

# **Topology Optimization Guidelines for 3D Printing of Lightweight Structures**

Methods, Considerations, and Applications

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# **Chapter 1 Introduction**

## **1.1 Topology Optimization (TO)**

Topology optimization (TO) is a computational method used to optimize the shape and layout of structures or components, while satisfying certain performance criteria such as minimizing weight or maximizing stiffness. The goal of topology optimization is to find the optimal distribution of material within a given design space, subject to certain constraints and objectives. This involves iteratively removing or adding material from the design space to achieve the desired performance criteria using finite element analysis (FEA). Topology optimization is competent at optimizing the shape of complex structures such as aircraft wings, car frames, or medical implants, and has applications in many fields such as aerospace, automotive, biomedical, and civil engineering. The optimization results can lead to more efficient and lightweight designs, reduced material usage and production costs, and improved performance and reliability. The design processes can benefit from topology optimization in terms of time and weight savings.

## **1.2 Topology Optimization with 3D Printing**

While topology optimization is a powerful tool for designing optimal structures, it often produces complex and irregular shapes that can be difficult to interpret and manufacture. This makes it challenging for engineers to understand and implement the optimal designs, particularly if they are not familiar with the optimization algorithm. 3D printing, which is also known as Additive Manufacturing, can help bridge the gap between topology optimization and practical engineering applications, allowing designers to take full advantage of the benefits of topology optimization while overcoming some of its limitations.

(1) Manufacturing complex geometries

Topology optimization often produces complex and irregular shapes that can be challenging to manufacture using traditional manufacturing methods. 3D printing, however, can easily produce these shapes, making it an ideal manufacturing method for topology optimized designs.

(2) Rapid prototyping

3D printing allows for the rapid production of prototypes, which can be used to validate topology optimized designs quickly and iteratively. This can help reduce the time and cost associated with traditional prototyping methods.

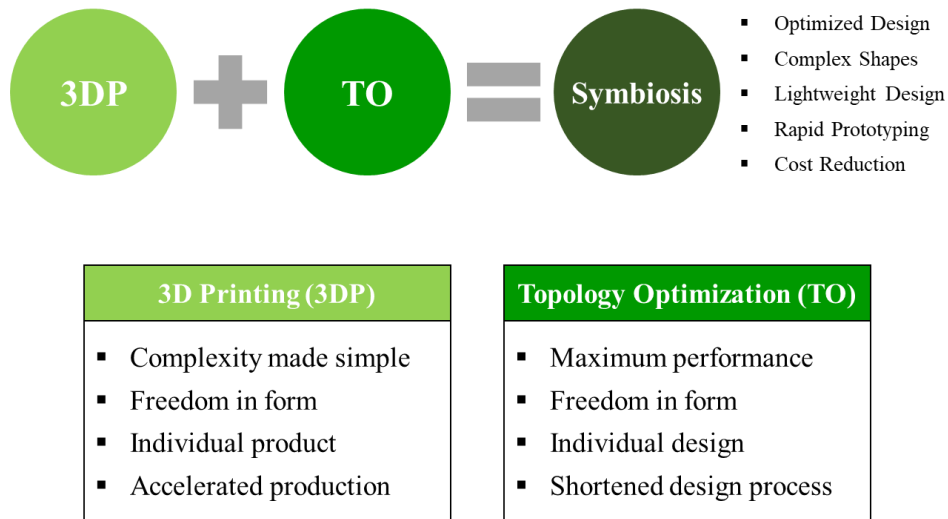


Figure 1.1: Prominent features of topology optimization with 3D printing

### (3) Material flexibility

With 3D printing, it is possible to print objects using a wide range of materials, including metals, polymers, and composites. This flexibility allows designers to choose materials that are most suitable for their specific application, taking into account factors such as strength, weight, and cost.

### (4) Design freedom

3D printing removes many of the constraints associated with traditional manufacturing methods, such as the need for moulds or tooling. This allows designers to explore more complex and unconventional shapes, which may result in more optimized designs.

### (5) Integration with simulation software

Many 3D printing software packages now have built-in simulation capabilities, allowing designers to simulate the behaviour of a part under load before it is printed. This can help validate topology optimized designs and ensure that they meet the desired performance criteria.

Overall, 3D printing can enable the implementation of topology optimization in practical engineering applications, as shown in Figure 1.1. Therefore, this guideline provides the methods and procedures on topology optimization for structures and components that are manufactured using 3D printing. Further applications of topology optimization for 3D printing is tabulated in Appendix A.

# Chapter 2    Topology Optimization Considerations

## 2.1    Selection considerations

Topology optimization is a powerful tool for designing lightweight structures, but it may not be necessary or appropriate for every part. Therefore, some considerations are proposed when deciding whether to perform topology optimization:

### (1) Weight consideration

Topology optimization is a good approach to achieve weight reductions while maintaining required functions for parts and components. This should be the key consideration when deciding on whether to undertake topology optimization.

### (2) Design complexity

Topology optimization can help reduce design time and improve performance for complex design requirements, such as multiple load cases or a combination of structural elements.

### (3) Material and manufacturing constraints

The material properties and manufacturing constraints should be considered when deciding whether to do topology optimization. The final design should be manufacturable within the constraints of the available materials and manufacturing process.

### (4) Cost consideration

The use of topology optimization can increase the cost of the design process. The additional design costs should be considered and justified by the potential benefits of the optimized design.

## 2.2 Design considerations

Several design considerations are proposed when performing topology optimization for 3D printing of lightweight structures, as follows:

### (1) Geometrical constraints:

The optimized design should be printable by the chosen 3D printing machine. The constraints and precision of the chosen 3D printing machine should be considered when performing topology optimization, such as the minimum feature size, the minimum thickness, the maximum overhang angle, and the maximum size of the build volume that can be printed.

### (2) Material properties

The properties of the 3D printing materials can significantly impact the topology optimization process. For example, the stiffness, strength, and ductility of the materials should be considered when optimizing the design.

### (3) Post-processing requirements

The post-processing requirements of the 3D printed parts should be considered, such as the surface finish, polishing, or painting. These requirements can influence the optimal design.

### (4) Performance requirements:

The performance of the optimized design should meet the criteria after it is printed, such as the weight, strength and stiffness, etc.

Overall, when performing topology optimization for 3D printing, it is important to take a holistic approach and consider all relevant design factors. This will help to ensure that the optimized design is suitable for 3D printing, meets the required performance criteria, and can be successfully manufactured.



## 2.3 Manufacturing Considerations

When considering the manufacturing of a 3D printed part that has been optimized through topology optimization, there are several important considerations to propose, as follows:

### (1) Printing orientation

The orientation of the part during printing has a significant impact on the final strength and quality. Therefore, the best orientation for the optimized design should be considered to ensure that the printed part meets the required performance criteria.

### (2) Support structures

Complex geometries often require the use of support structures during 3D printing. The optimized design should reduce the number of supports and make the part easier for post-processing.

### (3) Machine parameters

The machine parameters, such as the layer thickness, printing speed, and in-fill density can impact the quality of the printed parts. These parameters should be tuned and optimized for the chosen 3D printing technology

### (4) Post-processing

Depending on the chosen 3D printing technology and the specific design, post-processing may be required to achieve the desired surface finish or mechanical properties. The optimized design should be suitable for the required post-processing steps.

# Chapter 3 Topology Optimization Methods

## 3.1 Computational Setups

The TO algorithm is initialized with a design domain that is user-defined. This domain then undergoes finite element analysis to evaluate the stiffness or compliance of every element in the domain. After obtaining the results of finite element analysis, sensitivity of each element is checked. An element with high sensitivity would mean it has greater influence on the mechanical property of the overall structure if removed. Generally, elements with low sensitivity will be removed and the processed domain will be filtered to deal with two major numerical problems:

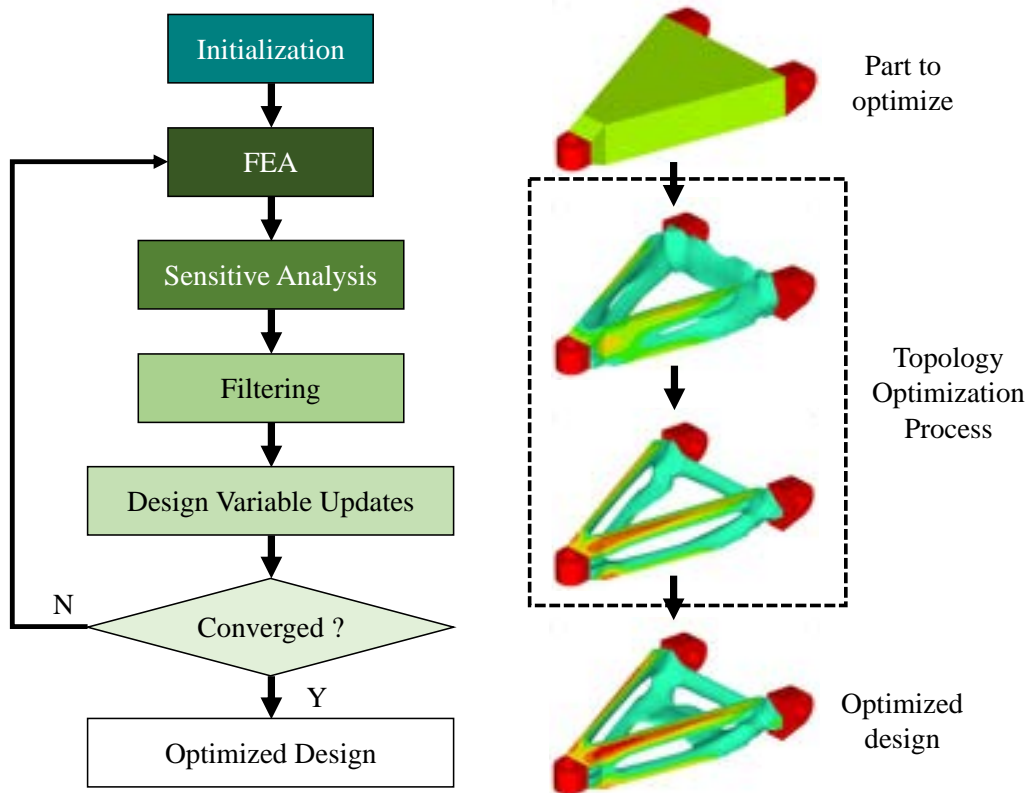


Figure 2.1: Algorithm and evolution of topology optimization

(1) Checkerboard problem in which elements are connected by edge nodes which introduces impractical mechanical properties.

(2) Mesh dependent designs that vary with the density of mesh. Domains with larger mesh tend to produce “chunkier” results while smaller mesh generate unreasonable fibrous thread-like configurations. The filtered domain is then evaluated to check for convergence.

The reiterative process is illustrated by the flowchart in Figure 2.1. A common form of a topological optimization problem with single constraint is formulated as:

$$\begin{array}{ll}
 \text{Minimize or maximize} & f(\rho) & (1) \\
 \\
 \text{Subject to volumetric constraint} & \int_{\Omega} \rho dV \leq V_0 \\
 \\
 \text{Other constraint} & 0 \leq \rho \leq 1
 \end{array}$$

where  $f(\rho)$  is the objective function,  $\Omega$  is the physical domain to be optimized,  $V_0$  is the total allowable volume of the final design and  $\rho$  is the constraint on normalized material density that is between 0 and 1 to describe the presence of material at each finite element within the physical domain; 1 represents locations where density is defined while 0 is for locations where material is either removed or absent at the start of initialization. The above formulation possess a single (volumetric) constraint and can be solved through the optimality criteria method.

On the other hand, to solve problems with multiple constraints, a general structural formulation is required. The multi-constraint problem can be formulated to find the set of design variables  $\mathbf{c}$ :

$$\begin{array}{ll}
 \text{Minimize or maximize} & f(\mathbf{c}) & (2) \\
 \\
 \text{Subject to constraints} & g(\mathbf{c}) = 0 \\
 & h(\mathbf{c}) \leq 0 \\
 \\
 \text{Other constraint} & c^l \leq c \leq c^u
 \end{array}$$

where  $f(\mathbf{c})$  is the objective function,  $g(\mathbf{c})$  and  $h(\mathbf{c})$  are general equality and inequality constraints, respectively,  $\mathbf{c}$  is the vector of design variables, and  $c^l$  and  $c^u$  are the lower and upper bounds on the design variables which is similar to the constraint on the normalized density as described in

the formulation of the single constraint problem. In the case of multi-constraint topological optimization, the design variable  $\mathbf{c}$  is the normalized material density  $\rho$ . Then  $f(c)$ ,  $g(c)$  and  $h(c)$  can be any mechanical response functions such as compliance, displacement, stress or even frequency. Therefore, a multiple constraint problem is more suitably solved by convex approximation method which utilizes the sensitivities between the current and previous design points for approximation of the objective and constraint functions, eventually leading to convergence towards optimized result.

## 3.2 Numerical Algorithms

### 3.2.1 Solid Isotropic Material with Penalization (SIMP)

As a direct product of the homogenization method, commercial topology optimization software was progressively replaced by a less rigorous and more efficient method called the SIMP. SIMP was less rigorous due to its use of virtual isotropic materials as compared to the reliance on true composite materials by homogenization method. Instead of using true composite materials during the penalization phase of intermediate densities, the simple material interpolation involved in SIMP eliminates expensive modelling and computational demands. The removal of unnecessary expensive and time-consuming procedures is key to the common adoption of SIMP method in commercial topological optimization software.

During the optimisation process, stiffness is evaluated using finite element method. Each finite element is then defined with a design variable, which is the normalized value for density between 0 and 1 and assumed to be directly scaled with stiffness or the elastic modulus of each element. The result is a collection of data fields within a design domain filled with element densities of between 0 (no material) to 1 (full solid material) inclusive. An illustration of a structural bracket design space and raw topological optimization result adopted from nTopology [1], shows the distribution and interpolation of densities where regions in red correspond to highest densities followed by regions in blue and green with densities between 0 and 1 along with empty spaces with 0 density (Figure 2.2). These blue and green regions are deemed as “intermediate densities” which are not physically meaningful for a solid isotropic material as the basic concept of SIMP is to achieve optimal distribution of elements with density of only 0 and 1. This lack of proper definition of material requires a user-controlled penalization factor  $\mathbf{P}$  to produce a more realistic

structure. The penalty factor mitigates the contribution of finite elements with intermediate densities to the total stiffness of the structures by steering these elements towards either full solid (density =1) or void (density = 0). A suitable penalty factor value of 3 is recommended from numerical experiments [2].

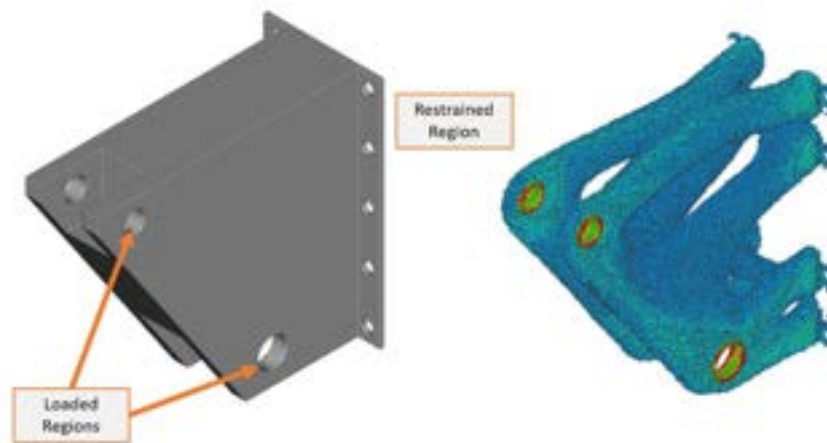


Figure 2.2: Structural bracket with topology optimization [1]

### 3.2.2 Level Set Method

Level set method (LSM) defines interfaces between material phases implicitly by iso-contours of a level-set function which facilitates the crystal-clear description of boundaries [3]. While SIMP directly removes the elements with low sensitivity, leaving a dispersion of holes with no inherent interconnectivity throughout the model, LSM approaches the problem by mapping out the distribution of relative sensitivity onto meshes in the form of contours shown in Figure 2.3. The aim of each iteration is to match the current target volume fraction with a threshold. Elements in contour regions with relative sensitivity less than this threshold (marked by dark blue and purple regions in Figure 2.3) are deleted and the analysis is rerun. Each newly updated domain will result in a new distribution of relative sensitivity and a new threshold is defined to match the current target volume fraction. This process is repeated till an optimum topology is achieved. The LSM approach is not suitable for 3D objects as it is immensely complicated to map out the sensitivity contours.

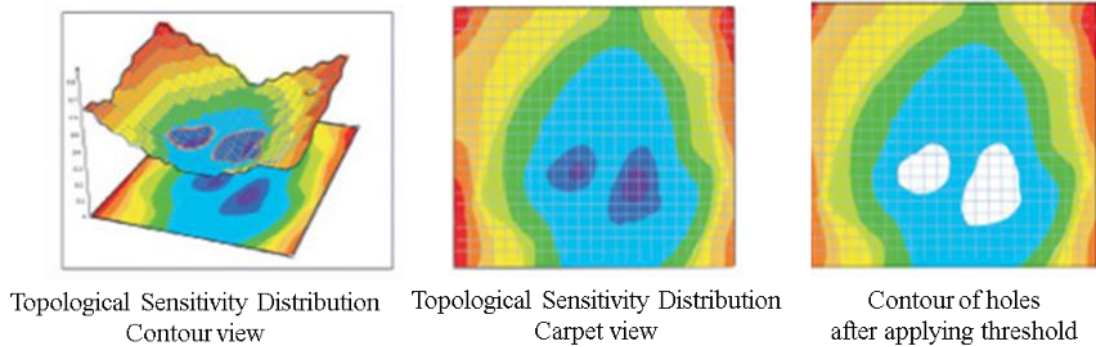


Figure 2.3: Level set process with iso-contour adopted from digital engineering [4]

The clear definition of boundary can greatly improve accuracy as mechanical responses are captured in the proximity of boundaries. Improved accuracy reduces the ambiguity resulting from intermediate density phases using density-based approach. The smooth topological treatment of boundary also overcomes the checkerboarding effect found in density-based approach where alternating solid elements are connected only by corner nodes. The illogical connectivity by point will lead to unrealistic and spurious mechanical responses in these regions.

LSM was reported to be highly reliant on the initial configuration, indicating a high degree of non-convexity and nonlinearity which increase the probability of the optimization process converging to local minima instead of global ones [3]. The introduction of holes as illustrated in Figure 2.4 can be useful but is not standardized across all designs which makes it difficult to guarantee that an improvement can be achieved in the optimization process. Even though the convergence problem can be solved with the use of regularization technique such as smoothening of sensitivity and geometrical mapping, the designer may not have a full control of the effect of regularization on the geometry of the final products leading to inconsistencies.

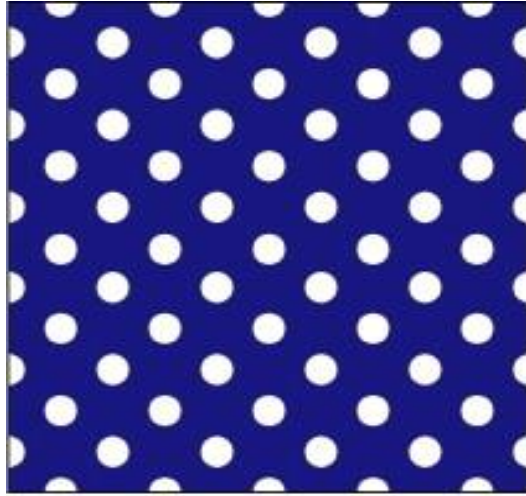


Figure 2.4: An initial design with hole nucleation [5]

To summarize, the downside of SIMP is the lack of clarity in the boundary or fuzzy interface and LSM requires initial seedings of holes which introduces a large number of intersecting elements, negatively affecting the computational efficiency, robustness and accuracy of analysis. In order to eliminate the downsides resulting from either method, a combination of these two methods was introduced through a penalty term in the objective function [6]. Instead of initial dependence on large arbitrary number of holes in LSM, holes are seeded continuously throughout the optimization process with the size and shape of holes optimized for different design problems.

### **3.2.3 Bi-direction Evolutionary Structural Optimization (BESO)**

Besides the three commonly used methods as discussed, Bi-direction Evolutionary Structural Optimization (BESO) is another commonly accepted method in commercial software. ESO method, where BESO originated from, is a process of gradual removal of unwanted, inefficient, and lowly-stressed material from an initially conservative design to achieve an optimal design [7]. The extent and speed of material removal in each iteration is controlled by user defined parameters, rejection ratio (RR) and evolution rate (ER), respectively. RR is the ratio of threshold Von Mises stress to a fixed stress, often defined by the yield stress of the material, such that elements with average stress below this threshold are removed. ER, on the other hand, controls the rate of increase of RR after each increment to facilitate the convergence of result toward the optimum. Typically,

1% of both RR and ER are sufficient for most cases [8]. Nonetheless, RR and ER should still be carefully adjusted to avoid premature convergence of results. Even with carefully determined RR and ER parameters, there is still uncertainty towards whether the solution is a local or global optimum.

ESO is also deemed as unidirectional ESO because the optimal design is achieved in one single direction that is the removal of materials whereas the “bi-directional” in BESO suggests that the optimal design is obtained using two directions, namely removal and addition of materials. BESO, as compared to ESO, offers better ability in finding global minima by allowing “backtracking” of elements to ensure all possible designs are thoroughly explored which not only include designs realised by just removal of materials but also the addition or re-introduction of materials to alleviate high stress regions [7]. In contrast to elemental sensitivities, BESO utilizes nodal sensitivities computed by the weighted average of the connected elemental sensitivities. Therefore, the distribution of density and sensitivities can be interpolated and smoothed across the voids of deleted elements. This approach allows for potential alleviation of concentration of extreme stresses to improve the overall stiffness of the structure. BESO was not as widely adopted as SIMP or LSM because the search space is related to the complexity of the design domain. A highly complex design domain would significantly increase the possible design space that the algorithm has to search, leading to potential convergence problem and higher computational cost.

### **3.3 Software for Topology Optimisation**

As shown in Table 2.1, it was reported that approximate fifty percent of the current commercial topology optimization software use purely density-based methods and a third of the market share belongs to a combination of both density-based and level-set methods, while the remainder are purely level-set or other evolutionary algorithms [9]. The most common density-based methods used to handle topological optimization in commercial finite element codes are Solid Isotropic Microstructure with Penalization (SIMP) and Bi-directional Evolutionary structural Optimization (BESO).



Table 2.1: Commonly used commercial software for topology optimisation (non-exhaustive)

<b>Software</b>	<b>Company</b>	<b>Application</b>	<b>Algorithm</b>
Abaqus - TOSCA Structure	Dassault Systems	Multiphysics	Density-based
ANSYS Mechanical	ANSYS Inc.	Multiphysics	Density-based
MSC Nastran Optimisation	MSC	Structures	Density- based
OptiStruct	Altair Engineering	Structures	Density- based
Inspire	solidThinking Inc.	Structures	Density & Level-Set
FEMtools	Dynamic Design Solutions	Structures	Density-based
COMSOL	COMSOL Inc.	Multiphysics	Density & Level-Set
nTop Platform	nTopology, Inc.	Structures	Density-based

## Chapter 4 Applications

In this chapter, OptiStruct is utilized to demonstrate the approach to conduct topology optimization of lightweight structures. The step to a simple example is shown here and will be applicable to more complicated problems.

### 4.1 Set Up Model in HyperMesh

#### 4.1.1 Preparation and problem clarification

- To demonstrate the workflow of topology optimization in OptiStruct, a shell structure is selected as an example to minimize its volume while maintaining strength. The CAD model and boundary conditions are shown in Figure 4.1.

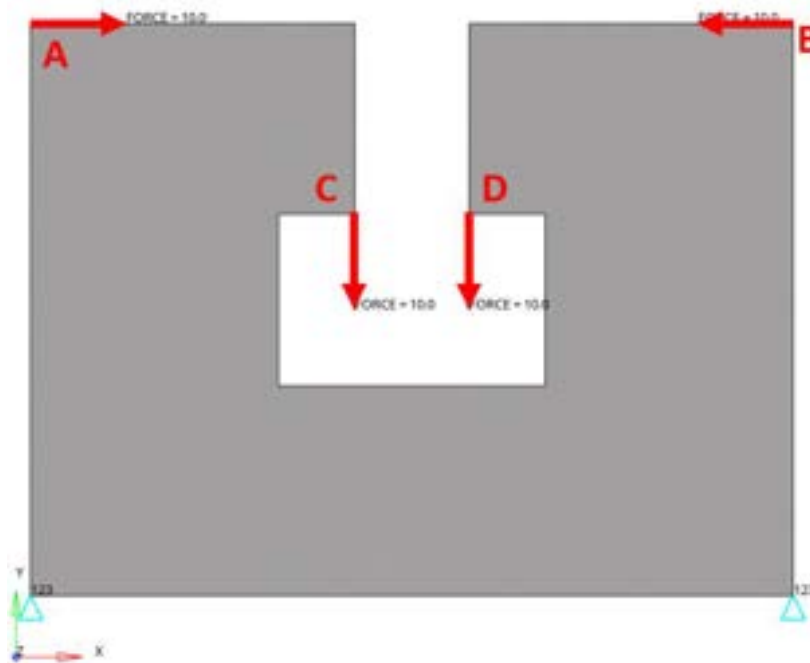


Figure 4.1: Geometry and boundary conditions

- There are **two constraints** at the lower left and right corners of the shell respectively to fix the structure on the ground.
- The shell structure is subjected to **4 force vectors** at Point A, B, C and D, respectively.

- The **objective** is to minimize the volume fraction of the shell while maintaining the strength to withstand the applied forces.
- Significant displacements can be found at Pont A, B, C and D due to the applied forces. Thus, the allowable displacements at these points must be predefined as a reference (dconstraints) for topology optimization.
- The design variable is density, varying from 0 to 1. The portion with a density value of 0 is the part removed during the optimization.

<b>Objective</b>	<b>Minimize volume fraction.</b>
<b>dconstraints</b>	Point A: displacement in the x-axis $0 < \Delta x < 0.002\text{mm}$ . Point B: displacement in the x-axis $-0.002\text{mm} < \Delta x < 0$ . Point C and D: displacement in the y-axis $-0.002\text{mm} < \Delta x < 0$ .
<b>Design variables</b>	The density of each element in the design space.

#### 4.1.2 Import Geometry and Generate Mesh

- Launch **HyperMesh** and select **OptiStruct** from the **User Profile** menu.
- From the **File** menu in the toolbar, select **Import > Geometry**.
- Select the geometry file from your working directory and then click **Import** to load the model into HyperMesh.

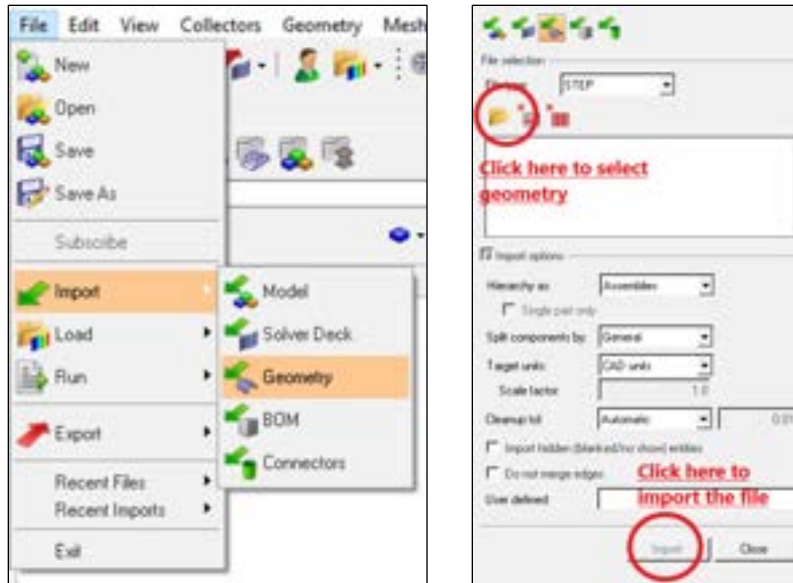


Figure 4.2: Import geometry

- From the **File** menu on the toolbar, select **Mesh > Create > 2D AutoMesh**.

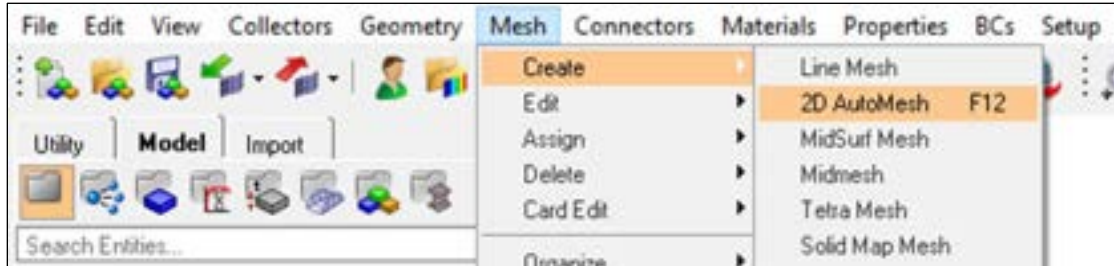


Figure 4.3: Create 2D AutoMesh

- Click on the geometry where you want to create a mesh.
- Enter an **element size** in the Panel. [**0.0001**]
- Select a suitable **mesh type** from the drop-down list. [**quads only**]
- Then, Click **mesh**.

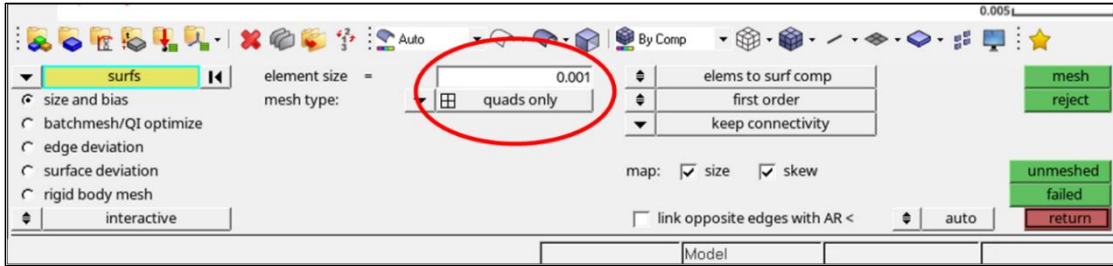


Figure 4.4: Mesh setup

### 4.1.3 Create Materials

- Click **Materials** from the **Panel** to create a material.
- Type in a **mat name** that you want to use. [**Steel**]
- Click **type** to select a suitable type from the drop-down list. [**Isotropic**]
- Click **card image** and select **MAT1**.
- Click **create/edit** to open the MAT1 table.

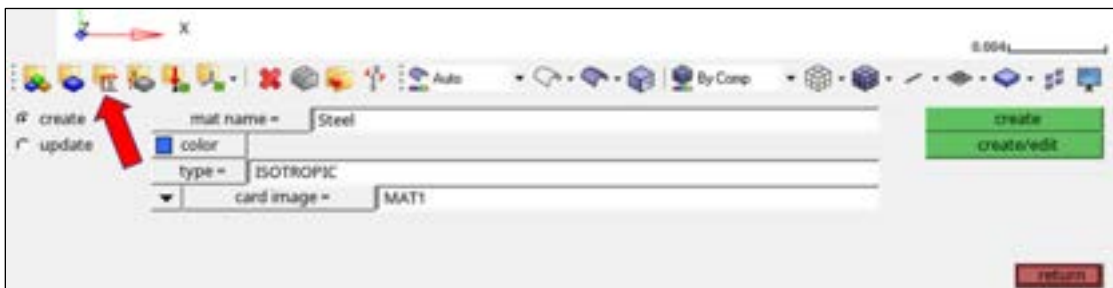


Figure 4.5: Create materials

- Click the material parameters which you want to define and type in their values, respectively.
- **E** is the Young's modulus, **Nu** is the Poisson's ratio, and **RHO** is the mass density.

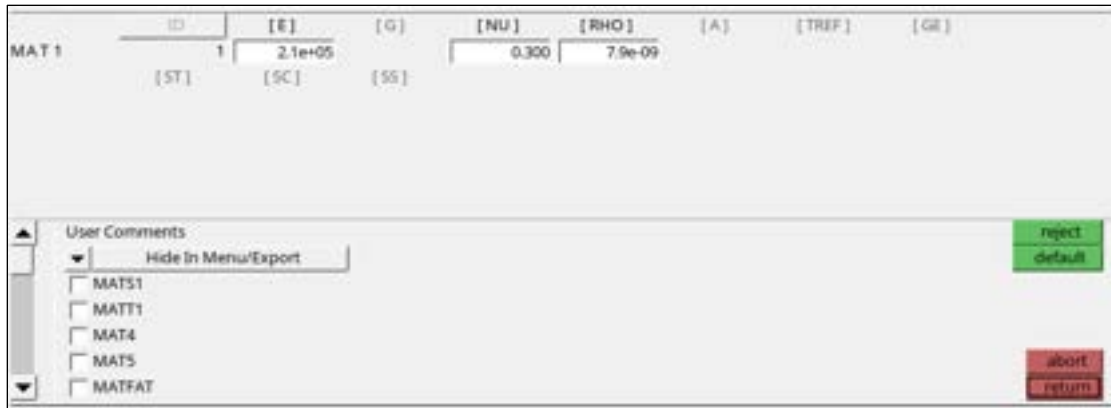


Figure 4.6: Material parameters

- Click **return** to go back to material collectors, and then click **create**.

#### 4.1.4 Create Properties

- Click **Properties** from **Panel**.
- Type in a **prop name**. [pshell]
- Click **type** and select a type from the drop-down list. [2D]
- Click **card image** and select **PSHELL** from the drop-down list.
- Click **material** and select the material that you have created in Figure 4.5. [Steel]

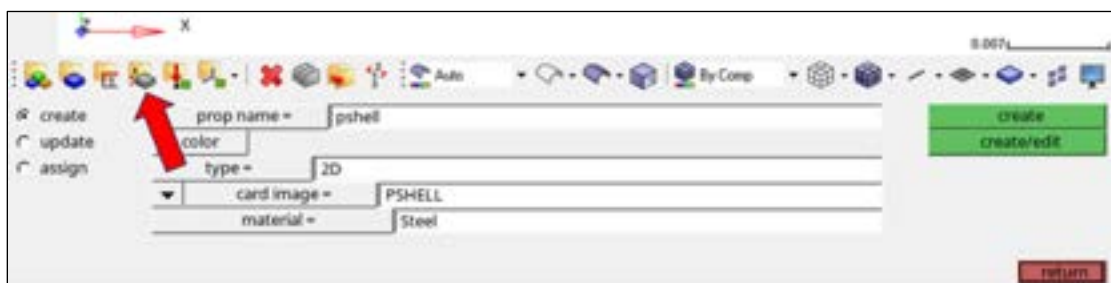


Figure 4.7: Create properties

- Click **create/edit** to open the PSHELL table.
- Click **[T]** to activate the thickness field for the shell component and accept the default value of **1**.



Figure 4.8: Thickness of shell

- Click **return** and go back to the **Properties**.
- Then click **create** and **return**.

#### 4.1.5 Assign Materials and Properties to Components

- Click **Components** from the **Panel**.
- Click **comps** and select the component which you want to assign the material and properties.
- For **property**, type in the **name of properties** created in Figure 4.7. [**pshell**]
- Click **update**.



Figure 4.9: Assign materials and properties to components

#### 4.1.6 Create Loader Collectors (Constraints and Forces)

- Click **Load Collectors** from **Panel** to create constraints.

- Type in a **loadcol name** in the Panel. [spc]
- Click **create** and **return**.

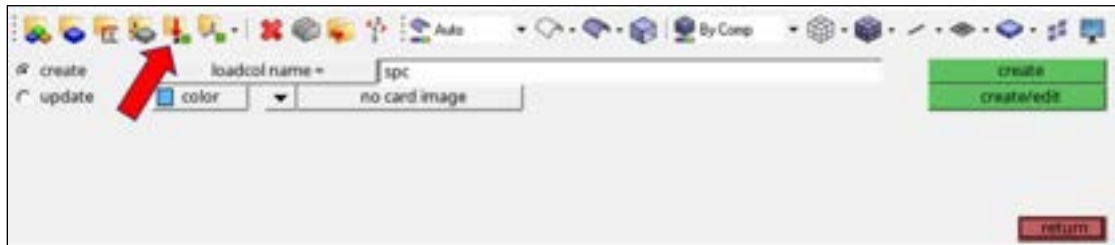


Figure 4.10: Create load collectors (constraints)

- On the right side of the Panel, select **Analysis**.

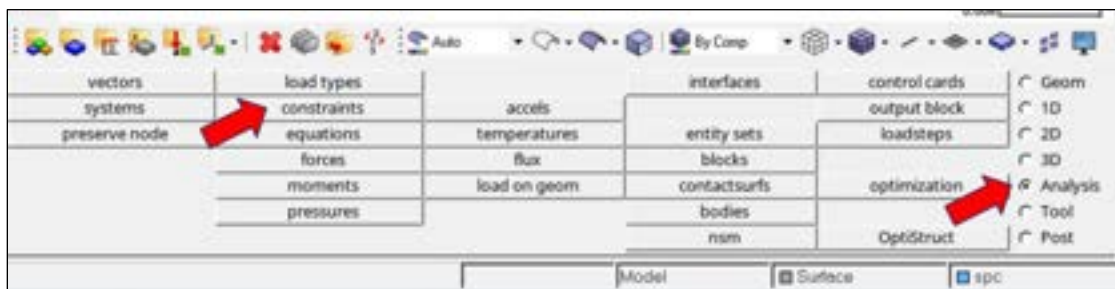


Figure 4.11: Analysis > constraints

- Then, click **constraints** to open the **constraint dialog**.
- From the **Panel**, click **nodes**.



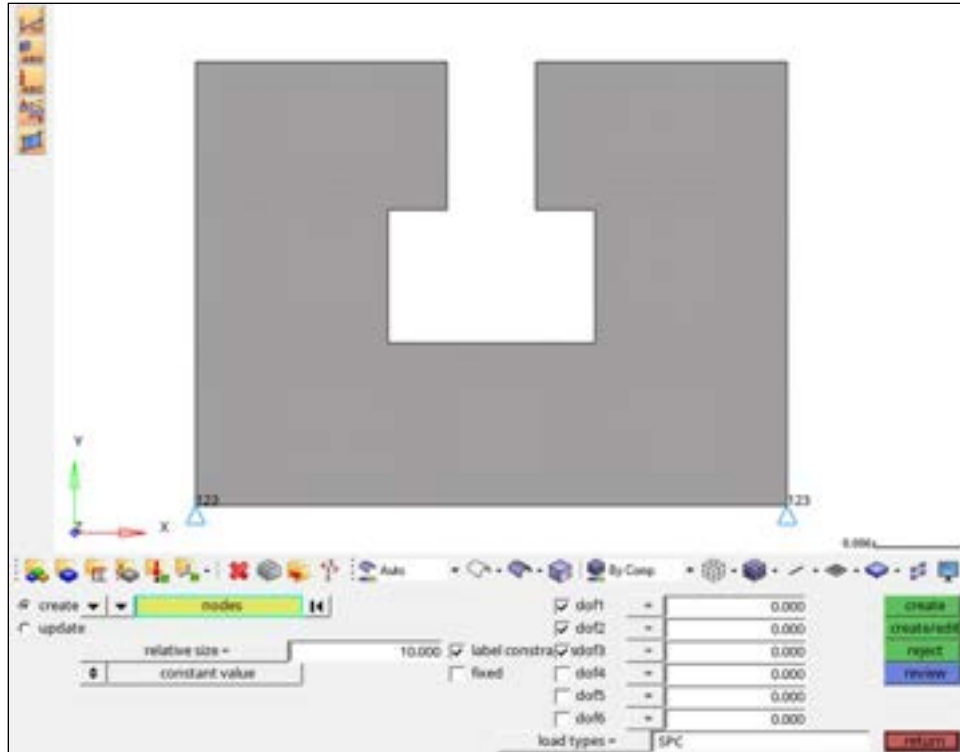


Figure 4.12: Constraints

- On your mesh, click **an element node** where you want to apply a constraint.
- Tick the **dof** which you want to constrain. In this case, **dof1**, **dof2** and **dof3** are selected.
- Click **create**.
- Repeat the procedure until all the constraints are created. In this case, there are 2 constraints on the left and right sides, as shown in Figure 4.12.



Figure 4.13: Create load collectors (forces)

- Click **Load Collectors** from **Panel** again to create the load collector for forces.

- Type in a **loadcol name** in the Panel to name the force boundary conditions.
- Click **create** and **return**.
- From Analysis panel, click **forces** to open the force dialog, as shown in Figure 4.14: Force Vectors.

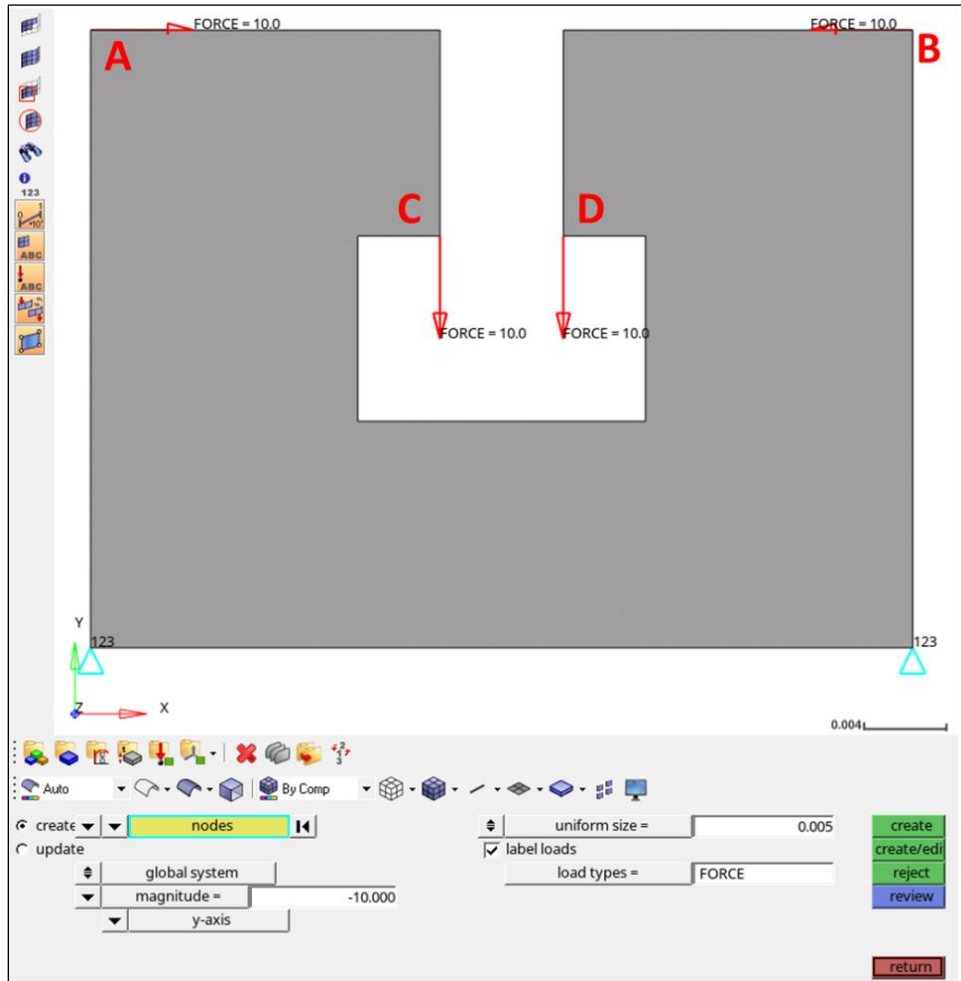


Figure 4.14: Force vectors

- From the **Panel**, click **nodes**.
- On your mesh, click **an element node** where you want to apply a **force vector**.
- Click **magnitude** and type in a value.
- Click the button below **magnitude** and select the **direction** of the force vector, such as, **x-axis**, **y-axis**, and **z-axis**, etc.

- Click **create**.
- Repeat the procedure until all the force vectors are created.
- In this case, there are 4 force vectors applied on Point A, B, C and D respectively, as shown above. The force directions at Point A and B are both **x-axis**, while the directions at Point C and D are both **y-axis**. The magnitudes of all the forces are 10.
- Then, Click **return**.

#### 4.1.7 Create Load Cases

- From the **Analysis** page, click **loadsteps**.
- Type in a **name** for the loadstep [**loadsteps1**].
- Set type as **linear static**.

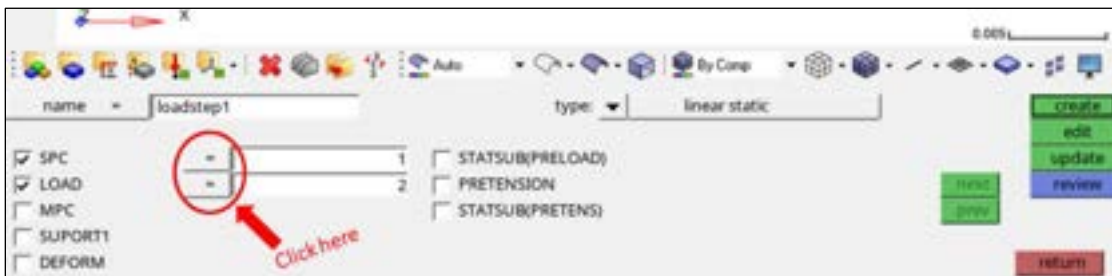


Figure 4.15: Create load cases

- Check the box for **SPC**. An entry field appears to the right of **SPC**.
- Click on the entry field next to **SPC**.
- From the drop-down list, select the **load collector of constraints**, which is under the **loadcol name [spc]** you have created in Figure 4.15.
- Similarly, check the box for **LOAD** and select the **load collector of forces** from the drop-down list. It is under the **loadcol name** of force boundary conditions [**forces**] created in Figure 4.15.
- Click **create** and **return** to go back to the Analysis page.

## 4.2 Linear static Analysis

A linear static analysis is performed before the topology optimization to investigate the responses of the structure, especially the displacements. Therefore, the linear static analysis provides references to define the target constraints in the topology optimization.

### 4.2.1 Model Setup

- From the Analysis panel, click **OptiStruct**.

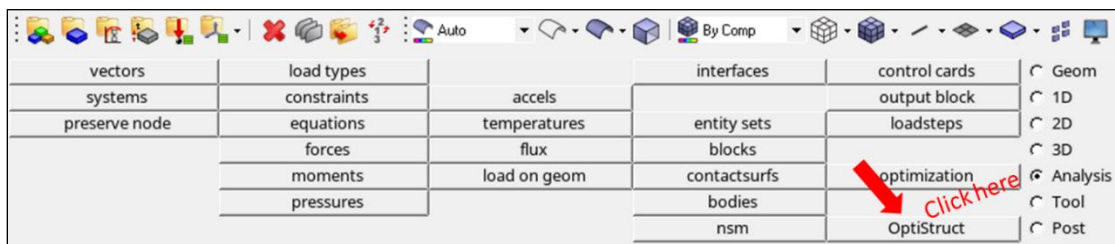


Figure 4.16: Launch OptiStruct

- Click **save as** and select the **directory** to write your OptiStruct model file.
- Click **run options** and select **analysis**.
- Click **OptiStruct** to run the simulation.

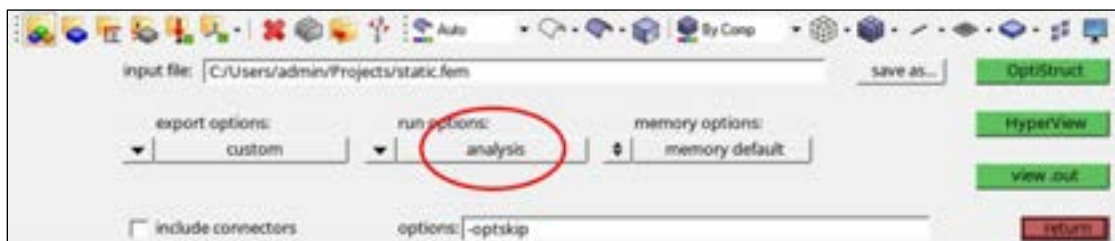


Figure 4.17: Set linear static analysis

- The simulation progress will be shown in a pop-up window. **Close** the window after the analysis has converged.

## 4.2.2 Displacement Analysis

- From the OptiStruct panel, click **HyperView** to check the results.
- Click **Plot**, and select **Displacement** as the **results type**, as shown in Figure 3.18.

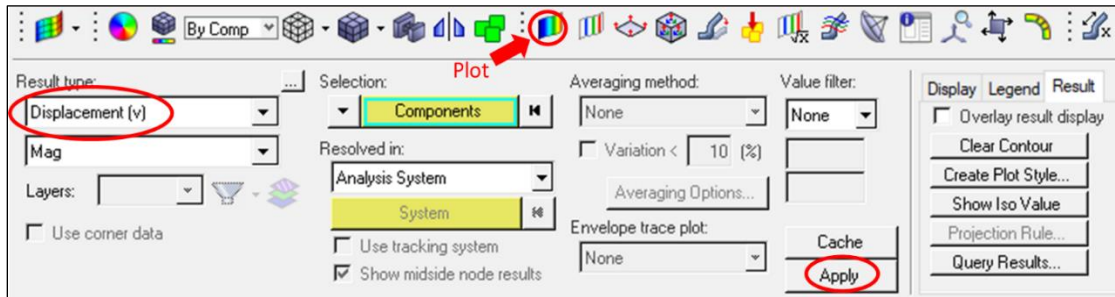


Figure 4.18: Plot displacement

- Click **Apply** to visualize the displacements contours.

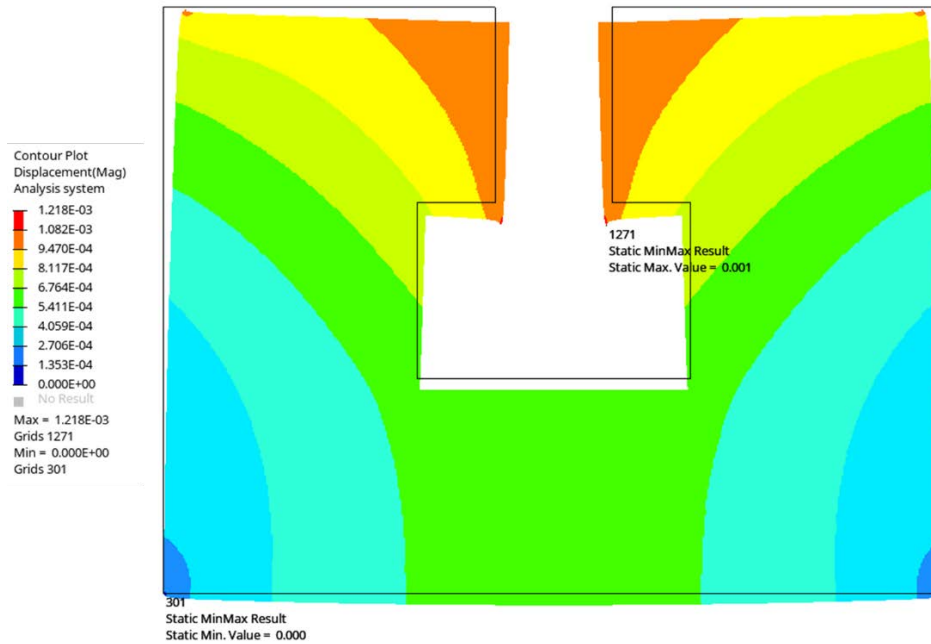


Figure 4.19: Displacement contour

- For this case, the maximal displacement is about 0.001. Therefore, the target maximal displacement after topology optimization can be set as 0.002.
- Close **HyperView** and click **return** in HyperMesh.

### 4.3 Topology Optimization

#### 4.3.1 Create Topology Design Variables

- From the **Analysis** page, click **optimization > topology**.
- Click **desvar** and type in a **name [design]**.
- Click **props** and select the properties defined in Figure 4.7 [**pshell**].
- Set **type [PSHELL]**.
- Set **base thickness** to be **0.0**.
- Click **create** and **return**.



Figure 4.20: Create design variables

#### 4.3.2 Create Volume Response

- From **optimization** panel, select **responses**.

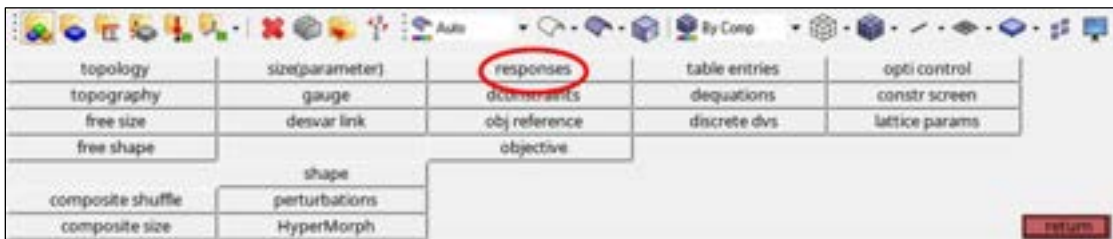


Figure 4.21: Create response

- Click **response** and name the response as **vol**, as shown in Figure 4.21: Create Volume Response.
- Switch the response type to **volume**.
- Click **create**.



Figure 4.22: Create volume response

### 4.3.3 Create Displacement Responses

- From **optimization** panel, select **responses** again.
- The displacement responses refer to as the behaviours induced by **the input force vectors**. Therefore, each force vector should correspond to a response.
- Type in a **name [displace1]** to create a response induced by the force at Point A.
- Switch the **response type** to **static displacement**.

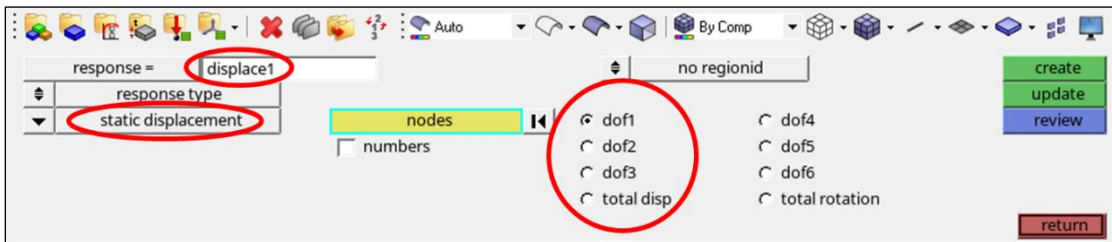


Figure 4.23: Create displacement response

- Click **nodes** and select **Point A** from the mesh.
- Select the **dof** according to the force **direction at Point A. [dof1]**
- Click **create**.

- Repeat the procedure and create the responses [**displace2**, **displace3**, **displace4**] at **Point B**, **C** and **D**.
- Click **return** to go back to the Optimization panel.

#### 4.3.4 Create Constraints on Displacement Responses

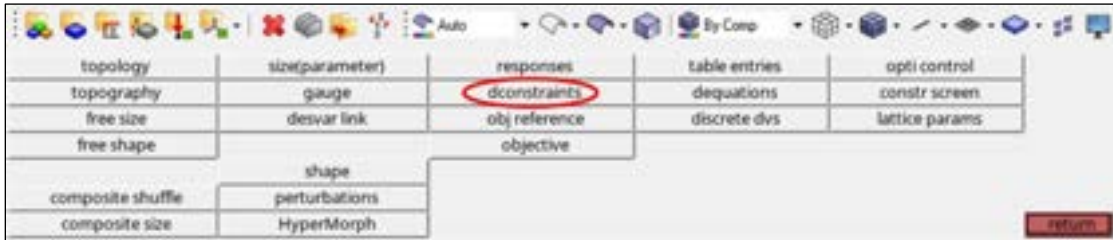


Figure 4.24: dconstraints

- From **optimization** panel, select the **dconstraints** and create constraints to each displacement response.

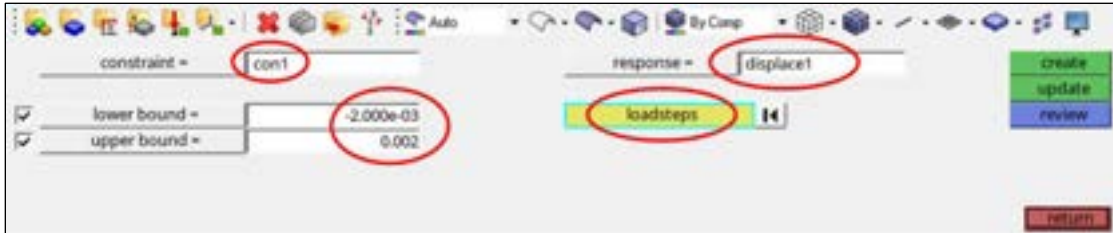


Figure 4.25: Create constraints on displacement responses

- Click **constraint** and name the constraint as **con1** for **displace1**.
- Click **response** and select **displace1**.
- Check the **boxes** for upper and lower bounds and set the values according to the maximal displacement calculated from the linear static analysis. [**0.002**]
- Click **loadsteps**.
- Check the box near **loadstep1** and click **select**.
- Click **create**.
- Follow the same step, create con2 for displace2, con3 for displace3 and con4 for displace4.



- Click **return** to go back to the **optimization** panel.
- In this case, the lower bound is -0.002 and the upper bound is 0.002. For con1, activate the upper bound, while for con2 to con4, activate the lower bound.

#### 4.3.5 Create Objective for Topology Optimization

- From **optimization** panel, select the **objective**.

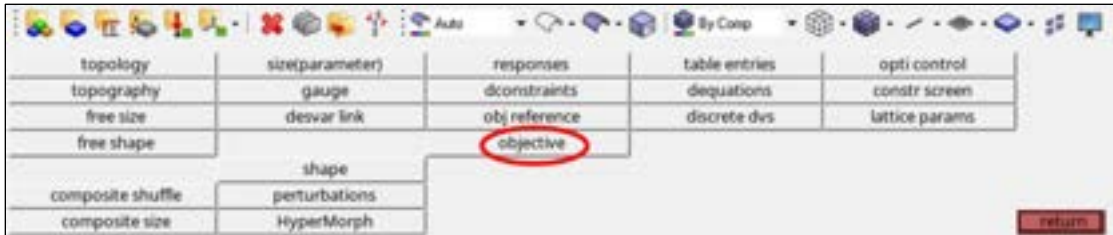


Figure 4.26: Objective

- Set the objective as **min** to reduce the vol of the structure.

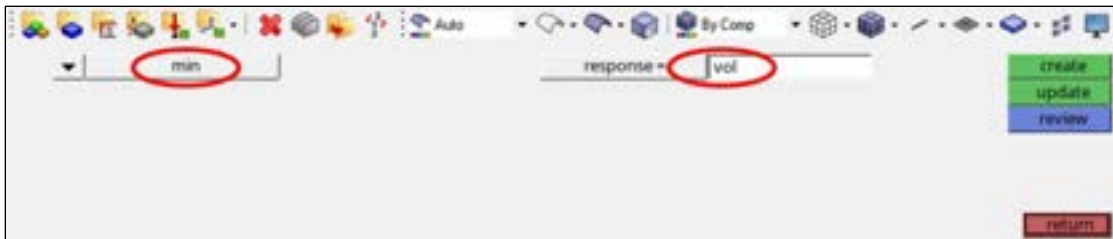


Figure 4.27: Create objective - volume optimization

- Click response and select **vol**.
- Click **create**.
- Click return and exit the **optimization** panel.

#### 4.3.6 Implement Topology Optimization in OptiStruct

- From the **Analysis** panel, click **OptiStruct**.
- Click **save as** and select the **directory** where you would like to save the model file.

- Click **run options** and select **optimization**.
- Click **OptiStruct** to run the simulation.
- The simulation progress will be shown in a pop-up window. **Close** the window after the analysis has converged.

#### 4.3.7 Post-process Optimization Results

- Go back to **HyperMesh** and click **HyperView**, which is the post processing tool inside HyperMesh. HyperView will load your optimization results and pop up on your screen.
- From the result browser, select the **last iteration**.

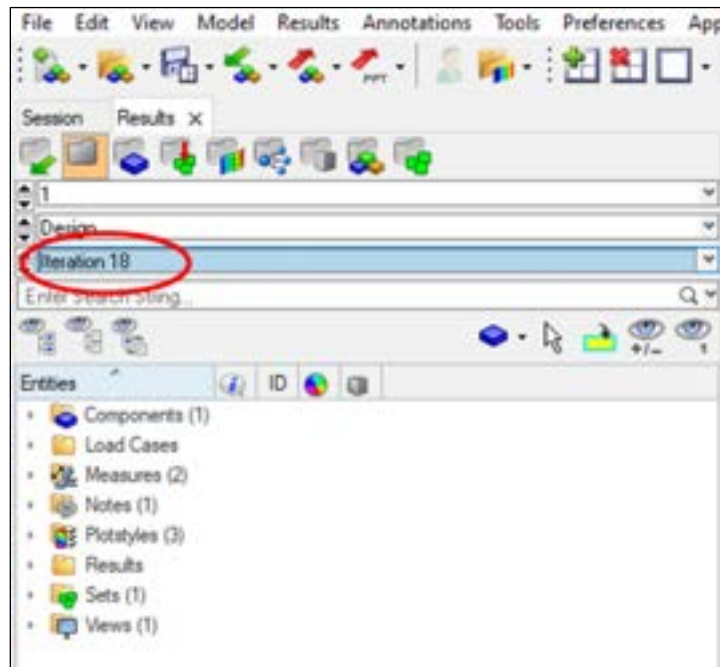


Figure 4.28: Launch the last iteration

- From the panel, click **Iso** to plot the optimization results.
- For Result type, select **Element Densities**.
- Click **Apply**.
- To change the density threshold, drag the slider under the **Current value**.

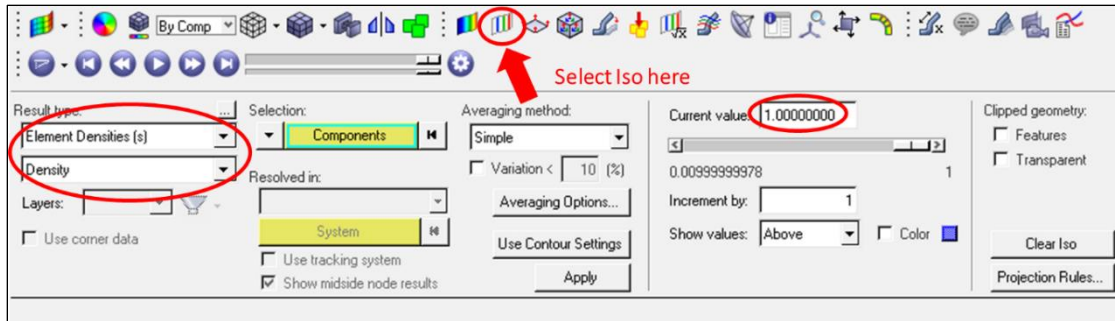


Figure 4.29: Plot topology optimization results – iso values

- The optimization result will be plotted in HyperView, as shown below.

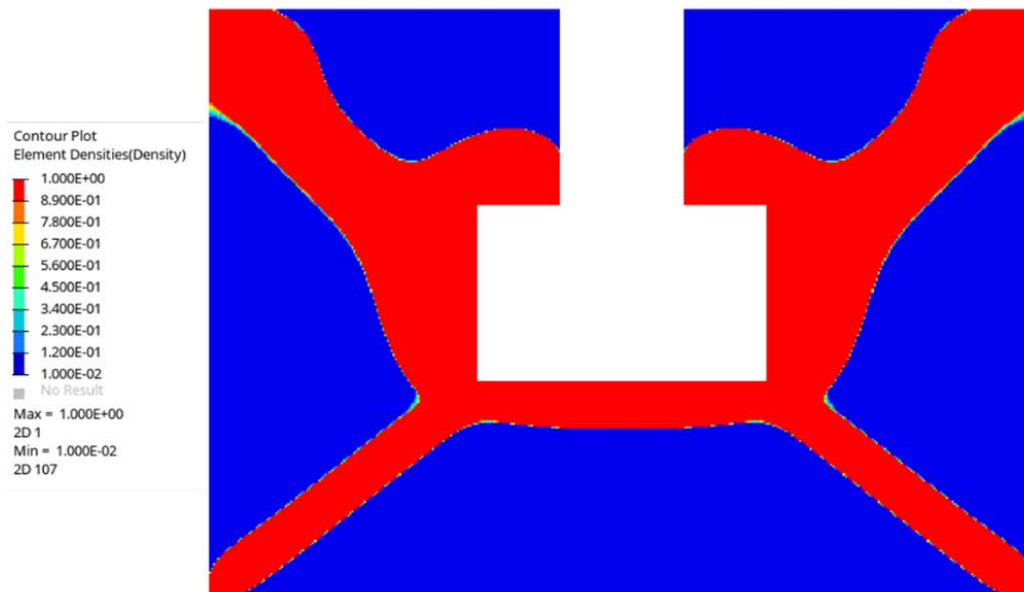


Figure 4.30: Topology optimization (element densities)

- Click **Next Page** on the upper right corner to plot the displacement contour.
- Click **Contour** and select **Displacement** as the **result type**, as shown in Figure 3.31.
- Slide the status to the end. This will show the deformations induced by the applied forces.

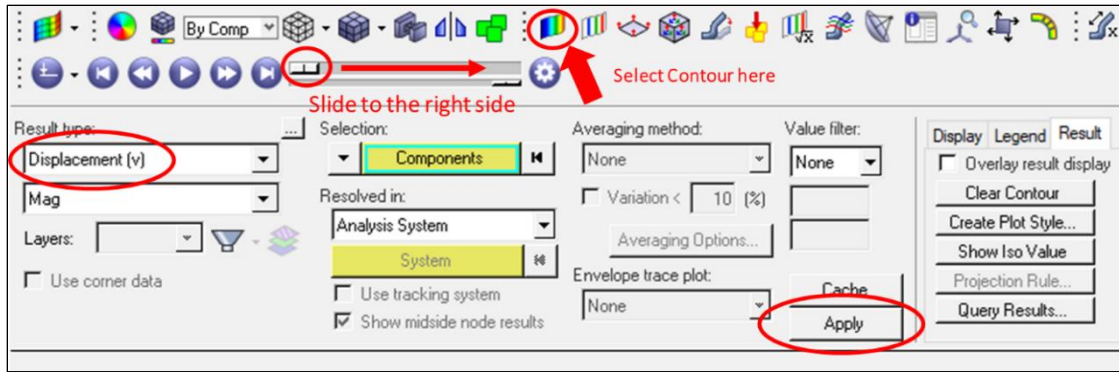


Figure 4.31: Plot displacement results

- Click **Apply** and you will see the **displacement contour** as below.

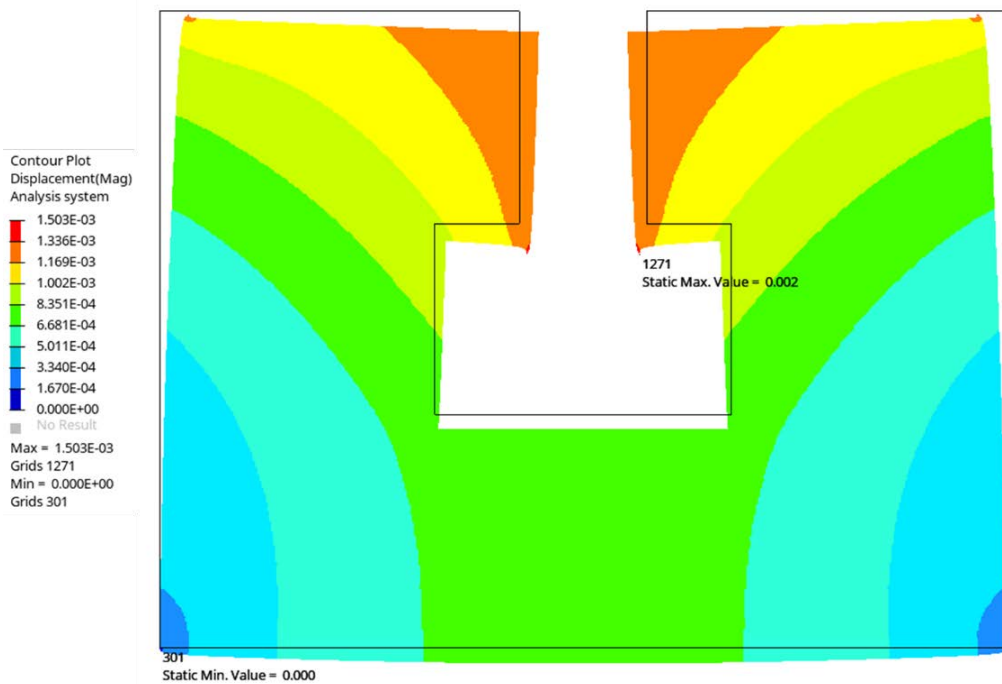
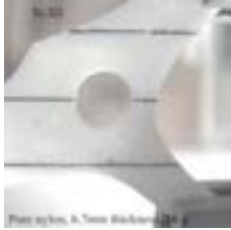








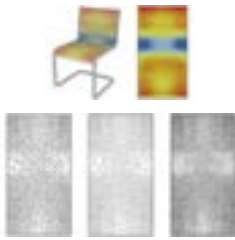


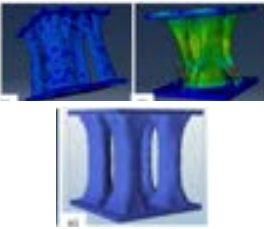




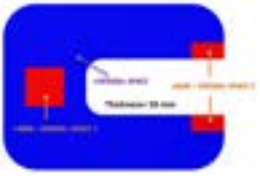

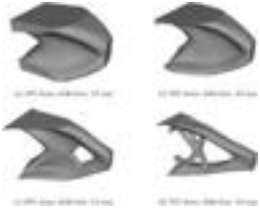
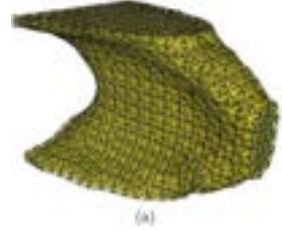
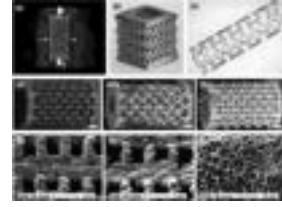
Figure 4.32: Displacement distribution after optimization


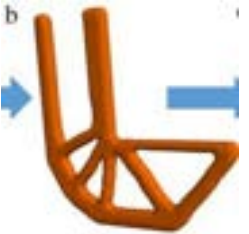
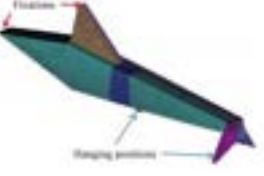




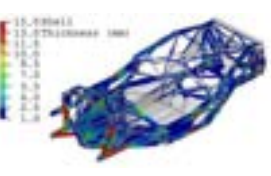
## Appendix A Applications of Topology Optimization

Table A-1: Summary of applications to topology optimization

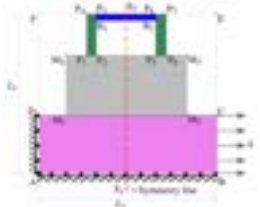
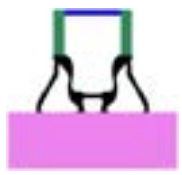
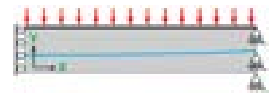

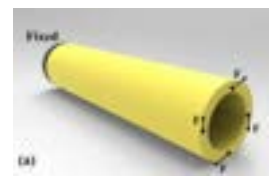
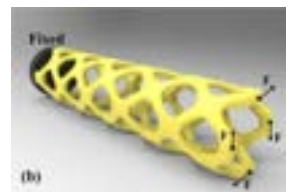
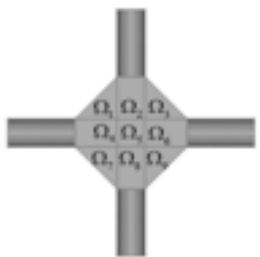

Papers	Reference	Original part	Optimised part	Objective	Method/ algorithms
Path-designed 3D printing for topological optimized continuous carbon fibre reinforced composite structures	[10]			Propose a path-designed 3D (PD-3D) printing approach that takes into consideration of the load transmission path, and the anisotropic property of continuous carbon fibre reinforced filaments.	SIMP
Comprehensive View on Racing Car Upright Design and Manufacturing	[11]			Design of a racing car upright using topological optimization	SIMP
Design and analysis of prosthetic foot using additive manufacturing technique	[12]			Design and analysis of Prosthetic foot using additive manufacturing technique dealing with the complete design process of a motion prosthetic foot manufactured by using Poly lactic acid (PLA) material	SIMP



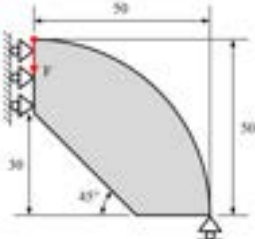





<p>Impacts of the settings in a design for additive manufacturing process based on topological optimization</p>	<p>[13]</p>			<p>To assess the impacts on part geometry of different design optimization settings used in the additive manufacturing process.</p>	<p>SIMP, Level-Set</p>
<p>Case Studies in Topological Design and Optimization of Additively Manufactured Cable-nets</p>	<p>[14]</p>			<p>Discusses research in novel approaches to the topological design and optimization of cable-nets enabled by the additive manufacturing of elastomeric materials.</p>	<p>SIMP, BESO</p>
<p>Experimental and numerical thermal analysis of open-cell metal foams developed through a topological optimization and 3D printing process</p>	<p>[15]</p>			<p>thermal analysis and comparing a lattice model and an optimized model of open-cell metal foams manufactured using metal casting process</p>	<p>FEM</p>
<p>Topology optimization and additive manufacturing: Comparison of conception methods using industrial codes</p>	<p>[16]</p>			<p>Comparison of TO results using various industrial codes, including Abaqus and Optistruct</p>	<p>SIMP</p>







<p>The design of lightweight gas turbine engine parts using topology optimization</p>	<p>[17]</p>			<p>Address a new approach to designing aircraft engine parts using the topological optimization algorithm tailored for production by additive manufacturing.</p>	<p>SIMP</p>
<p>Additive manufacturing integration with topology optimization methodology for innovative product design</p>	<p>[18]</p>			<p>Evaluate the potentiality offered by the integration of two structural optimization approaches (topological and lattice structures design) to generate novel and better performing structures</p>	<p>SIMP</p>
<p>An efficient and scalable approach for generating topologically optimized cellular structures for additive manufacturing</p>	<p>[19]</p>			<p>Non-concurrent TO approach, choosing a uniform microstructure or Representative Volume Element (RVE) to optimize the macrostructure.</p>	<p>Homogenization Method, SIMP, ESO, BESO, Level-Set</p>
<p>Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review</p>	<p>[20]</p>			<p>Reviews topological design and manufacturing processes of various types of porous metals, in particular for titanium alloys, biodegradable metals and shape memory alloys.</p>	<p>SIMP, ESO, BESO, Level-Set</p>





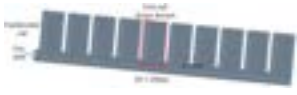

<p>Support structure constrained topology optimization for additive manufacturing</p>	<p>[21]</p>			<p>Develop a TO methodology for limiting the support structure volume, thereby leading to designs that are AM friendly.</p>	<p>Level-Set</p>
<p>Topology Optimization in Aircraft and Aerospace Structures Design</p>	<p>[22]</p>			<p>Review recent advances of topology optimization techniques applied in aircraft and aerospace structures design.</p>	<p>SIMP, ESO, Level Set, Bubble method, Smooth Heaviside parameterization, Finite circle method</p>
<p>Living on the Moon: Topological Optimization of a 3D-Printed Lunar Shelter</p>	<p>[23]</p>			<p>To assess the concept of 3D printing technology as a potential method to build a habitat on the Moon.</p>	<p>D-Shape</p>
<p>High performance automotive chassis design: a topology optimization based approach</p>	<p>[24]</p>			<p>Simulate chassis weight reduction</p>	<p>SIMP, Level-set</p>

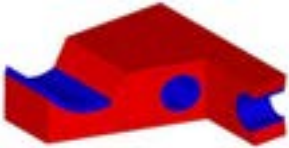
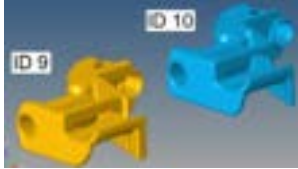

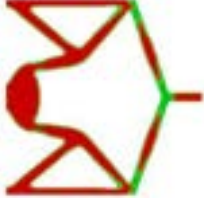
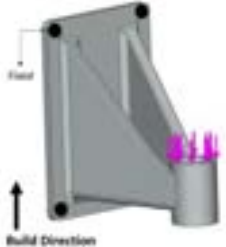



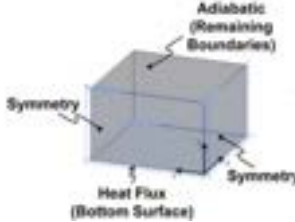

<p>Topology optimization and 3D printing of large deformation compliant mechanisms for straining biological tissues</p>	<p>[25]</p>			<p>To design large deformation compliant mechanisms for inducing desired strains in biological tissues</p>	<p>FEM</p>
<p>3D printing of a post-tensioned concrete girder designed by topology optimization</p>	<p>[26]</p>			<p>To present a novel design and manufacturing process that combines 3D concrete printing, topology optimization, and post-tensioning of concrete structures.</p>	<p>FEM</p>
<p>Multidisciplinary topology optimization incorporating process-structure-property-performance relationship of additive manufacturing</p>	<p>[27]</p>			<p>To incorporate the PSPP relationships of laser sintered material with topology optimizer to provide a guideline for TO collaborative AM design.</p>	<p>FEM</p>
<p>A novel bionic-based substructure division method for topology optimization</p>	<p>[28]</p>			<p>To propose a bionic-based substructure division method, which achieves better performances than traditional topology optimization methods.</p>	<p>FEM</p>

<p>Full-scale topology optimization for fiber-reinforced structures with continuous fiber paths</p>	<p>[29]</p>			<p>To propose a topology optimization method that is capable of simultaneous design for the structural topology, continuous fiber path, and morphology for fiber-reinforced composite structures.</p>	<p>FEM</p>
<p>Topology optimization of self-supporting structures for additive manufacturing with B-spline parameterization</p>	<p>[30]</p>			<p>To present a B-spline based topology optimization method to design self-supporting structures for additive manufacturing</p>	<p>B-spline parameterization</p>
<p>Development of a patient-specific immobilisation facemask for radiation therapy using additive manufacturing, pressure sensors and topology optimisation</p>	<p>[31]</p>			<p>TO of the 3D printed facemask (FDM) for volume reduction + maintaining mechanical strength</p>	<p>SIMP</p>
<p>Design and Development of an Additive Manufactured Component by Topology Optimisation</p>	<p>[32]</p>			<p>TO of a rear uprights for a suspension assembly fabricated by EBM</p>	<p>SIMP</p>

<p>Bidirectional Evolutionary Structural Optimization (BESO) based design method for lattice structure to be fabricated by additive manufacturing</p>	<p>[33]</p>			<p>TO of thickness distribution of lattice struts to be fabricated through AM</p>	<p>BESO</p>
<p>An aerospace bracket designed by thermo-elastic topology optimization and manufactured by additive manufacturing</p>	<p>[34]</p>			<p>TO of both Thermo-Elastic and Mechanical stresses on an aerospace bracket to obtain optimal design fabricated through SLM</p>	<p>RAMP</p>
<p>Design and experimental validation of self-supporting topologies for additive manufacturing</p>	<p>[35]</p>			<p>TO of Messerschmidt–Bölkow–Blohm (MBB) beams to validate the manufacturability of self-supporting topological structures (FDM)</p>	<p>SIMP</p>

<p>Topology Optimization of 3D- printed joints under crash loads using Evolutionary Algorithms</p>	<p>[36]</p>			<p>Optimisation of 3D-printed metal joint in a hybrid S-rail structure under axial crash loading, and comparing the effectiveness of the design with other state of the art methods (Equivalent Static Loads (ESL) and Hybrid Cellular Automata (HCA))</p>	<p>EA-LSM</p>
<p>Material extrusion additive manufacturing and experimental testing of topology-optimised passive heat sinks using a thermally- conductive plastic filament</p>	<p>[37]</p>			<p>TO is used to generate novel heat sink designs for passive cooling through natural convection, which are printed using Fused Filament Fabrication (FFF) and tested for its thermal performance</p>	<p>MMA</p>
<p>Optimal design and experimental validation of 3D printed soft pneumatic actuators</p>	<p>[38]</p>			<p>TO is used to optimise the design of a soft pneumatic actuator that is to be prototyped by 3D printing and tested under pneumatic pressure, and compared with the traditional rectangular unit cells design of a non-optimised actuator</p>	<p>MIST</p>

<p>Hands-free printed door opener to limit the spread of Coronavirus: Design through topology optimization</p>	<p>[39]</p>			<p>Hands-free door openers were designed using TO and the efficiency of both the classic SIMP approach and the NURBS based SIMP approach were compared based on both mechanical and manufacturing constraints</p>	<p>SIMP</p>
<p>Multiple-Material Topology Optimization of Compliant Mechanisms Created Via PolyJet Three-Dimensional Printing</p>	<p>[40]</p>			<p>The design of multimaterial compliant mechanisms was optimised using the 2-phase SIMP approach, 3-phase combinational SIMP approach and the 3-phase multi-phase SIMP approach, and the efficacy of these optimisation approaches are tested through the multimaterial Polyjet printing of force inverter compliant mechanisms</p>	<p>SIMP</p>
<p>Support structure constrained topology optimization for additive manufacturing</p>	<p>[21]</p>			<p>A topology optimisation framework was tested for both a 2D MBB beam and a 3D mount bracket to reduce the amount of support materials needed in fabricating these parts (through FDM)</p>	<p>PareTO</p>

<p>Topology Optimization, Additive Layer Manufacturing, and Experimental Testing of an Air-Cooled Heat Sink</p>	<p>[41]</p>			<p>The design of design a heat sink for confined jet impingement air cooling is optimised, printed using additive layer manufacturing (ALM) and tested against benchmark plate and pin-fin heat sink geometries</p>	<p>MMA</p>
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## References

- [1] Topology Optimization in a World of Fields and Implicit Geometry n.d. <https://ntopology.com/blog/topology-optimization-in-a-world-of-fields-and-implicit-geometry/> (accessed April 2, 2023).
- [2] SIMP Method for Topology Optimization n.d. [https://help.solidworks.com/2019/English/SolidWorks/cworks/c\\_simp\\_method\\_topology.htm?id=734b8a2653d34388bffa7ff1e202aeec#Pg0](https://help.solidworks.com/2019/English/SolidWorks/cworks/c_simp_method_topology.htm?id=734b8a2653d34388bffa7ff1e202aeec#Pg0) (accessed April 2, 2023).
- [3] Dijk NP van, Maute K, Langelaar M, Keulen F van. Level-set methods for structural topology optimization: a review. *Struct Multidisc Optim* 2013;48:437–72. <https://doi.org/10.1007/s00158-013-0912-y>.
- [4] Topology Optimization Methods n.d. <https://www.digitalengineering247.com/article/topology-optimization-methods/>.
- [5] Luo Z, Tong L, Wang MY, Wang S. Shape and topology optimization of compliant mechanisms using a parameterization level set method. *J Comput Phys* 2007;227:680–705. <https://doi.org/10.1016/j.jcp.2007.08.011>.
- [6] Geiss MJ, Maute K. Topology Optimization of Active Structures using a Higher-Order Level-Set-XFEM-Density Approach. 2018 Multidiscip Analysis Optim Conf 2018. <https://doi.org/10.2514/6.2018-4053>.
- [7] Querin OM, Steven GP, Xie YM. Evolutionary structural optimisation (ESO) using a bidirectional algorithm. *Eng Computation* 1998;15:1031–48. <https://doi.org/10.1108/02644409810244129>.
- [8] Xie YM, Steven GP. Evolutionary Structural Optimization 1997:126–47. [https://doi.org/10.1007/978-1-4471-0985-3\\_8](https://doi.org/10.1007/978-1-4471-0985-3_8).
- [9] Plocher J, Panesar A. Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures. *Mater Design* 2019;183:108164. <https://doi.org/10.1016/j.matdes.2019.108164>.
- [10] Li N, Link G, Wang T, Ramopoulos V, Neumaier D, Hofele J, et al. Path-designed 3D printing for topological optimized continuous carbon fibre reinforced composite structures. *Compos Part B Eng* 2020;182:107612. <https://doi.org/10.1016/j.compositesb.2019.107612>.
- [11] Hunar M, Jancar L, Krzikalla D, Kaprinay D, Srnicek D. Comprehensive View on Racing Car Upright Design and Manufacturing. *Symmetry* 2020;12:1020. <https://doi.org/10.3390/sym12061020>.
- [12] Vijayan V, Kumar SA, Gautham S, Masthan MM, Piraichudan N. Design and analysis of prosthetic foot using additive manufacturing technique. *Mater Today Proc* 2021;37:1665–71. <https://doi.org/10.1016/j.matpr.2020.07.195>.

- [13] Morretton E, Vignat F, Pourroy F, Marin P. Impacts of the settings in a design for additive manufacturing process based on topological optimization. *Int J Interact Des Manuf Ijidem* 2019;13:295–308. <https://doi.org/10.1007/s12008-018-00524-9>.
- [14] Tish D, McGee W, Schork T, Thün G, Velikov K. Case Studies in Topological Design and Optimization of Additively Manufactured Cable-nets. *Struct* 2019;18:83–90. <https://doi.org/10.1016/j.istruc.2018.11.002>.
- [15] Merabtine A, Gardan N, Gardan J, Badreddine H, Zhang C, Zhu F, et al. Experimental and numerical thermal analysis of open-cell metal foams developed through a topological optimization and 3D printing process★. *European Phys J Appl Phys* 2018;83:10904. <https://doi.org/10.1051/epjap/2018180060>.
- [16] Saadlaoui Y, Milan J-L, Rossi J-M, Chabrand P. Topology optimization and additive manufacturing: Comparison of conception methods using industrial codes. *J Manuf Syst* 2017;43:178–86. <https://doi.org/10.1016/j.jmsy.2017.03.006>.
- [17] Dubrovskaya A, Dongauzer K, Faskhutdinov R. The design of lightweight gas turbine engine parts using topology optimization. *Matec Web Conf* 2017;129:01067. <https://doi.org/10.1051/mateconf/201712901067>.
- [18] Primo T, Calabrese M, Prete AD, Anglani A. Additive manufacturing integration with topology optimization methodology for innovative product design. *Int J Adv Manuf Technology* 2017;93:467–79. <https://doi.org/10.1007/s00170-017-0112-9>.
- [19] Robbins J, Owen SJ, Clark BW, Voth TE. An efficient and scalable approach for generating topologically optimized cellular structures for additive manufacturing. *Addit Manuf* 2016;12:296–304. <https://doi.org/10.1016/j.addma.2016.06.013>.
- [20] Wang X, Xu S, Zhou S, Xu W, Leary M, Choong P, et al. Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review. *Biomaterials* 2016;83:127–41. <https://doi.org/10.1016/j.biomaterials.2016.01.012>.
- [21] Mirzendehtdel AM, Suresh K. Support structure constrained topology optimization for additive manufacturing. *Comput Aided Design* 2016;81:1–13. <https://doi.org/10.1016/j.cad.2016.08.006>.
- [22] Zhu J-H, Zhang W-H, Xia L. Topology Optimization in Aircraft and Aerospace Structures Design. *Arch Comput Method E* 2015;23:595–622. <https://doi.org/10.1007/s11831-015-9151-2>.
- [23] Benvenuti S, Ceccanti F, Kestelier XD. Living on the Moon: Topological Optimization of a 3D-Printed Lunar Shelter. *Nexus Netw J* 2013;15:285–302. <https://doi.org/10.1007/s00004-013-0155-7>.
- [24] Cavazzuti M, Baldini A, Bertocchi E, Costi D, Torricelli E, Moruzzi P. High performance automotive chassis design: a topology optimization based approach. *Struct Multidisc Optim* 2010;44:45–56. <https://doi.org/10.1007/s00158-010-0578-7>.



- [25] Kumar P, Schmidleithner C, Larsen NB, Sigmund O. Topology optimization and 3D printing of large deformation compliant mechanisms for straining biological tissues. *Struct Multidisc Optim* 2021;63:1351–66. <https://doi.org/10.1007/s00158-020-02764-4>.
- [26] Vantighem G, Corte WD, Shakour E, Amir O. 3D printing of a post-tensioned concrete girder designed by topology optimization. *Automat Constr* 2020;112:103084. <https://doi.org/10.1016/j.autcon.2020.103084>.
- [27] Li S, Yuan S, Zhu J, Zhang W, Zhang H, Li J. Multidisciplinary topology optimization incorporating process-structure-property-performance relationship of additive manufacturing. *Struct Multidisc Optim* 2021;63:2141–57. <https://doi.org/10.1007/s00158-021-02856-9>.
- [28] Zhang F, Du W, Zhang H. A novel bionic-based substructure division method for topology optimization. *Struct* 2021;29:937–46. <https://doi.org/10.1016/j.istruc.2020.11.061>.
- [29] Li H, Gao L, Li H, Li X, Tong H. Full-scale topology optimization for fiber-reinforced structures with continuous fiber paths. *Comput Method Appl M* 2021;377:113668. <https://doi.org/10.1016/j.cma.2021.113668>.
- [30] Wang C, Zhang W, Zhou L, Gao T, Zhu J. Topology optimization of self-supporting structures for additive manufacturing with B-spline parameterization. *Comput Method Appl M* 2021;374:113599. <https://doi.org/10.1016/j.cma.2020.113599>.
- [31] Asfia A, Novak JI, Rolfe B, Kron T. Development of a patient-specific immobilisation facemask for radiation therapy using additive manufacturing, pressure sensors and topology optimisation. *Rapid Prototyping J* 2022;28:945–52. <https://doi.org/10.1108/rpj-09-2021-0241>.
- [32] Walton D, Moztarzadeh H. Design and Development of an Additive Manufactured Component by Topology Optimisation. *Proc Cirp* 2017;60:205–10. <https://doi.org/10.1016/j.procir.2017.03.027>.
- [33] Tang Y, Kurtz A, Zhao YF. Bidirectional Evolutionary Structural Optimization (BESO) based design method for lattice structure to be fabricated by additive manufacturing. *Comput Aided Design* 2015;69:91–101. <https://doi.org/10.1016/j.cad.2015.06.001>.
- [34] SHI G, GUAN C, QUAN D, WU D, TANG L, GAO T. An aerospace bracket designed by thermo-elastic topology optimization and manufactured by additive manufacturing. *Chinese J Aeronaut* 2020;33:1252–9. <https://doi.org/10.1016/j.cja.2019.09.006>.
- [35] Fu Y-F, Rolfe B, Chiu LNS, Wang Y, Huang X, Ghabraie K. Design and experimental validation of self-supporting topologies for additive manufacturing. *Virtual Phys Prototyp* 2019;14:382–94. <https://doi.org/10.1080/17452759.2019.1637023>.
- [36] Bujny M, Olhofer M, Aulig N, Duddeck F. Topology Optimization of 3D-printed joints under crash loads using Evolutionary Algorithms. *Struct Multidisc Optim* 2021;64:4181–206. <https://doi.org/10.1007/s00158-021-03053-4>.

- [37] Huttunen E, Nykänen MT, Alexandersen J. Material Extrusion Additive Manufacturing and Experimental Testing of Topology-Optimised Passive Heat Sinks Using a Thermally-Conductive Plastic Filament. *Ssrn Electron J* 2022. <https://doi.org/10.2139/ssrn.4094532>.
- [38] Lu Y, Tong L. Optimal design and experimental validation of 3D printed soft pneumatic actuators. *Smart Mater Struct* 2022;31:115010. <https://doi.org/10.1088/1361-665x/ac95e3>.
- [39] Panettieri E, Bertolino G, Montemurro M. Hands-free printed door opener to limit the spread of Coronavirus: Design through topology optimization. *Compos Part C Open Access* 2022;9:100316. <https://doi.org/10.1016/j.jcomc.2022.100316>.
- [40] Gaynor AT, Meisel NA, Williams CB, Guest JK. Multiple-Material Topology Optimization of Compliant Mechanisms Created Via PolyJet Three-Dimensional Printing. *J Manuf Sci Eng* 2014;136:061015. <https://doi.org/10.1115/1.4028439>.
- [41] Dede EM, Joshi SN, Zhou F. Topology Optimization, Additive Layer Manufacturing, and Experimental Testing of an Air-Cooled Heat Sink. Volume 3 *Adv Fabr Manuf Emerg Technology Frontiers Energy Heal Water- Appl Nano- Micro- Mini-Scale Devices Mems Nems Technology Updat Talks Therm Management Micro Channels Jets Sprays* 2015:V003T03A001-V003T03A001. <https://doi.org/10.1115/ipack2015-48027>.