Lattice Structures Design Based on Topology Optimization: Modeling, Additive Manufacturing and Experimental Analysis

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Abstract. Materials made with architected microstructures present tunable mechanical properties and can be used to obtain lightweight structures and, at the same time, with high strength. In lattice structures, for example, topology and truss diameter can be varied so that the material is efficiently distributed in the design domain. Due to the complex geometries of these structures, designing them using computer-aided design tools is a challenging task.

In this work, a parametric modeling was developed in the Rhinoceros program using the Grasshopper extension to assist in the construction of models of lattice structures with varying truss diameters. The developed parametric modeling allows defining the topology and the diameter of the truss bars, which greatly simplifies the generation of models of porous solids. Microstructure models were generated and manufactured in polyamide 12 through selective laser sintering to assess whether it is feasible to print the trusses from the established parameters. The problem of a simply supported beam with a concentrated load at the center was solved using the topology optimization method and the density field was used to generate the variable density models.

Both regular and variable density beam models have been designed to have the same mass and additively manufactured with the use of the selective laser sintering technique. Experimental analyzes were carried out using three-point bending tests and the results show that the solution using variable density has a large increase in stiffness when compared to solutions with uniform density.

Keywords: Lattice structures, topological optimization, additive manufacturing, SLS printing

1 Introduction

In recent years, the design and fabrication of lightweight, high-performance structures with intricate geometries and Industry 4.0 processes have garnered significant attention across industries [1], including aerospace, automotive [2], biomedical [3], and civil engineering. To meet the demands of these sectors, researchers and engineers have increasingly focused on lattice structures, which exhibit complex network-like patterns.

Lattice structures offer numerous advantages over traditional solid materials, such as superior mechanical properties, exceptional energy absorption capabilities, and substantial weight reduction [4]. These properties make them highly desirable for applications where strength-to-weight ratio, stiffness, and resilience are crucial factors. Additionally, lattice structures demonstrate excellent material efficiency by utilizing materials only where necessary, resulting in minimal waste.

To fully exploit the potential of lattice structures, a systematic approach encompassing design and fabrication is imperative. Topology optimization has emerged as a powerful technique for developing lattice structures that are optimized for specific performance criteria [5]. By employing advanced mathematical algorithms, topology optimization identifies the ideal distribution of materials within a designated design space, yielding structures with exceptional mechanical properties.

In this article, we delve into the interdisciplinary domain of lattice structure design, incorporating topology optimization, additive manufacturing, and experimental analysis. We explore the underlying principles and methodologies of topology optimization algorithms, discussing their pivotal role in creating efficient and high-performing lattice structures. Moreover, we investigate various cutting-edge additive manufacturing techniques employed for fabricating lattice structures, elucidating their advantages and limitations [6].

Furthermore, we delve into the experimental analysis of lattice structures, encompassing mechanical testing, characterization, and performance validation [6]. We explore how experimental findings contribute to refining the design process and bridging the gap between theoretical optimization and practical implementation.

By comprehensively addressing the modeling, additive manufacturing, and experimental analysis aspects of lattice structures, this article aims to provide a comprehensive understanding of the design process. We underscore the potential of this emerging field to revolutionize industries reliant on lightweight and robust structures [7]. Through this exploration, we aim to inspire further research and development in the realm of lattice structures, fostering innovation and unlocking new possibilities across various engineering dies.

The primary aim of this article is to establish three-dimensional models of cellular structures composed of a variable-density lattice network, achieved through topological optimization [8], to be fabricated using additive manufacturing via selective laser sintering. The study encompasses the accomplishment of the following specific objectives:

- Development of a programming algorithm capable of generating the desired three-dimensional models based on specified truss configurations;
- Feasibility assessment of the lattice fabrication process within the additive manufacturing methodology;
- Characterization of the mechanical properties of the PA2200 material, intended for deployment in the 3D printing process;
- Experimental analysis of the cellular structures formed by the lattice network through the implementation of the three-point bending test.

2 Proposed Work

The concept of structural optimization is a fundamental engineering pursuit with the primary objective of enhancing the efficiency and quality of various structures while taking into consideration the intricate web of production constraints and conditions. This optimization process seeks to achieve significant improvements in the performance of engineered systems, leading to the development of lightweight and yet robust models. As postulated by Bendsøe and Sigmund [9], optimization embodies a sophisticated computational method that empowers engineers to explore and derive optimal topologies within the design space, fostering innovation and efficiency in engineering design.

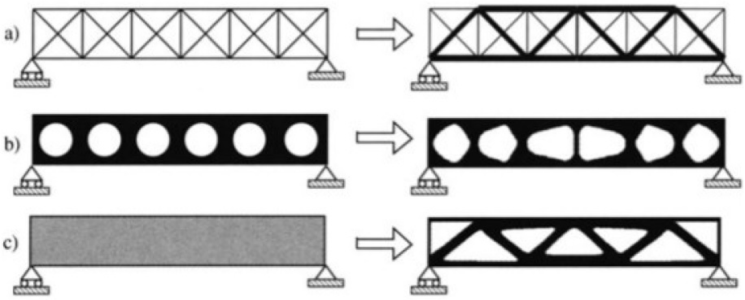


Figure 1. Types of Optimization (a) Parametric Optimization. (b) Shape Optimization. (c) Topological Optimization.

Broadly speaking, structural optimization can be categorized into three distinctive approaches (see Figure 1), each serving specific objectives and design requirements:

- Parametric Optimization: The parametric optimization approach aims to fine-tune the dimensions of individual components in the design, based on well-defined and predetermined objectives set by the designer;
- Shape Optimization: In contrast to parametric optimization, the shape optimization approach focuses on reshaping the structural contours of a given component to achieve an optimal design;
- Topological Optimization: Topological optimization represents a more radical approach, enabling engineers to redefine the overall layout and distribution of material within the design domain.

The pursuit of these three optimization approaches empowers engineers to push the boundaries of traditional design paradigms, enabling the development of structures that deliver superior performance while adhering to stringent manufacturing constraints. As the field of structural optimization continues to evolve and synergize with advancements in computational power and optimization algorithms, engineers can look forward to unleashing a new era of innovative, lightweight, and resilient engineering solutions across diverse industries and applications.

2.1 Lattice Structures and Optimization

Cellular structures, represented by lattices, have been studied in various fields to provide solutions for the medical, automotive and aeronautical industries. The first structures were based on the crystal structures of metals, such as CCC (cubic body centered), CFC (cubic face centered) and HC (compact hexagonal)(Figure 2) [10].

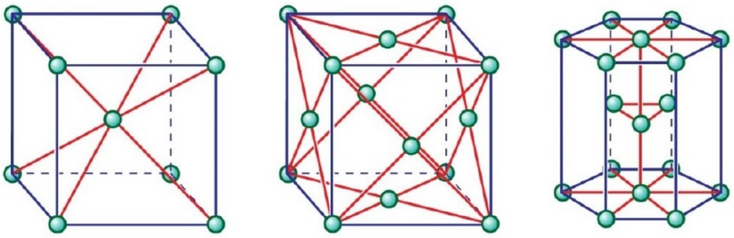


Figure 2. crystal structures (a) CCC (b) CFC (c) HC [11]

The optimization using a single structure consists in varying parameters such as diameter, thickness and cell size using only one type of lattice structure to compose the specimen. The aim of this optimization is to increase or decrease the size of the microstructure, ensuring a load distribution and optimizing the total mass of the parts [12]. These microstructures have been widely used in recent years, due to DMLS and SLS technology, making an analogy to the grain size of a structure and its influence on the mechanical behavior of materials.

Another type of optimization is the use of multiple cellular truss structures to maintain or increase certain mechanical characteristics. It is very advantageous, because each structure has a certain mechanical property, so varying different microstructures according to the loading requirements of the part can improve the mechanical performance of the part, as presented in [13] (see Figure 3).

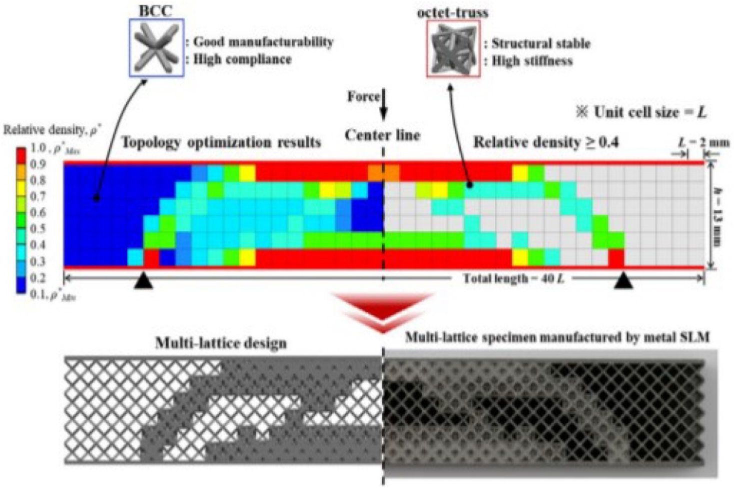


Figure 3. Distribution of trusses according to density field [13]

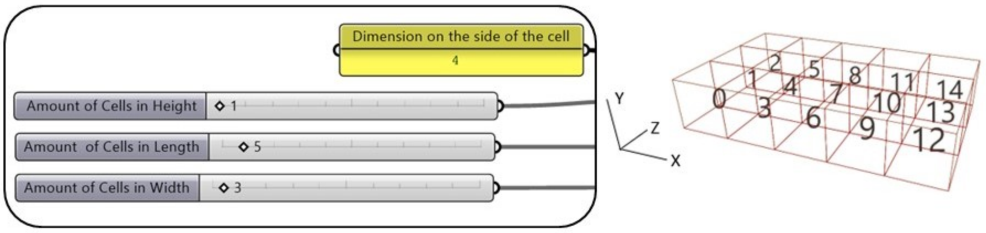
2.2 Parametric Modeling

The algorithm modeling can be defined by a finite sequence of instructions and routines, well defined, performed in several steps. It is a system of logical principles that leads us to the development of solutions of a generic problem involving abstraction, induction, generalization, deduction and structured logic. These routines can produce error messages and warnings if some pre-established conditions are not met [14].

Two examples of software that work with this type of structure are: Generative Components® which is a module of the Microstation application of the company Bentley Systems and the other is Grasshopper® a plugin for the Rhinoceros® program.

The program used for the development of three-dimensional models in this article is Grasshopper®. In this software, the parametric diagrams that control the geometries are created, which can represent primitive shapes or operations. Meanwhile, in parallel, the plugin with Rhinoceros® software is used, which is the 3D environment where the generated modeling is visualized.

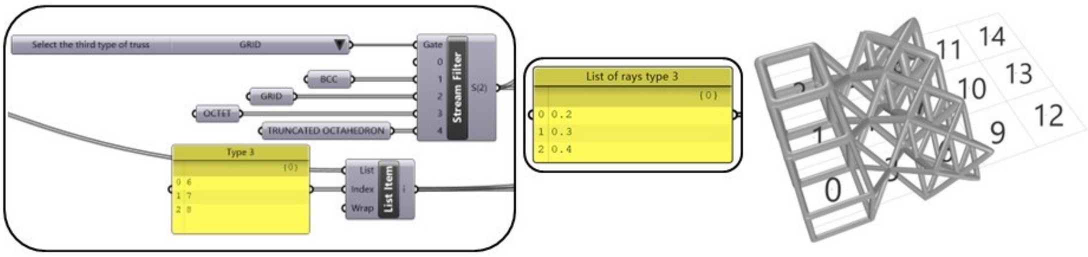
For the construction, we define the size of the lattice cell, and the number of cells in the height, length and width of the lattice, as illustrated in Figure 4. From the interaction of these data, a Grid with empty voxels is constructed, and each of these voxels receives a numbering.



Dimension on the side of the cell: 4
Amount of Cells in Height: 1
Amount of Cells in Length: 5
Amount of Cells in Width: 3

Figure 4. Representative figure showing the construction of the voxels, after data insertion.

After that the empty voxels are filled with the desired geometries. Each voxel must have its number imputed in a list, named type 1, type 2, type 3 or filled. In the list type 1, type 2, type 3, the user must determine lattice topologies that the listed voxels will receive, the options being: Grid, BCC, Octet or Truncated Octahedron. In the list named filled, the voxels are a solid cube. And if a voxel is not specified in any of the 4 lists mentioned, it will be considered empty. Then, the user must add the radius value of the structure for each item informed in the previous step in the same sequence, as illustrated in Figure 5.



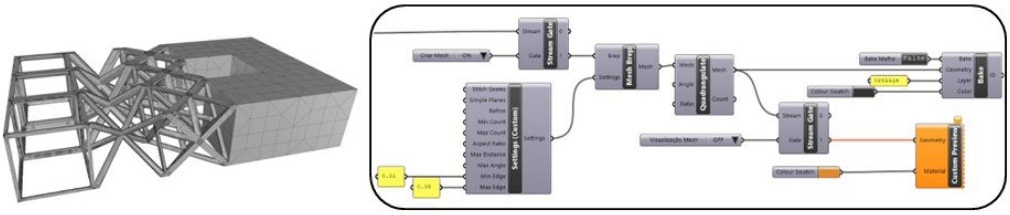
Select the third type of truss: GRID

Type 3
{0}
0 6
1 7
2 8

List of rays type 3
{0}
0 0.2
1 0.3
2 0.4

Figure 5. Representative figure showing the typology definition step: Type 2 list, Grid, BCC, Octet or Truncated Octahedron model selector and Type 2 ray list.

After that, the algorithm join the cells and as the purpose of the model is 3D printing, it is necessary to generate an stl extension file. By turning on the Create Mesh option, Grasshopper® will transform this polysurface into a mesh. By activating the Mesh Visualization option, the operator will be able to visualize the generated mesh. To add it to the Rhinoceros® interface and export it in the.stl extension, the Bake Mesh button must be set to True and then set to False, as shown in Figure 6.



Criar Mesh: ON
Bake Malha: False
Visualização Mesh: OFF

Figure 6. Mesh visualization and STL model.

The topological optimization without penalization of the variable density truss models was performed using the Polytop software developed in MATLAB [15]. For this, the parameters and constraints were defined based on the study by [13], thus generating a continuous density field, with a total volume fraction of 0.446, in the standards of the article. To perform the bending test, the model was built with two solid bars, one at the top and one at the bottom. In addition, the zero value of the density field will be replaced by the minimum density possible to be manufactured. This may result in models with a total volume fraction higher than 0.446.

In order to analyze and compare different variable density models, comparison groups were created, consisting sequentially of uniform, variable and mixed density truss models. For each type of model, the developed programming uses a list of specific spokes that should be distributed according to the density field.

3 Discussion and Results

The variable models were created based on the density field generated in PolyTop, with adjustments required for fabrication as described in the previous section. It is important to note that the Grid and BCC models have the same relative density field where the density varies from 0.1 to 0.5 and 1.0 in both models.

It is important to note that the algorithm developed in grasshopper was extremely effective in the construction of the specimens, even with complex and varied structures, obeying the parameters estimated in the mathematical modeling, as presented in the Figure 7.

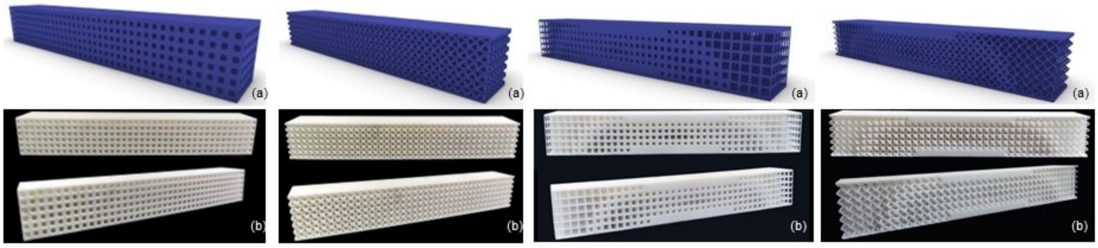


Figure 7. Comparative of modeled and printed specimen (uniform and variable density, with one structure - GRID and BCC)

In addition, pieces of varying structure and densities were imposed, with the algorithm having an excellent performance, as shown in Figure 8.

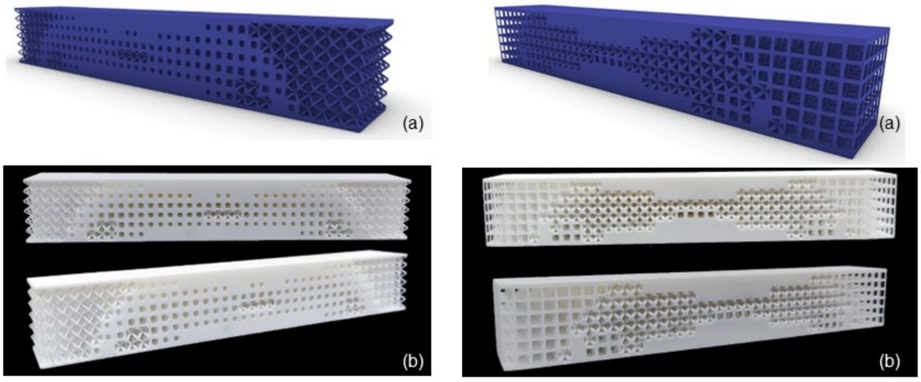


Figure 8. Comparative of mixed structure (printed and by software)

All the specimen were tested by three-point flexion test, as shown in the Figure 9:

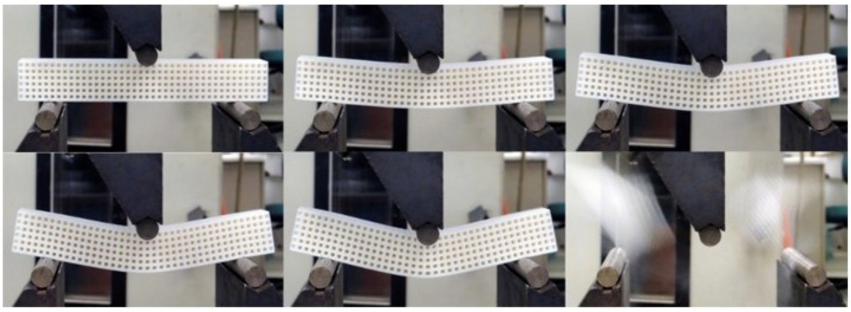


Figure 9. example of three-point flexion test - Uniform density, GRID Structure

The figure 10 presents the Force vs Elongation graph of BCC ans GRID structures in different topologies.

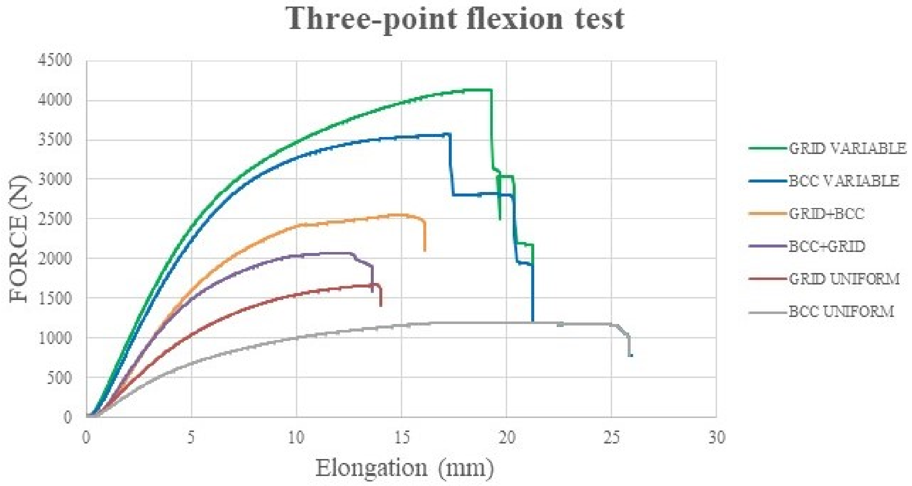


Figure 10. Force vs Elongation graph of BCC ans GRID structures in different topologies

The topological optimization model fabricated to solve the bi-axis beam problem with concentrated load at the center has been shown to be efficient and experimental analyses with the three-point test indicate that the solution using variable density shows a significant increase of at least double the stiffness when compared to solutions with uniform density.

4 Conclusions and Remarks

Based on the presented results, it is possible to affirm that parametric modeling using Grasshopper® is effective in creating three-dimensional models of structures formed by truss networks, of variable density to solve engineering problems. The complex models were developed quickly and efficiently, meeting the project requirements, which demonstrated the potential of this tool for the construction of three-dimensional models, which in the future will contribute to the advancement of engineering and 3D printing technologies, creating solutions to the challenge of highly complex models.

It is important to note that additive manufacturing can be used to fabricate variable density truss structures, but there are limitations in the process, which must be understood to produce models suitable for SLS fabrication in Polyamide12, including the size of the voxels used and the diameter of the trusses.

The results obtained in this work suggest possible directions for further research in future studies, such as improvement of the programming so that it performs a transition that avoids stress concentration points during the generation of variable density truss models and evaluation and comparison models manufactured by additive manufacturing using micro-CT, as it allows an accurate three-dimensional analysis of the internal structures of the objects.

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Authorship statement

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