Proceedings of the Eighteenth International Conference on
Civil, Structural and Environmental Engineering Computing
Edited by: P. Iványi, J. Kruis and B.H.V. Topping
Civil-Comp Conferences, Volume 10, Paper 3.6
Civil-Comp Press, Edinburgh, United Kingdom, 2025
ISSN: 2753-3239, doi: 10.4203/ccc.10.3.6

A Novel Design and Optimization Scheme for Components with Heterogeneous Lattice Infill

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Abstract

This paper introduces a novel methodology for designing optimized components with lattice structure infill. The lattice unit cells are generated through an algorithm that enables continuous variations in topology, and are thoroughly characterized using a numerical implementation of Asymptotic Homogenization. The resulting effective material properties and their gradients are interpolated to create geometry-dependent scaling functions, enabling efficient use of gradient-based optimization schemes. The approach is both fast and robust, capable of handling complex 3D structural problems with high computational efficiency. Thanks to specific features of the unit cell generation algorithm, the resulting heterogeneous lattices are inherently printable, making the method particularly suited for real-world additive manufacturing applications.

Keywords: printable heterogeneous lattices, design algorithm, asymptotic homogenization, architected materials, metamaterials, additive manufacturing

1 Introduction

Additive Manufacturing (AM) has enabled the fabrication of components with intricate geometries and high complexity, spurring growing interest in the use of lattice structures as advanced construction materials [1, 2]. A key advantage of lattice structures lies in the ability to tailor the material composition and geometry of their unit cells (UCs), allowing for optimization of their properties to meet specific performance requirements. Graded Lattice Structures (GLS), in particular, offer enhanced performance by enabling spatial variation of the unit cell within the lattice domain [3–6], resulting in a heterogeneous and performance-optimized structure.

Various approaches for the optimization of these lattice structures are currently available; however, gradient-based approaches are the forerunners for convergence speed and accuracy, especially when dealing with high-resolution designs and large-scale problems. These methods rely on the sensitivity of the objective function with respect to the design variables, enabling efficient navigation of the design space [7, 8]. When applied to GLS, gradient-based optimization can handle the continuous variation of geometrical and material parameters across the domain, allowing for fine-tuned control over the spatial distribution of mechanical properties. One prominent challenge in optimizing GLS lies in the multiscale nature of the problem: the macroscopic performance of the structure is influenced by microscopic design parameters such as unit cell topology, size, and orientation. This has motivated the development of multiscale optimization frameworks, where the macroscale behavior is informed by homogenized properties computed from microscale simulations [9, 10]. These frameworks are essential for capturing the complex interactions between scale levels, ensuring that the optimized designs are both feasible and manufacturable. In this context, the present work introduces an automated pipeline for the design and optimization of 3D graded lattice structures tailored for Additive Manufacturing. The proposed methodology combines parametric unit cell modeling, multiscale finite element analysis for the characterization of the homogenized geometry-dependent material properties, and gradient-based optimization driven by adjoint methods [11]. Special attention is given to ensuring compatibility with AM constraints, enabling the generation of designs that are not only optimal in performance but also feasible for fabrication.

2 Methods

In a previous work (currently under review), the authors proposed a novel algorithm for generating cubic-symmetric unit cells composed of truss elements. The topology of the truss, i.e., the interconnection pattern of the elements, is continuously tunable through two geometric parameters, denoted as a_1 and a_2. The radius of the beams is governed by the volume fraction V_f. This algorithm enables a smooth spatial variation of the unit cell topology while preserving connectivity between adjacent cells, effectively avoiding disconnected beam ends. As a result, it guarantees the printability of the lattice structure, even in the presence of topological heterogeneity. The algorithm is capable of generating three distinct classes of geometries. Within each class, interconnectivity is ensured by the presence of fixed points located at the unit cell boundaries, allowing seamless connection between adjacent cells. The unit cell geometries are defined as $\mathbf{C}\boldsymbol{\alpha} - \boldsymbol{\beta} - \boldsymbol{\gamma}$, where α identifies the initial starting point V_i and it gives the class number; β and γ are the endpoint coordinates a_1 and a_2 expressed in percentage terms. Samples from the three proposed classes are visually shown in Figs. 1- 2- 3.

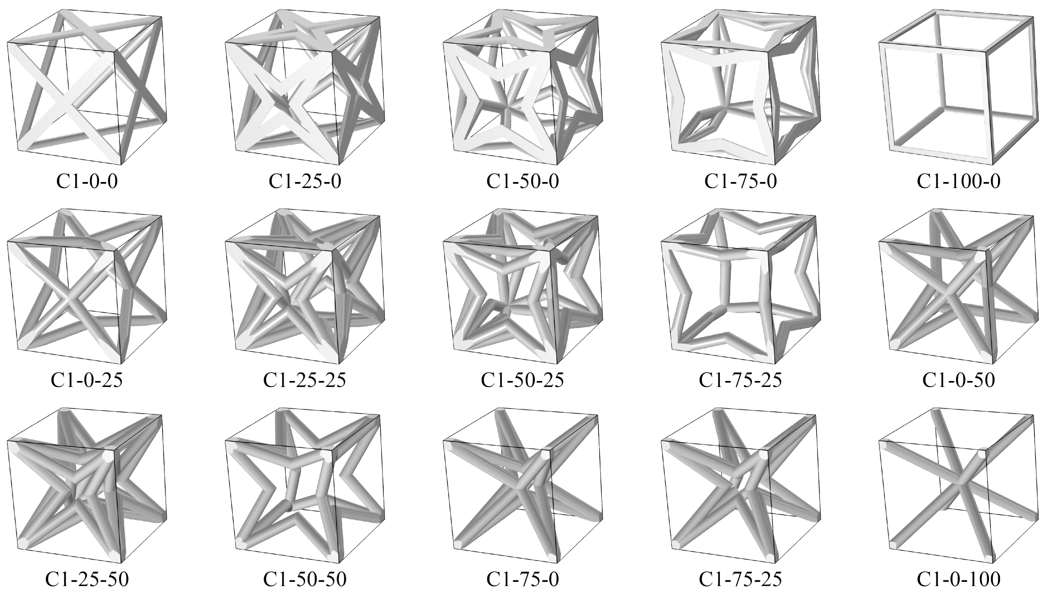


Figure 1: Sample of geometries from the first class **C1**.

Fig. 4- 6 shows the CAD renderings and the corresponding printed parts for a test component. The parts were printed without internal supports, allowing the inner lattice structure to serve as the infill for shelled components.

The sampled unit cell geometries are characterized through a numerical implementation of the Asymptotic Homogenization Method (AHM), which enables the computation of their effective macroscopic material properties. These include, in particular, the homogenized stiffness tensor and the linear thermal conductivity tensor. The computed values are employed in a linearized interpolation scheme to define the geometry-

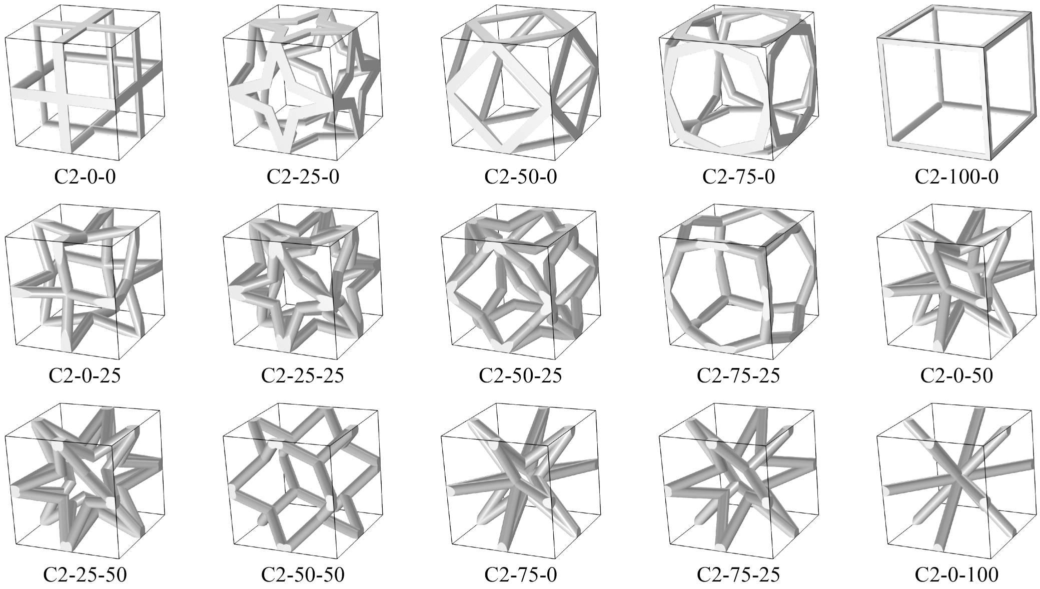


Figure 2: Sample of geometries from the second class **C2**.

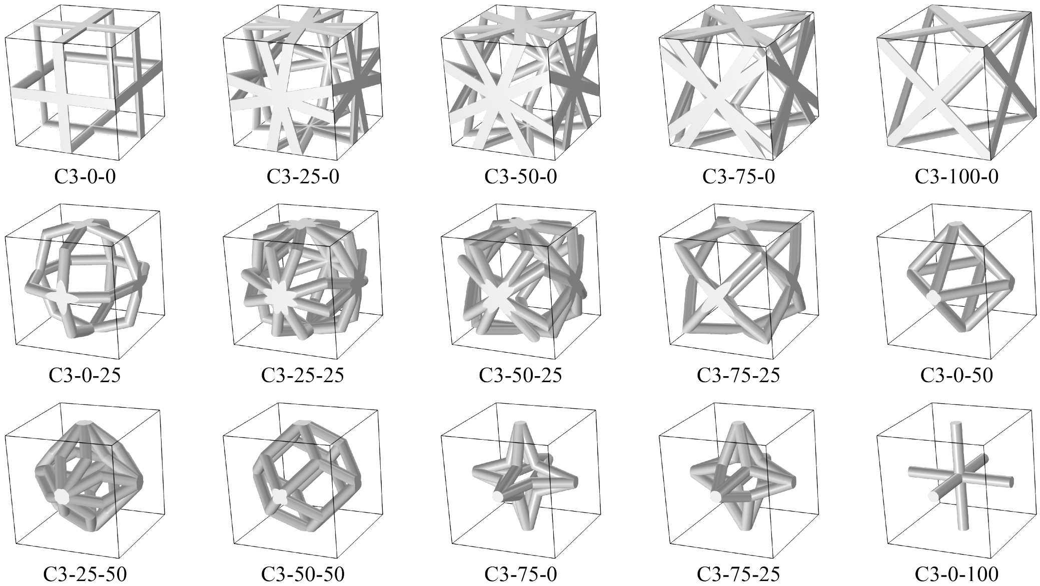
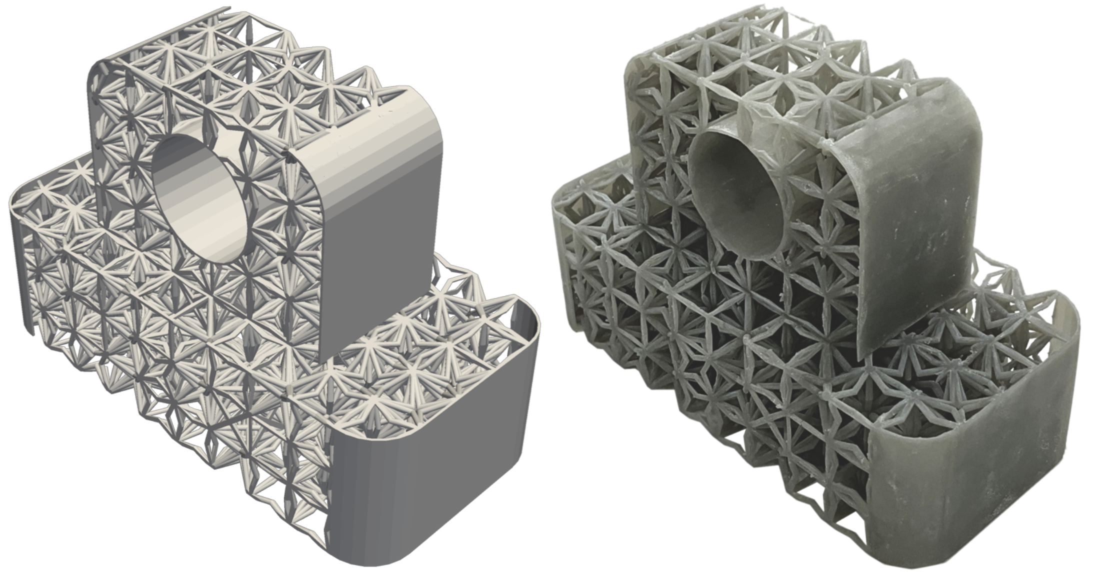


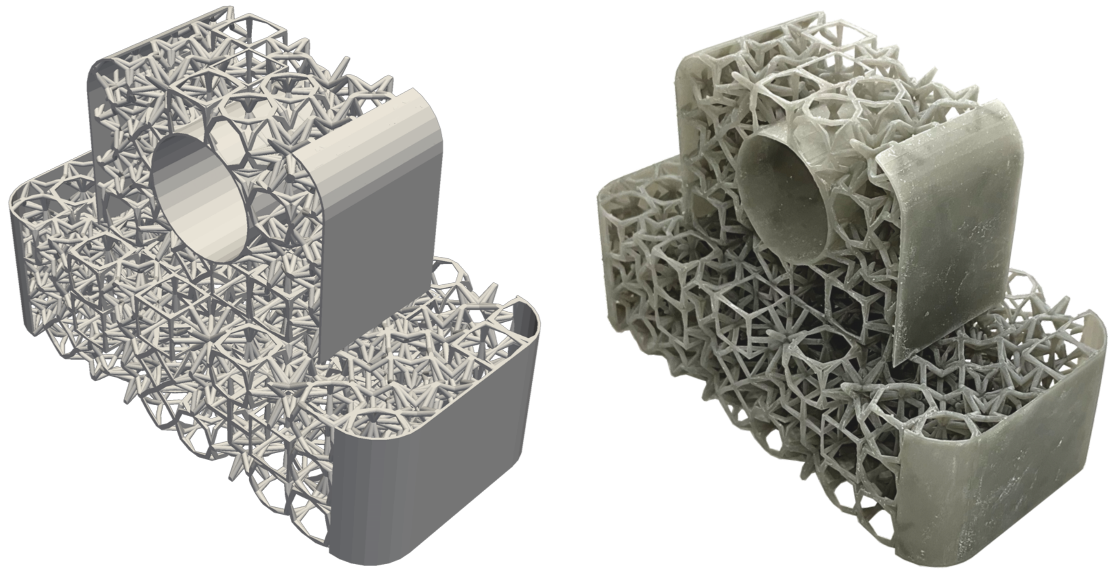
Figure 3: Sample of geometries from the third class **C3**.

dependent material properties and their gradients with respect to the design parameters. This continuous representation of the effective material behavior forms the basis for the finite element analysis (FEM) of the graded structure, enabling simulations of both mechanical and thermal responses at a reduced computational cost. PDE-constrained optimization schemes can be employed to maximize the performance of real-world components through numerical simulations that operate on a homogenized representation of the material, without explicitly modeling the microstructure. The availability of gradient information enables the use of efficient gradient-based opti-



a) b)

Figure 4: Class 1 random topology cells: a) CAD render b) corresponding printed part



a) b)

Figure 5: Class 2 random topology cells: a) CAD render b) corresponding printed part

mization methods to identify optimal configurations within the design space. The classical approach to lattice optimization relies on the definition of continuous spatial fields for the design variables. As a result, the number of optimization degrees of freedom corresponds to the number of physical degrees of freedom, typically associ-

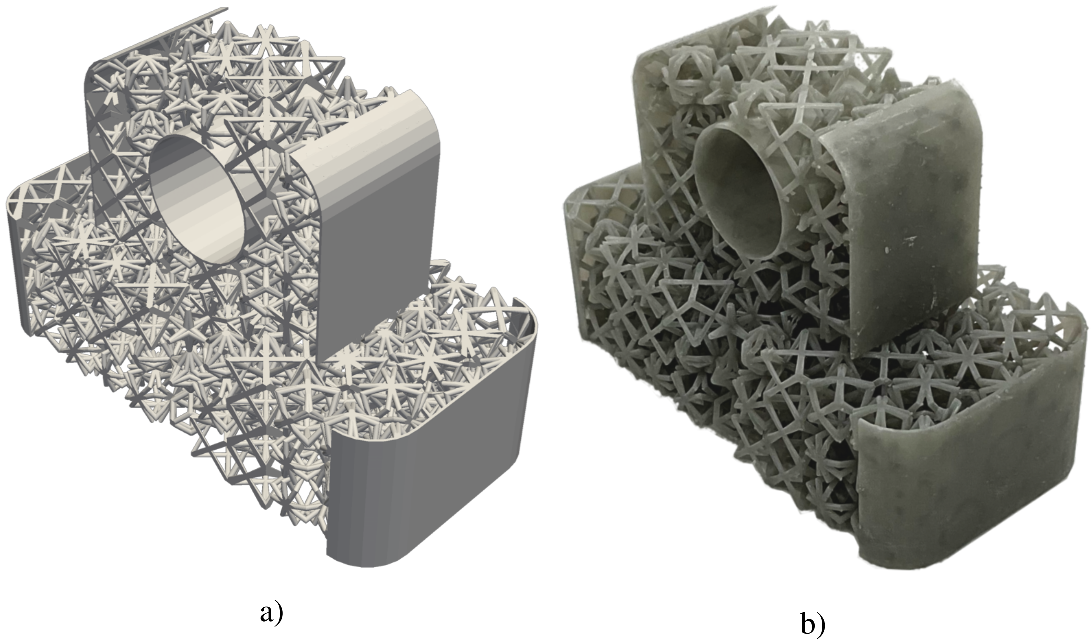


Figure 6: Class 3 random topology cells: a) CAD render b) corresponding printed part

ated with the mesh nodes. To mitigate numerical artifacts such as checkerboarding, a smoothing or regularization phase is often introduced. After the optimization process, the resulting geometric field is sampled and filtered to extract manufacturable unit cell parameters. However, in this workflow, constraints related to unit cell size and manufacturing feasibility are not directly incorporated into the optimization process, but rather addressed in a post-processing step. We present here a novel optimization scheme that defines the optimization degrees of freedom (DOFs) to be proportional to the number of lattice cells rather than the number of mesh nodes. This significantly reduces the dimensionality of the optimization problem, leading to improved computational efficiency and scalability, particularly for large-scale three-dimensional components. The material property fields are modeled as piecewise-continuous functions across the component, with each subregion corresponding to an individual lattice cell. This discretization naturally aligns with the physical structure of the lattice, allowing for a direct and interpretable mapping between optimization variables and the final fabricated geometry. Furthermore, manufacturability constraints — such as minimum feature size, printable beam radii, or maximum allowable gradients — are embedded directly into the optimization process via filtering strategies. Specifically, we employ Heaviside-type projection filters to encode manufacturing limits into the interpolated material properties. In this way, geometric and process constraints, such as cell size and printable range of design parameters, are not handled as post-processing adjustments but are instead integrated into the optimization loop. These constraints effectively become meta-parameters that shape the design space and influence the final structure, ensuring both performance and printability of the resulting lattice.

3 Results

We apply the design and optimization framework on a test case, chosen for its complex geometry and challenging load conditions. The model, shown in black in Fig. 7, functions as a connection flange for rods or beams.

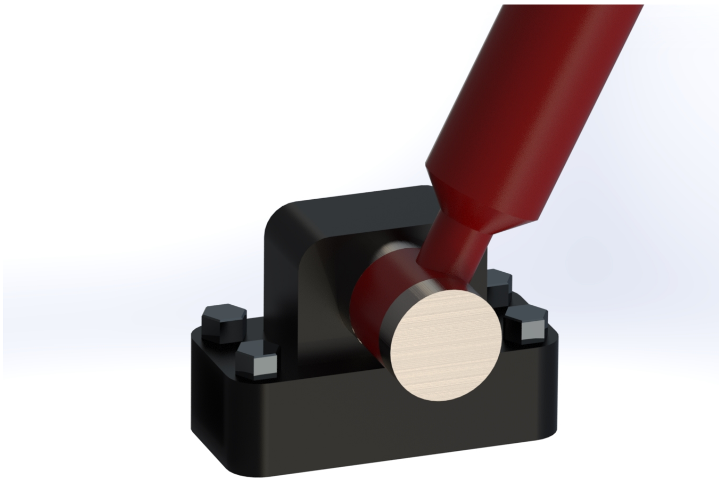
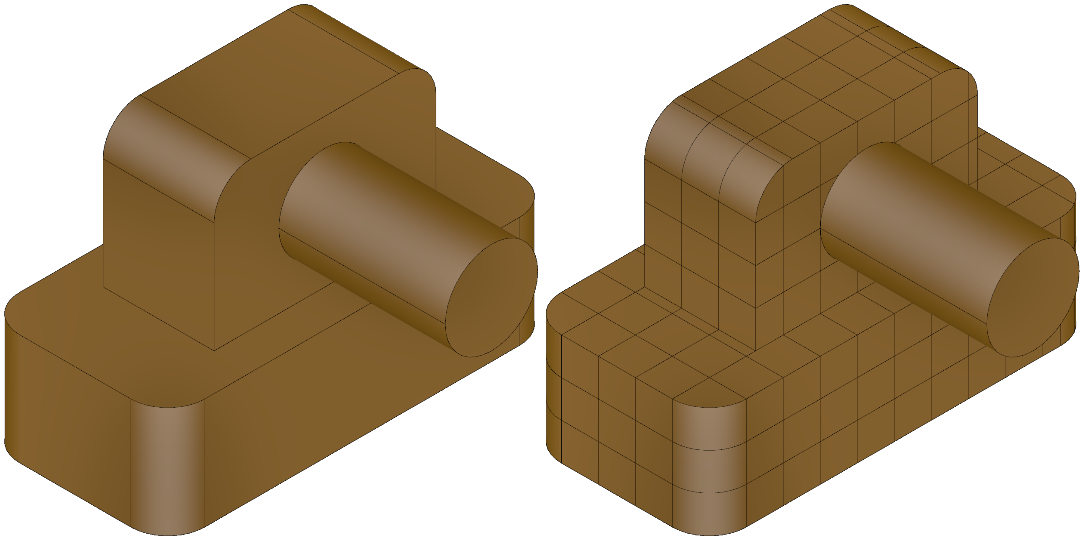


Figure 7: Rendering of the model case study.

The CAD model is shown in Fig. 8. The rod connector is modeled as a rigid cylindrical beam, with a force of $F = 1N$ applied to its top face in the direction $(-1, -1, -1)$. This load condition is intentionally chosen to induce a complex stress distribution within the lattice domain. The rigid condition on the rod is approximated by setting its Young's modulus to be 10^3 higher than the lattice's bulk material. The bottom surface of the model is fixed in any movement. Fig. 8-b illustrates the lattice structure of the model, composed of cubic cells, forming a lattice with at least three cells in each direction. Slicing the CAD model is essential to ensure that the meshing software conforms the tetrahedral elements to the lattice structure, preventing elements from crossing cell surfaces. This is necessary in order to represent the constant topology fields in each cell. The mesh of the model is visible in Fig. 9.

In our optimization framework, the objective is to minimize the tip vertical displacement of a rigid rod subjected to external loading, while enforcing a constraint that limits the total mass of the lattice structure to 30% of that of the equivalent fully solid component. Sensitivity analysis is performed using the adjoint method, which provides efficient gradient evaluations with respect to the design variables. The optimization problem is solved using a Sequential Quadratic Programming (SQP) algorithm with a BFGS approximation of the Hessian, enabling robust and efficient convergence toward locally optimal designs. In this example, manufacturability constraints



a) b)

Figure 8: CAD model: a) unsliced b) sliced

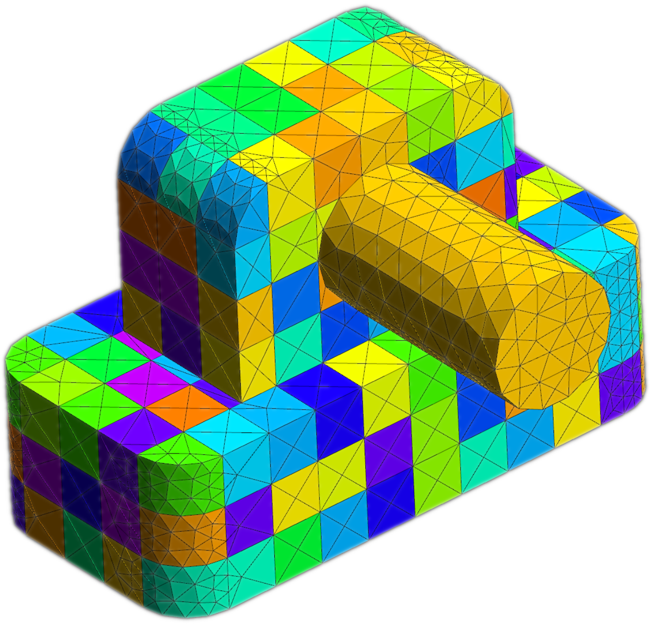


Figure 9: Mesh of the model.

are explicitly enforced by imposing a lower bound of 20% on the volume fraction. This ensures that all structural members maintain a minimum cross-sectional thickness compatible with typical additive manufacturing capabilities. While this threshold provides a practical guideline, the precise values for manufacturability limits are highly case-dependent and require detailed knowledge of the specific tolerances, resolution, and material behavior associated with the selected additive manufacturing process and equipment. Fig. 10 shows the optimization history for the minimization of the z component of the displacement of the beam. The optimization exhibits a monotonic decrease in the objective function and reaches convergence in fewer than 50 iterations, starting from a randomly initialized design.

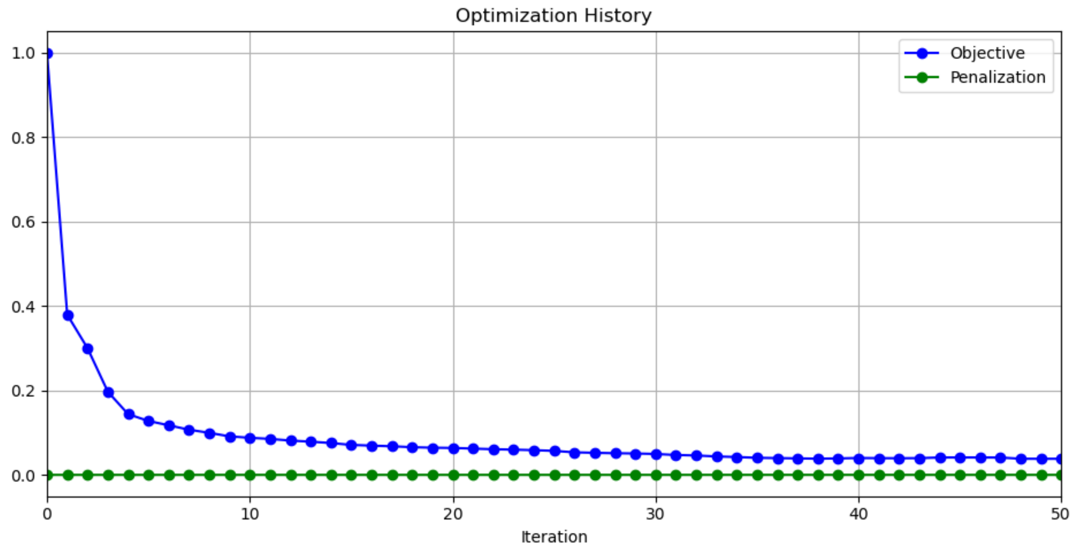


Figure 10: History of objective minimization.

After optimization, the z displacement is reduced by 96% while the total mass of the lattice remains strictly below the prescribed volume constraint throughout the entire optimization process, indicating consistent and active enforcement of the mass limitation. These results highlight not only the effectiveness of the proposed method in satisfying both performance and resource constraints but also its potential applicability to the design of compliant mechanisms, where targeted displacements and material efficiency are critical. Fig. 11-13 shows the design variable distribution inside the component, showcasing the null z displacement achieved by heterogeneity of the topology.

4 Conclusions & Contributions

This work introduces a computational framework for the optimization of three-dimensional graded lattice structures with direct applicability to additive manufacturing. By employing a multiscale modeling strategy based on asymptotic homogenization, the method enables accurate and efficient analysis of structures composed of parametrized unit cells without requiring explicit microstructural resolution in the finite element mesh. Unlike classical topology optimization approaches that rely on continuous design fields defined over the entire mesh, our method defines optimization variables at the scale of the lattice cells. This significantly reduces the dimensionality of the design space, resulting in faster convergence and lower computational cost. Gradient-based optimization is performed using adjoint sensitivity analysis and a quasi-Newton solver

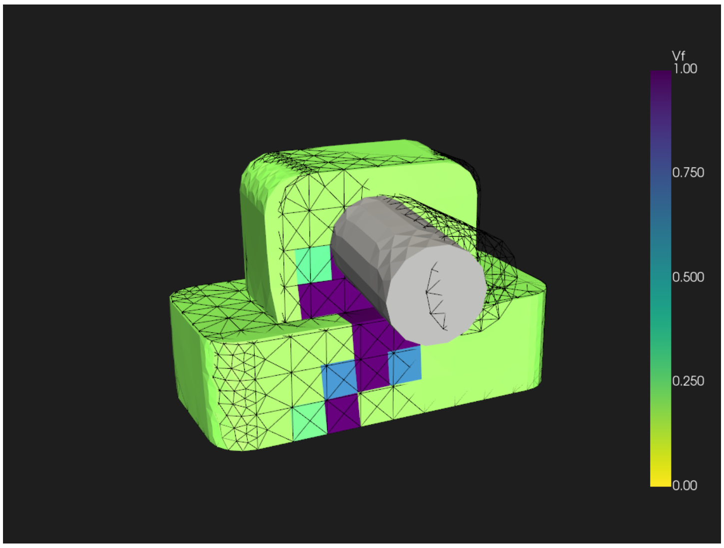


Figure 11: Optimized V_f distribution.

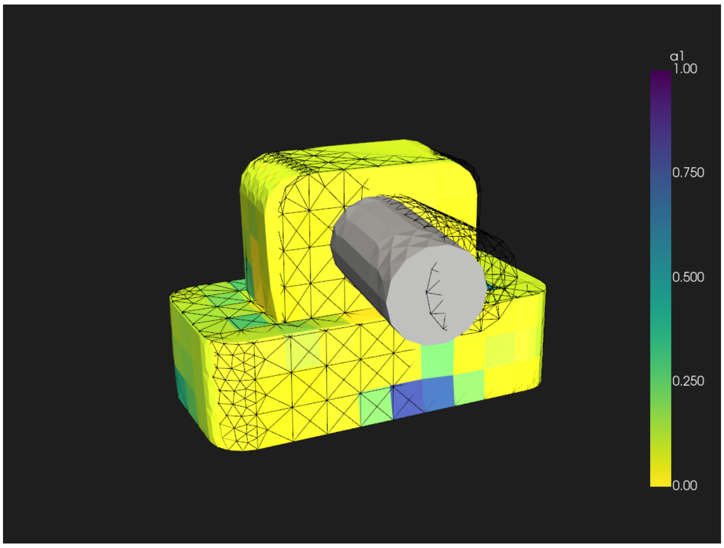


Figure 12: Optimized a_1 distribution.

with BFGS updates, demonstrating rapid and robust convergence from randomly initialized designs. The framework ensures that all optimized designs are manufacturable by construction, as the geometry is always mapped to physically manufacturable unit cell configurations. This makes the proposed approach particularly well-suited for integration into industrial additive manufacturing pipelines. Numerical results demonstrate substantial performance improvements under mechanical loading, with strict enforcement of mass constraints and convergence achieved in under 50 iterations. Overall, the proposed methodology provides a practical and efficient tool for the design of functionally graded lattice materials, balancing mechanical performance with manufacturability constraints and computational cost.

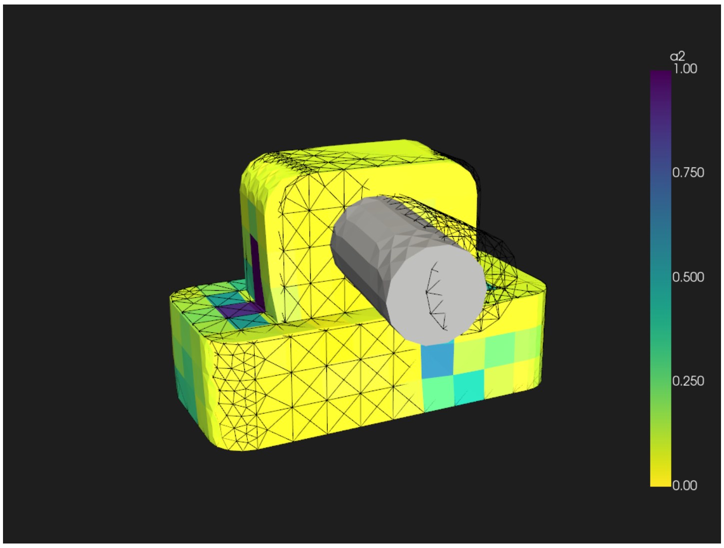


Figure 13: Optimized a_2 distribution.

Acknowledgements

This work has been supported by European Union - Next Generation EU , by MIUR , project: PNRR - CN1- Spoke 6 (CUP: B83C22002940006).

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