IIT Hyderabad

Soft Robotics Project

Submitted by:
ME21BTECH11001 Abhishek Ghosh
ME21BTECH11002 Aditya Verma

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Dr. Prabhat Kumar

1 Part 1

Problem Statement

Soft robotic grippers, inspired by biological systems, offer compliance and adaptability essential for manipulating delicate or irregular objects. Kirigami structures, which incorporate cuts into a flat sheet to enable complex deformation patterns, offer an innovative solution for soft gripping mechanisms. The goal of this project is to optimize the topology of a 2D kirigami-based soft gripper design using a computational technique known as topology optimization. The aim is to design a structure that uses minimal material while maximizing structural stiffness (minimizing compliance) under specific loading and boundary conditions.

Design Domain

The design domain is a rectangular 2D region discretized into finite elements. Each element can either be solid (material present) or void (no material). The gripper domain is fixed on one side to simulate attachment to a base and loaded on another side to simulate gripping force.

- Grid resolution: `nelx` $\times$ `nely` elements.
- Fixed boundary: One edge is fully constrained.
- Load: Applied downward on selected node(s) to mimic actuation.
- Volume fraction: Controls the proportion of material available for design.

Objective Function

The objective function is the total structural compliance:

$$c = \sum_{e=1}^{n_{el}} E_e \cdot \mathbf{u}_e^T \mathbf{K}_e \mathbf{u}_e$$

where:

- $E_e = E_{min} + x_e^p (E_0 - E_{min})$: effective Young's modulus of element e under SIMP interpolation.
- $\mathbf{u}_e$: displacement vector for element e.
- $\mathbf{K}_e$: stiffness matrix for element e.

Constraints

- **Volume Constraint**: Total volume of material must not exceed the desired fraction:

$$\frac{1}{n_{el}} \sum_{e=1}^{n_{el}} x_e \leq \text{volfrac}$$

- **Design Bounds**: $0.001 \leq x_e \leq 1$ for all elements.

Implementation Details

SIMP Method Overview

The Solid Isotropic Material with Penalization (SIMP) method uses a set of design variables x_e, each corresponding to the material density of an element e in the design domain. These design variables are interpolated to compute the material properties, such as Young's modulus, for each element. The basic approach involves minimizing the compliance (maximizing the stiffness) of a structure while ensuring that the total material usage does not exceed a specified volume fraction.

Design Variables

The design variable x_e represents the material density of element e in the design domain. It is a scalar value between 0 and 1:

$$x_e = \begin{cases} 0 & \text{if the element is void (no material)} \\ 1 & \text{if the element is fully solid (material)} \end{cases}$$

Intermediate values between 0 and 1 represent a mix of material and void, and these are penalized to encourage the solution to contain only fully solid or void regions.

Material Property Interpolation

The material properties of each element, such as Young's modulus $E(x_e)$, are interpolated as a function of the design variable x_e:

$$E(x_e) = E_{\min} + x_e^p \cdot (E_0 - E_{\min})$$

where: - E_0 is the Young's modulus of solid material. - $E_{\min}$ is the Young's modulus of void material (typically very small). - p is the penalization exponent (typically $p > 1$, such as $p = 3$).

Objective Function

The goal in topology optimization is typically to minimize compliance, which is a measure of the total strain energy of the structure. The compliance C is given by:

$$C = U^T K U$$

where: - U is the displacement vector obtained by solving the system of equations. - K is the global stiffness matrix.

The element stiffness matrix $K_e(x_e)$ is computed based on the material properties of each element, and the global stiffness matrix is assembled by summing the contributions of all individual elements.

Finite Element Analysis (FEA)

Finite element analysis (FEA) is used to calculate the displacements and stresses within the structure. The global stiffness matrix K is assembled from the element stiffness matrices $K_e(x_e)$. The system of equations is then solved for the displacement vector U under the applied loads F:

$$KU = F$$

where F is the external load vector. The compliance is computed based on the displacements and the stiffness matrix.

Sensitivity Analysis

The sensitivity of the compliance function with respect to the design variable x_e is calculated to update the design variables in the optimization loop. The sensitivity is given by:

$$\frac{\partial C}{\partial x_e} = -p(E_0 - E_{\min})x_e^{p-1} \cdot c_e$$

where: - c_e is the compliance of element e. - x_e^{p-1} is the sensitivity of the stiffness matrix with respect to the design variable.

The sensitivity information is used to guide the update of the design variables in the optimization process.

Optimality Criteria Update

The Optimality Criteria (OC) method is used to update the design variables in each iteration. The update rule is given by:

$$x_e^{\text{new}} = \max\left(0.001, \min\left(1, x_e \cdot \sqrt{-\frac{\frac{\partial C}{\partial x_e}}{dv \cdot l}}\right)\right)$$

where: - dv is the filtering sensitivity. - l is a scalar that ensures the volume fraction constraint is satisfied.

Volume Fraction Constraint

The total material usage in the design domain is constrained by a volume fraction vf, which limits the total amount of material used:

$$\sum_e x_e \leq \text{vf} \cdot \text{total number of elements}$$

The volume fraction ensures that the optimization does not use more material than allowed.

Filter Technique

To avoid checkerboarding and other numerical artifacts, a filtering technique is often applied to smooth the sensitivities. The filtered sensitivities $\frac{\partial C}{\partial x_e}$ are calculated as:

$$\frac{\partial C}{\partial x_e} \leftarrow H\left(\frac{\frac{\partial C}{\partial x_e}}{H_s}\right)$$

where H is the filter matrix, and H_s is the normalization factor.

Iterative Optimization

The process of solving the FEA, calculating sensitivities, and updating the design variables is repeated iteratively. Convergence is achieved when: - The change in compliance is below a specified threshold. - The changes in design variables are small.

Compliance vs Volume Fraction Description

In this study, we evaluate the effect of the volume fraction on the resulting compliance to explore material-efficiency trade-offs. By running the topology optimization for different values of volume fraction (e.g., 0.2, 0.3, ..., 0.6), we observe how structural stiffness changes. Lower volume fractions yield lighter but more compliant (less stiff) structures, while higher volume fractions allow stiffer structures but use more material. The plot shows diminishing returns in stiffness gains at higher volumes, helping us choose an optimal material budget.

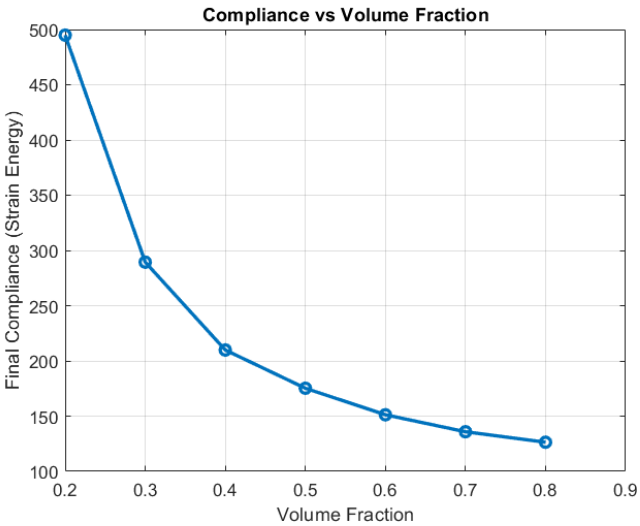

Figure 1: Compliance Vs Volume Fraction Plot

Graphical Interpretations and Analysis

1. Design Evolution

The grayscale plot evolves through iterations. Initially, the design is uniform. Over iterations, the algorithm redistributes material to form a compliant yet stiff structure.

High-load paths retain material.

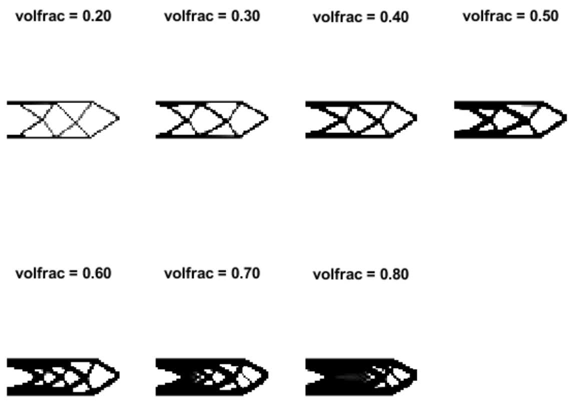

Figure 2: Gray scale plot for Structural Optimization at different Volume Fraction

2. Filtered Sensitivity Plot

Displays elements with high impact on compliance. Higher values indicate locations where adding material most improves stiffness. These are reinforced over iterations.

3. Strain Energy Overlay

Indicates where strain energy accumulates. Optimized designs focus material in these zones to improve energy efficiency.

4. Compliance and Volume vs Iteration

- Compliance starts high and decreases monotonically, showing improved structural performance.
- Volume remains constant due to volume constraint enforcement.

5. Final Strain Energy Distribution

In the final layout, strain energy is channeled efficiently. Material is concentrated in high-stress paths, ensuring mechanical efficiency and compliance reduction.

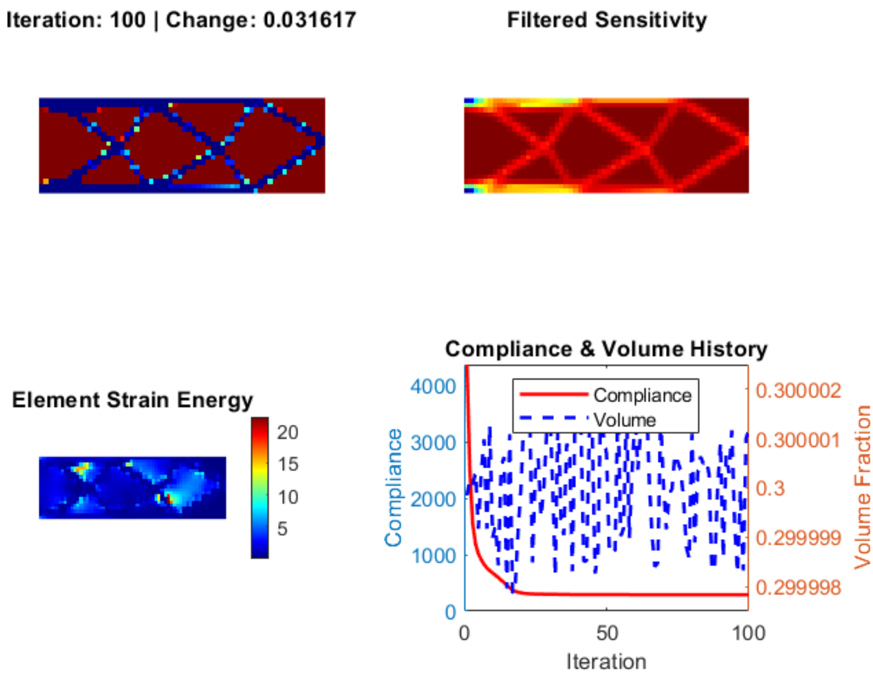

Figure 3: Different Plots at a Target Volume Fraction

Conclusion

Using sensitivity-based SIMP topology optimization, we designed a lightweight kirigami-based soft gripper that meets stiffness and material constraints. The plots validate convergence and effectiveness of the method:

- Compliance reduces over iterations.
- Filtered sensitivities guide material placement.
- Final energy distribution reflects efficient structural behavior.

This methodology can be extended to 3D soft actuators and integrated with manufacturing constraints for practical robotic deployment.

2 Part 2: Topology Optimization

The aim of the optimization problem is to find the optimal material distribution, in terms of minimum compliance, with a constraint on the total amount of material.

2.1

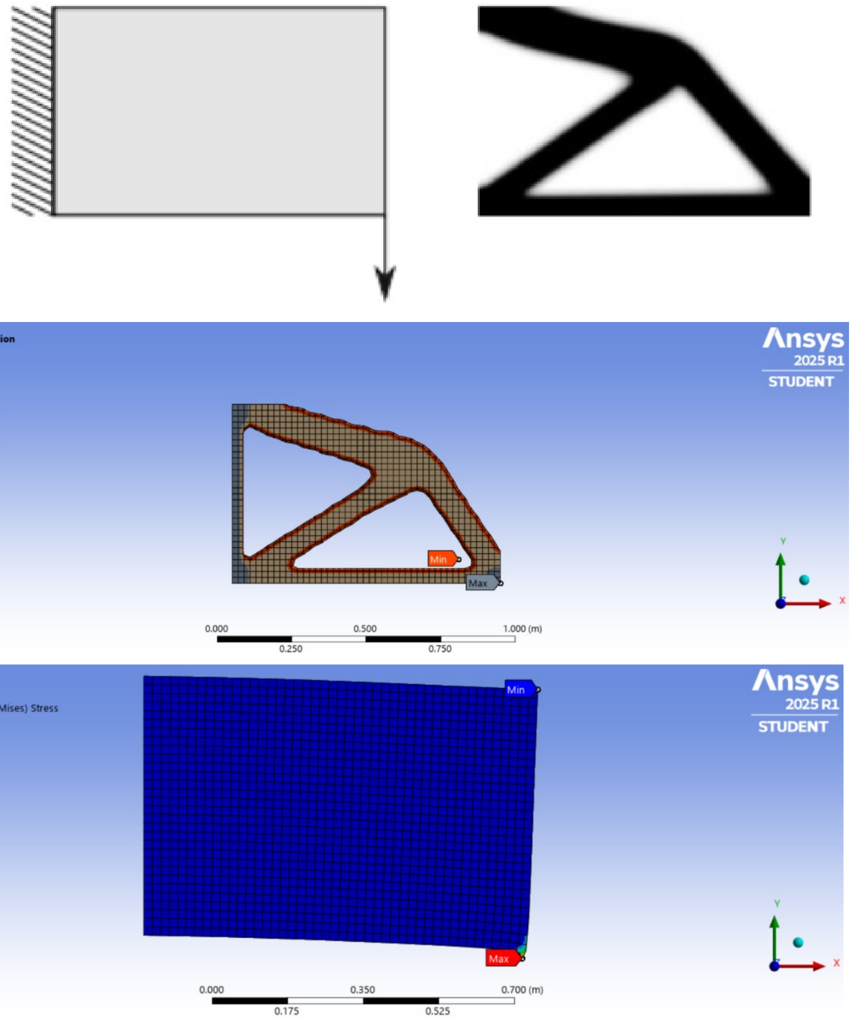

Figure 4: Cantilever Beam

Parameters	Values
Dimensions	900 X 600 mm
Material	Structural Steel
Mesh Size	20 mm
Volume Fraction	0.4
Force	1e6 N

Table 1: Parameters

2.2

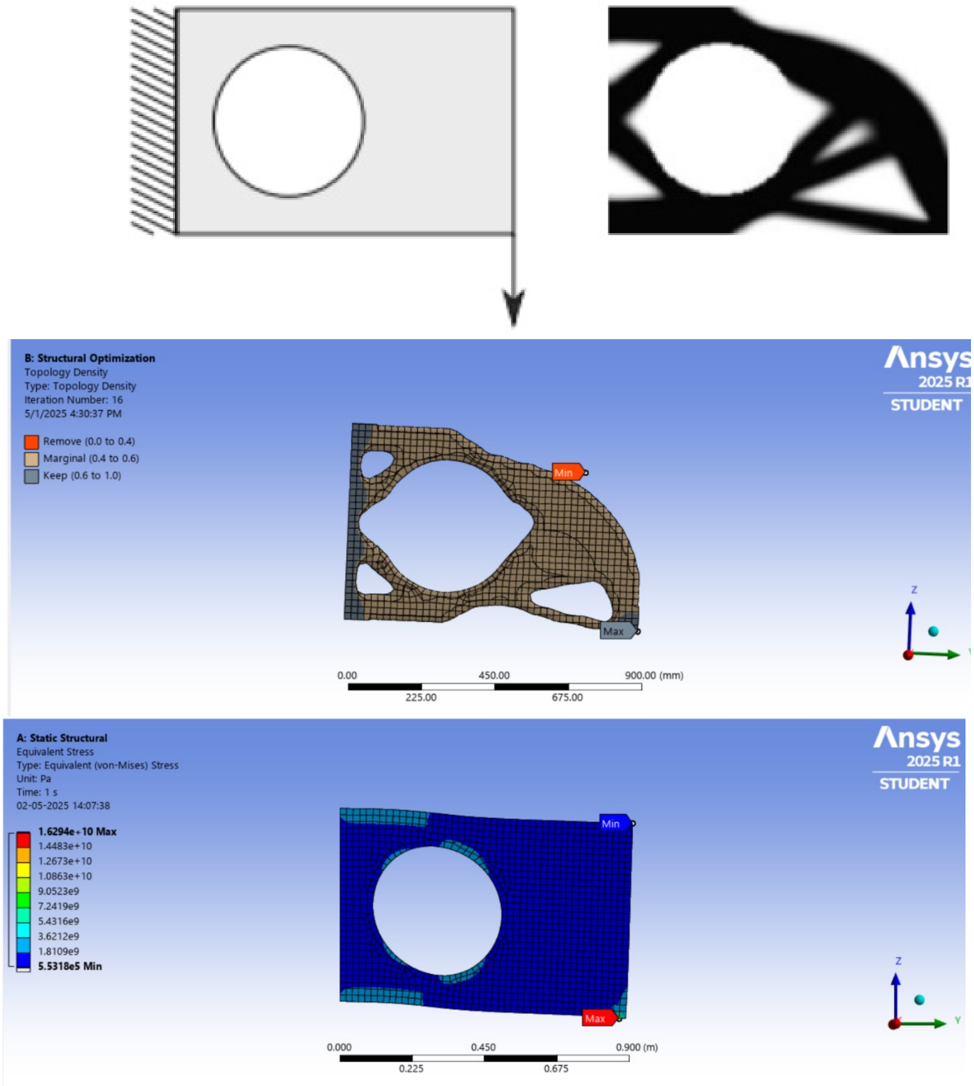

Figure 5: Cantilever Beam with Hole

Parameters	Values
Dimensions	900 X 600 mm
Material	Structural Steel
Mesh Size	20 mm
Volume Fraction	0.64
Force	1e6 N

Table 2: Parameters

2.3

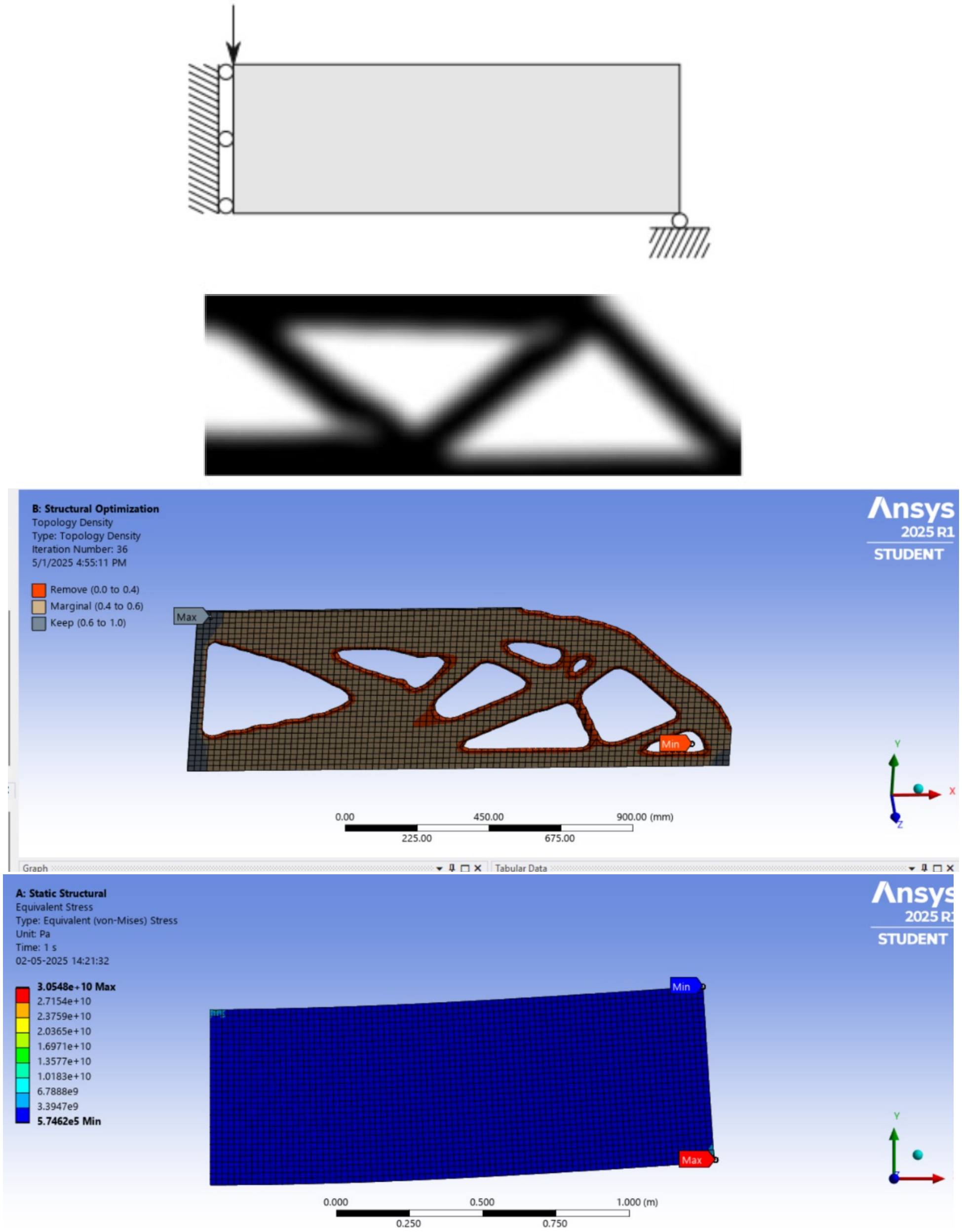

Figure 6: Messerschmitt-Bölkow-Blohm Beam

Parameters	Values
Dimensions	1700 X 600 mm
Material	Structural Steel
Mesh Size	20 mm
Volume Fraction	0.61
Force	1e6 N

Table 3: Caption

References

1 The code used to generate plots is in the zip file.

2 https://ieeexplore.ieee.org/document/8206527

3 https://www.researchgate.net/publication/326276821$_{T}opology_{o}ptimized_{d}esign_{f}abrication_{a}nd_{e}va$