

# Topology Optimization for Weight Reduction in Structural Components under Static Loading

Dr. Elena Voralova<sup>1</sup>, and Dr. Thomas H. Kreutzberg<sup>2</sup>

<sup>1,2</sup>Baltic Institute of Engineering, Estonia.

---

**Abstract**---Topological Optimization (TO) is a method for identifying the ideal configuration of a structure under certain boundaries and loading circumstances while preserving its original efficiency. Every building has a particular weight that is incorporated into the TO process. This study delineates the mathematical methodology for the TO of systems under self-weight conditions. This work examines the impact of self-weight on the topology of buildings under static loading circumstances, with a range of 200-20% of the fixed load values. The structures are meshed using quadrilateral 4-node components, and under self-weight conditions, the weight of every element is uniformly distributed to all nodes. The MATLAB implementation of the suggested mathematical method has been completed and contrasted with traditional structural issues. The penalization strategy is employed to ascertain the optimal distribution of substance and voids. The optimum criteria approach maximizes structures according to loads and boundary circumstances. Various computational instances have been examined to illustrate the impact of self-weight (SW) on static loading architectures and the ideal morphologies achieved by altering static loading with respect to SW.

**Keywords**--- Topology Optimization, Weight Reduction, Structural Components, Static Loading.

---

**Received:** 09 - 12 - 2024; **Revised:** 27 - 01 - 2025; **Accepted:** 17 - 02 - 2025; **Published:** 31 - 03 - 2025

---

## I. Introduction

Structural Topology Optimization (TO) represents a complex domain within the design of buildings (Wu et al., 2021). In recent decades, structural TO approaches have been swiftly and comprehensively developed, owing to the persistent efforts of several researchers, and they've been effectively used in various practical engineering challenges. The continuous structure's weight, mass, relocation, rigidity, speed, and stress are targets and restrictions for TO to determine the ideal structural shape. To attain these objectives, numerous methods like Solid Isotropic Materials with Punishment (SIMP) (Yarlagadda et al., 2022), Ecological Structural Optimizing (ESO) (Zhao & Zhu, 2022), Rational Approximate of Material Parameters (RAMP) (Lee et al., 2024), and Level Set Methodology (LSM) (Strömberg, 2021) have been devised.

Initial TO analyses often overlook body loads, including self-weight (SW), heat, centrifugal forces from spinning components, and inertial loads due to speed (Li et al., 2025). These density-dependent stresses are intricately linked to the efficacy of civil and aeronautical engineering uses. They assume significant responsibilities in the initial design of buildings.

## II. Background

TO is a novel domain of structural optimization that originates from the established optimality requirements for minimal-weight truss systems, particularly for disparate allowable stresses in compression and strain. Numerical TO originated from research that established an approach for calculating the optimal geographic distribution of an anisotropic substance, achieved by incorporating an infimum of frequently arranged small voids within a homogeneous, isotropic material, ensuring that the resultant structure can support specified loads while adhering to additional design criteria. This methodology was termed the SIMP method, characterized by a gray density-like interpolated functional. The traditional TO issue involves identifying the most rigid framework by reducing compliance while adhering to a material volumetric limit, as optimum layout theory describes.

In TO (Mukherjee et al., 2021), the total volume of an object's framework, loads exerted, support illnesses, and specific design constraints, such as the position and dimensions of specified holes or solid areas, are known variables. In contrast, the material's physical form, dimension, and connection remain unidentified.

The research defines the TO issue within the architectural domain  $S$ , which experiences different loads, specific boundary limitations, and SW (Zhang et al., 2021). The primary objective is to determine the optimal placement of materials within the framework to effectively transfer the load to the supports. The study provided the TO of load-bearing structures with limitations on mass phases of gravity. The ideal topology derived from the optimal criterion approach displays a distinct zigzag border form to address issues associated with methods like non-local Shepard interpolation and dynamic TO. The non-local Shepard interpolation approach treats nodal design variables as points positioned anywhere within a specified circular influence area. In contrast, the adaptable TO approach alters the mesh thickness of the structure through iterations, featuring finer components in proximity to sensitive areas.

### **III. Materials and Methods**

#### ***3.1 Material Selection***

The selected connecting rod is fabricated and employed in the second version of the fracture-split materials. The current technique used in the production of connecting rods involves producing the element as a single entity, which is then divided into two parts at the crank side. The weight of the first linking rod, determined by the chosen material, was 650 g. The primary constituents of this low-alloy steel are chromium and vanadium, which enhance its resilience to endure compression, tensile, and bending stresses. Additional components such as carbon, silicon, sulfate, phosphate, and chromium are in minor amounts.

#### ***Design of Engine Elements***

Additional engine elements were engineered to provide low speeds and high acceleration, predicated on the following expected variables: 4-cylinder linear engine with a cylinder diameter of 81 mm and a stroke width of 82.25 mm, capable of operating at a maximum velocity of 1000 rpm.

#### ***Assembling of Engine Elements***

The system was exclusively developed for motion research and kinematic evaluation, minimizing components to four primary elements: the crankshaft, pistons, linking rod, and cylinder liners, while excluding smaller components such as piston rings and bushings. The accuracy of the other components was deprioritized, and the pieces were engineered for a snug fit only to assess the dynamics of unknown response events and forces affecting the linkage rods. The system was constructed with revolving, static, and translating joints. The assembled design has been exported from Inventor for interoperability with ANSYS Exploration and Workbench.

### 3.2 Methodology

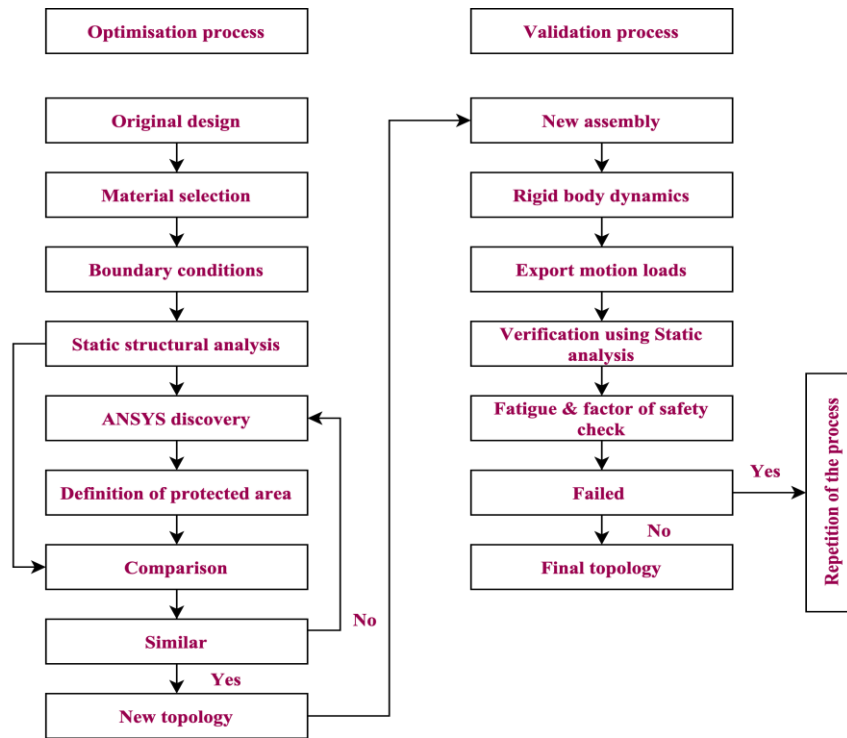


Figure 1: TO & verification process

This research used the finite element approach, multibody motion, and TO with ANSYS. The procedure was executed for many percentages using a trial-and-error approach to ascertain the minimal von Mises stress, and the findings were validated for durability under dynamic settings. The whole management, from the connection rod through static structural evaluation to the confirmation of topologies in multibody motion, is portrayed in Figure. 1.

### 3.3 Static Structural Topology

It was conducted in ANSYS workspace, and engineering information was included in the material database. The first linkage rod's Computer-Aided Design (CAD) file was loaded into the ANSYS system. The study delineates the boundary constraints and mesh characteristics of the static analysis method utilized for the preliminary design of the linkage rod. Mesh characteristics are crucial in structural evaluation, since increased mesh resolution produces more precise simulation outcomes. The large end of the linkage rod was constrained, while a force of 64500 N was exerted on the small side.

Determination of the force exerted on the piston due to combustion (fc). The highest peak stress for engines with gasoline ranges from 70 bar to 140 bar. The large end of the linkage rod was established as fixed, and a combustion pressure of 65500 N was immediately delivered to the cylinder and transmitted to the small portion of the linkage rod. Upon the application of ignition pressure to the smaller end of the linking rod, a buckle load was exerted on the shanks, resulting in compressive stresses that have induced bends or distortion.

Meshing was executed, generating 302500 nodes and 209500 components, with an accuracy of 5, a gradual transition, and a precise span angle center. Upon generating the mesh, the requirements for loading were implemented according to the highest pressure. According to the limiting illnesses, the most significant stress that von Mises recorded was  $5.97 \times 108$  Pa, and the highest von Mises stretch was 0.0029.

## IV. Results and Findings

### 4.1. Model 1: Brief Cantilever Beam

A cantilever beam with a thickness of 1 mm is examined in this instance. The cantilever is subjected to plane strain and bears an intense load at the bottom right quadrant. The left-hand border is secured. The structure is meshed with 32 elements in the x-direction and 20 components in the y-direction. The physical properties of

the structural material designated for distribution in the domain are a Young's modulus of  $1 \text{ N/m}^2$  and a Poisson's ratio of 0.3. The fractional volume limitation is established at 0.4, and the penalty ratio  $p$  has been adjusted to 3. The meshing utilizes a 4-node quadrilateral component with an edge length of 0.1 for each side. To confirm the optimum criteria, the procedure for the cantilever beam's performance under static stress is contrasted with the results obtained from the combination of simulated heating and the SIMP method. The ideal configuration of the cantilever structure has been derived using MATLAB-based optimization criteria. The optimum topologies derived using MATLAB-based optimal management techniques are almost identical.

After topographical improvement using MATLAB's optimum criteria, the ultimate compliance number is 59.50 N m after 71 repetitions. In contrast, the method provides values of 54.42 N m and 54.28 N m. The convergence criterion of 0.01 is specified in the MATLAB-based technique. The mesh density is consistent across all approaches. The result above indicates that the MATLAB-based approach is successful for topological improvement.

#### 4.2. Type 2: Messerschmitt-Bolkow-Blohm (MBB) Beams

The beam is subjected to plane stress and has a width of 1 mm. The beam is engineered for minimal resistance. MBB Beams subjected to plane stress conditions, including limits at the bottom left corners in both axes and a restriction at the top right corner along the  $y$ -direction. A point load is exerted at the center of the top edge. The framework is meshed with eighty components in the  $x$ -direction and 20 in the  $y$ -direction. The mechanical characteristics of the structural material designated for distribution within the realm are listed below: Young's modulus is  $2.1 \times 10^9 \text{ N/m}^2$ , Poisson's ratio is 0.3, the constrained volume percentage is 0.5, and the penalty component  $p$  is 3. The results indicate that topology variations occur as the magnitude of the point load diminishes. At the same time, the MBB beams are subjected to both point load and SW. The conformity value for a fixed load of 210% of the SW is  $1400.8 \text{ N/m}^2$ , while the standard deviation for the SW alone is  $131.2 \text{ N/m}^2$ .

## V. Conclusion

This study applies an optimum criteria technique for the TO of linear elastic isotropic structures under static and SW loading conditions. The outcome of static stress on the cantilever structure has been juxtaposed with the results derived from integrating simulated heating and the SIMP methodology. An algorithm addressing the impact of a structure's SW under static loads has been introduced, and various resultant topologies have been illustrated. These findings demonstrate that SW substantially influences optimal layout. When both SW and the load being applied are concurrently evaluated, the building's structure is contingent upon how much load is placed relative to the SW. Therefore, the framework's SW must be considered in topological planning. TO is the first phase of structural improvement; hence, the planar stress constructions are suitable for form and size improvement. In form optimizing, the layout factors are the positions of the nodes, but in size optimization, they pertain to any dimension. The goal variable in both instances is the framework's size. A substance optimization process will be investigated for future study.

## References

- [1] Wu, J., Sigmund, O., & Groen, J. P. (2021). Topology optimization of multi-scale structures: a review. *Structural and Multidisciplinary Optimization*, 63, 1455-1480. <https://doi.org/10.1007/s00158-021-02881-8>
- [2] Yarlagadda, T., Zhang, Z., Jiang, L., Bhargava, P., & Usmani, A. (2022). Solid isotropic material with thickness penalization-A 2.5 D method for structural topology optimization. *Computers & Structures*, 270, 106857. <https://doi.org/10.1016/j.compstruc.2022.106857>
- [3] Zhao, J., & Zhu, Q. (2022). China's Energy Structure Optimization Based on Data Mining from the Perspective of Circular Economy: Take Qujing City as an Example. *Mobile Information Systems*, 2022(1), 7905576. <https://doi.org/10.1155/2022/7905576>
- [4] Lee, S., Oh, M. K., Kim, C., Jung, M., & Yoo, J. (2024). Multi-scale design of composite material structures for maximizing fundamental natural frequency. *Computer Methods in Applied Mechanics and Engineering*, 425, 116928. <https://doi.org/10.1016/j.cma.2024.116928>
- [5] Strömberg, N. (2021). Optimal grading of TPMS-based lattice structures with transversely isotropic elastic bulk properties. *Engineering Optimization*, 53(11), 1871-1883. <https://doi.org/10.1080/0305215X.2020.1837790>

- [6] Li, Z., Xu, H., Zhang, S., Cui, J., & Liu, X. (2025). Multi-Material Structures Topology Optimization for Thin-Walled Tube Used by Vehicles Under Static Load: A Review. *Archives of Computational Methods in Engineering*, 1-41. <https://doi.org/10.1007/s11831-025-10285-w>
- [7] Mukherjee, S., Lu, D., Raghavan, B., Breitkopf, P., Dutta, S., Xiao, M., & Zhang, W. (2021). Accelerating large-scale topology optimization: state-of-the-art and challenges. *Archives of Computational Methods in Engineering*, 1-23. <https://doi.org/10.1007/s11831-021-09544-3>
- [8] Zhang, S., Li, H., & Huang, Y. (2021). An improved multi-objective topology optimization model based on SIMP method for continuum structures including self-weight. *Structural and Multidisciplinary Optimization*, 63, 211-230, <https://doi.org/10.1007/s00158-020-02685-2>.