Topology Optimization with Enforced Patterns and Applications for Additive Manufacturing

Juan Pablo Leiva, Brian C. Watson

Vanderplaats Research and Development, Inc.

Novi, Michigan, United States of America

Email: **jp@vrand.com**

Web: **www.vrand.com**

Summary

Topology optimization is often used by designers and engineers to generate novel and sometimes organic shaped designs. In addition, additive manufacturing processes are becoming more and more capable to print organic shaped structures and lattice structures. While, lattice structures may sometimes occur naturally in topology optimization, usually some design constraint must be imposed in the optimization process to produce a lattice-like result. In this paper, we discuss how to enforce topology patterns to get final topology result to match certain desirable shapes that can be both easier to manufacture and/or to enforce a design requirement. The methods presented are implemented in the GENESIS structural optimization software and its preprocessor Design Studio. These two computer programs can be accessed in ANSYS using the GTAM and GSAM ACT extensions.

Keywords

Structural optimization, topology optimization, fabrication constraints, additive manufacturing

Introduction

In this paper we will discuss the use of topology optimization to generate design proposals targeted to be printed with 3D printers. In particular, we will discuss how to generate lattice-like structural designs. We will present two examples. In the first example, we will generate lattice structures directly using only topology optimization with some basic fabrication constraints. In the second example, we will generate the lattice structures using a Design Studio plugin that uses the topology density levels obtained by standard topology runs. Before discussing the problems we will briefly discuss what the topology optimization problem looks like and some basic concepts associated with it.

The Topology Optimization Problem

The topology optimization problem can be stated as:

$$Min\, F(\rho_1, \rho_2, \ldots, \rho_n)$$

$$\text{such that:}$$
$$g_j(\rho_1, \rho_2, \ldots, \rho_n) \le 0; \quad j = 1, m$$
$$0.0 \le \rho_i \le 1.0; \quad i = 1, n$$

Figure 1: Optimization Problem Statement

In the above equations *m* is the number of constraint functions, *n* is the number of design variables, *F* is the objective function, g_j are the constraints, ρ_i are the design variables.

Objective Function

Strain energy, mass, displacements, and natural frequencies are typically used as objective functions. In our implementation, practically any of the finite element responses or combination of them can be used as the objective function for minimization or maximization.

Constraints

As with the objective function, practically any of the finite element responses can be used as a constraint. In most problems, mass, displacements, velocities, accelerations, and natural frequencies are used as constraints. In addition, bucking load factors, stresses, strains, and/or temperatures can be also used as constraints.

Design Variables

In topology optimization, the design variables are parameters that can change the Young’s modulus and the density of each element. The variables are usually defined to take a value between 0.0 and 1.0. A value close to 0.0 corresponds to an element that should be discarded, while a value close to 1.0 corresponds to an element that should be kept.

Solving the optimization problem

To solve the optimization problem we used the GENESIS software [1] that uses approximation concepts to efficiently solve the optimization problem. For details in the topology optimization in GENESIS see ref. [2]. Details in topology optimization theory can be found in ref. [3] while details on structural optimization and numerical optimization can be found in ref. [4].

Directly Generated Lattices

When a low mass fraction is used, topology optimization, may produce a truss or lattice structure. When the results of the topology produce long members, it becomes harder to print due to the need of creating support structures. To reduce the need to support structures, we can force topology to create repeated short distance patterns to reduce the need of support structures. Our first example, will show this case.

Indirectly Generated Lattices

When topology optimization is used with solid elements and when higher mass fractions are used, it is possible to convert part or all topology results into a lattice pattern. Our second example, will show this case.

Examples

Two examples that show how to generate lattice structures will be presented next. The first example will show directly generated lattice structures. The second example will show how to convert a topology result into a lattice structure design. Details of these two example can be found in ref. [5].

Topology Optimization to Directly Generate Lattice Structures

Description of the Example

The purpose of this example is to demonstrate that optimization can be used to get lattice structures using simple fabrication constraints.

Designable Region

The dimensions of the design domain are 200 length unities by 50 length unities. A vertical load is applied in the middle of the bottom edge of the structure. The structure is simply supported by constraining the two corners of the bottom edge.

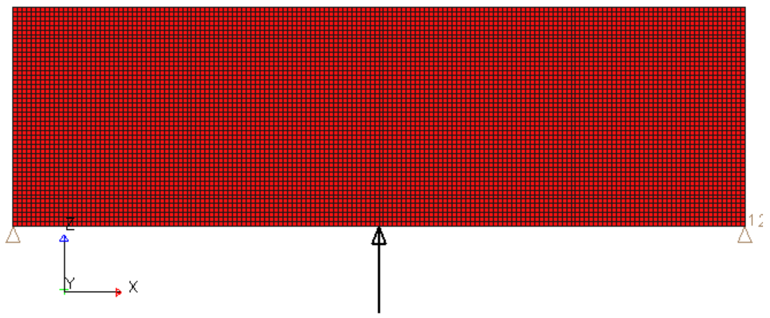

Figure 2: Initial Design, Loads and Boundary Conditions

The designable domain was discretized with 7,680 QUAD4 elements.

Problem Statement

The following optimization problem will be created, solved, and post-processed:

Minimize Strain energy
Subject to:
Mass fraction < 0.45

Case Studies

Several cases studies are run to show the impact of using different periodic constraints. Comparing the results, will show that some of the results are more suitable to be printed than other.

Case 1

A simple topology optimization is performed without any fabrication constraints being used.

Result 1

Figure 3, below, shows a reference answer. This structure has long members that would require a support structure to be built.

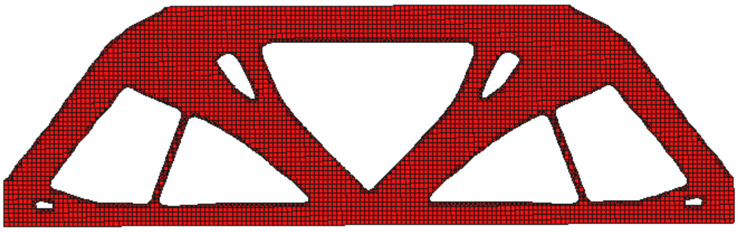

Figure 3: Final Design, Case 1

Case 2

A periodic fabrication constraint with a pitch of 50 is used to get a pattern repeated 2 times on each side of a symmetry plane located in the middle of the structure.

Result 2

Figure 4 shows the results of imposing symmetry and a periodic pitch of 50 units. This result is better than the one in case 1, but still produces long members, so this might not be as good as case 3 or 4 as candidate for printing.

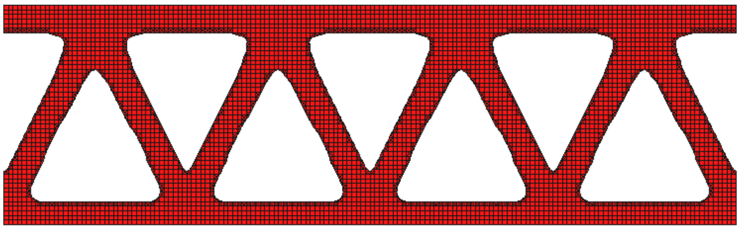

Figure 4: Final Design, Case 2

Case 3

A periodic fabrication constraint with a pitch of 25 is used to get a pattern repeated 4 times on each side of a symmetry plane located in the middle of the structure.

Result 3

Figure 5 shows the results of imposing symmetry and a periodic pitch of 25 units. This case, as case 4, is a more suitable candidate for printing. This case however, is not as good as case 4 in term of member lengths.

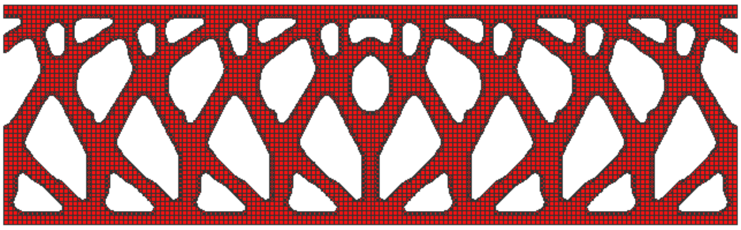

Figure 5: Final Design, Case 3

Case 4

A periodic fabrication constraint with a pitch of 25 is used to get a pattern repeated 4 times on each side of a vertical symmetry plane located in the middle of the structure. In addition, a second periodic fabrication constraint with a pitch of 12.5 is used to get a pattern repeated 2 times on each side of a horizontal symmetry plane located in the middle of the structure.

Result 4

Figure 6 shows the results of imposing double symmetry and periodic constraints that produced a lattice structure with multiple short members. This case is the most suitable candidate for printing when compared with the other 3 cases.

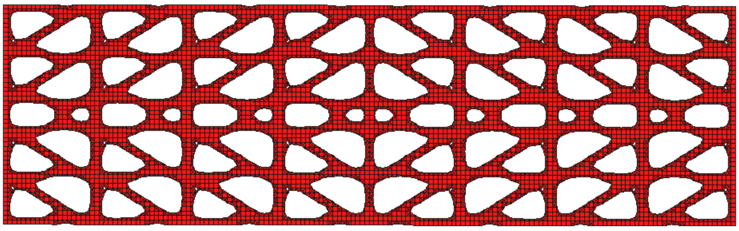

Figure 6: Final Design, Case 4

Lattice Structure Design

Description of Problem

The purpose of this example is to show how to create a lattice structure using results of a standard topology optimization run.

Problem Statement

The following optimization problem is solved:

Minimize Mass, Subject to:
Displacement (load case 1) < target 1
Displacement (load case 2) < target 2

Designable region

The topology design region is shown in red in Figure 7. There are two loadcases in this problem which are also shown in the Figure.

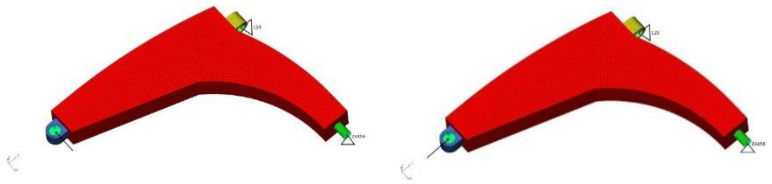

Figure 7: Initial Design, Two Load cases, and Boundary Conditions

The topology optimization results are shown in Fig. 8.

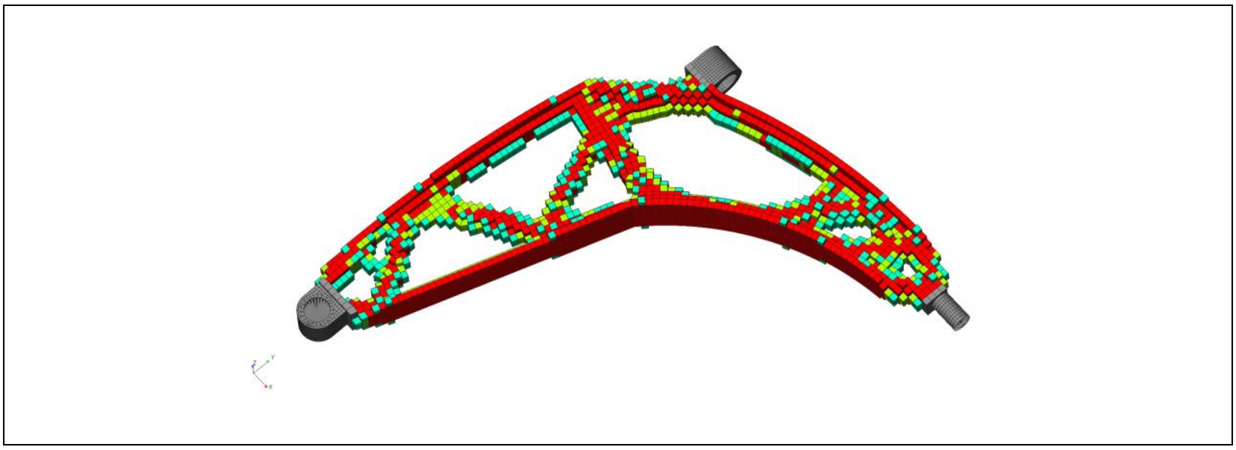

Figure 8: Topology Optimization Results

The elements with high density are shown in red. Elements with intermediate density are shown in green and light blue.

Lattice Pattern

To create a lattice structure, elements with intermediate densities will be converted using a lattice pattern available in Design Studio software. Figure 9 shows 3 available patterns.

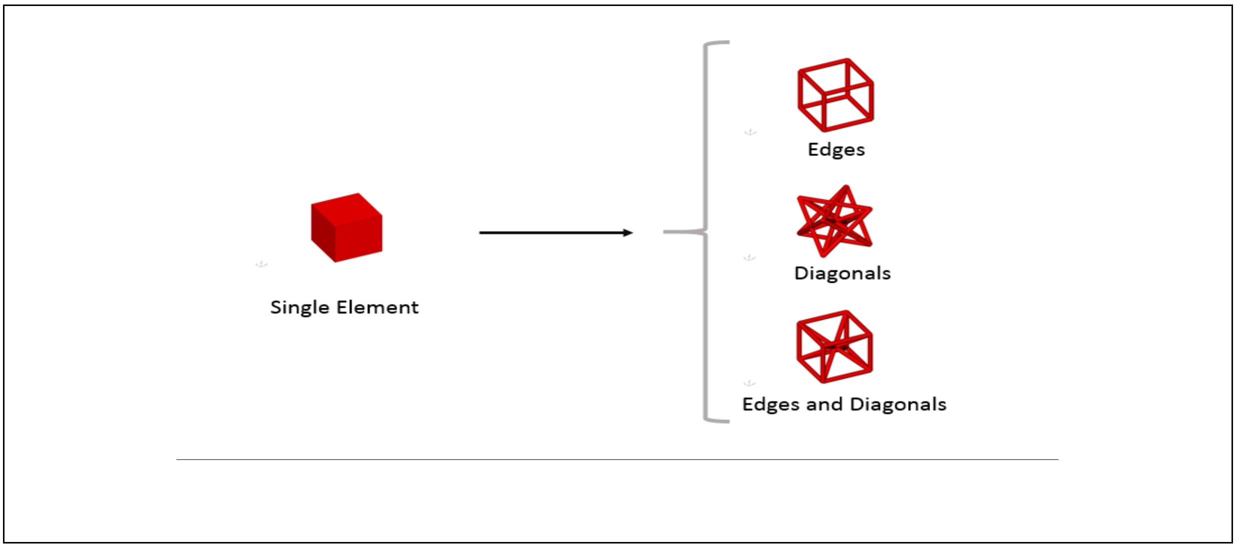

Figure 9: Lattice Patterns

Lattice Structure

Figure 10 shows the final results using the Edges and Diagonals pattern.

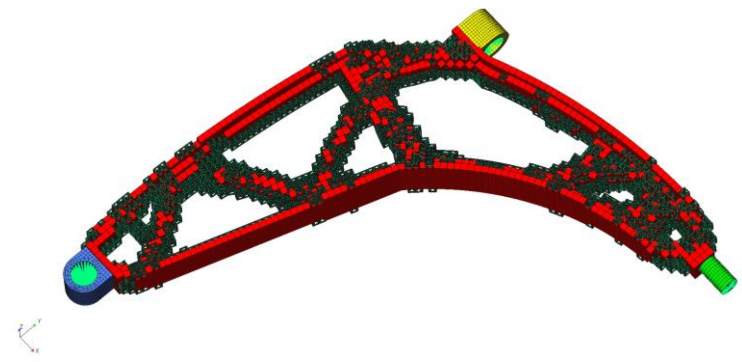

Figure 10: Lattice Structure

Alternative Lattice Structure Patterns

Figure 11 shows details of alternative lattice patterns.

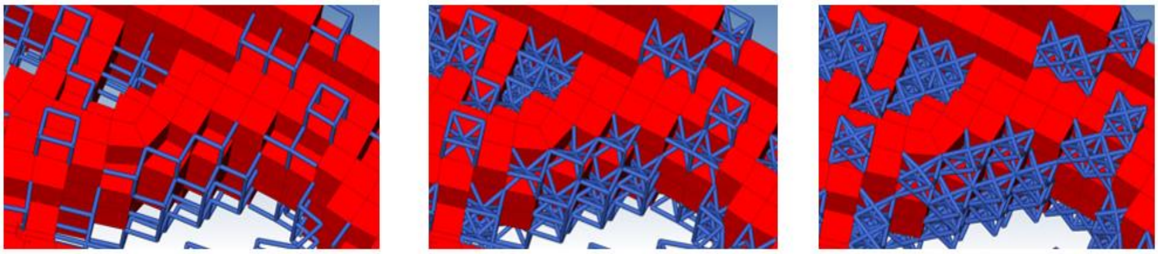

Figure 11: Details of Alternative Lattice Patterns

Discussion on Example 2

Lattice elements where successfully created with Design Studio. A lattice structure could also be created over the whole structure or in all elements above a density cutoff. The generated lattice could be further optimized using sizing, topometry or topology optimization.

Conclusions

Topology optimization can be used directly or indirectly to generate lattice structures. Lattice structures offer the opportunity of creating light, strong and innovative designs.

Acknowledgements

The authors would like to thank Mr. Om Joshi of VR&D for his help on solving the second example used in this paper.

References

[1] GENESIS User's Manual, Version 16.0 Vanderplaats Research & Development, Inc., Colorado Springs, CO, March 2017.

[2] Leiva, J. P., Watson, B. C., and Kosaka, I., “Modern Structural Optimization Concepts Applied to Topology Optimization,” Proceedings of the 40th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Material Conference. St. Louis, MO, April 12-15, 1999, pp. 1589-1596.

[3] Bendsoe, M. P., Kikuchi, N., Generating Optimal Topologies in Structural Design Using a Homogenization method, Computer Methods In Applied Mechanics And Engineering, 71, 197-224, 1988.

[4] Vanderplaats, G. N., “Multidiscipline Design Optimization”, Colorado Springs, CO, 2007.

[5] Design Studio Examples Manuals, Version 16.0 Vanderplaats Research & Development, Inc., Colorado Springs, CO, March 2017.