The World Congress of Structural and Multidisciplinary Optimization, May 20-24, 2019, Beijing, China

STRUCTURAL OPTIMIZATION METHODS AND TECHNIQUES FOR ADDITIVE MANUFACTURING

Juan Pablo Leiva[1*], Hong Dong[1], Brian Watson[1]

[1]*Vanderplaats Research & Development, Inc., Michigan, USA*
* *jp@vrand.com*

Abstract

Additive Manufacturing (AM) is a relatively new manufacturing process that can be used to generate complex parts which sometimes conventional processes cannot create. In recent years, users of AM technologies have started to use results from structural and topology optimization techniques to generate better AM designs. However, results from optimization cannot always be successfully or easily printed. In this paper, we describe some methods and techniques that allow the end user to generate structural design proposals which could be manufactured using 3D printing with minimum changes. In general, the methods and techniques described in this work are based on parameterizing the design domain and are developed for gradient-based topology optimization and can optionally be used together with other optimization methods such as shape and sizing. The proposed methods take into consideration irregular FEA meshes commonly used in industrial applications. The main focus of the methods discussed in this paper is to prevent that the final design contains overhang members with shallow angles as such features would either fail or require non-structural supports. The manufacturing requirements are built in the parameterization of the design space and will also be able to impose minimum member size which are also necessary to print 3D printed parts. The methods are discipline independent and have been implemented to be used with responses calculated from different analysis types such as statics, heat transfer, and/or dynamic problems. The discussed methods have been implemented in the GENESIS program and examples, that show their effectiveness, are included.

Keywords: *Structural Optimization, Additive Manufacturing, Topology Optimization, Overhang Constraints*

1. Introduction

Additive Manufacturing (AM) also known as 3D printing is a manufacturing process in which a structure or a part is built with a 3D printing machine in a layer-by-layer fashion. In contrast to other fabrication methods, such as casting or forging, AM has the unique ability to generate complex parts without the need of expensive molds, presses and/or tooling. On the other hand, in contrast to milling, AM does not waste too much material. AM has experienced a rapid growth since the 1980s when important work and first patents were granted. This type of manufacturing technique was first conceived and used to generate prototypes and today is beginning to be used to create final products. The market of AM machine is growing rapidly and the fact that many of the initial patents have expired is allowing new companies to enter the market and reduce the cost of the 3D printers and the material used to print [1].

3D printing technologies according to the ISO/ASTM 52990 Standard (2015) can be categorized in seven processes: a) Material Extrusion; b) Vat Polymerization; c) Powder Bed Fusion; d) Material Jetting; e) Binder Jetting; f) Direct Energy Deposition; and g) Sheet Lamination. Details on these processes can be found in references [1] and [2]. Here we will briefly discuss 3 of the most popular processes to give an idea of the variety of technologies available today:

a) Material Extrusion is an AM process in which material is selectively dispensed through a nozzle or orifice. This process uses FFF (Fused Filament Fabrication) technology or FDM (Fused Deposition Modeling). A notable printer manufacturer that uses FDM is Stratasys who has a trademark for FDM. This type of printer makes use of thermoplastics in the form of filament on spools. The type of material to use depends on the quality of results needed. Machines that use material extrusion are found in a wide variety of applications, from personal use to industrial use;

b) Vat Polymerization is an AM process in which a liquid polymer is selectively cured in a vat using a light source. This process uses SLA (Stereolithography) technology. The term SLA was coined by Charles W. Hull, founder of 3D Systems Corporation which is a major producer of 3D printers;

c) Powder Bed Fusion is an AM process in which a thermal energy selectively fuses a region of powder bed. Technologies associated are Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser

Melting (SLM), and Electron Beam Melting (EDM). With these technologies, parts can be made of polymers or metals. A notable producer of SLS machines is EOS from Germany.

Users of AM technologies have started to use results from optimization to generate better AM designs. However, results from optimization cannot always be successfully or easily printed. Brackett et al. [3], in 2011, summarizes the main challenges in topology optimization for AM. In their publication, they describe the challenge of having to generate support structures. Since the time of this publication, several publications have been presented on the subject of self-supporting structures and the use of overhang constraints to avoid the use of non-structural supports. Among the most useful publications applicable to our implementations are of Gaynor [4], Gaynor and Guest [5], and Langelaar [6]. These publications propose filters to the design variable that avoid the creation of overhangs which exceed a critical angle that would require non-structural supports.

2. Overhang Constraints

Overhangs are design features which raise in an angle that deviates from the build directions. Overhangs which are below a certain critical value are undesirable because they may be unstable and might require non-structural supports. These non-structural supports are typically costly, as they require extra material and extra post-processing of the 3D printed parts that contain them. The overhang angles are normally measured from the build plate. The value of the critical overhang angle depends on many factors, among them the 3D process itself and the material used. For FFF process a typical value is 45^o [2]. There are several ways to tackle overhang constraints. One way is to create actual constraints that are added to the optimization problem. Another way is to parameterize the design domain so that the creation of overhangs is avoided. We have tried both ways but the latter has produced better results for us.

3. Design Variable Definition

In our work we have used the following design variable parameterization to avoid the growth of shallow overhangs:

$$Y_j = f\,(x_j, S_j) \tag{1}$$

In this parametrization, x_j is an independent design variable measured at a level j of the design space. Y_j is a dependent design variable that is being filtered and used to update the FEA model. S_j is also a dependent design variable that is used to measure the density of the area under the point on space represented by design variable Y_j.

The core of the parameterization is to define the function f and the support $S_{j.}$ The function f is defined is such a way that the final density (or printed density) should not exceed the density S_j in the supporting region.
In Langelaar's work, the function f is defined as:

$$f\,(x_j, S_j) = MIN(x_j, S_j) \tag{2}$$

Since the MIN function is not differentiable, Langelaar proposes the use of the following approximation to the MIN function:

$$SMIN(x,S) = ½*(x+S-((x-S)^{2} + \varepsilon)^{(1/2)} + \varepsilon^{(1/2)}) \tag{3}$$

In the above equation ε is a small number e.g. 0.001 or 0.0001 and its usage allows us to avoid dividing by 0 on sensitivity calculations.
In Gaynor and Guest's work the function f is defined as:

$$f\,(x_j, S_j) = x_j * S_j \tag{4}$$

The dependent design variable S_j in Langelaar's work is defined as:

$$S_j = MAX(Y_{j-1}) \quad Y_{j-1} \in \Omega_j \tag{5}$$

In the above equation Ω_j is a set that contains all variables that can support point j. Y_{j-1} are dependent (printed) variables located at a level below level j. On a 2D structure, the Ω_j set usually contains 3 supporting points (at corner and edges it contains less points). While in 3D structures the Ω_j set usually has 5 members. Fig 1 shows in dark 3 $Y_{j\,-1}$ points. In Fig. 1 the built direction is assumed to be vertical, in other words the structure is assumed to be built upward by the 3 D printing machine.

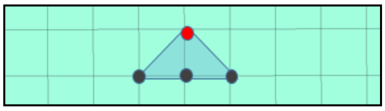

Figure 1. Flat Support region

As with the MIN function the MAX function is not differentiable, to overcome that Langelaar proposes the use of the following approximation to the MAX function:

$$\mathrm{SMAX}(Y_{j-1}) = (\Sigma\ (Y_{j-1})^{\ P}\ )^{(1/Q)} \quad Y_{j-1} \in \Omega_j \tag{6}$$

In the above equation P is power that when it grows to infinite would make SMAX converge to MAX. A suggested value is 40.0, Q = P + Log(Ns)/Log(p0), where NS is number of supporting points, and p0 is a number between 0 and 1. A suggested value of p0 is 0.5.

The dependent design variable S_j in Gaynor and Guest's work is defined as:

$$S_j = H_T(\mu^j{}_S(Y_{j-k})) \quad Y_{j-k} \in \Omega_j \tag{7}$$

In the above equation $\mu^j{}_S(Y_{j-k})$ is the average of all points that are in the support region underneath the point j. In this case the support region is a conical region situated under the point j and it can be constructed by defining a radial distance R; k is 1, 2 or larger and depend on R. The angle that defines the cone is equal to two times the allowable overhang angle. Fig. 2 shows the support region. In this figure the build direction is assumed upward as in Fig. 1.

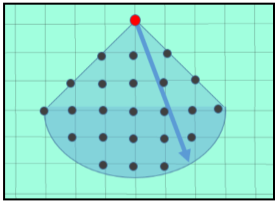

Figure 2. Conical Support region

H_T in Eq.(7) is a thresholding Heaviside function that polarizes the average density to determine whether or not there is enough support for point j.

$$H_T(\mu^j s) = \frac{\left[\tanh(\mathrm{Beta}_T \cdot T) + \tanh(\mathrm{Beta}_T(\mu^j s - T))\right]}{\tanh(\mathrm{Beta}_T \cdot T) + \tanh(\mathrm{Beta}_T(1 - T))} \tag{8}$$

In in Eq.(8) Beta_T and T are parameters to tune up. As shown in Fig. 3, higher values of Beta_T allows the equation to produce sharper polarization (values near 0/1). T is a threshold value that set the amount of density deemed to support adding material.

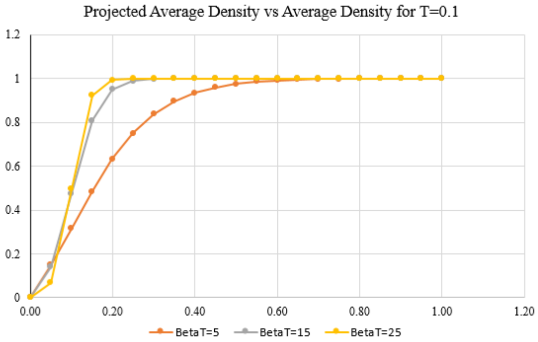

Figure 3. Thresholding Heaviside function for different Beta_T values and for threshold T=0.1

Since the dependent design variable Y_j is dependent on the value S_j which in turn is dependent of other values of Y_{j-1} or Y_{j-k} located at lower levels, the evaluation of the design variables has to be performed from the bottom level to the top level. It should be mentioned here that variables on the first (lower) level are assumed to be supported by the build platform, so in that level Eq. (2) is reduced to: $Y_j = x_j$ and $S_j = 1$; if j=1.

4. Implementation

In our work, we have included the support functions and dependent support variables from both Langelaar and Gaynor and Guest. In our implementation the selection of which support function to use is an option for the user. Our implementation is done in the GENESIS structural optimization software [7] and in such a way, that the overhang constraints can be used with any of the existing responses and can be used simultaneously with other existing optimization types such as sizing, shape, etc.

In GENESIS, the structural optimization problem is solved using the approximation concepts approach [8]. In this approach, an approximate analysis model is created and optimized at each design cycle. The design solution of the approximate optimization is then used to update the finite element model, and a full system analysis is performed to create the next approximate analysis model. The sequence of design cycles continues until the approximate optimum design converges to the actual optimum design. In the mid-seventies Schmit et al. introduced approximation concepts for traditional structural optimization [9-10]. In the late seventies and eighties Starnes et al. [11] and Fleaury et al. [12] introduced conservative approximation to improve the approximation used. In the eighties and early nineties, Vanderplaats et al. further improved the quality of approximations by introducing the use of intermediate responses [13-16] also referred as second generation approximations. The approximate problem is solved using either the BIGDOT [17, 18] or DOT [19] optimizers. The purpose of using the approximation concepts approach, conservative approximations and second generation approximations is to reduce the number of design cycles to reduce time. With these approximations, a good answer can be typically found in 10 to 25 design cycles. However, in problems with overhang angle constraint the number of design cycles can grow above 25.

5. Examples

5.1 MBB Example

In this example, the classical MBB beam is designed with and without additive overhang constraint. The optimization is to minimize the overall strain energy (compliance) utilizing no more than 50% of the mass. For additive, the build direction is chosen to be along positive Y direction, and the allowable overhang angle is 45 degrees.

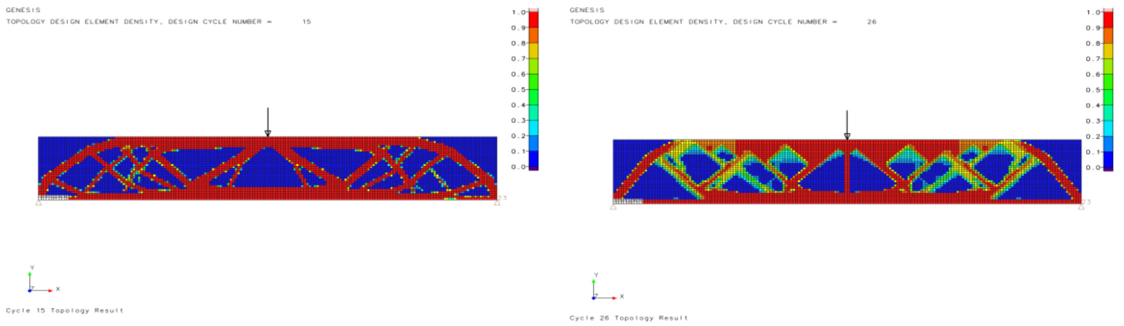

Figure 4. Element densities. On the left without and on the right with overhang constraints

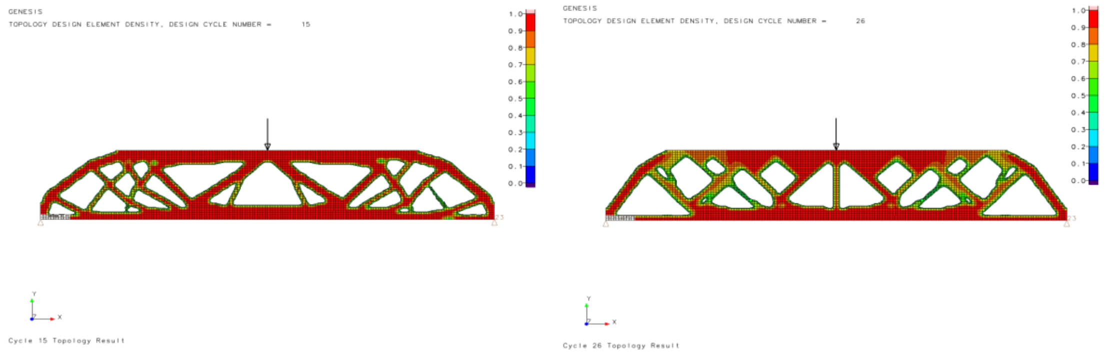

Figure 5. Isosurface densities. On the left without and on the right with overhang constraints

5.2 MBB Example Results

As shown in Fig. 4 and 5, the topology design without overhang constraint forms members with shallow angles. While with overhang constraint, the members are at least at a 45-degree angle as requested. The strain energy for topology without overhang constraint is 2.7578. The strain energy with overhang constraint is 3.0340, which is about 10% higher.

5.3 Topology Optimization of a 3D Beam

In this example, a cantilever beam is designed with and without overhang angle constraint. The objective in the problem is to minimize the strain energy with a mass fraction constraint of 30%. The build direction is along positive Y direction, and the allowable overhang angle is 45 degrees. The structure is fixed at one side and subject to vertical edge loads at the lower edge of the opposite side.

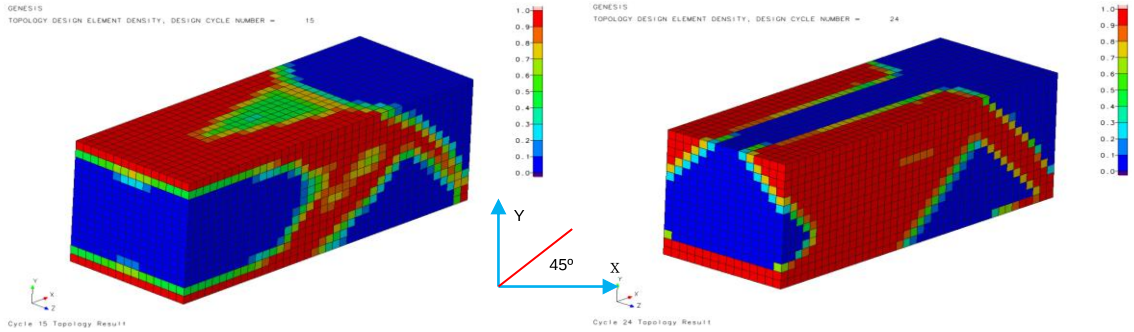

Figure 6. Element density results. On the left without and on the right with overhang angle constraints

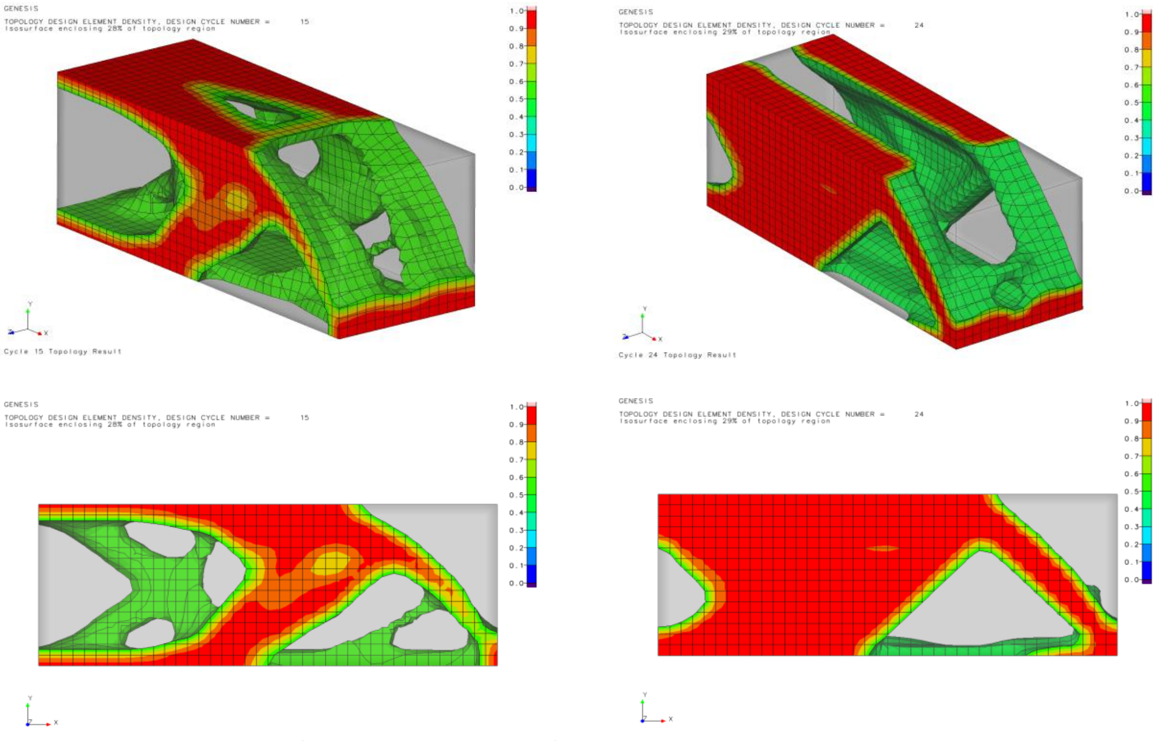

Figure 7. Isosurface density results. On the left without and on the right with overhang angle constraints

5.4 Topology Optimization of a 3D Beam Example Results

As shown in Fig. 6 and 7, the results without overhang constraint would need support at the members/surfaces with shallow angles. While with the results using overhang constraints, the members are formed with at least 45 degrees as requested.

6. Conclusion

This paper discussed methods to design structures that can be additively manufactured. The implementation presented allows the user to generate optimal topology design that avoids or reduces the presence of overhang members that would require unnecessary waist of material and expensive trimming. The implementation is general in the sense that it can be used with any response already available in the GENESIS software and it can also be used together with other types of structural optimization types as sizing and shape optimization.

References

1. Gibson I, Rosen D and Stucker B. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, Second Edition. Springer, 2015.
2. Redwood B, Schöffer F and Garrett B. The 3D Printing Handbook: Technologies, design and applications, 3D Hubs B.V., lib.hpu.edu.vn, 2017.
3. Brackett D, Ashcroft I, Hague R. Topology optimization for additive manufacturing. In: 22nd annual solid freeform fabrication symposium, pp 348–362, 2011.
4. Gaynor A T. Topology optimization algorithms for additive manufacturing, Doctoral dissertation, The Johns Hopkins University, Baltimore, US-MD,57-84, 2015.
5. Gaynor A T and Guest J K. “Topology optimization considering overhang constraints: Eliminating sacrificial support material in additive manufacturing through design,”Struct. Multidiscip.Optim., pp. 1–16, 2016.
6. Langelaar M. An additive manufacturing filter for topology optimization of print-ready designs, Structural and Multidisciplinary Optimization, 55 (3), 871-883, 2017.
7. GENESIS User's Manual, Version 17.0 VR&D, Colorado Springs, CO, May 2018.
8. 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, pp. 1589-1596, April 12-15, 1999.
9. Schmit L A and Farshi B. Some Approximation Concepts for Structural Synthesis, AIAA J., Vol. 12(5), pp 692-699, 1974.
10. Schmit, L A and Miura H. Approximation Concepts for Efficient Structural Synthesis, NASA CR-2552, March 1976.
11. Starnes Jr. J H and Hafka, R T. Preliminary Design of Composite Wings for Buckling, Stress and Displacement Constraints, Journal of Aircraft, Vol. 16, pp. 564-570, Aug. 1979.
12. Fleury C and Braibant V. Structural Optimization: A new Dual Method using Mixed variables, Int. J. of Numerical Methods in Engineering, Vol. 23, No 3, pp. 409-429, 1986.
13. Vanderplaats G N and Salajegheh, E. An Efficient Approximation Technique for Frequency Constraints in Frame Optimization, International Journal for Numerical Methods, Vol. 26, pp. 1057-1069, 1988.
14. Yoshida N and Vanderplaats G N. Structural Optimization Using Beam Elements, AIAA J., Vol. 26, No. 4, pp. 454-462, April 1988
15. Vanderplaats G N and Salajegheh E. A New Approximation Method for Stress Constraints in Structural Synthesis, AIAA Journal, Vol. 27, No. 3, pp. 352-358, March 1989.
16. Canfield R A. High Quality Approximations of Eigenvalues in Structural Optimization of Trusses, AIAA J.,Vol 28, No. 6, pp. 1116-1122, 1990.
17. Vanderplaats G N. Very Large Scale Continuous and Discrete Variable Optimization, Proceedings of the 10th AIAA/ISSMO Conference on Multidisciplinary Analysis and Optimization, Albany, New York, Aug 30-Sept.1, 2004.
18. BIGDOT User's Manual, Version 4.0, VR&D, Colorado Springs, CO, 2012.
19. DOT User's Manual, Version 7.2, VR&D, Colorado Springs, CO, 2017.