

Cellular Structures for Optimal Performance

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Abstract

Cellular material structures, such as honeycombs and lattice structures, enable unprecedented stiffness and strength characteristics, for a given weight. New design and CAD technologies to construct cellular materials are presented in this paper. Such materials have very complex geometries, hence the need for additive manufacturing processes to produce them. A series of experiments was performed to build and test parts fabricated using Selective Laser Sintering. Variations in mechanical properties were quantified and related to processing conditions. Examples help illustrate the variety of applications of cellular materials in the aerospace, automotive, motorsports, energy, electronics, and related industries. A software tool is being developed to enable users to design and construct parts with cellular structures.

Keywords: cellular materials, conformal lattice structures, selective laser sintering, additive manufacturing.

1 INTRODUCTION

1.1 Cellular Materials

The concept of designed cellular materials is motivated by the desire to put material only where it is needed for a specific application. From a mechanical engineering viewpoint, a key advantage offered by cellular materials is high strength accompanied by a relatively low mass. These materials can provide good energy absorption characteristics and good thermal and acoustic insulation properties as well [1]. Cellular materials include foams, honeycombs, lattices, and similar constructions. When the characteristic lengths of the cells are in the range of 0.1 to 10 mm, we refer to these materials as mesostructured materials. Mesostructured materials that are not produced using stochastic processes (e.g. foaming) are called designed cellular materials. In this paper, we focus on designed lattice materials.

Cellular materials have a biomimetic - or bio-inspired - origin. Many naturally occurring materials have a porous construction that enables them to be light, stiff or compliant, and multifunctional, for example to conduct heat well or to convey fluids and nutrients. Ashby and co-workers [7] provide a good motivation for the study of cellular materials: “When modern man builds large load-bearing structures, he uses dense solids; steel, concrete, glass. When nature does the same, she generally uses **cellular materials**; wood, bone, coral. There must be a reason for it.” In this context, the term “cellular” does not just mean that the material is composed of living cells; rather it refers to the construction using struts, webs, pores, and/or channels.

In the past 10 years, the area of lattice materials has received considerable research attention due to their inherent advantages over foams in providing light, stiff, and strong materials [1]. Lattice structures tend to have geometry variations in three dimensions; some of our designs are shown in Figure 1. As pointed out in [5], the strength of foams scales as $\rho^{1.5}$, whereas lattice structure strength scales as ρ , where ρ is the volumetric density of the material. As a result, lattices with a $\rho = 0.1$ are about 3 times stronger than a typical foam. The strength differences lie in the nature of material deformation: the foam is governed by cell wall bending, while lattice elements stretch and compress. The examples in Fig. 1 utilize the octet-truss (shown on the left), but many other lattice structures have been developed and studied (e.g., kagome, Kelvin foam). We have developed methods for designing lattice mesostructure for parts [8,10] and have developed design-for-manufacturing rules for their fabrication in SL.

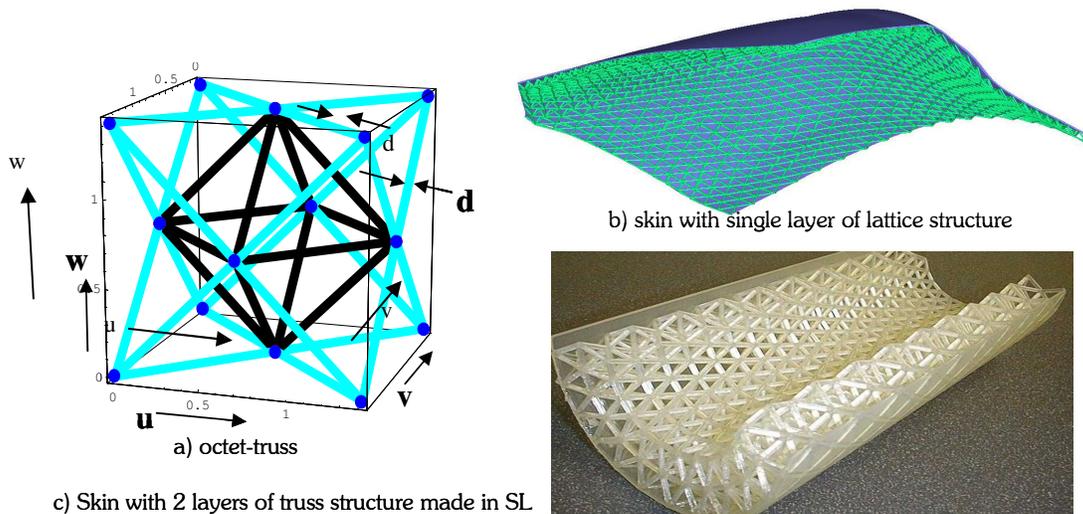


Figure 1. Octet-truss unit cell and example parts with octet-truss mesostructures.

1.2 Design for Additive Manufacturing

Design for manufacturing (DFM) has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize costs. However, the improvement of rapid prototyping, or Additive Manufacturing (AM), technologies provides an opportunity to re-think DFM to take advantage of the unique capabilities of these technologies. Several companies are now using AM technologies for production manufacturing. For example, Siemens, Phonak, Widex, and the other hearing aid manufacturers use selective laser sintering (SLS) and stereolithography (SL) machines to produce hearing aid shells, Align Technology uses stereolithography to fabricate molds for producing clear braces (“aligners”), and Boeing and its suppliers use SLS to produce ducts and similar parts for F-18 fighter jets. In the first three cases,

AM machines enable one-off, custom manufacturing of 10's to 100's of thousands of parts. In the last case, AM technology enables low volume manufacturing and, at least as importantly, piece part reductions to greatly simplify product assembly. More generally, the unique capabilities of AM technologies enable new opportunities for customization, improvements in product performance, multi-functionality, and lower overall manufacturing costs. These unique capabilities include:

- **Shape complexity:** it is possible to build virtually any shape, lot sizes of one are practical, customized geometries are achieved readily, and shape optimization is enabled.
- **Material complexity:** material can be processed one point, or one layer, at a time, enabling the manufacture of parts with complex material compositions and designed property gradients.
- **Hierarchical complexity:** hierarchical multi-scale structures can be designed and fabricated from the microstructure through geometric mesostructure (sizes in the millimeter range) to the part-scale macrostructure.

In this paper, we cover two main topics. First, we are interested in developing geometric construction methods that enable designers to take advantage of the shape complexity capabilities of AM processes. Specifically, we develop a method for constructing cellular materials that conform to the shapes of part surfaces; when restricted to lattice structures we call such constructs Conformal Lattice StructuresTM (CLS). Second, we quantify the variations in mechanical properties of CLSTM designs seen in parts fabricated by Selective Laser Sintering (SLS).

2 PARAMOUNT AND GEORGIA TECH COLLABORATION

Paramount and Georgia Tech first started collaborating in Fall 2006 to study conformal lattice structures and to explore their potential in aerospace and related industries. Concisely stated, our objectives included 1) developing cellular structure design and manufacturing technologies, 2) identifying applications, 3) protecting intellectual property related to cellular structure design and manufacturing, and 4) commercializing these technologies.

At the time, Georgia Tech had software and design technologies to generate conformal lattice structure that could be applied to simple surfaces. It was not possible to create CLS on arbitrarily complex surfaces or to fill arbitrary volumes with CLS. Paramount had extensive experience with SLS technologies and materials, but had not experimented with cellular structures to any large extent.

In the first year, Paramount and GT studied the strength and stiffness characteristics of several types of lattice structures. We conducted many finite-element analyses of lattice structures under various loading conditions. We identified the Cantley truss [2] as a being very efficient for stiffness and strength. The octet was reasonably good for some loading conditions, particularly when bending was prevalent.

In the second year, we embarked on a two-part approach. First, we wanted to develop software that could create CLS on any surface or to fill a complex-shaped volume. Second, we wanted to identify process parameters and conditions to enable the manufacture of CLS with SLS machines. In particular, it was important to identify how small lattice struts could be fabricated and to determine process conditions that enabled their fabrication. As a by-product of these efforts, we also have insight into the failure mechanisms of CLS that provide progressive,

gradual failure, instead of catastrophic fracture. Each of these two avenues of work will be reported in this paper.

3 CLS DESIGN METHOD

The basic idea of how cellular materials are created is presented here. Four example primitive cell types are shown in Figure 2, three of which are lattice structures and the fourth is a foam. These cell types are 2-dimensional for simplicity of presentation. The octet lattice in Figure 1a is an example 3-D cell type. Lattice structures consist of a set of struts (beams) that connect the nodes of the lattice.

To generate the cellular designs in Figure 1, the primitive cell types must be mapped into a mesh. In 2-D, the mesh consists of a set of connected quadrilaterals. In 3-D the mesh consists of hexahedra (6-sided volume elements with planar sides). The uniqueness of our work is our use of conformal cellular structures, rather than uniform “lattice block” materials, that can be used to stiffen or strengthen a complex, curved surface. To see the difference between conformal and uniform structures, Figure 3a is an example uniform lattice structure, while Figure 3b shows a conformal lattice. Meshes for uniform structures consist of cube elements in 3-D (squares in 2-D), while for conformal structures, the mesh elements are general hexahedra. We have developed a new algorithm for generating conformal meshes that are used to create conformal lattice and cellular structures. An older algorithm for generating conformal lattice structures based on a mapped meshing approach [10] has been updated significantly. For our CLS meshes, we prefer that mesh elements are as cubic as possible; i.e., are of uniform thickness and uniform size. Such meshes are typically not generated by the free meshing methods in finite-element analysis codes, while typical part geometries are too complex for mapped meshing methods.

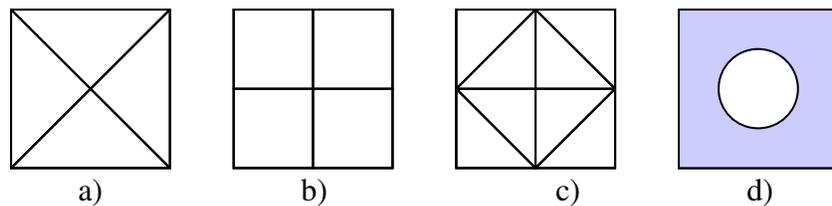


Figure 2. Cellular primitives: three lattice structures and one web structure.

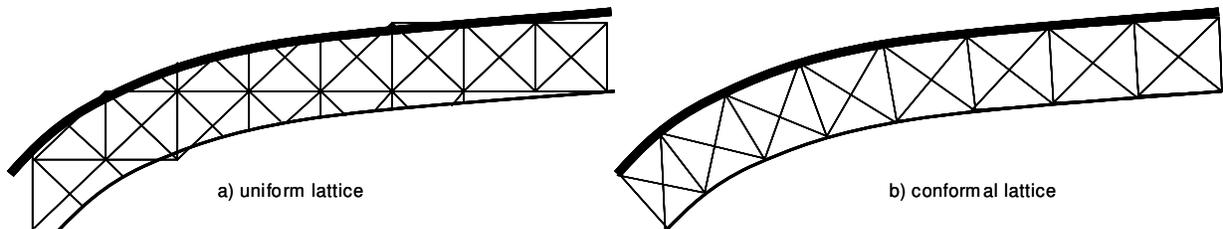


Figure 3. Uniform and conformal lattice structures.

3.1 CLS Construction Method

The overall method for generating conformal cellular structures is shown in Figure 4. It consists of two main steps, indicated by the shaded rectangles: computing 3D conformal mesh,

and populating the mesh with cells. Inputs and outputs of the steps are shown as ovals. Each step is detailed below.

The objective of the meshing algorithm is to generate a conformal hexahedral mesh into which cells from the cell library can be placed. One or more layers of cellular structure can be placed to support the part's skin. The input to the algorithm may be a CAD solid model of the part, a surface model of the part, or a triangulated surface model of the part. The triangulated surface model is very common in the rapid prototyping industry; it is known as an STL model and consists of a collection of triangles that approximate the curved surfaces of the part CAD model. A method of constructing solid and STL models of lattice structures was presented in [9]; the method utilized the conformal lattice generation algorithm from [10].

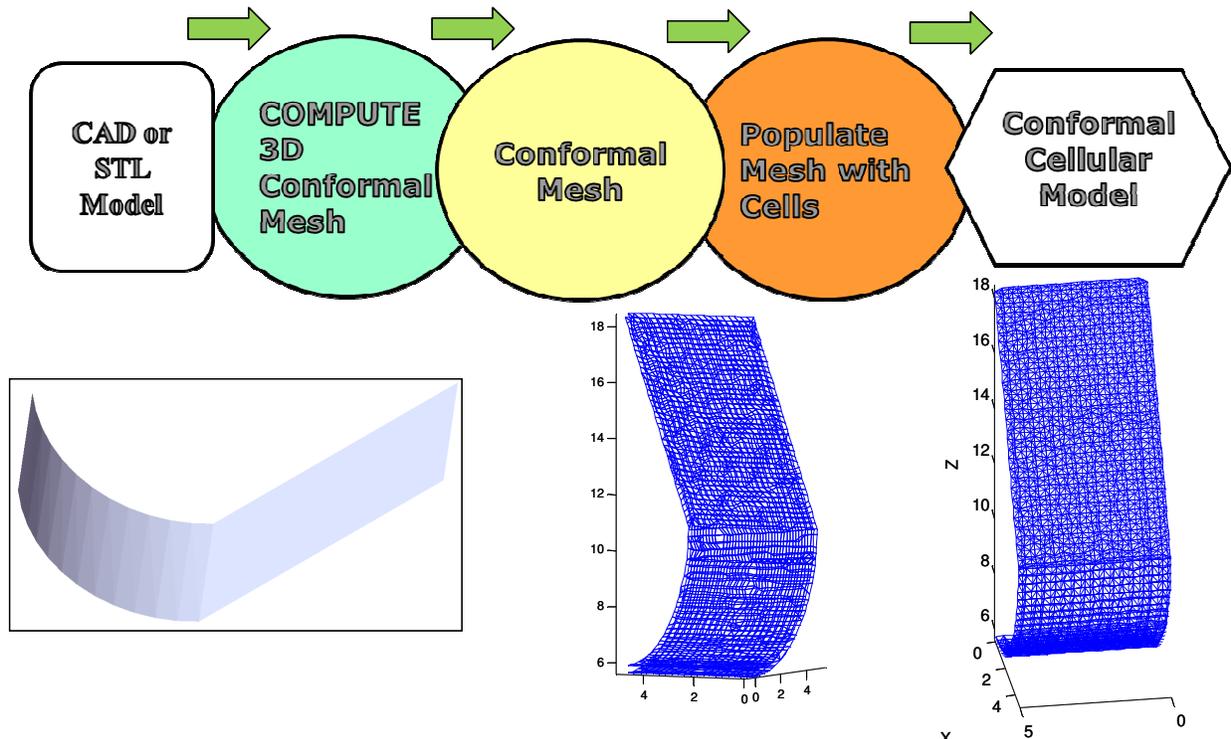


Figure 4. Method for CLSTM construction.

3.2 Construct 3D Conformal Mesh

The algorithm to generate a 3-D conformal mesh is shown in Figure 5. The first step is to divide the part boundary into regions, each of which is relatively flat. It is easier to control the mesh generation method if regions are flat. We implement an absolute angular deviation measure between surface or triangle normal vectors to determine if that surface or triangle should be added to the region being generated. For the purposes of presentation, we will assume that a STL file was given. Then, one triangle is chosen as the first triangle of a region. The normal vector of each connected triangles is compared to the normal of the first triangle; if they differ by less than a given tolerance, the triangle is added to the region. As an example, the tolerance for the simple part in Figure 4 was chosen so that the model consists of two regions: the cylindrical surface and the planar surface.

For each region, three main steps are performed as indicated by lines 3, 4, 5 of Figure 5. The first of these steps is to compute the offset of the object boundary. An offset is a collection of points that are at a specified distance away from the starting surface (distance is called the offset distance). As an example, an offset of a circle is a circle that is concentric with the first circle. If you want the offset of a circle of radius 10 inches centered at the origin, and the offset distance is 1 inch, you would get a circle of radius 11 inches also centered at the origin. The offset of the curve from Figure 3 is shown in Figure 6. The positive offset curve (shown with a long-dashed curve) is offset in the direction of the original curve's normal vector. Generally speaking, a positive offset results in a larger object, while a negative offset results in a smaller object. Offsets are standard geometric modeling operations that are typically available in mechanical CAD systems. We use an offset method developed for tessellated part surfaces [3], but any offsetting method could be applied.

Algorithm Construct Conformal Mesh

Input: CAD or STL model, desired element size

Output: hexahedral mesh that conforms to the outer surface of the given model

1. Partition part model into relatively flat regions.
 2. For each region,
 3. compute offset of region boundary
 4. construct tri-parameter volume
 5. divide parameterized volume into hexahedra
 6. End for each region.
 7. Ensure region boundaries match.
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Figure 5. Algorithm for constructing a conformal mesh.

The second step is to construct a tri-parameter volume between the original surface and its offset. Conceptually, this is simpler than it may sound. Typically, curves and surfaces in CAD systems are defined using parametric equations. For example, the curve in Figure 6 would be parameterized by one parameter, u , that varies from 0 to 1, as in the well known Bezier, B-spline, or NURBS curves. Surfaces are parameterized using two parameters. Volumes are parameterized using three parameters and, hence, are called tri-parametric solids. This step of the algorithm assumes that the original boundary surface of the object is parameterized. The same parameterization is transferred to the offset surface. Finally, a lofting is constructed from the original surface to the offset surface. Parameterized equations and the operations of lofting and offsetting are all standard, well known geometric operations in the field.

However, a complication arises since the original boundary surface of the object consists of triangles. That is, the original boundary surface, which was assumed to be parameterized in the paragraph above actually is not parameterized. Hence, a parameterization must be

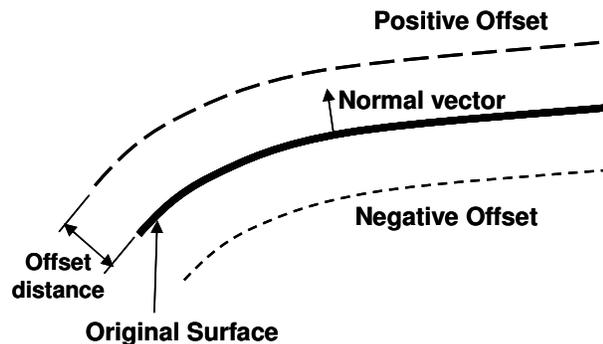


Figure 6. Positive and negative offset curves of a curve.

developed, the details of which are presented in [6].

The third step is to generate the conformal mesh by dividing the parameterized volume into individual elements (hexahedra). This is a very straightforward step. After selecting either the number of elements or their typical size, increments in each of the three parameters are computed, which are used to generate elements of the mesh. For example, if the increment in u is chosen to be 0.1, then 10 elements in the u direction will be generated, since $(1 - 0) / 0.1 = 10$. Note that the numerator of the expression $(1 - 0)$ is the difference between the maximum and minimum u values. By successively incrementing each of the three parameters that define the tri-parametric volume, mesh elements are created.

The final step in Algorithm Construct Conformal Mesh (line 7) is to ensure that region boundaries match by adjusting node positions and by adding elements, if necessary. Since the regions are parametrized separately, the hexahedral elements may not match well. Nodes from neighboring regions may be moved and merged to achieve matched boundaries. Also, a series of hexahedral or tetrahedral elements may be added in gaps between meshes in neighboring regions [6].

3.3 Construct CLS

The algorithm for the second step (populate mesh with cells) of the overall conformal cellular structure design method from Figure 4 is shown in Figure 7. One input to the algorithm is the conformal hexahedral mesh that was generated in the first step. The other input is the cell types contained within a library. The first step is to partition the mesh elements into regions such that within each region the loading conditions are similar on each element. These need not be the same regions that were used for mesh construction. For each region, a cell type from the cell type library is selected to populate the mesh elements in that region. The idea is to match the region's loading conditions to the cell type, such that the cell type is effective at supporting the loading conditions. In this manner, the resulting cellular structure is more likely to be lighter for a given level of stress or deflection. The dashed gray box surrounding the "Select Mesh Elements" and "Select Cell Types" operation boxes indicate that these operations may be performed concurrently or maybe performed sequentially, depending upon the designer's preference. Note that each of the Select operations may be performed automatically by an algorithm or may be performed by the designer directly.

The final step in Figure 7, "Apply Selected Cell Types to Selected Mesh Elements," is where the actual cellular geometric model is constructed. This operation has been called population of mesh elements earlier. This operation is straightforward. One simply maps a cell type into a mesh element. Since both the cell type and the mesh element are defined parametrically, a simple parametric mapping algorithm can be applied to directly construct cell geometry.

To construct a STL or solid model of the CLS, additional geometric construction operations must be performed. We utilize the approach described in [9], where solid models of the half-struts incident at each node of the mesh are constructed using Boolean operations in a solid modeling system. Then, each solid "node" is tessellated and the triangles are written to a STL file.

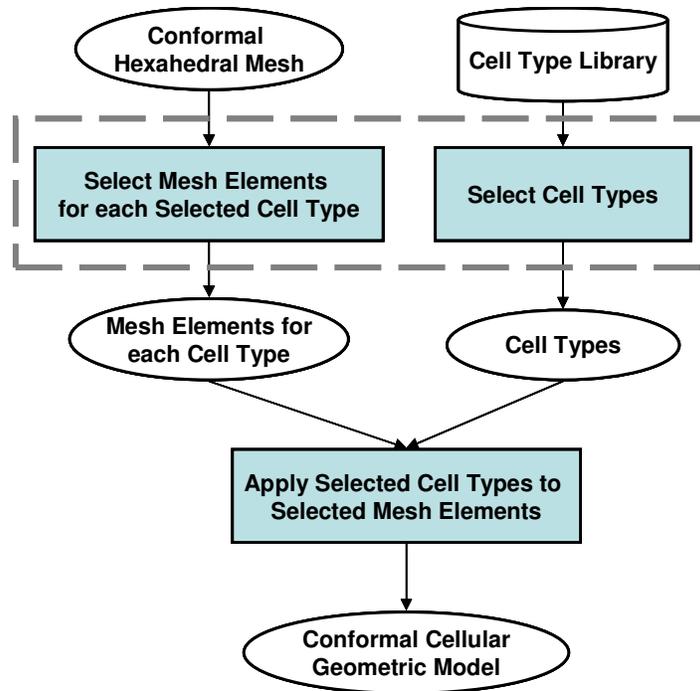


Figure 7. Algorithm to compute the conformal cellular geometric model.

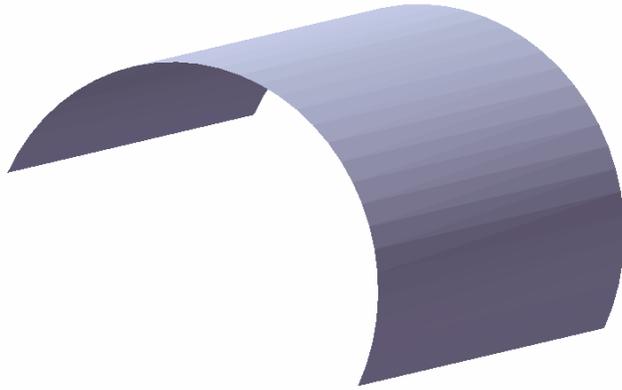
The resulting conformal cellular geometric model can be subjected to optimization methods in order to reduce weight, increase strength, increase stiffness, achieve some other objective, or achieve some combination of objectives. Such methods have been applied by a number of research groups [4,11].

4 EXAMPLE OF CLS CONSTRUCTION METHODS

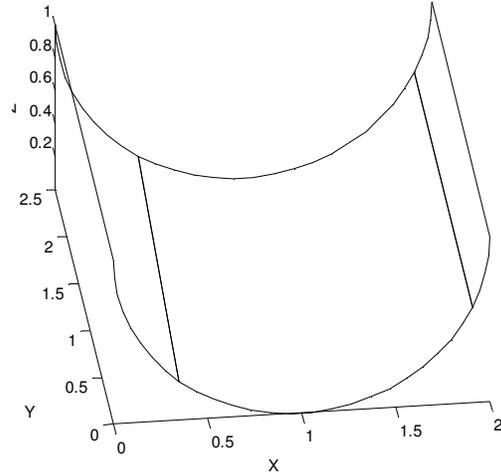
As an example, a simple cylindrical surface will be stiffened by one layer of conformal lattice structure using the method presented in Section 3. Figure 8a shows the original cylindrical surface defined by a STL file. The surface is 2 units in diameter and 2.5 units long. Constructed lattice structure is intended to be 0.25 units on a side. With an angular deviation measure of 50 degrees, the surface is partitioned into three regions, as shown in Figure 8b. A quadrilateral mesh is created in each region, then the mesh boundaries are adjusted and merged. The result is shown in Figure 8c, where the different colors indicate the different regions. After offsetting the surfaces and mesh, the tri-parameter volumes and hexahedral mesh can be constructed (Figure 8d). The final step is inserting lattice geometry into each mesh element, resulting in the CLS model shown in Figure 8e.

5 SLS FABRICATION

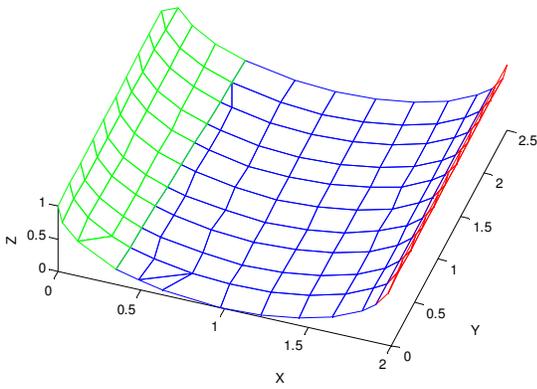
The concept of reinforcing components with CLS has an inherent fabrication challenge due to the complexity of the geometries and features that are impossible to manufacture via conventional fabrication process. Indirect casting techniques can generate some complex CLS from a master pattern, but the approach is very expensive, time consuming, and requires a lot of trials before an accurate part can be achieved. SLS technology has become one of the most acceptable additive manufacturing technologies for the fabrication of end-use parts and functional components. In addition, the increasing number of composite materials available for



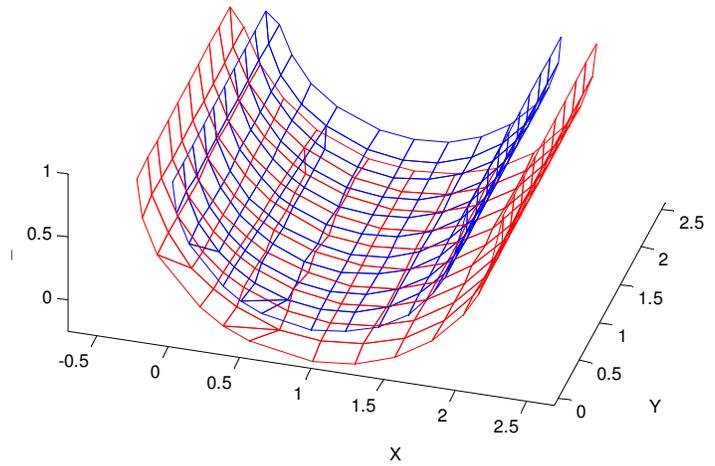
a) cylindrical surface



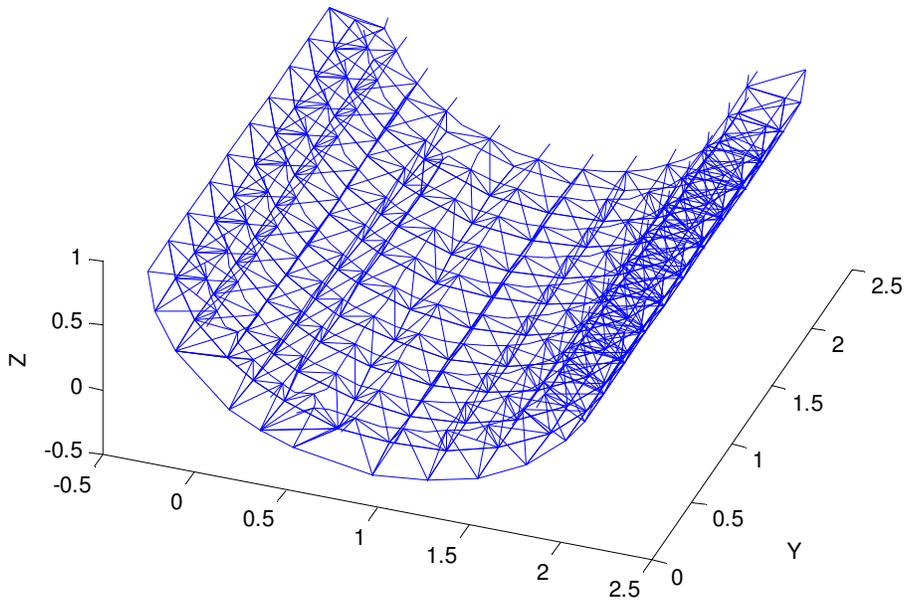
b) surface partitioned into 3 regions



c) quadrilateral mesh on regions



d) offset surface and 3D hex mesh



e) resulting conformal lattice structure

Figure 8. Example of CLS construction method.

SLS made this technology and ideal candidate for the fabrication of engineered components optimized with CLS.

Paramount Industries Inc. identified a part on an unmanned air vehicle (UAV) with properties and a geometry suitable for reinforcement and optimization with CLS. The part has a characteristic saddle surface and serves as a hatch-cover on the UAV. The CAD files of this part were optimized using the design algorithms from Georgia Tech. Figure 9 illustrates the hatch-cover files ready for SLS fabrication after optimization with CLS.

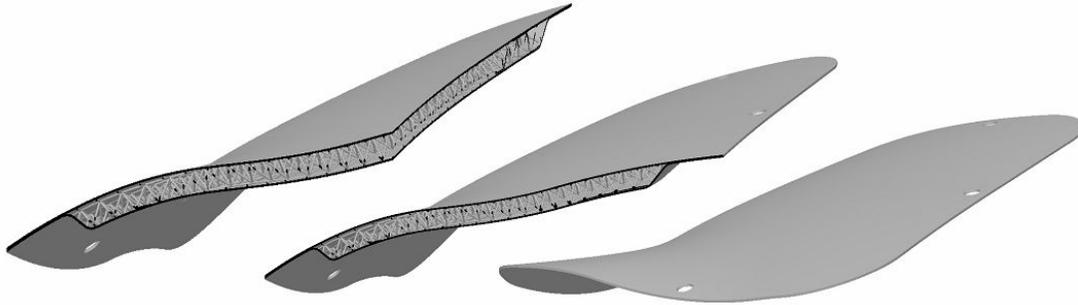


Figure 9. Paramount Industries Inc. Hatch-Cover Component Reinforced with CLS

Paramount Industries Inc. successfully fabricated the hatch-cover via SLS and developed internal processes to overcome the many significant challenges when considering SLS for the fabrication of CLS. The SLS process has 4 variables that are extremely critical when the requirement is repeatable mechanical performance from a truss-like structure made out of struts that are ~1-mm thick. The most critical variable is the spatial orientation of the CLS during fabrication. Any CLS has an optimal orientation in the x-y-z plane which yields the best mechanical response when compared to FEA models performed prior to fabrication. The next three most important variables of our SLS process are laser power, scan-speed or hatch speed, and scan-spacing or hatch distance. Other critical process variables include the material quality, heat distribution, laser beam profile, the control of scales-and-offsets, and outline settings.

The SLS-CLS process was dialed-in by testing the effect of orientation on the mechanical properties of parts; this study used 64 samples. The orientation and position of each sample was recorded and the test analyses of the first 8 samples revealed the optimal orientation. Mechanical test results, however, showed significant inconsistencies which were determined to originate from multiple process variables. The parts were labeled according to their position (top or bottom, left or right, and front or back) so the first sample in Figure 10 “TLF” for example refers to the hatch-cover on the Top-Left-Front corner.

The preliminary test results for the first 16 samples are presented in Figure 10. These test results show inconsistencies in the failure mode of the struts. The parts were fabricated in 2 layers with 4 parts per layer. The stress-strain curves for the compression loading samples show gradual drops during the loading cycle which relate to the fracture failure of a complete row of struts within the lattice structure. This failure mode indicates a variation of mechanical properties among different struts. Using infrared imaging equipment and thermocouple sensors it was determined that the build envelop and the machine had hot and cold spots that had to be improved before uniform properties could be achieved. It was also determined that the parts on top created thermal gradients that affected the mechanical properties of the parts at the bottom of the cake.

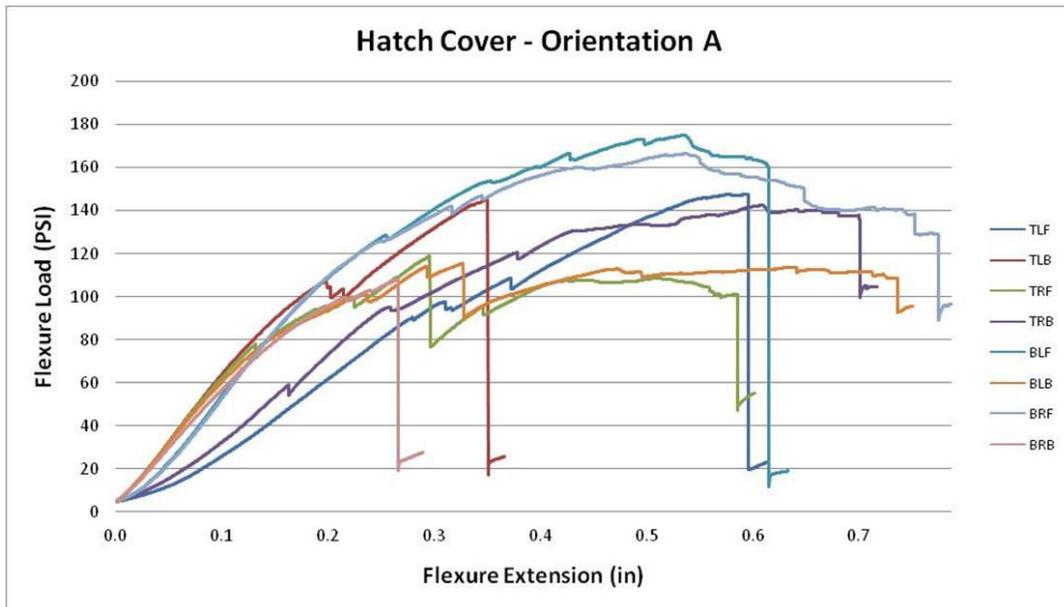


Figure 10. Hatch Cover Test Results Orientation A – No Process Optimization

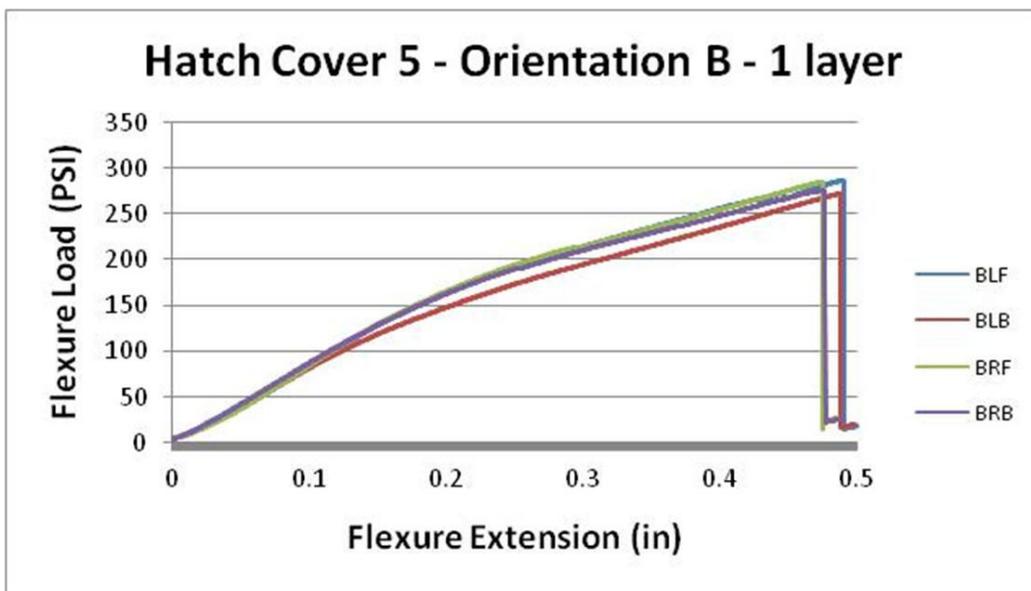


Figure 11. Hatch Cover Test Results Orientation B – With Process Optimization

The next sets of hatch-covers were fabricated after all the process parameters and variables were dialed-in, optimized, and measured. Figure 11 shows the mechanical results of the compression loading test after the process optimizations. The significant difference is not only the shape of the stress-strain curve during the compression loading cycle and the repeatability of results, but also the maximum flexural load before failure going from 120 psi on results from Figure 10 to about 270 psi after optimization of orientation and processing parameters.

6 CONCLUSIONS

Methods to construct cellular material structures, specifically conformal lattice structures, were presented in this paper. Their fabrication using SLS was described and it was shown that process conditions and settings have a significant impact on mechanical properties of fabricated structures. Based on this work, the following conclusions can be made:

- the presented CLS construction methods produced lattice structures on a wide variety of surface shapes, demonstrating the generality of the methods;
- these methods produced CLS that was of high quality, as measured by aspect ratios, skew, and related metrics, as well as of nearly uniform size;
- the geometric construction methods resulted in standard STL files that have been built in several AM machines, including stereolithography and SLS machines;
- mechanical properties of CLS are highly dependent on appropriate part orientation, as well as process variables of laser power, scan speed, scan spacing, and several others; by fine-tuning these variables it is possible to repeatedly build arrays of CLS parts with consistent, good mechanical properties.

Future work includes converting the CLS construction software from Matlab to C++ and integrating the software with commercial CAD systems so that it can be disseminated and commercialized easily. Additional lattice structure types must be added to the cellular material library. More investigation into the SLS fabrication of CLS is needed so that little, if any, experimentation is required to build a new CLS design.

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