**.

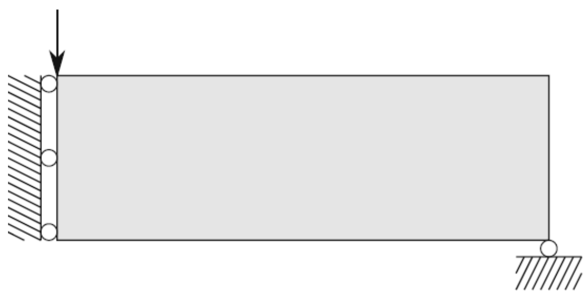

***Figure 7**: Design Domain, boundary conditions, and external load for the optimization of a symmetric MBB beam[2]*

ii. Short Cantilever Beam

A short cantilever beam is a simpler case as opposed to the MBB beam where a rectangular-shaped beam is fixed on one end and a downward force is applied to it on the other end. This case is depicted below in **Figure 8**.

Figure 8: *The design domain, boundary conditions, and external load for the optimization of a cantilever beam* [2]

Furthermore, several cases of a short cantilever beam were simulated for this project. This includes one with multiple forces on the end of the beam and another modeling a cantilever that contains porous material (see **Figure 9** below).

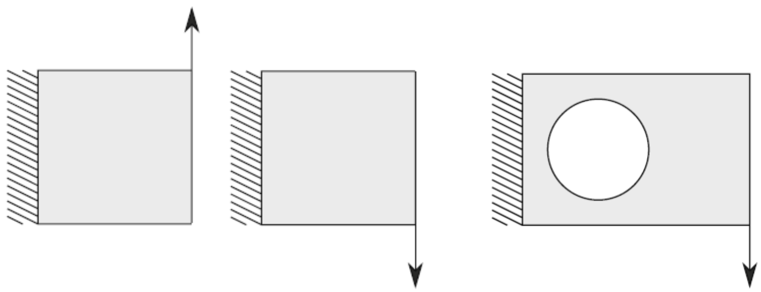

Figure 9: *Short Cantilever beam with multiple forces (two from left) and with porous material (one on right)* [2]

VI. Filtering and Sensitivity Analysis

The program produced in MATLAB has the ability to filter out certain node values in order to "avoid the formation of checker-board patterns. The two most common approaches were used, including a filter placed on the sensitivities or the densities. The for-loops utilized in order to iterate the *iH(k), jH(k),* and, *sH(k)* and to prepare the filter are depicted below in **Figure 10**.

```
%% PREPARE FILTER
iH = ones(nelx*nely*(2*(ceil(rmin)-1)+1)^2,1);
jH = ones(size(iH));
sH = zeros(size(iH));
k = 0;
for i1 = 1:nelx
  for j1 = 1:nely
    e1 = (i1-1)*nely+j1;
    for i2 = max(i1-(ceil(rmin)-1),1):min(i1+(ceil(rmin)-1),nelx)
      for j2 = max(j1-(ceil(rmin)-1),1):min(j1+(ceil(rmin)-1),nely)
        e2 = (i2-1)*nely+j2;
        k = k+1;
        iH(k) = e1;
        jH(k) = e2;
        sH(k) = max(0,rmin-sqrt((i1-i2)^2+(j1-j2)^2));
      end
    end
  end
end
```

***Figure 10**: for-loops from MATLAB code (see **Appendix**)*

As shown in the sensitivity analysis portion of the MATLAB code below in **Figure 11**, the compliance, c, and the sensitivities *dc* and *dv* of the objective function are calculated within the volume constraint and with respect to the physical node densities.

```
%% OBJECTIVE FUNCTION AND SENSITIVITY ANALYSIS
ce = reshape(sum((U(edofMat)*KE).*U(edofMat),2),nely,nelx); % element-wise strain energy
c = sum(sum((Emin+xPhys.^penal*(E0-Emin)).*ce)); % total strain energy
dc = -penal*(E0-Emin)*xPhys.^(penal-1).*ce; % design sensitivity
dv = ones(nely,nelx);

%% FILTERING/MODIFICATION OF SENSITIVITIES
if ft == 1
  dc(:) = H*(x(:).*dc(:))./Hs./max(1e-3,x(:));
elseif ft == 2
  dc(:) = H*(dc(:)./Hs);
  dv(:) = H*(dv(:)./Hs);
end

%% OPTIMALITY CRITERIA UPDATE OF DESIGN VARIABLES AND PHYSICAL DENSITIES
l1=0; l2=1e9; move=0.2;
while (l2-l1)/(l1+l2) > 1e-3
    lmid = 0.5*(l2+l1);
    xnew = max(0,max(x-move,min(1,min(x+move,x.*sqrt(-dc./dv/lmid)))));
    if ft == 1
        xPhys = xnew;
    elseif ft == 2
        xPhys(:) = (H*xnew(:))./Hs;
    end
    if sum(xPhys(:)) > volfrac*nelx*nely, l1 = lmid ; else l2 = lmid; end
end
change = max(abs(xnew(:)-x(:)));
x = xnew;
```

***Figure 11**: Sensitivity Analysis within MATLAB code (see **Appendix**)*

VII. Plotting

```
%% PRINT RESULTS
fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f ch.:%7.3f\n',loop,c, ...
  mean(xPhys(:)),change);

%% PLOT DENSITIES
colormap(gray); imagesc(1-xPhys); caxis([0 1]); axis equal; axis off; drawnow;
```

Figure 12*:Printing the results and plotting the densities in MATLAB (see* ***Appendix****)*

Finally, the densities are plotted using the colormap feature on MATLAB as shown below in **Figure 12**.

VIII. Results and Discussion

i. Test Script

The different loading scenarios mentioned above in **MBB Beam** and **Short Cantilever Beam** were written into separate MATLAB scripts and ultimately condensed into a control panel so that each run could be simulated section by section. As shown below in **Figure 13**, the function is called in by file name and the simulation scenarios are inputted into the function. The variables include *nelx*, *nely* as previously discussed in **Finite Elements**. Other variables are inputted as well, including *volfrac* which is the volume fraction, a penalization power *penal*, and a filter radius *rmin*. Lastly, the filter *ft* is selected, with (1) being the sensitivity and (2) being density.

```
%Testing several Beam Scenarios, Boundary Conditions, and Loadings
% Format Scenario(nelx, nely,volfrac, penal, rmin, ft)
%nelx = number of elements in x
%nely= number of elements in y
% volfrac = volume fraction
%penal = penalization power
%rmin = the filter radius (divided by the element size)
%ft = sensitivity filter (1) or density filter (2)
```

Figure 13*:Test script inputs for simulation (see* ***Appendix****)*

ii. MBB Beam

Figure 14 shows the parameters used for the MBB beam. A function file named MBB was called into the control panel. A mesh size of 60 x 20 was established as well as s penalization power of 3. The filter radii differ slightly because the density filter creates a finer mesh and requires more computing power. Therefore, making *rmin* slightly larger for the density filter still creates a visually worthy comparison.

```
%% Sigmund (2001) : Optimization of a symmetric MBB Beam via Sensitivity Filtering
% Mesh size: 60 x 20
%volfrac = 0.5
%penal = 3
%rmin = 1.5
% sensitivity filtering: ft=1
MBB(60,20,0.5,3,1.5,1)

%% Sigmund (2001) : Optimization of a symmetric MBB Beam via Density Filtering
% Mesh size: 60 x 20
%volfrac = 0.5
%penal = 3
%rmin = 2.4
% density filtering: ft=2
MBB(60,20,0.5,3,2.4,2)
```

***Figure 14**: script of MBB optimization (see **Appendix**)*

As shown below in **Figure 15**, the density filter is able to create a slightly finer and less pixelated material compliance distribution. The spaces between the cross-members on the sensitivity filter contain a lot of noise and some extraneous material where the joints are located. However, this noise is barely seen in the simulation conducted with the density filter.

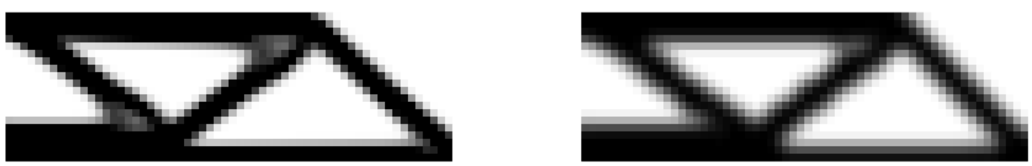

***Figure 15**: Sigmund (2001) Optimization of a symmetric MBB Beam via Sensitivity Filtering (left) and Density Filtering (right) (see **Appendix**)*

iii. Simple Cantilever Beam

As shown in **Figure 16**, the function file SC was called into the control panel. A mesh size of 160 x 100 was utilized as well as a penalization power of 3. The filter radii for this case were kept the same for both filters since the geometry was simplified greatly, making the computing power approximately equivalent for both filters.

```
%% Optimization of Short Cantilever Beam via Sensitivity Filtering
% Mesh size: 160 x 100
%volfrac = 0.4
%penal = 3
%rmin = 6
% sensitivity filtering: ft=1
SC(160,100,0.4,3,6,1)

%% Optimization of Short Cantilever Beam via Density Filtering
% Mesh size: 160 x 100
%volfrac = 0.4
%penal = 3
%rmin = 6
% density filtering: ft=2
SC(160,100,0.4,3,6,2)
```

Figure 16*: script of Short Cantilever Beam Optimization via sensitivity (top) and density(bottom) filtering (see* ***Appendix****)*

Figure 17 shows a side-by-side comparison of utilizing the sensitivity filter versus the density filter when applied to a short cantilever beam. As you can recall, a downward force is placed on the right-hand side of the beam. For the sensitivity filtering case, the right cross-body member seems to be thicker than the same member for the density case. However, when it comes to the cross-body member and the joint located on the top of the beam, the density case seems to be larger than the sensitivity case. This coincides with the overall pattern that the density filter seems to give priority to the joints of the structure when it pertains to material compliance.

Figure 17*: Optimization of a Short Cantilever Beam via Sensitivity Filtering (left) and Density Filtering (right) (see* ***Appendix****)*

iv. Implementing Multiple Forces to a Simple Cantilever Beam

As shown in **Figure 18**, the function file SC_ML was called into the control panel. A mesh size of 150 x 150 was utilized as well as a penalization power of 3. The filter radii for this case were kept the same for both filters since the geometry was simplified greatly, making the computing power approximately equivalent for both filters.

```
%% Optimization of Short Cantilever Beam with Multiple Forces via Sensitivity Filtering
% Mesh size: 150 x 150
%volfrac = 0.4
%penal = 3
%rmin = 6
% sensitivity filtering: ft=1
SC_ML(150,150,0.4,3,6,1)

%% Optimization of Short Cantilever with Multiple Forces via Density Filtering
% Mesh size: 150 x 150
%volfrac = 0.4
%penal = 3
%rmin = 6
% sensitivity filtering: ft=2
SC_ML(150,150,0.4,3,6,2)
```

Figure 18*: script of Short Cantilever Beam with Multiple Forces via sensitivity(top) and density(bottom) filtering (see* ***Appendix****)*

Figure 19 shows a side-by-side comparison of utilizing the sensitivity filter versus the density filter when applied to a short cantilever beam with multiple forces. As you can recall, both a downward and upward force are placed on the right-hand side of the beam. For the sensitivity filtering case, the cross-body members seem to join further away from the edge as opposed to the density case. However, when it comes to the cross-body members and the joint located in the middle, the density case seems to be larger than the sensitivity case. Once again, this coincides with the overall pattern that the density filter seems to give priority to the joints of the structure when it pertains to material compliance.

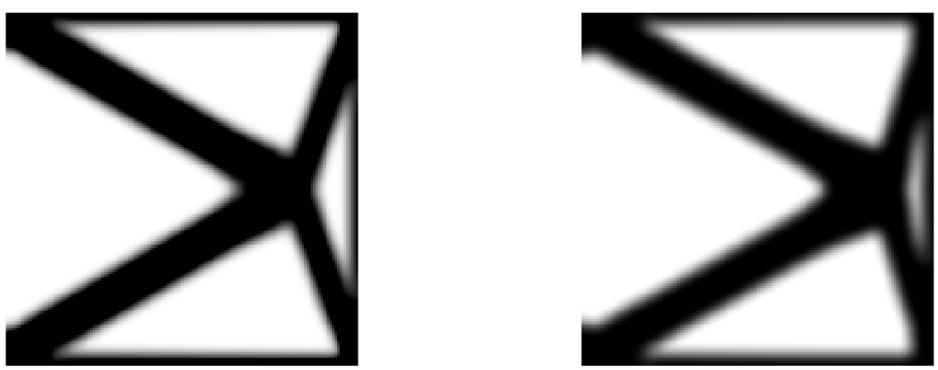

Figure 19*: Optimization of a Short Cantilever Beam with Multiple Forces via Sensitivity Filtering (left) and Density Filtering (right) (see* ***Appendix****)*

v. Implementing Passive Elements to a Simple Cantilever Beam

As shown in **Figure 20**, the function file SC_P was called into the control panel. A mesh size of 150 x 150 was utilized as well as a penalization power of 3. The filter radii differ slightly because although this is a simpler geometry, the density filter creates a finer mesh and requires more computing power. Therefore, making *rmin* slightly larger for the density filter still creates a visually worthy comparison.

```
%% Impelementing Passive Elements on a Short Cantilever Beam via Sensitivity Filtering
% Mesh size: 150 x 150
%volfrac = 0.5
%penal = 3
%rmin = 5
% sensitivity filtering: ft=1
SC_P(150,150,0.5,3,5,1)

%% Impelementing Passive Elements on a Short Cantilever Beam via Density Filtering
% Mesh size: 150 x 150
%volfrac = 0.5
%penal = 3
%rmin = 5
%density filtering: ft=2
SC_P(150,150,0.5,3,5,2)
```

***Figure 20**: script of Short Cantilever Beam with Passive Elements via sensitivity(top) and density(bottom) filtering (see **Appendix**)*

Lastly, **Figure 21** shows a side-by-side comparison of utilizing the sensitivity filter versus the density filter when applied to a short cantilever beam with a passive element. As you can recall, only a downward force is applied to the right-hand side of the beam and a passive element is introduced for any modern application such as a pipe or wiring. Surprisingly enough, both cases take on very similar distributions for material compliance. However, the density case seems to distribute more material around the passive element.

***Figure 21**: Optimization of a Short Cantilever Beam with Passive Elements via Sensitivity Filtering (left) and Density Filtering (right) (see **Appendix**)*

IX. Conclusion

Overall, several key components were discovered through the construction of this project. Young's Modulus and Poisson's Ratio were used to numerically describe any given **Material**

Properties. In addition, geometries can be deconstructed into **Finite Elements** and further simplified mathematically in order to establish a stiffness matrix. Once that has been determined, **Loads and Boundary Conditions** can be applied in order to simulate material compliance for any geometry or loading condition. **Filtering and Sensitivity Analysis** can then be conducted on the aforementioned scenarios in order to simulate and mathematically compare the same model from two different lenses. Lastly, each simulation was depicted using **Plotting** functions and compared on a visual basis.

X. References

[1] Sigmund O (2001) A 99-line topology optimization code written in Matlab. Struct Multidisc Optim 21(2):120–127

[2] Andreassen, Erik, et al. "Efficient Topology Optimization in MATLAB Using 88 Lines of Code." Structural and Multidisciplinary Optimization, vol. 43, no. 1, 2011, pp. 1–16, https://doi.org/10.1007/s00158-010-0594-7.

[3] Ren, M. Y. (n.d.). Application of Reduced Gradient - Topology Optimization. Application of reduced gradient - topology optimization. Retrieved December 6, 2022, from https://designinformaticslab.github.io/designopt_tutorial/2017/10/26/topologyopt.html

[4] Hibbeler, R. C. (2014). Mechanical Properties of Materials. In Mechanics of Materials, 9th ed. (9th ed.). essay, Prentice Hall.

XI. Appendix

i. MBB script

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```
%Daniel Rivera | Project 2: Topology Optimization| Prof. Max Yi Ren
% MAE 598: Design Optimization | Fall 2022

%Therefore, if you work on this project,
% please at least make all of the following extensions:
% Change boundary conditions
% Change loadings
% Write your own solver and document clearly each step of the solver.

%%%% Modified by Max Yi Ren (ASU) %%%%%%%%%%%%%%%%%%%%%%%

%%%% AN 88 LINE TOPOLOGY OPTIMIZATION CODE Nov, 2010 %%%%

function top88(nelx,nely,volfrac,penal,rmin,ft)
```

MATERIAL PROPERTIES

```
%Youngs Modulus is E0
E0 = 1;
Emin = 1e-9;
%Let nu be Poisson's Ratio
nu = 0.3;
```

PREPARE FINITE ELEMENT ANALYSIS

```
A11 = [12  3 -6 -3;  3 12  3  0; -6  3 12 -3; -3  0 -3 12];
A12 = [-6 -3  0  3; -3 -6 -3 -6;  0 -3 -6  3;  3 -6  3 -6];
B11 = [-4  3 -2  9;  3 -4 -9  4; -2 -9 -4 -3;  9  4 -3 -4];
B12 = [ 2 -3  4 -9; -3  2  9 -2;  4  9  2  3; -9 -2  3  2];
KE = 1/(1-nu^2)/24*([A11 A12;A12' A11]+nu*[B11 B12;B12' B11]);
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
edofVec = reshape(2*nodenrs(1:end-1,1:end-1)+1,nelx*nely,1);
edofMat = repmat(edofVec,1,8)+repmat([0 1 2*nely+[2 3 0 1] -2 -1],nelx*nely,1);
iK = reshape(kron(edofMat,ones(8,1))',64*nelx*nely,1);
jK = reshape(kron(edofMat,ones(1,8))',64*nelx*nely,1);
% DEFINE LOADS AND SUPPORTS (HALF MBB-BEAM)
% F is a sparse column vector that specifies the loading on the beam
F = sparse(2,1,-1,2*(nely+1)*(nelx+1),1);
U = zeros(2*(nely+1)*(nelx+1),1);
%This section defines your boundary conditions/degrees of freedom
fixeddofs = union([1:2:2*(nely+1)],[2*(nelx+1)*(nely+1)]);
alldofs = [1:2*(nely+1)*(nelx+1)];
freedofs = setdiff(alldofs,fixeddofs);
```

```
Not enough input arguments.

Error in MBB (line 28)
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
```

PREPARE FILTER

```
iH = ones(nelx*nely*(2*(ceil(rmin)-1)+1)^2,1);
jH = ones(size(iH));
sH = zeros(size(iH));
k = 0;
for i1 = 1:nelx
  for j1 = 1:nely
    e1 = (i1-1)*nely+j1;
    for i2 = max(i1-(ceil(rmin)-1),1):min(i1+(ceil(rmin)-1),nelx)
      for j2 = max(j1-(ceil(rmin)-1),1):min(j1+(ceil(rmin)-1),nely)
        e2 = (i2-1)*nely+j2;
        k = k+1;
        iH(k) = e1;
        jH(k) = e2;
        sH(k) = max(0,rmin-sqrt((i1-i2)^2+(j1-j2)^2));
      end
    end
  end
end
H = sparse(iH,jH,sH);
Hs = sum(H,2);
```

INITIALIZE ITERATION

```
x = repmat(volfrac,nely,nelx);
xPhys = x;
loop = 0;
change = 1;
```

START ITERATION

```
while change > 0.01
```

```
  loop = loop + 1;
```

FE-ANALYSIS

```
  sK = reshape(KE(:)*(Emin+xPhys(:)'.^penal*(E0-Emin)),64*nelx*nely,1);
  K = sparse(iK,jK,sK); K = (K +K')/2;
  U(freedofs) = K(freedofs,freedofs)\F(freedofs);
```

OBJECTIVE FUNCTION AND SENSITIVITY ANALYSIS

```
  ce = reshape(sum((U(edofMat)*KE).*U(edofMat),2),nely,nelx); % element-wise strain energy
  c = sum(sum((Emin+xPhys.^penal*(E0-Emin)).*ce)); % total strain energy
  dc = -penal*(E0-Emin)*xPhys.^(penal-1).*ce; % design sensitivity
  dv = ones(nely,nelx);
```

FILTERING/MODIFICATION OF SENSITIVITIES

```
if ft == 1
  dc(:) = H*(x(:).*dc(:))./Hs./max(1e-3,x(:));
elseif ft == 2
  dc(:) = H*(dc(:)./Hs);
  dv(:) = H*(dv(:)./Hs);
end
```

OPTIMALITY CRITERIA UPDATE OF DESIGN VARIABLES AND PHYSICAL DENSITIES

```
l1=0; l2=1e9; move=0.2;
while (l2-l1)/(l1+l2) > 1e-3
    lmid = 0.5*(l2+l1);
    xnew = max(0,max(x-move,min(1,min(x+move,x.*sqrt(-dc./dv/lmid)))));
    if ft == 1
        xPhys = xnew;
    elseif ft == 2
        xPhys(:) = (H*xnew(:))./Hs;
    end
    if sum(xPhys(:)) > volfrac*nelx*nely, l1 = lmid ; else l2 = lmid; end
end
change = max(abs(xnew(:)-x(:)));
x = xnew;
```

PRINT RESULTS

```
fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f ch.:%7.3f\n',loop,c, ...
  mean(xPhys(:)),change);
```

PLOT DENSITIES

```
colormap(gray); imagesc(1-xPhys); caxis([0 1]); axis equal; axis off; drawnow;
```

```
end
```

```
end
```

Function Call

```
%Sigmund (2001): Optimization of a symmetric MBB Beam

%top88(60,20,0.5,3,1.5,1)

%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This Matlab code was written by E. Andreassen, A. Clausen, M. Schevenels,%
% B. S. Lazarov and O. Sigmund,  Department of Solid  Mechanics,           %
%  Technical University of Denmark,                                        %
```

```
%  DK-2800 Lyngby, Denmark.                                           %
% Please sent your comments to: sigmund@fam.dtu.dk                    %
%                                                                     %
% The code is intended for educational purposes and theoretical details %
% are discussed in the paper                                          %
% "Efficient topology optimization in MATLAB using 88 lines of code,  %
% E. Andreassen, A. Clausen, M. Schevenels,                           %
% B. S. Lazarov and O. Sigmund, Struct Multidisc Optim, 2010          %
% This version is based on earlier 99-line code                       %
% by Ole Sigmund (2001), Structural and Multidisciplinary Optimization, %
% Vol 21, pp. 120--127.                                               %
%                                                                     %
% The code as well as a postscript version of the paper can be        %
% downloaded from the web-site: http://www.topopt.dtu.dk              %
%                                                                     %
% Disclaimer:                                                         %
% The authors reserves all rights but do not guaranty that the code is %
% free from errors. Furthermore, we shall not be liable in any event  %
% caused by the use of the program.                                   %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

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ii. Short Cantilever Beam

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```
%Daniel Rivera | Project 2: Topology Optimization| Prof. Max Yi Ren
% MAE 598: Design Optimization | Fall 2022

%Therefore, if you work on this project,
% please at least make all of the following extensions:
% Change boundary conditions
% Change loadings
```

```
% Write your own solver and document clearly each step of the solver.

%%%% Modified by Max Yi Ren (ASU) %%%%%%%%%%%%%%%%%%%%%%%

%%%% AN 88 LINE TOPOLOGY OPTIMIZATION CODE Nov, 2010 %%%%

function top88(nelx,nely,volfrac,penal,rmin,ft)
```

MATERIAL PROPERTIES

```
%Youngs Modulus is E0
E0 = 1;
Emin = 1e-9;
%Let nu be Poisson's Ratio
nu = 0.3;
```

PREPARE FINITE ELEMENT ANALYSIS

```
A11 = [12  3 -6 -3;  3 12  3  0; -6  3 12 -3; -3  0 -3 12];
A12 = [-6 -3  0  3; -3 -6 -3 -6;  0 -3 -6  3;  3 -6  3 -6];
B11 = [-4  3 -2  9;  3 -4 -9  4; -2 -9 -4 -3;  9  4 -3 -4];
B12 = [ 2 -3  4 -9; -3  2  9 -2;  4  9  2  3; -9 -2  3  2];
KE = 1/(1-nu^2)/24*([A11 A12;A12' A11]+nu*[B11 B12;B12' B11]);
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
edofVec = reshape(2*nodenrs(1:end-1,1:end-1)+1,nelx*nely,1);
edofMat = repmat(edofVec,1,8)+repmat([0 1 2*nely+[2 3 0 1] -2 -1],nelx*nely,1);
iK = reshape(kron(edofMat,ones(8,1))',64*nelx*nely,1);
jK = reshape(kron(edofMat,ones(1,8))',64*nelx*nely,1);
% DEFINE LOADS AND SUPPORTS (SHORT CANTILEVER (SC) EXAMPLE)
% F is a sparse column vector that specifies the loading on the beam
F = sparse(2*(nely+1)*(nelx+1),1,-1,2*(nely+1)*(nelx+1),1);
U = zeros(2*(nely+1)*(nelx+1),1);
%This section defines your boundary conditions/degrees of freedom
fixeddofs = [1:2*nely+1];
alldofs = [1:2*(nely+1)*(nelx+1)];
freedofs = setdiff(alldofs,fixeddofs);
```

```
Not enough input arguments.

Error in SC (line 28)
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
```

PREPARE FILTER

```
iH = ones(nelx*nely*(2*(ceil(rmin)-1)+1)^2,1);
jH = ones(size(iH));
sH = zeros(size(iH));
k = 0;
for i1 = 1:nelx
  for j1 = 1:nely
    e1 = (i1-1)*nely+j1;
```

```
    for i2 = max(i1-(ceil(rmin)-1),1):min(i1+(ceil(rmin)-1),nelx)
      for j2 = max(j1-(ceil(rmin)-1),1):min(j1+(ceil(rmin)-1),nely)
        e2 = (i2-1)*nely+j2;
        k = k+1;
        iH(k) = e1;
        jH(k) = e2;
        sH(k) = max(0,rmin-sqrt((i1-i2)^2+(j1-j2)^2));
      end
    end
  end
end
H = sparse(iH,jH,sH);
Hs = sum(H,2);
```

INITIALIZE ITERATION

```
x = repmat(volfrac,nely,nelx);
xPhys = x;
loop = 0;
change = 1;
```

START ITERATION

```
while change > 0.01
```

```
  loop = loop + 1;
```

FE-ANALYSIS

```
  sK = reshape(KE(:)*(Emin+xPhys(:)'.^penal*(E0-Emin)),64*nelx*nely,1);
  K = sparse(iK,jK,sK); K = (K +K')/2;
  U(freedofs) = K(freedofs,freedofs)\F(freedofs);
```

OBJECTIVE FUNCTION AND SENSITIVITY ANALYSIS

```
  ce = reshape(sum((U(edofMat)*KE).*U(edofMat),2),nely,nelx); % element-wise strain energy
  c = sum(sum((Emin+xPhys.^penal*(E0-Emin)).*ce)); % total strain energy
  dc = -penal*(E0-Emin)*xPhys.^(penal-1).*ce; % design sensitivity
  dv = ones(nely,nelx);
```

FILTERING/MODIFICATION OF SENSITIVITIES

```
  if ft == 1
    dc(:) = H*(x(:).*dc(:))./Hs./max(1e-3,x(:));
  elseif ft == 2
    dc(:) = H*(dc(:)./Hs);
    dv(:) = H*(dv(:)./Hs);
  end
```

OPTIMALITY CRITERIA UPDATE OF DESIGN VARIABLES AND PHYSICAL DENSITIES

```
l1=0; l2=1e9; move=0.2;
while (l2-l1)/(l1+l2) > 1e-3
    lmid = 0.5*(l2+l1);
    xnew = max(0,max(x-move,min(1,min(x+move,x.*sqrt(-dc./dv/lmid)))));
    if ft == 1
        xPhys = xnew;
    elseif ft == 2
        xPhys(:) = (H*xnew(:))./Hs;
    end
    if sum(xPhys(:)) > volfrac*nelx*nely, l1 = lmid ; else l2 = lmid; end
end
change = max(abs(xnew(:)-x(:)));
x = xnew;
```

PRINT RESULTS

```
fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f ch.:%7.3f\n',loop,c, ...
  mean(xPhys(:)),change);
```

PLOT DENSITIES

```
colormap(gray); imagesc(1-xPhys); caxis([0 1]); axis equal; axis off; drawnow;
```

```
end
```

```
end
```

Function Call

```
%Sigmund (2001): Optimization of a symmetric MBB Beam

%top88(60,20,0.5,3,1.5,1)

%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This Matlab code was written by E. Andreassen, A. Clausen, M. Schevenels,%
% B. S. Lazarov and O. Sigmund,  Department of Solid  Mechanics,           %
%  Technical University of Denmark,                                        %
%  DK-2800 Lyngby, Denmark.                                                %
% Please sent your comments to: sigmund@fam.dtu.dk                         %
%                                                                          %
% The code is intended for educational purposes and theoretical details    %
% are discussed in the paper                                               %
% "Efficient topology optimization in MATLAB using 88 lines of code,       %
% E. Andreassen, A. Clausen, M. Schevenels,                                %
% B. S. Lazarov and O. Sigmund, Struct Multidisc Optim, 2010               %
% This version is based on earlier 99-line code                            %
% by Ole Sigmund (2001), Structural and Multidisciplinary Optimization,    %
```

```
% Vol 21, pp. 120--127.                                                %
%                                                                      %
% The code as well as a postscript version of the paper can be         %
% downloaded from the web-site: http://www.topopt.dtu.dk               %
%                                                                      %
% Disclaimer:                                                          %
% The authors reserves all rights but do not guaranty that the code is %
% free from errors. Furthermore, we shall not be liable in any event   %
% caused by the use of the program.                                    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

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iii. Short Cantilever with Multiple Loads

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```
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% MAE 598: Design Optimization | Fall 2022

%Therefore, if you work on this project,
% please at least make all of the following extensions:
% Change boundary conditions
% Change loadings
% Write your own solver and document clearly each step of the solver.

%%%% Modified by Max Yi Ren (ASU) %%%%%%%%%%%%%%%%%%%%%%%

%%%% AN 88 LINE TOPOLOGY OPTIMIZATION CODE Nov, 2010 %%%%

function top88(nelx,nely,volfrac,penal,rmin,ft)
```

MATERIAL PROPERTIES

```
%Youngs Modulus is E0
E0 = 1;
Emin = 1e-9;
%Let nu be Poisson's Ratio
nu = 0.3;
```

PREPARE FINITE ELEMENT ANALYSIS

```
A11 = [12  3 -6 -3;  3 12  3  0; -6  3 12 -3; -3  0 -3 12];
A12 = [-6 -3  0  3; -3 -6 -3 -6;  0 -3 -6  3;  3 -6  3 -6];
B11 = [-4  3 -2  9;  3 -4 -9  4; -2 -9 -4 -3;  9  4 -3 -4];
B12 = [ 2 -3  4 -9; -3  2  9 -2;  4  9  2  3; -9 -2  3  2];
KE = 1/(1-nu^2)/24*([A11 A12;A12' A11]+nu*[B11 B12;B12' B11]);
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
edofVec = reshape(2*nodenrs(1:end-1,1:end-1)+1,nelx*nely,1);
edofMat = repmat(edofVec,1,8)+repmat([0 1 2*nely+[2 3 0 1] -2 -1],nelx*nely,1);
iK = reshape(kron(edofMat,ones(8,1))',64*nelx*nely,1);
jK = reshape(kron(edofMat,ones(1,8))',64*nelx*nely,1);
% DEFINE LOADS AND SUPPORTS (SHORT CANTILEVER MULTIPLE LOAD (SC_ML) EXAMPLE)
% F is a sparse column vector that specifies the loading on the beam
F = sparse([2*(nely+1)*nelx+2,2*(nely+1)*(nelx+1)],[1 2], [1 -1],2*(nely+1)*(nelx+1),2);
U = zeros(2*(nely+1)*(nelx+1),2);
%This section defines your boundary conditions/degrees of freedom
fixeddofs = [1:2*nely+1];
alldofs = [1:2*(nely+1)*(nelx+1)];
freedofs = setdiff(alldofs,fixeddofs);
```

```
Not enough input arguments.

Error in SC_ML (line 28)
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
```

PREPARE FILTER

```
iH = ones(nelx*nely*(2*(ceil(rmin)-1)+1)^2,1);
jH = ones(size(iH));
sH = zeros(size(iH));
k = 0;
for i1 = 1:nelx
  for j1 = 1:nely
    e1 = (i1-1)*nely+j1;
    for i2 = max(i1-(ceil(rmin)-1),1):min(i1+(ceil(rmin)-1),nelx)
      for j2 = max(j1-(ceil(rmin)-1),1):min(j1+(ceil(rmin)-1),nely)
        e2 = (i2-1)*nely+j2;
        k = k+1;
        iH(k) = e1;
        jH(k) = e2;
        sH(k) = max(0,rmin-sqrt((i1-i2)^2+(j1-j2)^2));
      end
    end
```

```
  end
end
H = sparse(iH,jH,sH);
Hs = sum(H,2);
```

INITIALIZE ITERATION

```
x = repmat(volfrac,nely,nelx);
xPhys = x;
loop = 0;
change = 1;
```

START ITERATION

```
while change > 0.01
```

```
  loop = loop + 1;
```

FE-ANALYSIS

```
  sK = reshape(KE(:)*(Emin+xPhys(:)'.^penal*(E0-Emin)),64*nelx*nely,1);
  K = sparse(iK,jK,sK); K = (K +K')/2;
  U(freedofs,:) = K(freedofs,freedofs)\F(freedofs,:);
```

OBJECTIVE FUNCTION AND SENSITIVITY ANALYSIS

```
  ce = reshape(sum((U(edofMat)*KE).*U(edofMat),2),nely,nelx); % element-wise strain energy
  c =0;
  dc=0;
  for i = 1:size(F,2)
      Ui = U(:,i);
      ce = reshape(sum((Ui(edofMat)*KE).*Ui(edofMat),2),nely,nelx);
      c = c + sum(sum((Emin+xPhys.^penal*(E0-Emin)).*ce));
      dc = dc - penal*(E0-Emin)*xPhys.^(penal-1).*ce;
  end
  dv = ones(nely,nelx);
```

FILTERING/MODIFICATION OF SENSITIVITIES

```
  if ft == 1
    dc(:) = H*(x(:).*dc(:))./Hs./max(1e-3,x(:));
  elseif ft == 2
    dc(:) = H*(dc(:)./Hs);
    dv(:) = H*(dv(:)./Hs);
  end
```

OPTIMALITY CRITERIA UPDATE OF DESIGN VARIABLES AND PHYSICAL DENSITIES

```
l1=0; l2=1e9; move=0.2;
while (l2-l1)/(l1+l2) > 1e-3
    lmid = 0.5*(l2+l1);
    xnew = max(0,max(x-move,min(1,min(x+move,x.*sqrt(-dc./dv/lmid)))));
    if ft == 1
        xPhys = xnew;
    elseif ft == 2
        xPhys(:) = (H*xnew(:))./Hs;
    end
    if sum(xPhys(:)) > volfrac*nelx*nely, l1 = lmid ; else l2 = lmid; end
end
change = max(abs(xnew(:)-x(:)));
x = xnew;
```

PRINT RESULTS

```
fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f ch.:%7.3f\n',loop,c, ...
  mean(xPhys(:)),change);
```

PLOT DENSITIES

```
colormap(gray); imagesc(1-xPhys); caxis([0 1]); axis equal; axis off; drawnow;
```

```
end
```

```
end
```

Function Call

```
%Sigmund (2001): Optimization of a symmetric MBB Beam

%top88(60,20,0.5,3,1.5,1)

%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This Matlab code was written by E. Andreassen, A. Clausen, M. Schevenels,%
% B. S. Lazarov and O. Sigmund,  Department of Solid  Mechanics,           %
%  Technical University of Denmark,                                        %
%  DK-2800 Lyngby, Denmark.                                                %
% Please sent your comments to: sigmund@fam.dtu.dk                         %
%                                                                          %
% The code is intended for educational purposes and theoretical details    %
% are discussed in the paper                                               %
% "Efficient topology optimization in MATLAB using 88 lines of code,       %
% E. Andreassen, A. Clausen, M. Schevenels,                                %
% B. S. Lazarov and O. Sigmund, Struct Multidisc Optim, 2010               %
% This version is based on earlier 99-line code                            %
% by Ole Sigmund (2001), Structural and Multidisciplinary Optimization,    %
```

```
% Vol 21, pp. 120--127.                                              %
%                                                                    %
% The code as well as a postscript version of the paper can be       %
% downloaded from the web-site: http://www.topopt.dtu.dk             %
%                                                                    %
% Disclaimer:                                                        %
% The authors reserves all rights but do not guaranty that the code is %
% free from errors. Furthermore, we shall not be liable in any event  %
% caused by the use of the program.                                  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

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iv. Short Cantilever with Multiple Loadings

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```
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% MAE 598: Design Optimization | Fall 2022

%Therefore, if you work on this project,
% please at least make all of the following extensions:
% Change boundary conditions
% Change loadings
% Write your own solver and document clearly each step of the solver.

%%%% Modified by Max Yi Ren (ASU) %%%%%%%%%%%%%%%%%%%%%%%

%%%% AN 88 LINE TOPOLOGY OPTIMIZATION CODE Nov, 2010 %%%%

function top88(nelx,nely,volfrac,penal,rmin,ft)
```

MATERIAL PROPERTIES

```
%Youngs Modulus is E0
E0 = 1;
Emin = 1e-9;
%Let nu be Poisson's Ratio
nu = 0.3;
```

PREPARE FINITE ELEMENT ANALYSIS

```
A11 = [12  3 -6 -3;  3 12  3  0; -6  3 12 -3; -3  0 -3 12];
A12 = [-6 -3  0  3; -3 -6 -3 -6;  0 -3 -6  3;  3 -6  3 -6];
B11 = [-4  3 -2  9;  3 -4 -9  4; -2 -9 -4 -3;  9  4 -3 -4];
B12 = [ 2 -3  4 -9; -3  2  9 -2;  4  9  2  3; -9 -2  3  2];
KE = 1/(1-nu^2)/24*([A11 A12;A12' A11]+nu*[B11 B12;B12' B11]);
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
edofVec = reshape(2*nodenrs(1:end-1,1:end-1)+1,nelx*nely,1);
edofMat = repmat(edofVec,1,8)+repmat([0 1 2*nely+[2 3 0 1] -2 -1],nelx*nely,1);
iK = reshape(kron(edofMat,ones(8,1))',64*nelx*nely,1);
jK = reshape(kron(edofMat,ones(1,8))',64*nelx*nely,1);
% DEFINE LOADS AND SUPPORTS (SHORT CANTILEVER (SC) EXAMPLE)
% F is a sparse column vector that specifies the loading on the beam
F = sparse(2*(nely+1)*(nelx+1),1,-1,2*(nely+1)*(nelx+1),1);
U = zeros(2*(nely+1)*(nelx+1),1);
%This section defines your boundary conditions/degrees of freedom
fixeddofs = [1:2*nely+1];
alldofs = [1:2*(nely+1)*(nelx+1)];
freedofs = setdiff(alldofs,fixeddofs);
passive = zeros(nely,nelx);
```

```
Not enough input arguments.

Error in SC_P (line 28)
nodenrs = reshape(1:(1+nelx)*(1+nely),1+nely,1+nelx);
```

PREPARE FILTER

```
iH = ones(nelx*nely*(2*(ceil(rmin)-1)+1)^2,1);
jH = ones(size(iH));
sH = zeros(size(iH));
k = 0;
for i1 = 1:nelx
  for j1 = 1:nely
    e1 = (i1-1)*nely+j1;
    for i2 = max(i1-(ceil(rmin)-1),1):min(i1+(ceil(rmin)-1),nelx)
      for j2 = max(j1-(ceil(rmin)-1),1):min(j1+(ceil(rmin)-1),nely)
        e2 = (i2-1)*nely+j2;
        k = k+1;
        iH(k) = e1;
        jH(k) = e2;
        sH(k) = max(0,rmin-sqrt((i1-i2)^2+(j1-j2)^2));
      end
```

```
    end
  end
end
for i = 1:nelx
    for j = 1:nely
        if sqrt((j-nely/2)^2+(i-nelx/3)^2) < nely/3
        passive(j,i) = 1;
        end
    end
end

H = sparse(iH,jH,sH);
Hs = sum(H,2);
```

INITIALIZE ITERATION

```
x = repmat(volfrac,nely,nelx);
xPhys = x;
loop = 0;
change = 1;
```

START ITERATION

```
while change > 0.01
```

```
  loop = loop + 1;
```

FE-ANALYSIS

```
  sK = reshape(KE(:)*(Emin+xPhys(:)'.^penal*(E0-Emin)),64*nelx*nely,1);
  K = sparse(iK,jK,sK); K = (K +K')/2;
  U(freedofs) = K(freedofs,freedofs)\F(freedofs);
```

OBJECTIVE FUNCTION AND SENSITIVITY ANALYSIS

```
  ce = reshape(sum((U(edofMat)*KE).*U(edofMat),2),nely,nelx); % element-wise strain energy
  c = sum(sum((Emin+xPhys.^penal*(E0-Emin)).*ce)); % total strain energy
  dc = -penal*(E0-Emin)*xPhys.^(penal-1).*ce; % design sensitivity
  dv = ones(nely,nelx);
```

FILTERING/MODIFICATION OF SENSITIVITIES

```
  if ft == 1
    dc(:) = H*(x(:).*dc(:))./Hs./max(1e-3,x(:));
  elseif ft == 2
    dc(:) = H*(dc(:)./Hs);
    dv(:) = H*(dv(:)./Hs);
  end
```

OPTIMALITY CRITERIA UPDATE OF DESIGN VARIABLES AND PHYSICAL DENSITIES

```
  l1=0; l2=1e9; move=0.2;
  while (l2-l1)/(l1+l2) > 1e-3
      lmid = 0.5*(l2+l1);
      xnew = max(0,max(x-move,min(1,min(x+move,x.*sqrt(-dc./dv/lmid)))));
      if ft == 1
          xPhys = xnew;
      elseif ft == 2
          xPhys(:) = (H*xnew(:))./Hs;
      end
 xPhys(passive==1) = 0;
 xPhys(passive==2) = 0;
      if sum(xPhys(:)) > volfrac*nelx*nely, l1 = lmid ; else l2 = lmid; end
  end
  change = max(abs(xnew(:)-x(:)));
  x = xnew;
```

PRINT RESULTS

```
  fprintf(' It.:%5i Obj.:%11.4f Vol.:%7.3f ch.:%7.3f\n',loop,c, ...
    mean(xPhys(:)),change);
```

PLOT DENSITIES

```
  colormap(gray); imagesc(1-xPhys); caxis([0 1]); axis equal; axis off; drawnow;
```

```
end
```

```
end
```

Function Call

```
%Sigmund (2001): Optimization of a symmetric MBB Beam

%top88(60,20,0.5,3,1.5,1)

%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This Matlab code was written by E. Andreassen, A. Clausen, M. Schevenels,%
% B. S. Lazarov and O. Sigmund,  Department of Solid  Mechanics,           %
%  Technical University of Denmark,                                        %
%  DK-2800 Lyngby, Denmark.                                                %
% Please sent your comments to: sigmund@fam.dtu.dk                         %
%                                                                          %
% The code is intended for educational purposes and theoretical details    %
% are discussed in the paper                                               %
% "Efficient topology optimization in MATLAB using 88 lines of code,       %
% E. Andreassen, A. Clausen, M. Schevenels,                                %
% B. S. Lazarov and O. Sigmund, Struct Multidisc Optim, 2010               %
```

```
% This version is based on earlier 99-line code                           %
% by Ole Sigmund (2001), Structural and Multidisciplinary Optimization,    %
% Vol 21, pp. 120--127.                                                    %
%                                                                          %
% The code as well as a postscript version of the paper can be             %
% downloaded from the web-site: http://www.topopt.dtu.dk                   %
%                                                                          %
% Disclaimer:                                                              %
% The authors reserves all rights but do not guaranty that the code is     %
% free from errors. Furthermore, we shall not be liable in any event       %
% caused by the use of the program.                                        %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

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v. Test File (Control Panel)

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Optimization of Short Cantilever with Multiple Forces via Density Filtering 50

Impelementing Passive Elements on a Short Cantilever Beam via Sensitivity Filtering 57

Impelementing Passive Elements on a Short Cantilever Beam via Density Filtering 57


```
%Testing several Beam Scenarios, Boundary Conditions, and Loadings
% Format Scenario(nelx, nely,volfrac, penal, rmin, ft)
%nelx = number of elements in x
%nely= number of elements in y
% volfrac = volume fraction
%penal = penalization power
%rmin = the filter radius (divided by the element size)
%ft = sensitivity filter (1) or density filter (2)
```

Sigmund (2001) : Optimization of a symmetric MBB Beam via Sensitivity Filtering

Mesh size: 60 x 20

```
%volfrac = 0.5
%penal = 3
%rmin = 1.5
% sensitivity filtering: ft=1
MBB(60,20,0.5,3,1.5,1)
```

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```

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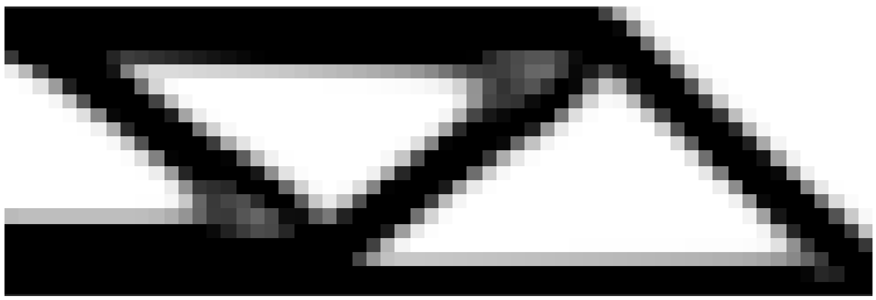

Sigmund (2001) : Optimization of a symmetric MBB Beam via Density Filtering

Mesh size: 60 x 20

```
%volfrac = 0.5
%penal = 3
%rmin = 2.4
% density filtering: ft=2
MBB(60,20,0.5,3,2.4,2)
```

```
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It.:   69 Obj.:   235.2857 Vol.:  0.500 ch.:  0.088
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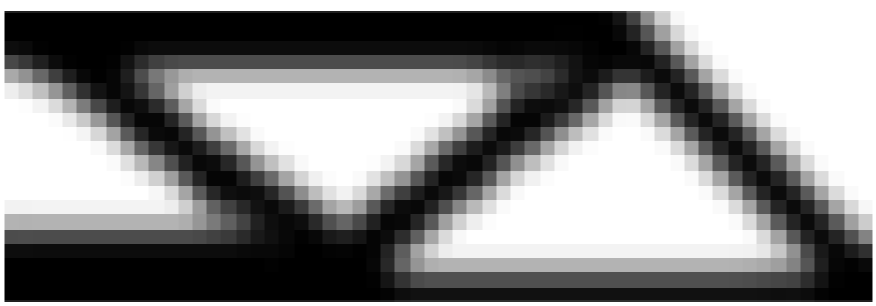

vi. Optimization of Short Cantilever Beam via Sensitivity Filtering

Mesh size: 160 x 100

```
%volfrac = 0.4
%penal = 3
%rmin = 6
% sensitivity filtering: ft=1
sc(160,100,0.4,3,6,1)
```

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 It.:   18 Obj.:    62.1537 Vol.:  0.400 ch.:  0.052
 It.:   19 Obj.:    62.0865 Vol.:  0.400 ch.:  0.043
 It.:   20 Obj.:    62.0238 Vol.:  0.400 ch.:  0.036
 It.:   21 Obj.:    61.9775 Vol.:  0.400 ch.:  0.031
 It.:   22 Obj.:    61.9373 Vol.:  0.400 ch.:  0.031
 It.:   23 Obj.:    61.9063 Vol.:  0.400 ch.:  0.030
 It.:   24 Obj.:    61.8791 Vol.:  0.400 ch.:  0.031
 It.:   25 Obj.:    61.8173 Vol.:  0.400 ch.:  0.029
 It.:   26 Obj.:    61.8250 Vol.:  0.400 ch.:  0.029
 It.:   27 Obj.:    61.7715 Vol.:  0.400 ch.:  0.028
 It.:   28 Obj.:    61.7508 Vol.:  0.400 ch.:  0.026
 It.:   29 Obj.:    61.7301 Vol.:  0.400 ch.:  0.025
 It.:   30 Obj.:    61.7185 Vol.:  0.400 ch.:  0.026
 It.:   31 Obj.:    61.6679 Vol.:  0.400 ch.:  0.024
 It.:   32 Obj.:    61.6840 Vol.:  0.400 ch.:  0.024
 It.:   33 Obj.:    61.6405 Vol.:  0.400 ch.:  0.023
 It.:   34 Obj.:    61.6268 Vol.:  0.400 ch.:  0.022
 It.:   35 Obj.:    61.6126 Vol.:  0.400 ch.:  0.021
 It.:   36 Obj.:    61.6068 Vol.:  0.400 ch.:  0.020
 It.:   37 Obj.:    61.6003 Vol.:  0.400 ch.:  0.020
 It.:   38 Obj.:    61.5575 Vol.:  0.400 ch.:  0.019
 It.:   39 Obj.:    61.5777 Vol.:  0.400 ch.:  0.019
 It.:   40 Obj.:    61.5396 Vol.:  0.400 ch.:  0.018
 It.:   41 Obj.:    61.5283 Vol.:  0.400 ch.:  0.017
 It.:   42 Obj.:    61.5172 Vol.:  0.400 ch.:  0.016
 It.:   43 Obj.:    61.5132 Vol.:  0.400 ch.:  0.016
 It.:   44 Obj.:    61.5089 Vol.:  0.400 ch.:  0.015
 It.:   45 Obj.:    61.5069 Vol.:  0.400 ch.:  0.015
 It.:   46 Obj.:    61.5054 Vol.:  0.400 ch.:  0.014
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It.:   47 Obj.:    61.5040 Vol.:  0.400 ch.:  0.014
It.:   48 Obj.:    61.4652 Vol.:  0.400 ch.:  0.014
It.:   49 Obj.:    61.4881 Vol.:  0.400 ch.:  0.013
It.:   50 Obj.:    61.4531 Vol.:  0.400 ch.:  0.013
It.:   51 Obj.:    61.4816 Vol.:  0.400 ch.:  0.012
It.:   52 Obj.:    61.4478 Vol.:  0.400 ch.:  0.012
It.:   53 Obj.:    61.4406 Vol.:  0.400 ch.:  0.011
It.:   54 Obj.:    61.4321 Vol.:  0.400 ch.:  0.011
It.:   55 Obj.:    61.4302 Vol.:  0.400 ch.:  0.010
It.:   56 Obj.:    61.4284 Vol.:  0.400 ch.:  0.010
It.:   57 Obj.:    61.4283 Vol.:  0.400 ch.:  0.010
```

vii. Optimization of Short Cantilever Beam via Density Filtering

Mesh size: 160 x 100

```
%volfrac = 0.4
%penal = 3
%rmin = 6
% density filtering: ft=2
SC(160,100,0.4,3,6,2)
```

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It.:    1 Obj.:   483.9052 Vol.:  0.400 ch.:  0.200
It.:    2 Obj.:   270.6036 Vol.:  0.400 ch.:  0.200
It.:    3 Obj.:   186.7347 Vol.:  0.400 ch.:  0.200
It.:    4 Obj.:   146.3224 Vol.:  0.400 ch.:  0.200
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It.:    5 Obj.:   130.7991 Vol.:  0.400 ch.:  0.200
It.:    6 Obj.:   117.1908 Vol.:  0.400 ch.:  0.200
It.:    7 Obj.:   106.3771 Vol.:  0.400 ch.:  0.200
It.:    8 Obj.:    97.3308 Vol.:  0.400 ch.:  0.200
It.:    9 Obj.:    90.6565 Vol.:  0.400 ch.:  0.200
It.:   10 Obj.:    85.7616 Vol.:  0.400 ch.:  0.200
It.:   11 Obj.:    81.8949 Vol.:  0.400 ch.:  0.200
It.:   12 Obj.:    78.9424 Vol.:  0.400 ch.:  0.200
It.:   13 Obj.:    76.5689 Vol.:  0.400 ch.:  0.200
It.:   14 Obj.:    74.4351 Vol.:  0.400 ch.:  0.200
It.:   15 Obj.:    72.4762 Vol.:  0.400 ch.:  0.200
It.:   16 Obj.:    70.6639 Vol.:  0.400 ch.:  0.200
It.:   17 Obj.:    69.1108 Vol.:  0.400 ch.:  0.200
It.:   18 Obj.:    67.8755 Vol.:  0.400 ch.:  0.200
It.:   19 Obj.:    67.0578 Vol.:  0.400 ch.:  0.200
It.:   20 Obj.:    66.5645 Vol.:  0.400 ch.:  0.200
It.:   21 Obj.:    66.2703 Vol.:  0.400 ch.:  0.200
It.:   22 Obj.:    66.0785 Vol.:  0.400 ch.:  0.187
It.:   23 Obj.:    65.9328 Vol.:  0.400 ch.:  0.197
It.:   24 Obj.:    65.8195 Vol.:  0.400 ch.:  0.165
It.:   25 Obj.:    65.7308 Vol.:  0.400 ch.:  0.173
It.:   26 Obj.:    65.6560 Vol.:  0.400 ch.:  0.146
It.:   27 Obj.:    65.5884 Vol.:  0.400 ch.:  0.155
It.:   28 Obj.:    65.5331 Vol.:  0.400 ch.:  0.127
It.:   29 Obj.:    65.4870 Vol.:  0.400 ch.:  0.152
It.:   30 Obj.:    65.4482 Vol.:  0.400 ch.:  0.143
It.:   31 Obj.:    65.4109 Vol.:  0.400 ch.:  0.132
It.:   32 Obj.:    65.3782 Vol.:  0.400 ch.:  0.127
It.:   33 Obj.:    65.3486 Vol.:  0.400 ch.:  0.149
It.:   34 Obj.:    65.3266 Vol.:  0.400 ch.:  0.137
It.:   35 Obj.:    65.3042 Vol.:  0.400 ch.:  0.122
It.:   36 Obj.:    65.2827 Vol.:  0.400 ch.:  0.104
It.:   37 Obj.:    65.2671 Vol.:  0.400 ch.:  0.120
It.:   38 Obj.:    65.2518 Vol.:  0.400 ch.:  0.123
It.:   39 Obj.:    65.2350 Vol.:  0.400 ch.:  0.117
It.:   40 Obj.:    65.2209 Vol.:  0.400 ch.:  0.105
It.:   41 Obj.:    65.2088 Vol.:  0.400 ch.:  0.112
It.:   42 Obj.:    65.1983 Vol.:  0.400 ch.:  0.103
It.:   43 Obj.:    65.1877 Vol.:  0.400 ch.:  0.104
It.:   44 Obj.:    65.1768 Vol.:  0.400 ch.:  0.119
It.:   45 Obj.:    65.1668 Vol.:  0.400 ch.:  0.109
It.:   46 Obj.:    65.1557 Vol.:  0.400 ch.:  0.102
It.:   47 Obj.:    65.1482 Vol.:  0.400 ch.:  0.099
It.:   48 Obj.:    65.1398 Vol.:  0.400 ch.:  0.112
It.:   49 Obj.:    65.1313 Vol.:  0.400 ch.:  0.089
It.:   50 Obj.:    65.1258 Vol.:  0.400 ch.:  0.103
It.:   51 Obj.:    65.1179 Vol.:  0.400 ch.:  0.085
It.:   52 Obj.:    65.1118 Vol.:  0.400 ch.:  0.068
It.:   53 Obj.:    65.1048 Vol.:  0.400 ch.:  0.073
It.:   54 Obj.:    65.1009 Vol.:  0.400 ch.:  0.080
It.:   55 Obj.:    65.0953 Vol.:  0.400 ch.:  0.091
It.:   56 Obj.:    65.0883 Vol.:  0.400 ch.:  0.101
It.:   57 Obj.:    65.0841 Vol.:  0.400 ch.:  0.090
It.:   58 Obj.:    65.0782 Vol.:  0.400 ch.:  0.099
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It.:   59 Obj.:    65.0745 Vol.:  0.400 ch.:  0.061
It.:   60 Obj.:    65.0700 Vol.:  0.400 ch.:  0.064
It.:   61 Obj.:    65.0665 Vol.:  0.400 ch.:  0.069
It.:   62 Obj.:    65.0626 Vol.:  0.400 ch.:  0.074
It.:   63 Obj.:    65.0604 Vol.:  0.400 ch.:  0.081
It.:   64 Obj.:    65.0559 Vol.:  0.400 ch.:  0.069
It.:   65 Obj.:    65.0528 Vol.:  0.400 ch.:  0.076
It.:   66 Obj.:    65.0487 Vol.:  0.400 ch.:  0.081
It.:   67 Obj.:    65.0467 Vol.:  0.400 ch.:  0.089
It.:   68 Obj.:    65.0426 Vol.:  0.400 ch.:  0.087
It.:   69 Obj.:    65.0406 Vol.:  0.400 ch.:  0.068
It.:   70 Obj.:    65.0373 Vol.:  0.400 ch.:  0.053
It.:   71 Obj.:    65.0352 Vol.:  0.400 ch.:  0.059
It.:   72 Obj.:    65.0308 Vol.:  0.400 ch.:  0.063
It.:   73 Obj.:    65.0281 Vol.:  0.400 ch.:  0.068
It.:   74 Obj.:    65.0271 Vol.:  0.400 ch.:  0.075
It.:   75 Obj.:    65.0236 Vol.:  0.400 ch.:  0.065
It.:   76 Obj.:    65.0215 Vol.:  0.400 ch.:  0.072
It.:   77 Obj.:    65.0185 Vol.:  0.400 ch.:  0.078
It.:   78 Obj.:    65.0168 Vol.:  0.400 ch.:  0.084
It.:   79 Obj.:    65.0124 Vol.:  0.400 ch.:  0.064
It.:   80 Obj.:    65.0108 Vol.:  0.400 ch.:  0.071
It.:   81 Obj.:    65.0083 Vol.:  0.400 ch.:  0.077
It.:   82 Obj.:    65.0064 Vol.:  0.400 ch.:  0.065
It.:   83 Obj.:    65.0039 Vol.:  0.400 ch.:  0.072
It.:   84 Obj.:    65.0016 Vol.:  0.400 ch.:  0.079
It.:   85 Obj.:    64.9997 Vol.:  0.400 ch.:  0.087
It.:   86 Obj.:    64.9976 Vol.:  0.400 ch.:  0.064
It.:   87 Obj.:    64.9961 Vol.:  0.400 ch.:  0.070
It.:   88 Obj.:    64.9948 Vol.:  0.400 ch.:  0.075
It.:   89 Obj.:    64.9933 Vol.:  0.400 ch.:  0.077
It.:   90 Obj.:    64.9905 Vol.:  0.400 ch.:  0.064
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It.:   92 Obj.:    64.9873 Vol.:  0.400 ch.:  0.048
It.:   93 Obj.:    64.9858 Vol.:  0.400 ch.:  0.051
It.:   94 Obj.:    64.9855 Vol.:  0.400 ch.:  0.057
It.:   95 Obj.:    64.9833 Vol.:  0.400 ch.:  0.060
It.:   96 Obj.:    64.9821 Vol.:  0.400 ch.:  0.065
It.:   97 Obj.:    64.9804 Vol.:  0.400 ch.:  0.071
It.:   98 Obj.:    64.9781 Vol.:  0.400 ch.:  0.074
It.:   99 Obj.:    64.9771 Vol.:  0.400 ch.:  0.068
It.:  100 Obj.:    64.9757 Vol.:  0.400 ch.:  0.074
It.:  101 Obj.:    64.9744 Vol.:  0.400 ch.:  0.054
It.:  102 Obj.:    64.9729 Vol.:  0.400 ch.:  0.058
It.:  103 Obj.:    64.9708 Vol.:  0.400 ch.:  0.063
It.:  104 Obj.:    64.9688 Vol.:  0.400 ch.:  0.069
It.:  105 Obj.:    64.9679 Vol.:  0.400 ch.:  0.076
It.:  106 Obj.:    64.9659 Vol.:  0.400 ch.:  0.082
It.:  107 Obj.:    64.9652 Vol.:  0.400 ch.:  0.066
It.:  108 Obj.:    64.9629 Vol.:  0.400 ch.:  0.058
It.:  109 Obj.:    64.9627 Vol.:  0.400 ch.:  0.062
It.:  110 Obj.:    64.9604 Vol.:  0.400 ch.:  0.065
It.:  111 Obj.:    64.9597 Vol.:  0.400 ch.:  0.062
It.:  112 Obj.:    64.9585 Vol.:  0.400 ch.:  0.067
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It.:  113 Obj.:    64.9572 Vol.:  0.400 ch.:  0.071
It.:  114 Obj.:    64.9569 Vol.:  0.400 ch.:  0.078
It.:  115 Obj.:    64.9550 Vol.:  0.400 ch.:  0.054
It.:  116 Obj.:    64.9538 Vol.:  0.400 ch.:  0.056
It.:  117 Obj.:    64.9525 Vol.:  0.400 ch.:  0.050
It.:  118 Obj.:    64.9515 Vol.:  0.400 ch.:  0.044
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It.:  122 Obj.:    64.9477 Vol.:  0.400 ch.:  0.047
It.:  123 Obj.:    64.9466 Vol.:  0.400 ch.:  0.050
It.:  124 Obj.:    64.9453 Vol.:  0.400 ch.:  0.055
It.:  125 Obj.:    64.9436 Vol.:  0.400 ch.:  0.059
It.:  126 Obj.:    64.9430 Vol.:  0.400 ch.:  0.065
It.:  127 Obj.:    64.9412 Vol.:  0.400 ch.:  0.070
It.:  128 Obj.:    64.9405 Vol.:  0.400 ch.:  0.075
It.:  129 Obj.:    64.9395 Vol.:  0.400 ch.:  0.067
It.:  130 Obj.:    64.9374 Vol.:  0.400 ch.:  0.073
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It.:  149 Obj.:    64.9224 Vol.:  0.400 ch.:  0.060
It.:  150 Obj.:    64.9217 Vol.:  0.400 ch.:  0.064
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It.:  165 Obj.:    64.9108 Vol.:  0.400 ch.:  0.071
It.:  166 Obj.:    64.9104 Vol.:  0.400 ch.:  0.078
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It.:  167 Obj.:    64.9092 Vol.:  0.400 ch.:  0.038
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It.:  169 Obj.:    64.9083 Vol.:  0.400 ch.:  0.037
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It.:  186 Obj.:    64.8992 Vol.:  0.400 ch.:  0.045
It.:  187 Obj.:    64.8981 Vol.:  0.400 ch.:  0.046
It.:  188 Obj.:    64.8981 Vol.:  0.400 ch.:  0.049
It.:  189 Obj.:    64.8968 Vol.:  0.400 ch.:  0.042
It.:  190 Obj.:    64.8967 Vol.:  0.400 ch.:  0.046
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It.:  219 Obj.:    64.8804 Vol.:  0.400 ch.:  0.070
It.:  220 Obj.:    64.8798 Vol.:  0.400 ch.:  0.034
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It.:  221 Obj.:    64.8794 Vol.:  0.400 ch.:  0.035
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It.:  225 Obj.:    64.8776 Vol.:  0.400 ch.:  0.040
It.:  226 Obj.:    64.8768 Vol.:  0.400 ch.:  0.036
It.:  227 Obj.:    64.8771 Vol.:  0.400 ch.:  0.039
It.:  228 Obj.:    64.8765 Vol.:  0.400 ch.:  0.040
It.:  229 Obj.:    64.8759 Vol.:  0.400 ch.:  0.042
It.:  230 Obj.:    64.8751 Vol.:  0.400 ch.:  0.041
It.:  231 Obj.:    64.8752 Vol.:  0.400 ch.:  0.045
It.:  232 Obj.:    64.8747 Vol.:  0.400 ch.:  0.049
It.:  233 Obj.:    64.8740 Vol.:  0.400 ch.:  0.053
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It.:  244 Obj.:    64.8695 Vol.:  0.400 ch.:  0.044
It.:  245 Obj.:    64.8692 Vol.:  0.400 ch.:  0.046
It.:  246 Obj.:    64.8687 Vol.:  0.400 ch.:  0.049
It.:  247 Obj.:    64.8682 Vol.:  0.400 ch.:  0.051
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It.:  249 Obj.:    64.8669 Vol.:  0.400 ch.:  0.033
It.:  250 Obj.:    64.8668 Vol.:  0.400 ch.:  0.035
It.:  251 Obj.:    64.8669 Vol.:  0.400 ch.:  0.038
It.:  252 Obj.:    64.8658 Vol.:  0.400 ch.:  0.039
It.:  253 Obj.:    64.8657 Vol.:  0.400 ch.:  0.042
It.:  254 Obj.:    64.8654 Vol.:  0.400 ch.:  0.044
It.:  255 Obj.:    64.8651 Vol.:  0.400 ch.:  0.046
It.:  256 Obj.:    64.8646 Vol.:  0.400 ch.:  0.049
It.:  257 Obj.:    64.8640 Vol.:  0.400 ch.:  0.052
It.:  258 Obj.:    64.8633 Vol.:  0.400 ch.:  0.053
It.:  259 Obj.:    64.8634 Vol.:  0.400 ch.:  0.057
It.:  260 Obj.:    64.8624 Vol.:  0.400 ch.:  0.037
It.:  261 Obj.:    64.8629 Vol.:  0.400 ch.:  0.040
It.:  262 Obj.:    64.8624 Vol.:  0.400 ch.:  0.035
It.:  263 Obj.:    64.8620 Vol.:  0.400 ch.:  0.037
It.:  264 Obj.:    64.8618 Vol.:  0.400 ch.:  0.040
It.:  265 Obj.:    64.8604 Vol.:  0.400 ch.:  0.040
It.:  266 Obj.:    64.8610 Vol.:  0.400 ch.:  0.043
It.:  267 Obj.:    64.8604 Vol.:  0.400 ch.:  0.045
It.:  268 Obj.:    64.8597 Vol.:  0.400 ch.:  0.047
It.:  269 Obj.:    64.8589 Vol.:  0.400 ch.:  0.048
It.:  270 Obj.:    64.8591 Vol.:  0.400 ch.:  0.052
It.:  271 Obj.:    64.8581 Vol.:  0.400 ch.:  0.041
It.:  272 Obj.:    64.8575 Vol.:  0.400 ch.:  0.043
It.:  273 Obj.:    64.8569 Vol.:  0.400 ch.:  0.044
It.:  274 Obj.:    64.8573 Vol.:  0.400 ch.:  0.047
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It.:  275 Obj.:    64.8565 Vol.:  0.400 ch.:  0.049
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It.:  277 Obj.:    64.8556 Vol.:  0.400 ch.:  0.057
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It.:  279 Obj.:    64.8541 Vol.:  0.400 ch.:  0.066
It.:  280 Obj.:    64.8540 Vol.:  0.400 ch.:  0.072
It.:  281 Obj.:    64.8528 Vol.:  0.400 ch.:  0.061
It.:  282 Obj.:    64.8531 Vol.:  0.400 ch.:  0.056
It.:  283 Obj.:    64.8520 Vol.:  0.400 ch.:  0.060
It.:  284 Obj.:    64.8519 Vol.:  0.400 ch.:  0.065
It.:  285 Obj.:    64.8515 Vol.:  0.400 ch.:  0.070
It.:  286 Obj.:    64.8511 Vol.:  0.400 ch.:  0.075
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It.:  293 Obj.:    64.8483 Vol.:  0.400 ch.:  0.025
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It.:  327 Obj.:    64.8399 Vol.:  0.400 ch.:  0.014
It.:  328 Obj.:    64.8400 Vol.:  0.400 ch.:  0.014
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It.:  382 Obj.:    64.8242 Vol.:  0.400 ch.:  0.044
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It.:  436 Obj.:    64.8087 Vol.:  0.400 ch.:  0.043
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It.:  488 Obj.:    64.7920 Vol.:  0.400 ch.:  0.024
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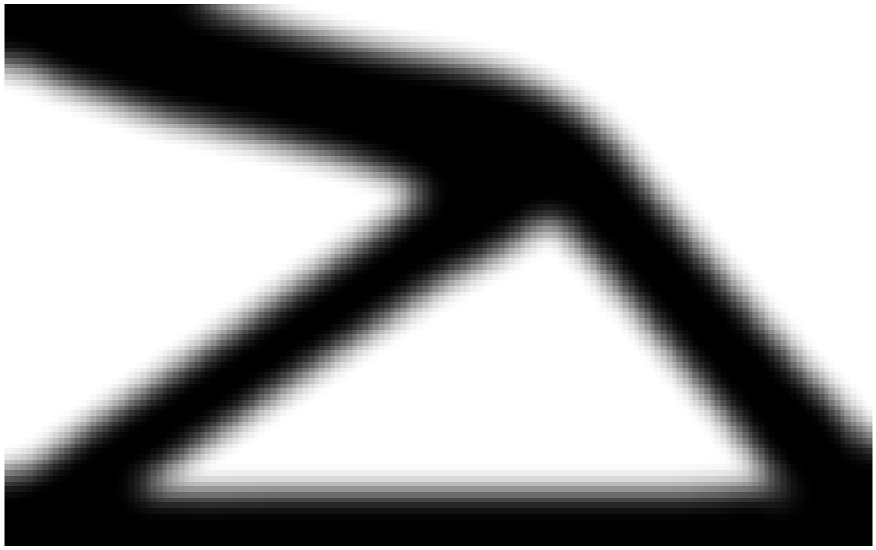
It.:  580 Obj.:    64.7631 Vol.:  0.400 ch.:  0.012
It.:  581 Obj.:    64.7635 Vol.:  0.400 ch.:  0.014
It.:  582 Obj.:    64.7634 Vol.:  0.400 ch.:  0.014
It.:  583 Obj.:    64.7632 Vol.:  0.400 ch.:  0.014
It.:  584 Obj.:    64.7632 Vol.:  0.400 ch.:  0.014
It.:  585 Obj.:    64.7631 Vol.:  0.400 ch.:  0.013
It.:  586 Obj.:    64.7631 Vol.:  0.400 ch.:  0.013
It.:  587 Obj.:    64.7630 Vol.:  0.400 ch.:  0.013
It.:  588 Obj.:    64.7630 Vol.:  0.400 ch.:  0.013
It.:  589 Obj.:    64.7630 Vol.:  0.400 ch.:  0.012
It.:  590 Obj.:    64.7631 Vol.:  0.400 ch.:  0.010
```



viii. *Optimization of Short Cantilever Beam with Multiple Forces via Sensitivity Filtering*

Mesh size: 150 x 150

```
%volfrac = 0.4
%penal = 3
%rmin = 6
% sensitivity filtering: ft=1
SC_ML(150,150,0.4,3,6,1)
```

```
It.:    1 Obj.:   553.5316 Vol.:  0.400 ch.:  0.200
It.:    2 Obj.:   301.2526 Vol.:  0.400 ch.:  0.200
It.:    3 Obj.:   220.0948 Vol.:  0.400 ch.:  0.200
It.:    4 Obj.:   181.6261 Vol.:  0.400 ch.:  0.194
It.:    5 Obj.:   157.8422 Vol.:  0.400 ch.:  0.200
It.:    6 Obj.:   130.9726 Vol.:  0.400 ch.:  0.200
It.:    7 Obj.:   105.2855 Vol.:  0.400 ch.:  0.200
It.:    8 Obj.:    87.4913 Vol.:  0.400 ch.:  0.200
It.:    9 Obj.:    78.3892 Vol.:  0.400 ch.:  0.200
It.:   10 Obj.:    74.1126 Vol.:  0.400 ch.:  0.191
It.:   11 Obj.:    72.0653 Vol.:  0.400 ch.:  0.135
It.:   12 Obj.:    71.0432 Vol.:  0.400 ch.:  0.098
It.:   13 Obj.:    70.5521 Vol.:  0.400 ch.:  0.079
It.:   14 Obj.:    70.2461 Vol.:  0.400 ch.:  0.075
It.:   15 Obj.:    70.0492 Vol.:  0.400 ch.:  0.072
```

```
It.:   16 Obj.:    69.9486 Vol.:  0.400 ch.:  0.070
It.:   17 Obj.:    69.8382 Vol.:  0.400 ch.:  0.066
It.:   18 Obj.:    69.7449 Vol.:  0.400 ch.:  0.062
It.:   19 Obj.:    69.6641 Vol.:  0.400 ch.:  0.058
It.:   20 Obj.:    69.5643 Vol.:  0.400 ch.:  0.061
It.:   21 Obj.:    69.4905 Vol.:  0.400 ch.:  0.065
It.:   22 Obj.:    69.3808 Vol.:  0.400 ch.:  0.067
It.:   23 Obj.:    69.2886 Vol.:  0.400 ch.:  0.058
It.:   24 Obj.:    69.2037 Vol.:  0.400 ch.:  0.037
It.:   25 Obj.:    69.1624 Vol.:  0.400 ch.:  0.020
It.:   26 Obj.:    69.1748 Vol.:  0.400 ch.:  0.017
It.:   27 Obj.:    69.1794 Vol.:  0.400 ch.:  0.015
It.:   28 Obj.:    69.1916 Vol.:  0.400 ch.:  0.013
It.:   29 Obj.:    69.2101 Vol.:  0.400 ch.:  0.011
It.:   30 Obj.:    69.2037 Vol.:  0.400 ch.:  0.010
```

ix. Optimization of Short Cantilever with Multiple Forces via Density Filtering

Mesh size: 150 x 150

```
%volfrac = 0.4
%penal = 3
%rmin = 6
% sensitivity filtering: ft=2
SC_ML(150,150,0.4,3,6,2)
```

```
It.:    1 Obj.:   553.5316 Vol.:  0.400 ch.:  0.200
It.:    2 Obj.:   301.2114 Vol.:  0.400 ch.:  0.200
It.:    3 Obj.:   220.1373 Vol.:  0.400 ch.:  0.200
It.:    4 Obj.:   182.6541 Vol.:  0.400 ch.:  0.200
It.:    5 Obj.:   159.4979 Vol.:  0.400 ch.:  0.200
It.:    6 Obj.:   133.6521 Vol.:  0.400 ch.:  0.200
It.:    7 Obj.:   108.4283 Vol.:  0.400 ch.:  0.200
It.:    8 Obj.:    91.5934 Vol.:  0.400 ch.:  0.200
It.:    9 Obj.:    83.2369 Vol.:  0.400 ch.:  0.200
It.:   10 Obj.:    79.2446 Vol.:  0.400 ch.:  0.200
It.:   11 Obj.:    77.1108 Vol.:  0.400 ch.:  0.200
It.:   12 Obj.:    75.9157 Vol.:  0.400 ch.:  0.200
It.:   13 Obj.:    75.2165 Vol.:  0.400 ch.:  0.200
It.:   14 Obj.:    74.7706 Vol.:  0.400 ch.:  0.199
It.:   15 Obj.:    74.4734 Vol.:  0.400 ch.:  0.200
It.:   16 Obj.:    74.2606 Vol.:  0.400 ch.:  0.191
It.:   17 Obj.:    74.0904 Vol.:  0.400 ch.:  0.185
It.:   18 Obj.:    73.9787 Vol.:  0.400 ch.:  0.172
It.:   19 Obj.:    73.8761 Vol.:  0.400 ch.:  0.164
It.:   20 Obj.:    73.7923 Vol.:  0.400 ch.:  0.162
It.:   21 Obj.:    73.7260 Vol.:  0.400 ch.:  0.131
It.:   22 Obj.:    73.6742 Vol.:  0.400 ch.:  0.151
It.:   23 Obj.:    73.6327 Vol.:  0.400 ch.:  0.128
It.:   24 Obj.:    73.5938 Vol.:  0.400 ch.:  0.126
It.:   25 Obj.:    73.5654 Vol.:  0.400 ch.:  0.134
It.:   26 Obj.:    73.5302 Vol.:  0.400 ch.:  0.125
It.:   27 Obj.:    73.5038 Vol.:  0.400 ch.:  0.105
It.:   28 Obj.:    73.4833 Vol.:  0.400 ch.:  0.110
It.:   29 Obj.:    73.4683 Vol.:  0.400 ch.:  0.098
It.:   30 Obj.:    73.4468 Vol.:  0.400 ch.:  0.092
It.:   31 Obj.:    73.4310 Vol.:  0.400 ch.:  0.095
It.:   32 Obj.:    73.4152 Vol.:  0.400 ch.:  0.106
It.:   33 Obj.:    73.4077 Vol.:  0.400 ch.:  0.087
It.:   34 Obj.:    73.3947 Vol.:  0.400 ch.:  0.090
It.:   35 Obj.:    73.3854 Vol.:  0.400 ch.:  0.074
It.:   36 Obj.:    73.3722 Vol.:  0.400 ch.:  0.081
It.:   37 Obj.:    73.3607 Vol.:  0.400 ch.:  0.088
It.:   38 Obj.:    73.3588 Vol.:  0.400 ch.:  0.098
It.:   39 Obj.:    73.3493 Vol.:  0.400 ch.:  0.074
It.:   40 Obj.:    73.3409 Vol.:  0.400 ch.:  0.080
It.:   41 Obj.:    73.3332 Vol.:  0.400 ch.:  0.085
It.:   42 Obj.:    73.3256 Vol.:  0.400 ch.:  0.072
It.:   43 Obj.:    73.3215 Vol.:  0.400 ch.:  0.067
It.:   44 Obj.:    73.3164 Vol.:  0.400 ch.:  0.072
It.:   45 Obj.:    73.3102 Vol.:  0.400 ch.:  0.077
It.:   46 Obj.:    73.3096 Vol.:  0.400 ch.:  0.065
It.:   47 Obj.:    73.3023 Vol.:  0.400 ch.:  0.067
It.:   48 Obj.:    73.2966 Vol.:  0.400 ch.:  0.066
It.:   49 Obj.:    73.2916 Vol.:  0.400 ch.:  0.064
It.:   50 Obj.:    73.2872 Vol.:  0.400 ch.:  0.067
It.:   51 Obj.:    73.2828 Vol.:  0.400 ch.:  0.072
It.:   52 Obj.:    73.2794 Vol.:  0.400 ch.:  0.073
It.:   53 Obj.:    73.2757 Vol.:  0.400 ch.:  0.055
It.:   54 Obj.:    73.2744 Vol.:  0.400 ch.:  0.055
```

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It.:   55 Obj.:    73.2729 Vol.:  0.400 ch.:  0.058
It.:   56 Obj.:    73.2709 Vol.:  0.400 ch.:  0.060
It.:   57 Obj.:    73.2689 Vol.:  0.400 ch.:  0.049
It.:   58 Obj.:    73.2636 Vol.:  0.400 ch.:  0.051
It.:   59 Obj.:    73.2647 Vol.:  0.400 ch.:  0.055
It.:   60 Obj.:    73.2592 Vol.:  0.400 ch.:  0.057
It.:   61 Obj.:    73.2603 Vol.:  0.400 ch.:  0.062
It.:   62 Obj.:    73.2556 Vol.:  0.400 ch.:  0.064
It.:   63 Obj.:    73.2567 Vol.:  0.400 ch.:  0.060
It.:   64 Obj.:    73.2525 Vol.:  0.400 ch.:  0.053
It.:   65 Obj.:    73.2494 Vol.:  0.400 ch.:  0.051
It.:   66 Obj.:    73.2469 Vol.:  0.400 ch.:  0.053
It.:   67 Obj.:    73.2447 Vol.:  0.400 ch.:  0.036
It.:   68 Obj.:    73.2433 Vol.:  0.400 ch.:  0.037
It.:   69 Obj.:    73.2417 Vol.:  0.400 ch.:  0.036
It.:   70 Obj.:    73.2446 Vol.:  0.400 ch.:  0.034
It.:   71 Obj.:    73.2419 Vol.:  0.400 ch.:  0.036
It.:   72 Obj.:    73.2395 Vol.:  0.400 ch.:  0.038
It.:   73 Obj.:    73.2367 Vol.:  0.400 ch.:  0.038
It.:   74 Obj.:    73.2386 Vol.:  0.400 ch.:  0.039
It.:   75 Obj.:    73.2354 Vol.:  0.400 ch.:  0.040
It.:   76 Obj.:    73.2326 Vol.:  0.400 ch.:  0.041
It.:   77 Obj.:    73.2343 Vol.:  0.400 ch.:  0.044
It.:   78 Obj.:    73.2302 Vol.:  0.400 ch.:  0.044
It.:   79 Obj.:    73.2306 Vol.:  0.400 ch.:  0.046
It.:   80 Obj.:    73.2298 Vol.:  0.400 ch.:  0.049
It.:   81 Obj.:    73.2293 Vol.:  0.400 ch.:  0.049
It.:   82 Obj.:    73.2283 Vol.:  0.400 ch.:  0.051
It.:   83 Obj.:    73.2270 Vol.:  0.400 ch.:  0.039
It.:   84 Obj.:    73.2261 Vol.:  0.400 ch.:  0.040
It.:   85 Obj.:    73.2247 Vol.:  0.400 ch.:  0.042
It.:   86 Obj.:    73.2234 Vol.:  0.400 ch.:  0.039
It.:   87 Obj.:    73.2227 Vol.:  0.400 ch.:  0.034
It.:   88 Obj.:    73.2180 Vol.:  0.400 ch.:  0.034
It.:   89 Obj.:    73.2190 Vol.:  0.400 ch.:  0.035
It.:   90 Obj.:    73.2196 Vol.:  0.400 ch.:  0.037
It.:   91 Obj.:    73.2153 Vol.:  0.400 ch.:  0.037
It.:   92 Obj.:    73.2159 Vol.:  0.400 ch.:  0.038
It.:   93 Obj.:    73.2159 Vol.:  0.400 ch.:  0.039
It.:   94 Obj.:    73.2153 Vol.:  0.400 ch.:  0.027
It.:   95 Obj.:    73.2146 Vol.:  0.400 ch.:  0.029
It.:   96 Obj.:    73.2145 Vol.:  0.400 ch.:  0.030
It.:   97 Obj.:    73.2141 Vol.:  0.400 ch.:  0.031
It.:   98 Obj.:    73.2134 Vol.:  0.400 ch.:  0.032
It.:   99 Obj.:    73.2127 Vol.:  0.400 ch.:  0.033
It.:  100 Obj.:    73.2115 Vol.:  0.400 ch.:  0.028
It.:  101 Obj.:    73.2104 Vol.:  0.400 ch.:  0.029
It.:  102 Obj.:    73.2095 Vol.:  0.400 ch.:  0.030
It.:  103 Obj.:    73.2083 Vol.:  0.400 ch.:  0.031
It.:  104 Obj.:    73.2068 Vol.:  0.400 ch.:  0.032
It.:  105 Obj.:    73.2049 Vol.:  0.400 ch.:  0.032
It.:  106 Obj.:    73.2072 Vol.:  0.400 ch.:  0.034
It.:  107 Obj.:    73.2040 Vol.:  0.400 ch.:  0.034
It.:  108 Obj.:    73.2056 Vol.:  0.400 ch.:  0.037
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It.:  109 Obj.:    73.2019 Vol.:  0.400 ch.:  0.037
It.:  110 Obj.:    73.2028 Vol.:  0.400 ch.:  0.038
It.:  111 Obj.:    73.2035 Vol.:  0.400 ch.:  0.035
It.:  112 Obj.:    73.2000 Vol.:  0.400 ch.:  0.034
It.:  113 Obj.:    73.2012 Vol.:  0.400 ch.:  0.037
It.:  114 Obj.:    73.1982 Vol.:  0.400 ch.:  0.037
It.:  115 Obj.:    73.2000 Vol.:  0.400 ch.:  0.031
It.:  116 Obj.:    73.1972 Vol.:  0.400 ch.:  0.031
It.:  117 Obj.:    73.1989 Vol.:  0.400 ch.:  0.033
It.:  118 Obj.:    73.1957 Vol.:  0.400 ch.:  0.032
It.:  119 Obj.:    73.1968 Vol.:  0.400 ch.:  0.033
It.:  120 Obj.:    73.1973 Vol.:  0.400 ch.:  0.029
It.:  121 Obj.:    73.1941 Vol.:  0.400 ch.:  0.029
It.:  122 Obj.:    73.1958 Vol.:  0.400 ch.:  0.031
It.:  123 Obj.:    73.1929 Vol.:  0.400 ch.:  0.030
It.:  124 Obj.:    73.1943 Vol.:  0.400 ch.:  0.028
It.:  125 Obj.:    73.1917 Vol.:  0.400 ch.:  0.027
It.:  126 Obj.:    73.1937 Vol.:  0.400 ch.:  0.029
It.:  127 Obj.:    73.1910 Vol.:  0.400 ch.:  0.029
It.:  128 Obj.:    73.1927 Vol.:  0.400 ch.:  0.031
It.:  129 Obj.:    73.1897 Vol.:  0.400 ch.:  0.030
It.:  130 Obj.:    73.1911 Vol.:  0.400 ch.:  0.031
It.:  131 Obj.:    73.1919 Vol.:  0.400 ch.:  0.033
It.:  132 Obj.:    73.1883 Vol.:  0.400 ch.:  0.032
It.:  133 Obj.:    73.1898 Vol.:  0.400 ch.:  0.035
It.:  134 Obj.:    73.1869 Vol.:  0.400 ch.:  0.033
It.:  135 Obj.:    73.1884 Vol.:  0.400 ch.:  0.035
It.:  136 Obj.:    73.1859 Vol.:  0.400 ch.:  0.032
It.:  137 Obj.:    73.1880 Vol.:  0.400 ch.:  0.033
It.:  138 Obj.:    73.1860 Vol.:  0.400 ch.:  0.020
It.:  139 Obj.:    73.1885 Vol.:  0.400 ch.:  0.022
It.:  140 Obj.:    73.1866 Vol.:  0.400 ch.:  0.017
It.:  141 Obj.:    73.1853 Vol.:  0.400 ch.:  0.018
It.:  142 Obj.:    73.1842 Vol.:  0.400 ch.:  0.017
It.:  143 Obj.:    73.1872 Vol.:  0.400 ch.:  0.018
It.:  144 Obj.:    73.1858 Vol.:  0.400 ch.:  0.019
It.:  145 Obj.:    73.1848 Vol.:  0.400 ch.:  0.019
It.:  146 Obj.:    73.1839 Vol.:  0.400 ch.:  0.019
It.:  147 Obj.:    73.1831 Vol.:  0.400 ch.:  0.019
It.:  148 Obj.:    73.1826 Vol.:  0.400 ch.:  0.019
It.:  149 Obj.:    73.1820 Vol.:  0.400 ch.:  0.020
It.:  150 Obj.:    73.1815 Vol.:  0.400 ch.:  0.018
It.:  151 Obj.:    73.1848 Vol.:  0.400 ch.:  0.020
It.:  152 Obj.:    73.1836 Vol.:  0.400 ch.:  0.019
It.:  153 Obj.:    73.1828 Vol.:  0.400 ch.:  0.020
It.:  154 Obj.:    73.1821 Vol.:  0.400 ch.:  0.020
It.:  155 Obj.:    73.1815 Vol.:  0.400 ch.:  0.020
It.:  156 Obj.:    73.1808 Vol.:  0.400 ch.:  0.021
It.:  157 Obj.:    73.1801 Vol.:  0.400 ch.:  0.021
It.:  158 Obj.:    73.1793 Vol.:  0.400 ch.:  0.020
It.:  159 Obj.:    73.1824 Vol.:  0.400 ch.:  0.021
It.:  160 Obj.:    73.1809 Vol.:  0.400 ch.:  0.021
It.:  161 Obj.:    73.1796 Vol.:  0.400 ch.:  0.022
It.:  162 Obj.:    73.1785 Vol.:  0.400 ch.:  0.021
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It.:  163 Obj.:    73.1813 Vol.:  0.400 ch.:  0.023
It.:  164 Obj.:    73.1797 Vol.:  0.400 ch.:  0.023
It.:  165 Obj.:    73.1782 Vol.:  0.400 ch.:  0.022
It.:  166 Obj.:    73.1806 Vol.:  0.400 ch.:  0.024
It.:  167 Obj.:    73.1786 Vol.:  0.400 ch.:  0.025
It.:  168 Obj.:    73.1767 Vol.:  0.400 ch.:  0.024
It.:  169 Obj.:    73.1788 Vol.:  0.400 ch.:  0.025
It.:  170 Obj.:    73.1764 Vol.:  0.400 ch.:  0.024
It.:  171 Obj.:    73.1782 Vol.:  0.400 ch.:  0.025
It.:  172 Obj.:    73.1755 Vol.:  0.400 ch.:  0.023
It.:  173 Obj.:    73.1774 Vol.:  0.400 ch.:  0.023
It.:  174 Obj.:    73.1788 Vol.:  0.400 ch.:  0.025
It.:  175 Obj.:    73.1759 Vol.:  0.400 ch.:  0.024
It.:  176 Obj.:    73.1773 Vol.:  0.400 ch.:  0.024
It.:  177 Obj.:    73.1783 Vol.:  0.400 ch.:  0.026
It.:  178 Obj.:    73.1750 Vol.:  0.400 ch.:  0.025
It.:  179 Obj.:    73.1761 Vol.:  0.400 ch.:  0.024
It.:  180 Obj.:    73.1770 Vol.:  0.400 ch.:  0.025
It.:  181 Obj.:    73.1738 Vol.:  0.400 ch.:  0.020
It.:  182 Obj.:    73.1752 Vol.:  0.400 ch.:  0.019
It.:  183 Obj.:    73.1765 Vol.:  0.400 ch.:  0.020
It.:  184 Obj.:    73.1735 Vol.:  0.400 ch.:  0.019
It.:  185 Obj.:    73.1749 Vol.:  0.400 ch.:  0.019
It.:  186 Obj.:    73.1760 Vol.:  0.400 ch.:  0.021
It.:  187 Obj.:    73.1729 Vol.:  0.400 ch.:  0.020
It.:  188 Obj.:    73.1742 Vol.:  0.400 ch.:  0.020
It.:  189 Obj.:    73.1752 Vol.:  0.400 ch.:  0.022
It.:  190 Obj.:    73.1720 Vol.:  0.400 ch.:  0.020
It.:  191 Obj.:    73.1733 Vol.:  0.400 ch.:  0.020
It.:  192 Obj.:    73.1744 Vol.:  0.400 ch.:  0.020
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It.:  194 Obj.:    73.1729 Vol.:  0.400 ch.:  0.016
It.:  195 Obj.:    73.1742 Vol.:  0.400 ch.:  0.017
It.:  196 Obj.:    73.1713 Vol.:  0.400 ch.:  0.017
It.:  197 Obj.:    73.1729 Vol.:  0.400 ch.:  0.017
It.:  198 Obj.:    73.1741 Vol.:  0.400 ch.:  0.018
It.:  199 Obj.:    73.1712 Vol.:  0.400 ch.:  0.018
It.:  200 Obj.:    73.1727 Vol.:  0.400 ch.:  0.019
It.:  201 Obj.:    73.1699 Vol.:  0.400 ch.:  0.018
It.:  202 Obj.:    73.1715 Vol.:  0.400 ch.:  0.019
It.:  203 Obj.:    73.1726 Vol.:  0.400 ch.:  0.020
It.:  204 Obj.:    73.1698 Vol.:  0.400 ch.:  0.019
It.:  205 Obj.:    73.1715 Vol.:  0.400 ch.:  0.021
It.:  206 Obj.:    73.1690 Vol.:  0.400 ch.:  0.020
It.:  207 Obj.:    73.1707 Vol.:  0.400 ch.:  0.020
It.:  208 Obj.:    73.1720 Vol.:  0.400 ch.:  0.022
It.:  209 Obj.:    73.1691 Vol.:  0.400 ch.:  0.021
It.:  210 Obj.:    73.1706 Vol.:  0.400 ch.:  0.021
It.:  211 Obj.:    73.1718 Vol.:  0.400 ch.:  0.023
It.:  212 Obj.:    73.1689 Vol.:  0.400 ch.:  0.021
It.:  213 Obj.:    73.1705 Vol.:  0.400 ch.:  0.023
It.:  214 Obj.:    73.1680 Vol.:  0.400 ch.:  0.022
It.:  215 Obj.:    73.1697 Vol.:  0.400 ch.:  0.024
It.:  216 Obj.:    73.1674 Vol.:  0.400 ch.:  0.023
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It.:  217 Obj.:    73.1693 Vol.:  0.400 ch.:  0.023
It.:  218 Obj.:    73.1672 Vol.:  0.400 ch.:  0.022
It.:  219 Obj.:    73.1693 Vol.:  0.400 ch.:  0.018
It.:  220 Obj.:    73.1672 Vol.:  0.400 ch.:  0.012
It.:  221 Obj.:    73.1695 Vol.:  0.400 ch.:  0.014
It.:  222 Obj.:    73.1675 Vol.:  0.400 ch.:  0.013
It.:  223 Obj.:    73.1697 Vol.:  0.400 ch.:  0.014
It.:  224 Obj.:    73.1677 Vol.:  0.400 ch.:  0.013
It.:  225 Obj.:    73.1698 Vol.:  0.400 ch.:  0.014
It.:  226 Obj.:    73.1678 Vol.:  0.400 ch.:  0.015
It.:  227 Obj.:    73.1661 Vol.:  0.400 ch.:  0.014
It.:  228 Obj.:    73.1686 Vol.:  0.400 ch.:  0.015
It.:  229 Obj.:    73.1669 Vol.:  0.400 ch.:  0.014
It.:  230 Obj.:    73.1692 Vol.:  0.400 ch.:  0.016
It.:  231 Obj.:    73.1673 Vol.:  0.400 ch.:  0.016
It.:  232 Obj.:    73.1656 Vol.:  0.400 ch.:  0.015
It.:  233 Obj.:    73.1680 Vol.:  0.400 ch.:  0.016
It.:  234 Obj.:    73.1661 Vol.:  0.400 ch.:  0.015
It.:  235 Obj.:    73.1682 Vol.:  0.400 ch.:  0.017
It.:  236 Obj.:    73.1661 Vol.:  0.400 ch.:  0.016
It.:  237 Obj.:    73.1681 Vol.:  0.400 ch.:  0.017
It.:  238 Obj.:    73.1659 Vol.:  0.400 ch.:  0.016
It.:  239 Obj.:    73.1677 Vol.:  0.400 ch.:  0.018
It.:  240 Obj.:    73.1654 Vol.:  0.400 ch.:  0.016
It.:  241 Obj.:    73.1671 Vol.:  0.400 ch.:  0.018
It.:  242 Obj.:    73.1648 Vol.:  0.400 ch.:  0.016
It.:  243 Obj.:    73.1667 Vol.:  0.400 ch.:  0.018
It.:  244 Obj.:    73.1647 Vol.:  0.400 ch.:  0.017
It.:  245 Obj.:    73.1669 Vol.:  0.400 ch.:  0.018
It.:  246 Obj.:    73.1650 Vol.:  0.400 ch.:  0.019
It.:  247 Obj.:    73.1636 Vol.:  0.400 ch.:  0.017
It.:  248 Obj.:    73.1660 Vol.:  0.400 ch.:  0.019
It.:  249 Obj.:    73.1643 Vol.:  0.400 ch.:  0.018
It.:  250 Obj.:    73.1666 Vol.:  0.400 ch.:  0.019
It.:  251 Obj.:    73.1647 Vol.:  0.400 ch.:  0.019
It.:  252 Obj.:    73.1632 Vol.:  0.400 ch.:  0.018
It.:  253 Obj.:    73.1656 Vol.:  0.400 ch.:  0.018
It.:  254 Obj.:    73.1640 Vol.:  0.400 ch.:  0.018
It.:  255 Obj.:    73.1627 Vol.:  0.400 ch.:  0.017
It.:  256 Obj.:    73.1654 Vol.:  0.400 ch.:  0.018
It.:  257 Obj.:    73.1639 Vol.:  0.400 ch.:  0.015
It.:  258 Obj.:    73.1629 Vol.:  0.400 ch.:  0.016
It.:  259 Obj.:    73.1622 Vol.:  0.400 ch.:  0.015
It.:  260 Obj.:    73.1653 Vol.:  0.400 ch.:  0.016
It.:  261 Obj.:    73.1642 Vol.:  0.400 ch.:  0.016
It.:  262 Obj.:    73.1634 Vol.:  0.400 ch.:  0.017
It.:  263 Obj.:    73.1627 Vol.:  0.400 ch.:  0.017
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It.:  265 Obj.:    73.1618 Vol.:  0.400 ch.:  0.016
It.:  266 Obj.:    73.1650 Vol.:  0.400 ch.:  0.018
It.:  267 Obj.:    73.1640 Vol.:  0.400 ch.:  0.018
It.:  268 Obj.:    73.1632 Vol.:  0.400 ch.:  0.018
It.:  269 Obj.:    73.1626 Vol.:  0.400 ch.:  0.019
It.:  270 Obj.:    73.1621 Vol.:  0.400 ch.:  0.019
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It.:  271 Obj.:    73.1616 Vol.:  0.400 ch.:  0.019
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It.:  273 Obj.:    73.1643 Vol.:  0.400 ch.:  0.020
It.:  274 Obj.:    73.1633 Vol.:  0.400 ch.:  0.020
It.:  275 Obj.:    73.1625 Vol.:  0.400 ch.:  0.020
It.:  276 Obj.:    73.1619 Vol.:  0.400 ch.:  0.015
It.:  277 Obj.:    73.1615 Vol.:  0.400 ch.:  0.015
It.:  278 Obj.:    73.1613 Vol.:  0.400 ch.:  0.015
It.:  279 Obj.:    73.1611 Vol.:  0.400 ch.:  0.015
It.:  280 Obj.:    73.1609 Vol.:  0.400 ch.:  0.016
It.:  281 Obj.:    73.1607 Vol.:  0.400 ch.:  0.016
It.:  282 Obj.:    73.1605 Vol.:  0.400 ch.:  0.016
It.:  283 Obj.:    73.1603 Vol.:  0.400 ch.:  0.016
It.:  284 Obj.:    73.1601 Vol.:  0.400 ch.:  0.016
It.:  285 Obj.:    73.1600 Vol.:  0.400 ch.:  0.016
It.:  286 Obj.:    73.1598 Vol.:  0.400 ch.:  0.015
It.:  287 Obj.:    73.1631 Vol.:  0.400 ch.:  0.017
It.:  288 Obj.:    73.1623 Vol.:  0.400 ch.:  0.017
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It.:  296 Obj.:    73.1590 Vol.:  0.400 ch.:  0.013
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It.:  311 Obj.:    73.1585 Vol.:  0.400 ch.:  0.017
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It.:  315 Obj.:    73.1577 Vol.:  0.400 ch.:  0.018
It.:  316 Obj.:    73.1575 Vol.:  0.400 ch.:  0.018
It.:  317 Obj.:    73.1574 Vol.:  0.400 ch.:  0.016
It.:  318 Obj.:    73.1574 Vol.:  0.400 ch.:  0.016
It.:  319 Obj.:    73.1574 Vol.:  0.400 ch.:  0.016
It.:  320 Obj.:    73.1575 Vol.:  0.400 ch.:  0.017
It.:  321 Obj.:    73.1576 Vol.:  0.400 ch.:  0.016
It.:  322 Obj.:    73.1577 Vol.:  0.400 ch.:  0.016
It.:  323 Obj.:    73.1579 Vol.:  0.400 ch.:  0.016
It.:  324 Obj.:    73.1581 Vol.:  0.400 ch.:  0.016
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It.:  325 Obj.:    73.1582 Vol.:  0.400 ch.:  0.013
It.:  326 Obj.:    73.1585 Vol.:  0.400 ch.:  0.013
It.:  327 Obj.:    73.1589 Vol.:  0.400 ch.:  0.010
It.:  328 Obj.:    73.1593 Vol.:  0.400 ch.:  0.010
It.:  329 Obj.:    73.1565 Vol.:  0.400 ch.:  0.010
```

x. Impelementing Passive Elements on a Short Cantilever Beam via Sensitivity Filtering

Mesh size: 150 x 150

```
%volfrac = 0.5
%penal = 3
%rmin = 5
% sensitivity filtering: ft=1
SC_P(150,150,0.5,3,5,1)
```

xi. Impelementing Passive Elements on a Short Cantilever Beam via Density Filtering

Mesh size: 150 x 150

```
%volfrac = 0.5
%penal = 3
%rmin = 5
%density filtering: ft=2
SC_P(150,150,0.5,3,5,2)
```

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It.:    3 Obj.:    49.0966 Vol.:  0.500 ch.:  0.200
It.:    4 Obj.:    36.9819 Vol.:  0.500 ch.:  0.200
It.:    5 Obj.:    36.2620 Vol.:  0.500 ch.:  0.200
It.:    6 Obj.:    35.9144 Vol.:  0.500 ch.:  0.200
It.:    7 Obj.:    35.7257 Vol.:  0.500 ch.:  0.200
It.:    8 Obj.:    35.6228 Vol.:  0.500 ch.:  0.200
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It.:   10 Obj.:    35.5164 Vol.:  0.500 ch.:  0.198
It.:   11 Obj.:    35.4912 Vol.:  0.500 ch.:  0.200
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It.:   13 Obj.:    35.4632 Vol.:  0.500 ch.:  0.190
It.:   14 Obj.:    35.4541 Vol.:  0.500 ch.:  0.146
It.:   15 Obj.:    35.4473 Vol.:  0.500 ch.:  0.144
It.:   16 Obj.:    35.4413 Vol.:  0.500 ch.:  0.120
It.:   17 Obj.:    35.4366 Vol.:  0.500 ch.:  0.131
It.:   18 Obj.:    35.4325 Vol.:  0.500 ch.:  0.116
It.:   19 Obj.:    35.4295 Vol.:  0.500 ch.:  0.116
It.:   20 Obj.:    35.4264 Vol.:  0.500 ch.:  0.103
It.:   21 Obj.:    35.4241 Vol.:  0.500 ch.:  0.097
It.:   22 Obj.:    35.4217 Vol.:  0.500 ch.:  0.109
It.:   23 Obj.:    35.4196 Vol.:  0.500 ch.:  0.115
It.:   24 Obj.:    35.4175 Vol.:  0.500 ch.:  0.083
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It.:   29 Obj.:    35.4089 Vol.:  0.500 ch.:  0.082
It.:   30 Obj.:    35.4075 Vol.:  0.500 ch.:  0.066
It.:   31 Obj.:    35.4064 Vol.:  0.500 ch.:  0.069
It.:   32 Obj.:    35.4055 Vol.:  0.500 ch.:  0.072
It.:   33 Obj.:    35.4048 Vol.:  0.500 ch.:  0.080
It.:   34 Obj.:    35.4040 Vol.:  0.500 ch.:  0.076
It.:   35 Obj.:    35.4033 Vol.:  0.500 ch.:  0.059
It.:   36 Obj.:    35.4026 Vol.:  0.500 ch.:  0.055
It.:   37 Obj.:    35.4022 Vol.:  0.500 ch.:  0.057
It.:   38 Obj.:    35.4017 Vol.:  0.500 ch.:  0.061
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It.:   44 Obj.:    35.3997 Vol.:  0.500 ch.:  0.055
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It.:   63 Obj.:    35.3961 Vol.:  0.500 ch.:  0.027
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It.:   75 Obj.:    35.3945 Vol.:  0.500 ch.:  0.027
It.:   76 Obj.:    35.3944 Vol.:  0.500 ch.:  0.026
It.:   77 Obj.:    35.3943 Vol.:  0.500 ch.:  0.028
It.:   78 Obj.:    35.3942 Vol.:  0.500 ch.:  0.028
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