# Automatic Generation of Strong, Light, Mutli-Functional Structures from FEA Output

D. Cook[*], B. Knier[*], V. Gervasi[*] and D. Stahl[†]
[*]Applied-Technology Center, Rapid-Prototyping Research, Milwaukee School of Engineering, Milwaukee, WI 53202
[†]Department of Architectural Engineering and Building Construction, Milwaukee School of Engineering, Milwaukee, WI 53202

**Abstract**

An automated process is being developed that will generate a minimal-mass lattice structure that is fabrication-ready for a selected solid-freeform-fabrication (SFF) process. The results of a standard, structural, finite-element analysis (FEA) are processed to define the selection, alignment and sizing of unit lattice elements, such that a minimal-mass structure can be defined. This process will allow for considerations of structural performance (e.g. safety factor), multiple loads, as well as process parameters (e.g. materials and min./max. sizes). Further development would lead to the definitions of composites and multi-functionality, as well as high-performance-computing (HPC) capabilities.

## I. Introduction

### *A. Purpose*

The purpose of this research was to determine an effective means of defining fabricatable geometry, representative of those results that may be obtained through structural optimization, for the design and fabrication of compact, efficient and effective fluid-power components.

While this research was conducted specifically for the advancement of fluid-power technologies (The Center for Compact and Efficient Fluid Power), the algorithms developed and knowledge gained may be applied to nearly all industries. In particular, the biomedical and aerospace industries also have immediate need for such variable-density, minimal-mass, multi-functional component designs. Apprehension to the adoption of additive-manufacturing processes for these industries necessitates the development of standards, such as ASTM's Committee F42 on Additive Manufacturing Technologies (ASTM International, 2010). One goal of this paper, therefore, is to convey the potential of these technologies to designers and manufacturers so that they may be further motivated to bring these capabilities to the mainstream.

A second goal is to further contribute to the growing community that seeks to capitalize on the combination of capabilities afforded by high-performance computing (HPC), multi-disciplinary design optimization (MDO) and additive manufacturing (AM).

### *B. Background*

1. Design Optimization:

Design optimization is a process of considering design alternatives having properties within the specified constraints, and selecting the design that most-closely matches the objective, within the allowable tolerance. For component designs, this can be achieved through structural optimization.

Topology optimization is the most common structural-optimization algorithm for defining complex three-dimensional designs. Two of the leading, commercially-available, software suites are Altair's Hyperworks® (Altair Engineering, Inc., 2007) and VR&D's Genesis® (Vanderplaats Research & Development, Inc., 2006), both of which employ the Solid Isotropic Material with Penalization (SIMP) method (Bendsoe & Sigmund, 2004) to iteratively define the optimal geometry (Equation 1).[1] This is an "artificial-material" approach because the algorithm computes the loads using a fractional value of the base-material's stiffness, $E_i$, at each element in the domain, and assumes that this stiffness can be achieved by altering the "density," $\rho_i$, of the element, without regard to how this gradient density may be achieved in fabrication (Figure 1). Most critically, the algorithm assumes isotropy, which must be realized in the fabrication to match the predicted performance.

(1) $$\frac{E_i}{E_0}=\left(\frac{\rho_i}{\rho_0}\right)^n$$

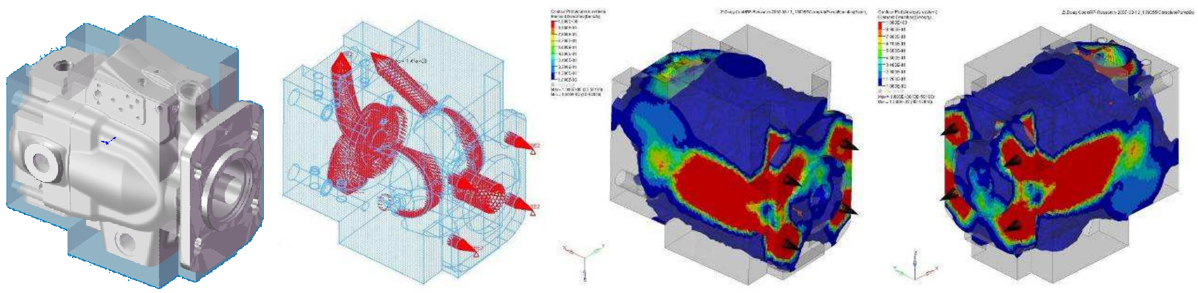

**Figure 1: Conventional topology optimization applied to housing of commercial axial-piston-pump housing. The component is contained within a design volume (far left) and boundary conditions are applied (mid left). The output is a gradient-density definition of the optimal design (mid and far right).**

This optimization approach is also limited in the resolution of its computed optimum. The minimal feature cross-sectional dimension must be larger than the minimum mesh size, typically by a factor of five. Altair's Optistruct® algorithm also imposes a maximum ratio between maximum and minimum element sizes of 5:1. Therefore, for multi-functional geometries requiring high resolution, i.e. a high surface-area-to-volume ratio, the state-of-the-art requires extremely fine meshes throughout the entire design domain, or locally via iterative mesh refinements. Both of these discretization approaches are computationally expensive over the course of the optimization.

The Homogenization approach is another structural-optimization algorithm, and explicitly considers the generally non-isotropic optimal structure; however, this approach has not yet been realized, to the authors' knowledge, for three-dimensional designs, and generally only considers orthogonal structures, limiting the optimization potential (Bendsoe & Kikuchi, 1988) (Hassani & Hinton, 1999). Shear stresses, arising prevalently in multiple-load-case optimizations, necessitate the oversizing of the beams, struts and joints in orthogonal structures.

[1] FE TOSCA Structure (FE-DESIGN GmbH, Technologiefabrik Bau A, EG.) is another commercial software; but, it's algorithm has not been confirmed as SIMP.

2. Multi-Functionality of Structures:

In addition to bearing mechanical load using minimal mass, engineered structures can also perform other functions, allowing for the design of multi-functional components and systems. Of particular interest, for the fluid-power industry and others, is the potential for metal-based structures to provide thermal management and even acoustic-pressure absorption. While these variable-density structures may be quite complex, their fabrication is now possible with additive-manufacturing processes.

3. Structure-Generation Options:

Once the optimized geometry is defined, the structure of corresponding properties must be generated within. The known algorithms for automatically generating lattice structures within geometric constraints have been grouped as follows:

a. *Space-filling lattice*

These algorithms simply copy a base unit-lattice geometry in their respective coordinate systems, typically in the Cartesian system, to the defined extents limits or specified number of units. Modifications to the geometry among the units must be performed manually. Fitting these structures within an irregular bounding geometry requires a Boolean intersection operation. The options are:

- Selective Space Structures® (Netfabb GmbH, 2010)
- TetraShell™ (Editors, DE, 2008)
- Conventional computer-aided-design (CAD) software
- Conventional modeling software

b. *Conformal lattice*

These algorithms place the structural junctions along the surface of the prescribing/bounding geometry, thereby conforming to its curvature, etc. Typically, the nodes of a surface mesh define these coordinates. Successive layers subdivide the space between the outer bounding surfaces, and have corresponding junction points for simple, point-to-point connectivity of the structure. Because each unit is dynamically defined, the geometry of each may be automatically modified by the selected algorithm. The options are:

- Truss Creator® - Georgia Tech. Systems' Realization Lab® – (Wang, 2005)
- Paracloud® (generative modeling) – requires pre-defined mapping
- Scripting within modeling software, e.g. Python® scripting within Blender®

## II. Approach

### *A. "Stress-Field-Compliant" Approach*

Stahl's approach was to physically realize the model used in the homogenization approach through AM processes (Stahl & Batdorff, 2004). Additionally, for maximum optimization, the resultant data was processed such that a "stress-field-compliant" mesh could be defined. This mesh connectivity, then, served as the connectivity for the mutually-orthogonal lattice structure that was to be generated (Figure 2).

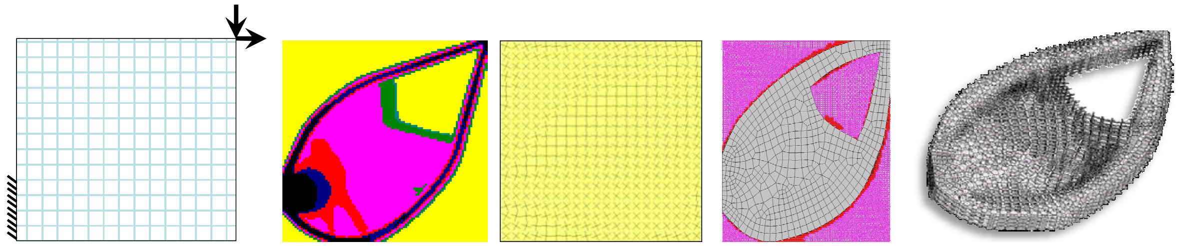

**Figure 2: Stress-field-compliant-lattice generation. The density distribution of the homogenization method (mid left) is re-meshed (mid right) to align the elements with the principal stresses (middle). The orthogonal "Jack" unit lattice was inserted into each quadrilateral element, thus aligned with the stress vectors; and the struts were sized accordingly. The resultant planar structure was then stacked five layers in the third dimension (right) (Stahl & Batdorff, 2004).**

***B. "Onioin-Skin Approach***

Seeking to expand Stahl's work into the third dimension (Gervasi & Stahl, 2004), (Stahl & Batdorff, 2004), a cube was loaded under shear, at diagonal corners (Figure 3), and structurally optimized using Altair's Hyperworks® suite (Altair Engineering, Inc., 2007). A mid-range iteration, one having a wide gradient of densities, was selected; and, this gradient was subdivided into levels of percent-density, every ten percent, between 30% and 100%. For three-dimensional objects, these levels are similar to the layers of an onion, hence the name.

These individual layers were then exported as stereolithography (STL) files for fabrication. Unfortunately, re-meshing these layers, within Altair's Hypermesh® (Altair Engineering, Inc., 2007), to align the elements with the principal stress directions, proved to be an insurmountable task. As an alternative, Magics RP® (Materialise, 2010) was used to realize these geometries as variable-density lattice structures. Each layer's geometry was Boolean intersected with a block of lattice geometry, having the desired density to match the layer, leaving a section of lattice matching the bounding geometry of the layer. The Tetralattice® structure (Gervasi V. R., 2001) was used here. Aligning the individual lattice layers and conducting a Boolean union, the resultant geometry was a "step-wise," gradient-density geometry, representing the results of the structural optimization (Figure 3). The component was fabricated using the Selective Laser Sintering™ (SLS™) machine in the Rapid Prototyping Center™ (RPC™) of the Milwaukee School of Engineering (MSOE).

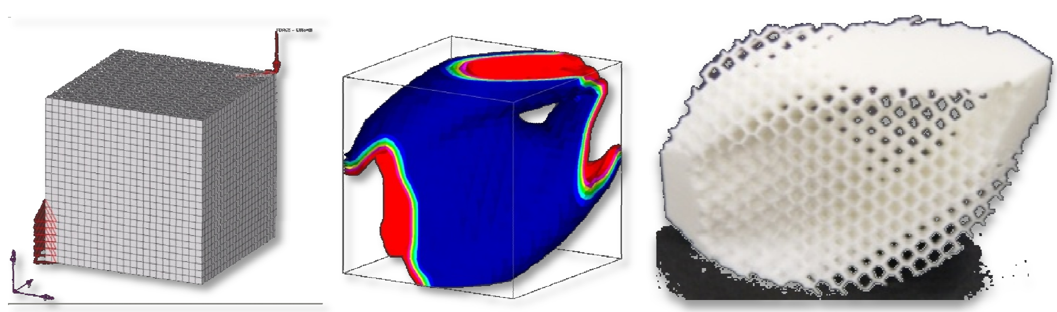

**Figure 3: "Onion-Skin" approach to generating variable-density, reduced-mass structures from the gradient-density output of conventional topology optimization. The loaded and constrained cube (left) is structurally optimized; and, the resulting density gradient is discretized into density ranges, like the layers of an onion (middle). These layers are cut**

**out from blocks of TetraLattice® of corresponding density, and joined into one structure (right).**

While the "Onion-Skin" process demonstrates the feasibility of directly defining a three-dimensional, reduced-mass, solid-freeform-fabricatable, variable-density structure: the process is not automated; the resultant geometry is not completely optimized, i.e. the lattice elements are not stress-field-directed or sized; and, the structure is weakened with stress concentrators at the layer interfaces, due to the instantaneous changes in cross-sectional areas. A conformal structure, one having junctions along these interfaces, could avert these stress concentrations by designing the proper geometry at each junction.

### *C. "Stress-Field-Directed" Approach*

The observation was made that, for such shear-dominate load cases, the Von Mises stress field closely approximated the end results of the topology optimization process. In an attempt, therefore, to shortcut the process, avoiding the often high computational costs, the Von Mises field, from a single finite-element analysis, was processed; such that, the lattice junctions would lie at regular intervals along the iso-surfaces of the stress field (Figure 4, middle). Using the basic "Cube" lattice unit cell (Figure 6) to make mutually-orthogonal connections, and sizing the lattice elements based on the enclosed area, a spider-web-like structure (Figure 4, right) was generated for this classic Michelle load case (Bendsoe & Sigmund, 2004). This semi-automated process: reads in the FEA output; determines the connectivity; sizes the lattice elements; and, then generates the structure within modeling software, e.g. Rhinoceros®, via a script. However, while reduced in mass, this structure is still not completely optimized.

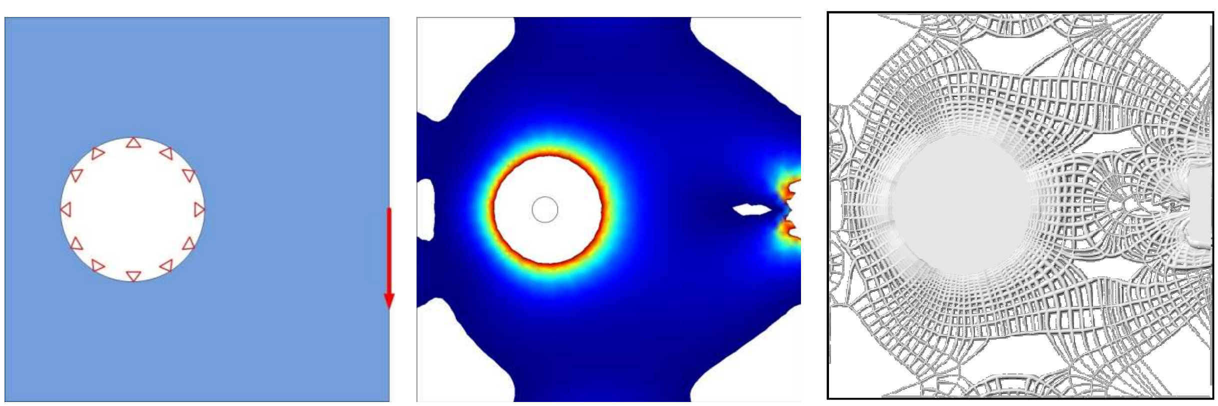

**Figure 4: Semi-automatic generation of a stress-field-directed, and sized, lattice structure (right) from the FEA output (middle) of the classic Michelle cantilever (left).**

### *D. "Non-Iterative Optimization" Approach*

The realization was then made that a single FEA analysis (per load case) provides all of the necessary load information to non-iteratively define the optimal structure. This data could be processed to estimate the distribution of stress requiring the least mass, including specification of the lattice spacing. Knowing this stress distribution, including total and principal stress, local definitions of the required unit lattices could be made.

In contrast to conventional optimization routines, this is a more "direct" approach, and, therefore, does not suffer convergence issues (once the initial FEA has successfully converged).

This process cannot be disclosed here; but, a conceptual model of the process for a multi-functional, i.e. load-bearing and heat-dissipating, tensile rod is shown in Figure 5. Once again, using the “Cube” unit-cell, the resulting structure looks like an inter-connected stack of spider webs. The suspicion is that this is not merely coincidental.

For further mass reduction, automated selection from the available unit lattice types is necessary. Multi-functional definition of this structure also requires geometry-dependent characterizations of these unit lattices for those functions.

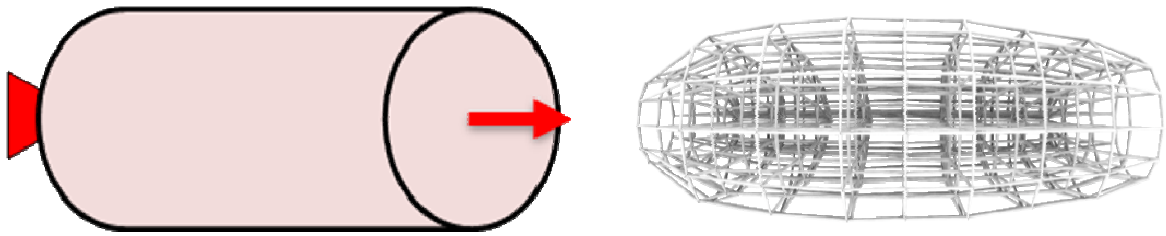

**Figure 5: Point-loaded tensile rod (left) and the concept model of the automatic generation of a load- and heat-dissipation-optimized structure (right).**

***E. Structure Characterization***

This non-iterative generation of lattice structures, however, requires the constitutive properties of all unit lattice structures to be employed. Hassani & Hinton showed structure-performance plots for the two-dimensional, orthogonal, variable-density structures that were used in their homogenization algorithms (Hassani & Hinton, 1999). These three-dimensional plots presented the variations in the constitutive-matrix components, i.e. elastic and shear moduli, with the varying widths of the orthogonal structural elements, for one unit-lattice type. The algorithm under development, however, requires full characterizations of multiple, three-dimensional unit lattices (Figure 4), in relation to their potential variations in geometry.

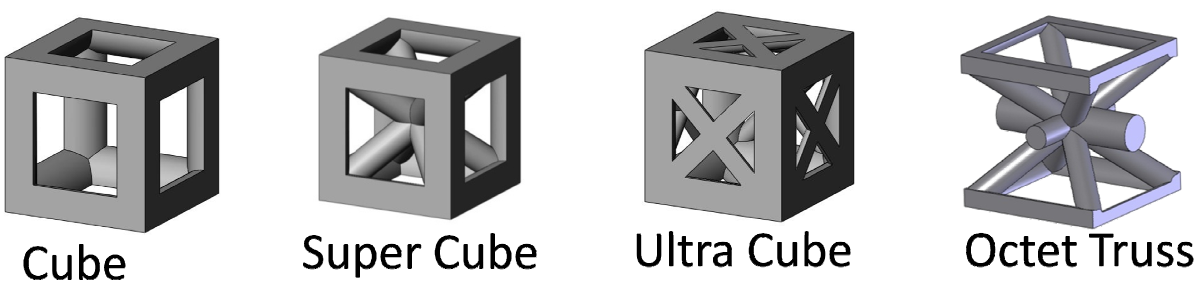


**Figure 6: Four of the five lattice unit cells considered in the automated structure-generation algorithm. Each hexahedral unit cell is comprised of eight mutually-orthogonal unit lattices.**

A “continuum-equivalence” approach, developed by Ostoja-Starzewski and Wang to characterize the general anisotropic continuum-equivalent constitutive properties of composite fiber networks based on stored strain energy (a variation of homogenization), was used here for determining the necessary constitutive relations of the identified unit-lattice structures (Ostoja-Starzewki & Wang, 1989) (Stahl & Cramer, 1998).

$$(2) \qquad \left(U_{\text{"black box"}}\right)_{\phi_{i,j,k}} \cong \frac{1}{2}\left\{D_b\right\}^T \left\{R_b\right\}_{\phi_{i,j,k}} = \frac{1}{2}\left(\forall_b\right)\left\{\varepsilon\right\}^T \left\{C_{eff}\right\}_{\phi_{i,j,k}} \left\{\varepsilon\right\}$$

The population of the resultant-force matrix, {Rb}, of Equation 2 required the application, through finite-element analyses (FEA), of the six, independent, prescribed, strain states of a unit lattice. From this strain and resultant-nodal-force data, for various geometric configurations of each unit lattice, their geometry-dependent constitutive relations could be determined.

## III. Results

### *A. Unit-Lattice Characterizations*

Preliminary analyses indicated that the solid, Isotropic Material with Penalization (SIMP) approach, used by the two leading commercial software suites (Altair's Optistruct® and VR&D's Genesis®), did not accurately represent the performance of the simple orthogonal "Jack" unit lattice, or "Cube" unit cell (Knier, 2009). Shown in Figure 7, there are significant discrepancies between the actual unit-lattice properties and the exponential SIMP relation, necessitating the complete characterization of the unit lattices to be fabricated for accurate representation.

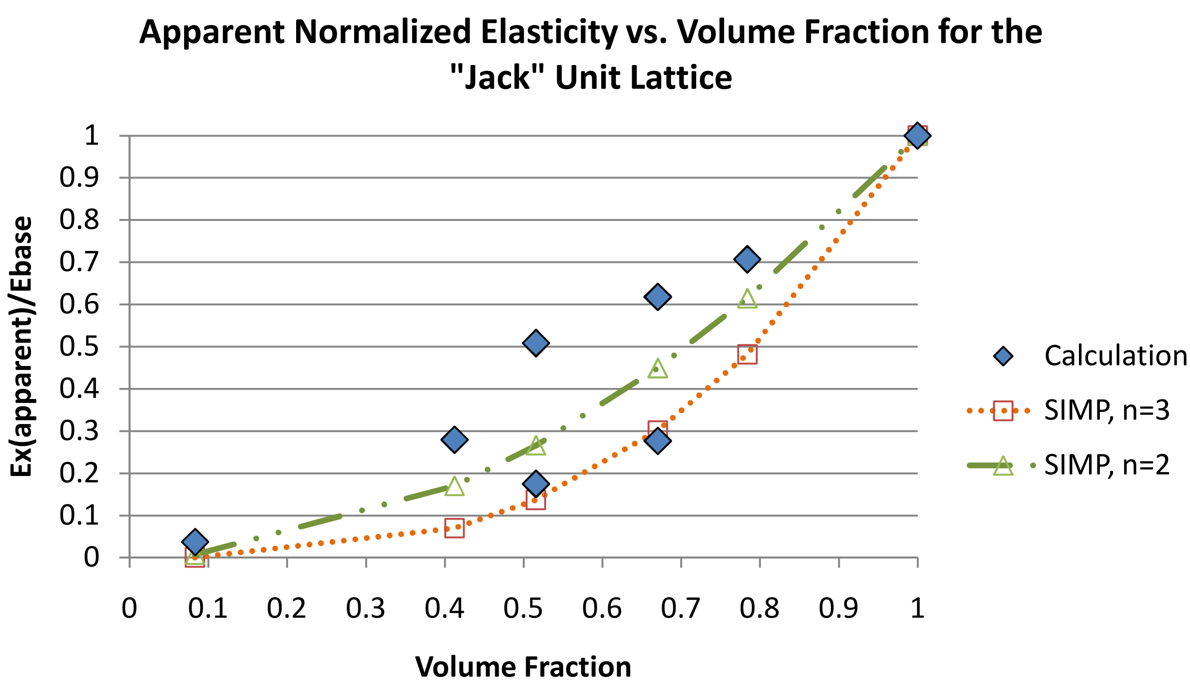


**Figure 7: Normalized Ex elasticity for the "Jack" unit lattice for a range of volume fractions resulting from varying combinations of orthogonal-strut diameters. Curves for the SIMP relation are also shown for comparison.**

Using nine different geometry configurations, i.e. x, y and z-strut diameters, the effective constitutive components were tabulated within Microsoft Excel, that has an integrated tool, Linest, for multi-variate regression. For example, assuming a 2nd-order, homogeneous, cross-multiplied polynomial for the “Super Cube" (Equation 3):

(3) $$E_x = 2.12e7\Phi_x^2 + 7.5e6\Phi_y^2 + 7.47e6\Phi_z^2 + 2.63e5\Phi_x\Phi_y + 2.91e5\Phi_x\Phi_z - 3.78\Phi_y\Phi_z$$

This regression process was repeated for all of the orthotropic properties of each of the unit-lattice structures; $E_x$, $E_y$, $E_z$, $G_{xy}$, $G_{yz}$, $G_{xz}$, $\nu_{xy}$, $\nu_{yz}$ and $\nu_{zx}$. Table 1 shows a comparison of two of the constitutive components, $E_x$ and $G_{xy}$, for each of the five unit lattices under consideration for equal orthogonal geometries. The “Ultra” and “Super” cubes have the highest components for this selected configuration.

**Table 1: Comparative, effective, constitutive components for the five unit lattices of consideration having equal orthogonal strut diameters. The Octet Truss has no vertical strut, hence zero.**

| Type | Φx (mm) | Φy (mm) | Φz (mm) | Ex (GPa) | Gxy (GPa) |
|---|---|---|---|---|---|
| Cube ("Jack") | 5.08 | 20.32 | 20.32 | 55.3 | 33.1 |
| Super Cube | 5.08 | 20.32 | 20.32 | 168.3 | 65.7 |
| Ultra Cube | 5.08 | 20.32 | 20.32 | 178.1 | 65.5 |
| Modified Super Cube | 5.08 | 20.32 | 20.32 | 95.8 | 36.3 |
| Octet | 5.08 | 20.32 | 0 | 85.5 | 32.0 |

Note that these values must be considered along with the structure’s volume fraction. While the “Super Cube” is significantly stiffer than the “Cube,” it is also more massive. These are the considerations to be made by the automated unit-lattice selection and sizing algorithm that is currently under development

## IV. Next Steps

1. ***Completion of Automation***
   The automated selection, population and sizing of other unit lattice elements into conformal geometries will be finalized. Additionally, considerations for the limitations of the selected AM technology will be included, e.g. minimum feature dimensions, layer thickness, etc.

2. ***Continue Characterizations***
   The unit-lattice structures will continue to be characterized for their performance in heat conduction/convection and acoustic absorption. Additionally, two-material composites will be considered.

3. ***Continue Development***
   Support will be sought to continue the development of the non-iterative optimization routines, to include; computational geometry, parallel processing, multi-disciplinary design optimization and meshless methods.

4. ***Compare Performance***
   Comparative determination of performance gains for the new algorithm will then be made against topology optimization and genetic algorithms.

5. ***Conduct Testing***
   Once components are designed and fabricated, physical testing is required to validate the design algorithm(s).

## V. Conclusions

The "Onion-skin" approach demonstrated the feasibility of defining variable-density geometry from topology optimization results; and, semi-automated structure definition and sizing were demonstrated with the "stress-field-directed" approach. Neither of these structures, however, was completely optimized.

The non-iterative method holds the greatest potential for multi-disciplinary structural optimization; but, the algorithm must be completed before testing can be conducted. To this end, the unit lattices under consideration for this method must also be completely characterized for all anticipated functional requirements, such as; load bearing, thermal management and acoustic absorption. Once this algorithm is completed, structures can be fabricated and physically tested; and, performance comparisons can be made against topology-optimization and genetic algorithms.

## VI. Aknowledgements


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- ☐ James Mallmann, Ph.D. (MSOE) – Physics insights.


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