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Application of Systems Engineering to Lattice Structure Design: A Framework for Requirements Flow Down

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Abstract

In the field of additive manufacturing, highly ordered cellular structures with repeating patterns in space, known as lattice structures or simply "lattices", have been shown to significantly improve the performance per unit mass of engineered components compared to traditionally machined designs. The characteristics of these lattices are dependent on many design decisions, leading to challenges in determining how to best utilize them. This issue is further complicated when the density, size, and topology of the lattice can spatially vary in the design domain. Many methods have been proposed to optimally distribute material within a lattice structure; however, these methods exist in a bubble, independent of broader engineering design criteria and processes. In this paper, we introduce a framework based on systems engineering to guide the design of lattice structures using the component requirements as inputs and outputting a verified and validated design based on those requirements. The framework translates component requirements down to the lattice structure and provides a means to verify and validate that the final design meets those requirements. We provide a walk-through of the framework by designing a lattice structure for an oil and gas component, and discuss future research to extend, verify, and validate the framework.

1 INTRODUCTION

Additive Manufacturing (AM) allows for the realization of greater freedom and complexity in design by offering access to previously *untapped design space* during the manufacturing process [1]. One type of complexity that is enabled by AM is *hierarchical complexity* where the features of the geometry are composed of one or more levels of smaller features [2]. This hierarchy can be achieved by incorporating cellular solids into the component [3]. Cellular solids are hierarchical materials that contain two or more phases; they are found both in natural materials such as wood and bone, as well as engineered materials including foams [4]. AM has enabled the creation of cellular solids with much greater control over their geometry compared to traditional engineered foams [5]. Highly-ordered cellular solids with repeating geometric patterns are known as *lattice structures* or simply lattices [6]. Integrating lattices into engineering designs offers the potential for significant reduction in weight compared to those designed for traditional manufacturing [7]. In

addition to reducing the amount of material consumed by the AM process, lattices can also reduce manufacturing time as the volume of deposited material directly correlates to manufacturing time for most AM processes, both of which directly relate to the total cost of production [8].

Lattice structures contain repeating patterns and can be generated by patterning a small portion of the structure in space. The smallest portion of the structure that can be patterned to produce a given lattice is known as its *unit cell*. The unit cell is often used in discussion and comparison of different lattice typologies. Unit cells can also be used to compute the *homogenized properties* of the lattice because of the repeating nature of the structure [9].

The hierarchical complexity of AM lattices offers unique challenges related to modeling, analysis, and inspection of the lattices due to the significant number of small features relative to the size of the whole component – this leads to a large number of elements needed to accurately represent the features of the lattice for manufacturing, or even more so, during analysis using finite element methods [10]. These three tasks become even more complex when the lattice is non-uniform (spatially varying) or optimized so that each cell of the lattice is tailored to meet the lattice level requirements of the application [11, 12, 13]. The number variables that must be controlled for effective lattice design is a potential reason why lattices have not seen wider adoption in application. Advances in software tools makes the modeling and analysis of lattice structures more accessible [14, 15, 16]. However, this still leaves engineers with a larger number of design decisions that must be made as well as the need to analyze and inspect the complex internal features [17] to verify its required performance.

The unique opportunities and limitations related to AM has given rise to the concept of Design for Additive Manufacturing (DfAM) [18]. Several frameworks or approaches based on DfAM principles and methods have been proposed, both broadly and tailored to specific DfAM opportunities including lattice structure design. For instance, Bikas et al. [19] noted the importance of consideration of DfAM principles early in the design process and proposes a framework that propagates AM process information back through the process to eliminate the need for iteration. Chennamkulam [20] developed a framework using inverse problem solving and a TRIZ-based method methodology to redesign components with DfAM considerations. Li et al. [21] proposed lattice optimization using homogenization to map between the properties and the volume fraction (VF) of a lattice. Y. Wang et al. [22] used topology optimization technique to optimize lattice structures, and C. Wang et al. [23] developed a two-step method of lattice optimization that first uses topology optimization, followed by sizing optimization of the elements of the lattice. Gorguluarslan et al. [24] proposed a two-step optimization first using ground structure optimization, with a secondary step that accounts for limitations of the additive process to produce manufacturable designs. Chen et al. [25] proposed a lattice generation and optimization method using finite element meshing to define the cells of the lattice and the MIST topology optimization scheme to optimize the cells [26]. Vaissier et al. [27] investigated lattice unit cell and parameter selection for static heat dissipation.

These frameworks provide the basis for *designing with lattices* but they lack direction and rigor when integrating components with lattices into a system – a problem that we address in our work herein. Moreover, existing lattice design frameworks do not incorporate considerations

for the selection of unit cell(s) based on the local loading; these decisions are therefore often made without explicit consideration of the performance required of the lattice. It is challenging to draw direct comparisons between different lattice structures because of the variance between studies that publish data (e.g., material properties, lattice parameters, process parameters, sample replicates, testing standards). However, by delaying the unit cell selection until performance requirements have been established, informed decisions can be made, allowing for more optimal material utilization [11]. Recent work to bring together and normalize data from the literature has offered a better understanding of the relative performance of different lattice structures [28]. A database of strut-based unit cells was developed and used in an optimization scheme that selects the topology of each cell in the lattice from the database [29]; however, determining the *independent* effects of most lattice parameters on the material properties is still difficult based on current data.

When it comes to translating requirements from a system to a subsystem or component, several models exist in the literature including the Waterfall [30], Spiral [31, 32], and System Vee [33] models. The System Vee was developed to resolve perceived short comings in prior models, including defining the role of systems engineering in the process [33]. The System Vee has been widely adopted into the System Engineering Process [34, 35]; however, multiple definitions of what the model encompasses and the steps involved exist [33, 35, 36, 37], as is the case with most of these methods.

The System Vee does highlight and accommodate the hierarchical structure of a system that is composed of subsystems and components. Most extensions and adaptations of the System Vee share the same starting point at the top left of the Vee which is the definition of user requirements for the system. These requirements flow down the left side in a process that mirrors the Waterfall model, and on the right side, incremental steps build up to the full system with verification and validation (V&V) [33]. Models at the system level, including the System Vee, do not specify the method for detail design of the subsystems and components of the system, leaving this to the design engineers to select appropriate processes.

Currently, there is no framework for the design of lattice structures within a requirement-driven engineering process. The development of such a framework would enable lattice structures within the design of complex engineering systems. The major contribution of this work to the literature is the development of an accessible, systematic, and extensible framework for using component requirements to inform the design, integration, and V&V of lattice structures. This framework serves as a single engineering process that enables engineers to more readily incorporate lattice design into system design. In Section 2 we introduce the *Lattice Vee Framework* and its steps along with the assumptions necessary to use the framework. To demonstrate the framework, we walk-through with an example component in Section 3. Based on this presentation and demonstration of the Lattice Vee, we discuss the implications and future research directions in Section 4, and end with closing remarks in Section 5.

2 FRAMEWORK BASIS AND DEVELOPMENT

This framework uses hierarchical decomposition drawing parallels between the hierarchical structure of a system composed of subsystems and components, to a component with an integrated

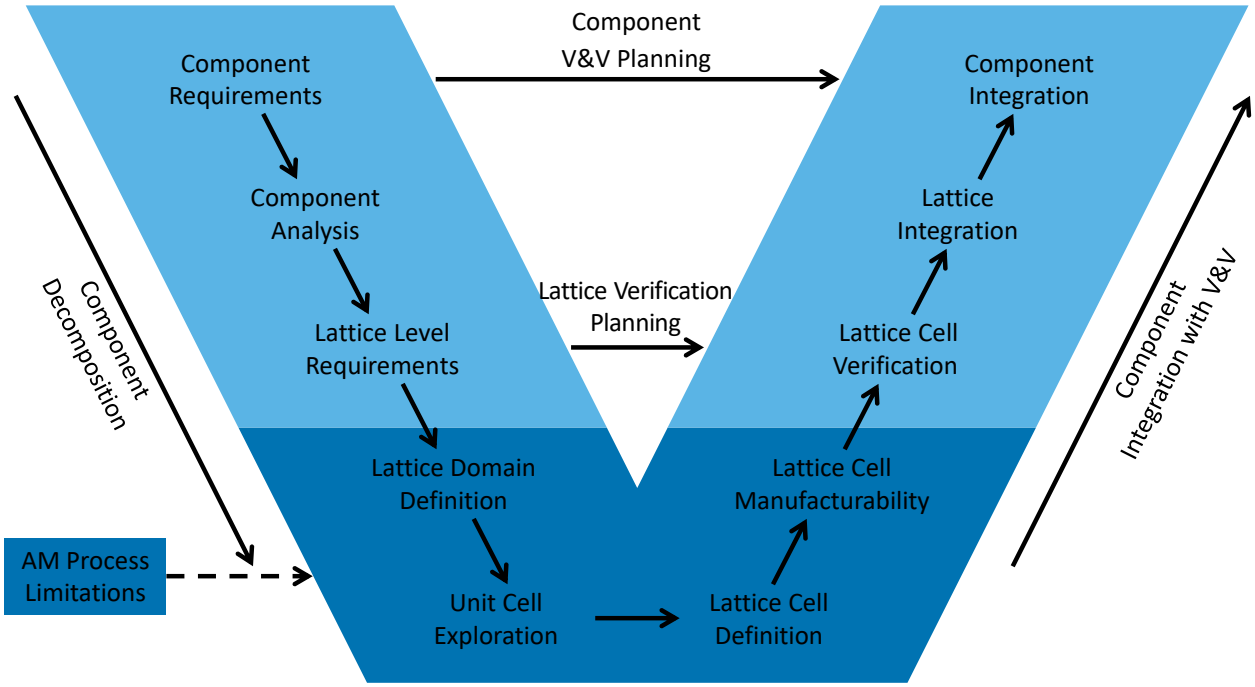


Figure 1: Lattice Vee Framework

lattice structure composed of solid regions and lattice domains that can be broken down further to the individual cells that make up the lattice. In both cases, the performance at the top-level is dependent on the performance of the elements of which it is built. Following systems thinking, it is then possible to follow this process in reverse in our framework and flow down requirements from the component to the cells of the lattice, allowing the requirements to drive design at the next level down in the hierarchy.

While the System Vee model is primarily a *descriptive model* without explicit actions, the Lattice Vee Framework is more *prescriptive*, dictating specific actions at some steps while intentionally omitting others to allow for different methods of defining lattice level requirements, optimization techniques, and levels of complexity in the lattice design. This allows the Lattice Vee to be extensible while providing guidance on specific steps and actions to take. The framework is presented graphically in Fig. 1.

Like the System Vee, moving down the left side of the Lattice Vee moves down a hierarchy, decomposing the component requirements into lattice level requirements that spatially vary across the component domain. At the bottom of the Vee, the detailed design decisions relating to the lattice geometry are made accommodating process limitations and the lattice level requirements. Moving up the right side, the lattice is integrated, verified, and validated against its requirements. Through this process, the Lattice Vee offers a requirement-driven, quantitative means of selecting lattice unit cells and optimizing lattice parameters.

As shown in Fig. 1, the Lattice Vee starts with the component requirements, which should be derived from the requirements one level up in the system hierarchy. In addition to component requirements, the Lattice Vee relies on three pragmatic assumptions for its use.

- Material and AM process are given, or have been selected.
- Component domain is of an appropriate scale for printing with the chosen process/machine.
- Database of sufficient lattice structure properties exists (current limitations discussed in Sections 3.8 and 4).

Note that these assumptions are not intended to and should not limit design freedom; rather, they are necessary to provide information to help traverse and implement the framework.

After establishing the (1) *Component Requirements* and (2) *AM Process Limitations*, and after satisfying the assumptions of the Lattice Vee, the following steps of the framework are performed:

(3) *Component Verification & Validation Planning*, where V&V tasks are defined relating to the component and manufacturing process;

(4) *Component Analysis*, where the component requirements are used to inform analysis of the component;

(5) *Lattice Level Requirements*, where the component analysis is used to define spatially varying material property requirements;

(6) *Lattice Verification Planning*, where verification tasks are defined for the performance of the lattice;

(7) *Lattice Domain Definition* where the lattice sub domain of the component is defined;

(8) *Unit Cell Exploration*, where the lattice unit cell(s) are selected using data driven decisions;

(9) *Lattice Cell Definition*, where the selected unit cells are implemented within the lattice domain with properties based on the lattice level requirements;

(10) *Lattice Cell Manufacturability*, where the cells of the lattice are tested to identify potential issues in manufacturing;

(11) *Lattice Cell Verification*, where the verification of the performance of different cells within the lattice takes place;

(12) *Lattice Integration*, where the cells of the lattice are joined and geometric discontinuities within the lattice are resolved; and

(13) *Component integration*, where the lattice joins with the rest of the component and V&V can be carried out.

The numbering of this list corresponds with the numbering of the following subsections, where each of these steps of the Lattice Vee Framework are discussed in more detail, as well as the numbering in Section 3 which contains a walk-thought of the framework.

2.1 Component Requirements

The requirements for the component flow down from the system level requirements. They serve as the starting point for this framework. Component requirements must include the design domain of the component and performance specifications for the component. This provides the framework the spatial volume in which it can operate, and defines what is trying to be achieved by incorporating lattice structures.

2.2 AM Process Limitations

All AM processes have a unique set of process limitations (e.g. allowable overhang angles, minimum feature sizes, and support removal requirements) [19, 38, 39] that are also effected by the machine, material, and the processing parameters used [39]. In this framework, these limitations are directly applied during the four steps located at the bottom of the Vee that are highlighted in Fig. 1 and discussed in Sections 2.7 to 2.10.

2.3 Component Verification & Validation Planning

Based on the component requirements, a plan for the V&V of the component prior to system integration must be defined. For most AM components, this plan should include production, Non-Destructive Evaluation (NDE), post-processing steps (e.g., heat treatment and machining), material characterization, and physical testing. In addition to these required steps, the plan should include any other performance evaluation needed to ensure that the component requirements are met, allowing for integration into the system design.

2.4 Component Analysis

Requirements of the component are used to inform boundary conditions to be used during simulation and analysis. This simulation will produce a metric or set of metrics for performance of material within the component domain that varies spatially. We do not specify metrics or a method for defining these metrics directly to allow for adaptability to different situations and applications. Metrics could be derived from a wide array of different means including: topology optimization, stress, strain or strain energy, buckling, fatigue, fluid interaction, heat transfer, thermal expansion, or any other relevant quantifiable measure [12, 22, 40, 41, 42, 43].

2.5 Lattice Level Requirements

From the result of the component analysis and the bulk material properties, we can derive the requirements that apply to the material as a function of spatial location. Since the cells of the lattice have not yet been defined, the *lattice level requirements are not specific requirements for each cell of the lattice as the boundaries of each cell have not yet been defined*, but rather, they are the *basis on which the cells will be verified once defined*.

2.6 Lattice Verification Planning

For the verification of the lattice level performance of the lattice structure, we suggest homogenization of the cells into constitutive relationships. Those homogenized properties can then be compared to the lattice level requirements within the volume of that cell. This verification can be applied to all cells or a representative set of cells (based on geometric similarity) to reduce the computational load and increase the speed of iteration and exploration.

Note, we can only compare the performance of the lattice to metrics derived from the component requirements, it is not possible to validate the lattice structure prior to integration with the rest of the component, leaving validation to take place during the component integration (Section 3.13) as planned in Section 3.3.

2.7 Lattice Domain Definition

The lattice domain is the space that remains when the solid regions of the component domain are removed. These solid regions come from three factors: (1) functional surfaces (with thickness) or volumes, (2) lattice level required properties (relative to material properties), and (3) limitation based on what size unit cells, and lattice features, the process and material are capable of producing. The space that remains after these factors are taken into consideration is the lattice domain, which is the volume (or volumes) that the lattice will fill within the component.

2.8 Unit Cell Exploration

The definition of the lattice level requirements and the lattice domain constrains the range of properties required from the lattice structure. Based on this range, this step of the framework calls for a selection of a unit cell, or multiple unit cells that will fill the lattice domain. By leaving the unit cell selection until this point in the process, intuition-based selection can be avoided and the decision can be data driven using a database of lattice properties [28].

2.9 Lattice Cell Definition

Each cell of the lattice must be defined to fill the lattice domain with structure. This includes definition of the size, shape, orientation, and position of each cell, as well as the amount of material in each cell, and how material is distributed within the cell — all of which can vary spatially throughout the lattice domain.

The definition of these different parameters need not happen in this order or serially. As discussed in Section 1, there exist a number of different methods for defining and optimizing a lattice. Therefore, the intent of this framework is not to supplant existing tools, but to offer a means to connect design and optimization of lattices to a requirement-driven design framework and analysis toolchain. To this end, we do not explicitly describe the pathway to defining the lattice parameters.

2.10 Lattice Cell Manufacturability

The unit cells typically used in lattices are generally considered manufacturable with common AM processes; however, the previous step leaves open the potential for significant variance within lattice structure that could lead to significant changes of the geometry. This creates the potential for cells that violate the specific manufacturability limits of the selected process and material combination, even when the original unit cell was manufacturable with the chosen AM process. In this step, the manufacturability of each geometrically unique cell, or a set of cells that adequately represents the different cells of the lattice, should be tested for problems relating to: minimum feature resolution (on material as well as voids), bridging, self-supporting angles, trapped feed stock or material, islands, and pinched off features as well as any other manufacturing or process constraints [44, 45].

2.11 Lattice Cell Verification

As with the manufacturability test in Section 2.10, the homogenization routine used for verification needs to be carried out *for each geometrically unique cell*, or a representative set of cells. A comparison of the homogenized properties of each unit cell to the *lattice level requirements* that fall within that cell (based on the plan developed in Section 2.6). This offers a verification of performance without the need to first integrate, mesh, and analyze the full-scale model of the complex lattice structure, which can be computational expensive [10].

2.12 Lattice Integration

By treating cells of the lattice independently, there is increased potential for sharp corners and transitions that could lead to stress concentrations. Smoothing operations should be applied to mitigate these issues. Although this will change the properties of the cells from the homogenization performed in Section 2.11, this can be done conservatively to avoid weakening the structure and maintain manufacturability. If the modeling technique produces separate geometric bodies within the lattice, then they would also be merged at this step to form a single, manifold geometry.

2.13 Component Integration

With the lattice cells modeled, integrated, and smoothed, the overall lattice structure can be integrated with the rest of the component domain, and the component V&V plan (see Section 2.3) can be carried out. After this step, the Lattice Vee has been implemented, and a manufacturable design that meets the component requirements has been produced, verified, and validated.

2.14 Iteration within the Framework

As with all design processes, iteration within the Lattice Vee may be necessary if the design fails to meet any requirements during the integration of the design. Such iteration could start with any step after “Lattice Cell Definition” leading back as far as “Lattice Domain Definition”. For visual clarity, the Lattice Vee shown in Fig. 1 does not show iteration loops within the framework. This type of iteration within the framework marks an additional departure from the System Vee model.

Table 1: Material properties for Inconel 718 taken from [46]

Young's Modulus	28800 ksi	199 GPa
Yield Stress	125 ksi	862 MPa
Density	0.289 lbm/in^3	8000 kg/m^3

In the System Vee iteration is limited within the process by the control/phase gates used for project management [33].

In addition, the system level design process is not linear and changes to the system level requirements result in changes to the component requirements. This often necessitates returning to the first step of the Lattice Vee. Application of the Lattice Vee framework is discussed next for an oil and gas component with a uniform lattice.

3 WALK-THROUGH OF FRAMEWORK

To demonstrate the application of the Lattice Vee, we present this walk-through of the framework applied to a component used in high pressure applications in the oil and gas industry. This component has been previously demonstrated to be a good candidate for lightweighting with lattice structures [46]. The component has large regions of material that do not significantly contribute to its functionality. Removing this material with a subtractive process would be both time-consuming and wasteful. Meanwhile, the internal passageways that give the part its functionality are difficult to machine, requiring multiple set-ups and operations. With AM, these internal channels are much easier to produce, and the weight of the part could be reduced simultaneously, which would reduce material and production cost.

3.1 Component Requirements

The domain of the component is a cylinder that is 127 mm long with a diameter of 76.2 mm and two non-intersecting internal fluid channels (see Fig. 2). The component must maintain a minimum Factor of Safety of 1.5 under the loads shown in Fig. 2. We take the minimum material thicknesses for the pressurized surfaces from [46] to allow for direct comparison of the lattices. For internal features, the minimum thickness is 5.08 mm, and the minimum thickness for the external cylindrical surface is 7.62 mm. The component is to be manufactured out of Inconel 718 using an EOS M280 Laser Powder Bed Fusion (LPBF) system. We present the material properties used in Table 1. We constrain the cells of the implemented lattice to be uniform for ease of inspection and to mirror the original design.

3.2 AM Process Limitations

Based on the material and process that were specified in the component requirements (see Section 3.1), there are limitations on feature size, unsupported overhanging angle, and bridging distance that impact the design of the lattice structure. For the purposes of this application, we define the limiting values as: 0.5 mm, 40°, and 5 mm, respectively.

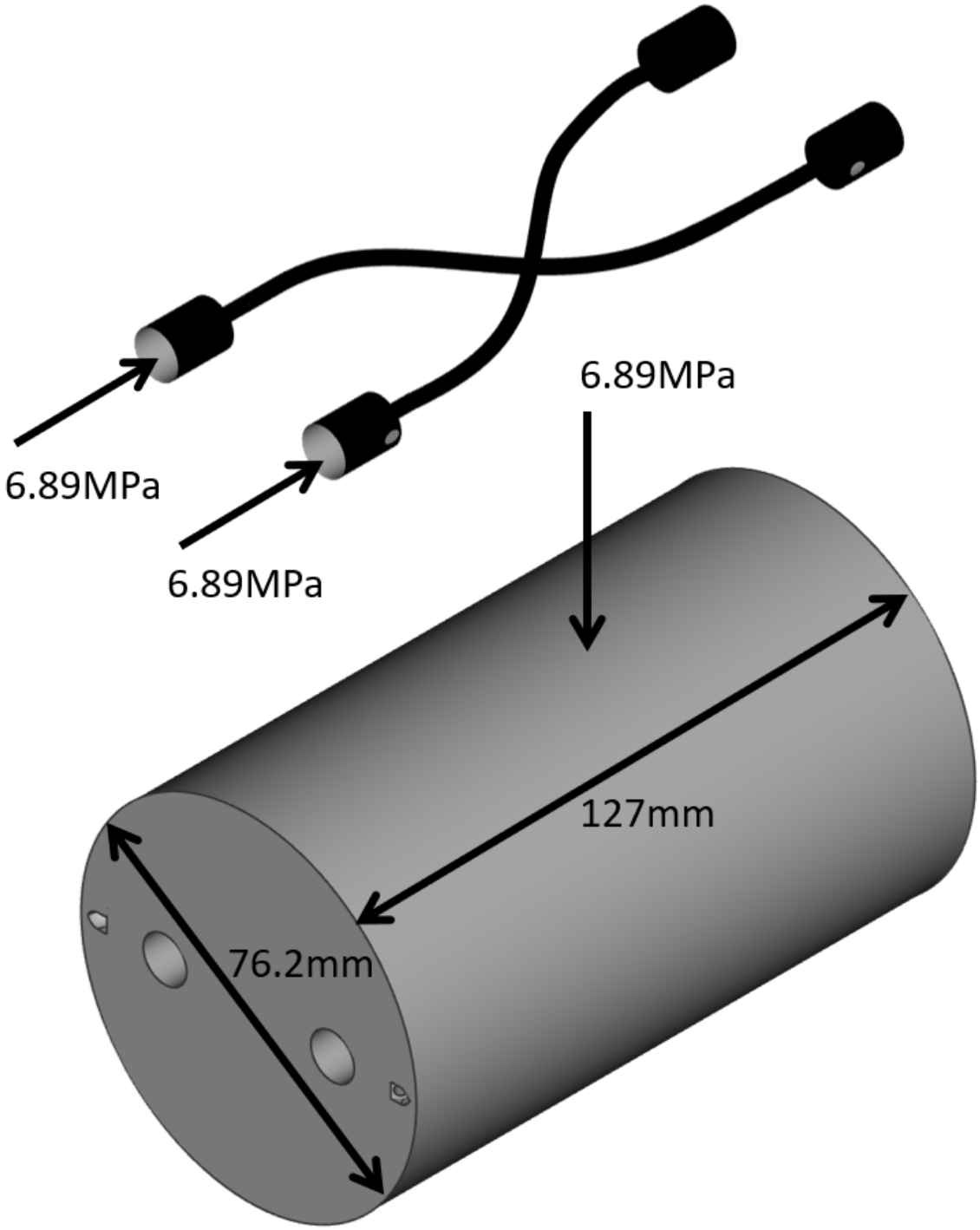


Figure 2: Primary dimensions and loads applied to internal channels and outer cylindrical surface

3.3 Component Verification & Validation Planning

At this point, the details of the design have not yet been defined, however, we are able to plan for the verification and validation of the design based on the component requirements. For the verification of this design, we plan to first perform a finite element analysis of the component with the final selected lattice integrated. After the component is built using LPBF and stress relieved, micro-CT scanning will be used for NDE of the surfaces of internal fluid channels and the lattice, as well as inspecting for porosity throughout the component domain. The component should then be heat treated and machined, after which the Geometric Dimensions and Tolerances (GD&T) would be evaluated, and the component would be pressure tested to ensure that the requirements are satisfied.

3.4 Component Analysis

Based on the component requirements, we define a static structural finite element model using the given load conditions, the component domain (see Fig. 2), and material properties (see Table 1). From this we obtain the von Mises stress, shown in Fig. 3a, throughout the component domain to inform the lattice level requirements.

3.5 Lattice Level Requirements

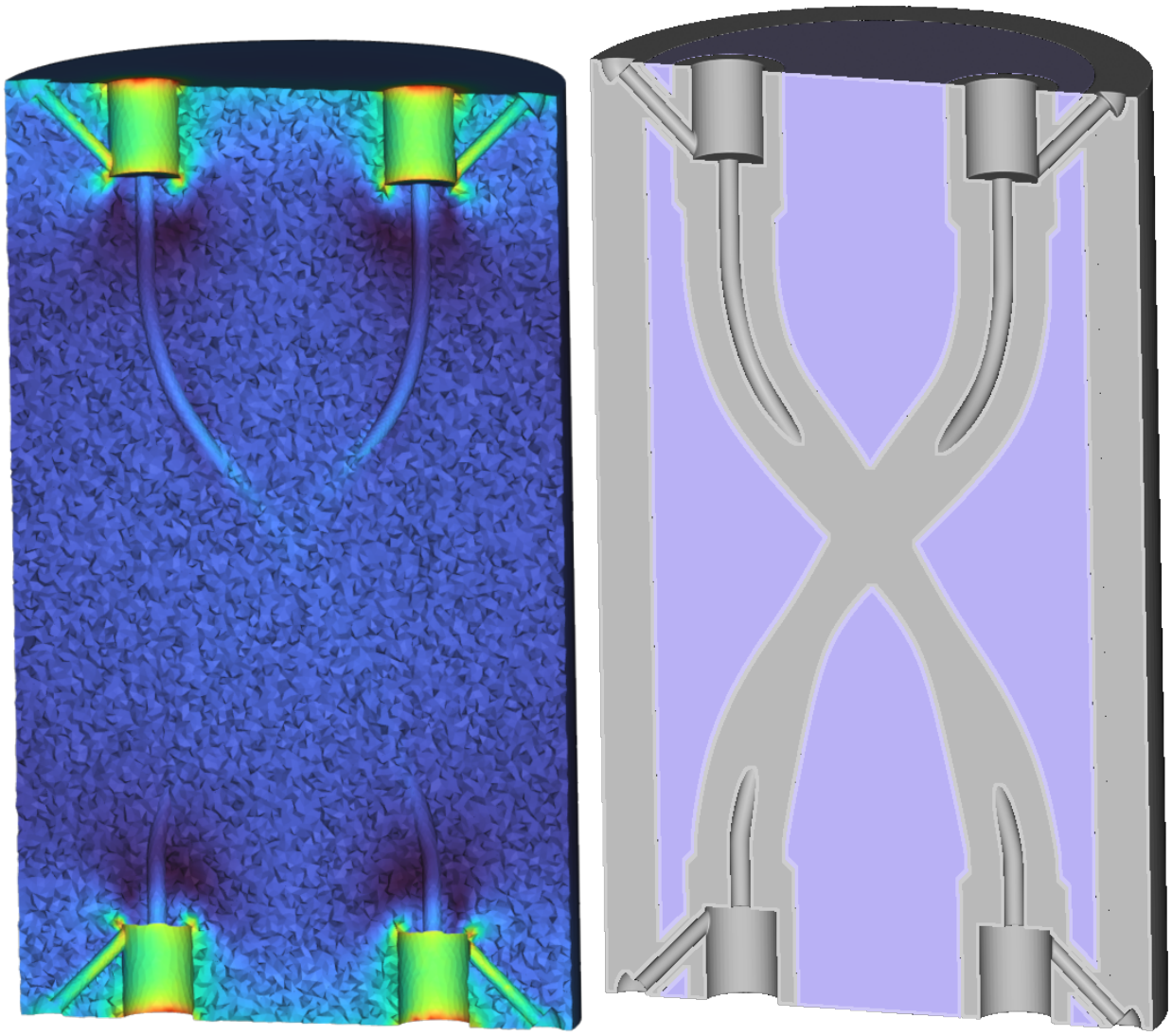
To determine the lattice level requirements of the lattice, we divide the yield stress of the material (see Table 1) by the required factor of safety to determine the allowable stress of 574 MPa. We then normalize the von Mises stress to the allowable stress. The result of this is an estimation of what fraction of the bulk material is needed spatially within the component to meet the stress requirement. The peak stress within the component domain corresponds to $\sim$6% of the allowable stress, indicating that significantly less material is needed to support the load. The peak stress falls within the solid sections defined in the component requirements. Once the lattice domain is established (in Section 3.7), we can find the peak stress within that sub-domain.

3.6 Lattice Verification Planning

When analyzing the cells of the lattice structure, a single homogenization routine is needed since a uniform cell size and density are being used. We can then compare the homogenized properties to the maximum of the lattice level requirements that falls within the lattice domain (see Section 3.7).

3.7 Lattice Domain Definition

As discussed in Section 2.7, there are three sources that we check to define the regions of the component that must be solid. From the component requirements, we have solid regions at the interior faces, and external cylindrical face. From the component analysis, we find no additional solid material is needed beyond what is already given. This makes intuitive sense, because we based the surface thickness on the solid domain of a prior study that used the same requirements [46]. Lastly, there are no small features on the remaining volume that necessitate exclusion from the lattice domain. The result, shown in purple in Fig. 3b, is the lattice domain.



(a) **(b)**

Figure 3: Cross-sections showing (a) the Von Mises Stress result from the component analysis and (b) the lattice domain (purple) with the non-lattice regions of the component domain (gray)

3.8 Unit Cell Exploration

The original study [46] used the self-supporting Face Centered Cubic (S-FCC) [47] lattice because it is *self-supporting* and it is *easy to model with traditional CAD tools*, which allows integration with solid sections of the component domain for analysis. Advances in software have simplified implementation of *more complex lattice unit cells*, including surface-based lattice structures [14] that can offer improved performance when compared to the S-FCC lattice [47]. This software advancement opens the design space significantly, allowing for selection of whichever unit cell *best meets the needs* of the specific application.

Based on the lattice level requirements and the lattice domain definition, we can define the range of properties that the lattice must achieve. From this, candidate unit cells can be identified and acceptable ranges of lattice parameters for each can be identified. For a uniform lattice, only the maximum value of the lattice level requirements within the lattice volume needs to be used to select a unit cell and its parameters.

The Lattice Unit-cell Characterization Interface for Engineering (LUCIE) [28] uses compiled published data from multiple sources offers a tool for the comparison and selection of lattices. The amount and variety of data needed to make informed decisions for the entire Lattice Vee framework is not available from current literature and must therefore be developed. Although the data set currently utilized by LUCIE is limited, it can be used to identify lattices that offer high stiffness and yield stress as a function of the relative percentage of the lattice that is solid, referred to as Volume Fraction (see Fig. 4). For this application, we use a lattice structure derived from the Gyroid Triply Periodic Minimal Surface (TPMS) surface, "thickening" it by adding material equally on both sides of the surface. We denote this lattice as the **T**riply **P**eriodic **S**ur**f**ace (TPSf) of the Gyroid (Fig. 5a); this nomenclature using "f" is used to differentiate the lattice from the zero thickness minimal surface that it visually resembles. This structure was chosen based on the lattice level requirements, the properties available in LUCIE, and manufacturability using LPBF.

In Section 3.9, we define the unit cell size and position based on the component geometry, leaving only VF to be defined. This allows us to apply linear elastic homogenization techniques across a range VFs for the Gyroid TPSf to yield a data set that is sufficient to map between material properties and the VF of the lattice to allow for demonstration of this framework [22]. More detail on the homogenization is discussed in Section 3.11.

3.9 Lattice Cell Definition

As discussed in Section 2.9, the Lattice Vee does not prescribe a single method for the definition of the cells of the lattice. This allows for the integration of different design and optimization approaches to be used.

To fully define the uniform cubic Cartesian TPSf Gyroid lattice selected in Section 2.9, the cell size, orientation, position, and VF must be defined. For this example, we define the lattice density by optimizing the homogenized properties of the lattice. Because the homogenization approach is independent of the component geometry and uses linear FEA, the cell size, orientation, and position are not defined by homogenization and instead defined separately based on the

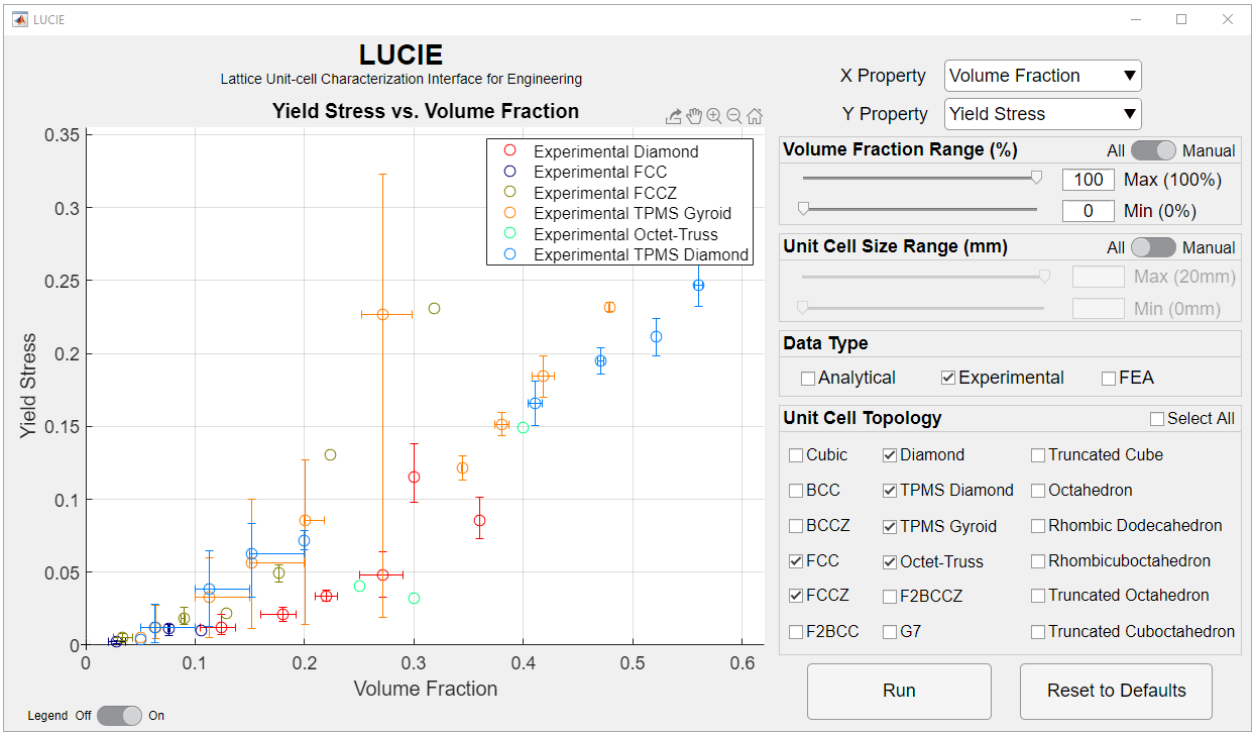


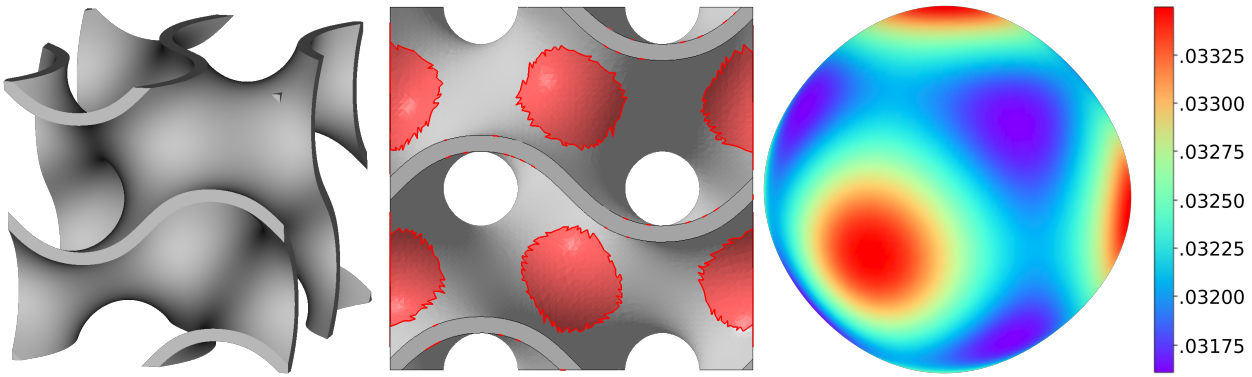
Figure 4: LUCIE tool comparing the yield stress of six different lattice structures as a function of volume fraction

component geometry. The lattice is oriented such that the z-axis of the Cartesian lattice aligns with the cylindrical axis of the component and is positioned such that the cells start at one end of the cylinder. The cell size was defined as smallest cell with an edge length greater than 20 mm such that there are an integer number of cells along the cylindrical axis of the component. With the component length of 127 mm, the cell size is 21.16 mm. This size was chosen to give a feasible thickness to lattice features for verification with FEA and production with LPBF. For the optimization, the target of the optimization is based on the component requirements (2.3% of the bulk material). A gradient based optimization scheme was used. A detailed description of the optimization is irrelevant to the primary focus of this work and is therefore omitted. A VF of 12.8% is needed to meet the component requirements.

$$C_x S_y + C_y S_z + C_z S_x = t \tag{1}$$

Equation (1) is the approximation of the gyroid surface used to generate gyroid based lattices. Where x, y, and z are the three axes of a Cartesian coordinate system, t is the level set value used to control the VF of the lattice, S_i and C_i are short hand as defined in Equation (2) and Equation (3) respectively where P_i is the periodicity of the lattice in direction i.

$$S_i = \sin\left(\frac{2\pi}{P_i} i\right) \tag{2}$$



(a) **(b)** **(c)**

Figure 5: (a) Single unit cell of the TPSf Gyroid at 12.8% VF, (b) view from below cell with overhangs that exceed limit highlighted in red, and (c) the normalized Young's modulus surface for the lattice

$$C_i = \cos\left(\frac{2\pi}{P_i} i\right) \tag{3}$$

To generate the TPSf, two level sets of equal magnitude and opposite sign are used. To achieve the VF target of 12.8%, level set values of $t = \pm 0.199$ are used and the lattice was modeled in nTopology [14].

3.10 Lattice Cell Manufacturability

Although the manufacturability of the TPSf Gyroid lattice at comparable cell size, VF, and aspect ratio has been demonstrated previously [48], we include an evaluation here for completeness.

Only one test of the manufacturability of the lattice must be carried out, because the cells and material distribution are uniform. We show the analysis of overhanging angles relative to an expected build orientation, with the cylindrical axis aligned vertically in the build direction, in Fig. 5b. Area's that exceed the limit of 40° from the build plate are shown in red. Because the red areas are supported on multiple sides, we consider them as bridges where the bridge lengths are below the limit of 5 mm, per the AM process limitations (see Section 2.2), and are acceptable to print using the LPBF process. To check minimum feature size, we use the Shape Diameter Function [49] implemented in MeshLab [50] to identify the location of thin regions within the cell, and the wall thickness measurement tool in Netfabb [51] was used to find the minimum thickness to be 0.774 mm. The minimum thickness in the cell is greater than the permissible minimum feature size of 0.5 mm. Also considered here but not explicitly shown are checks for trapped powder, islands, and pinched off features; no concerns were found. The cell thus has passed the manufacturability checks, allowing the process to continue.

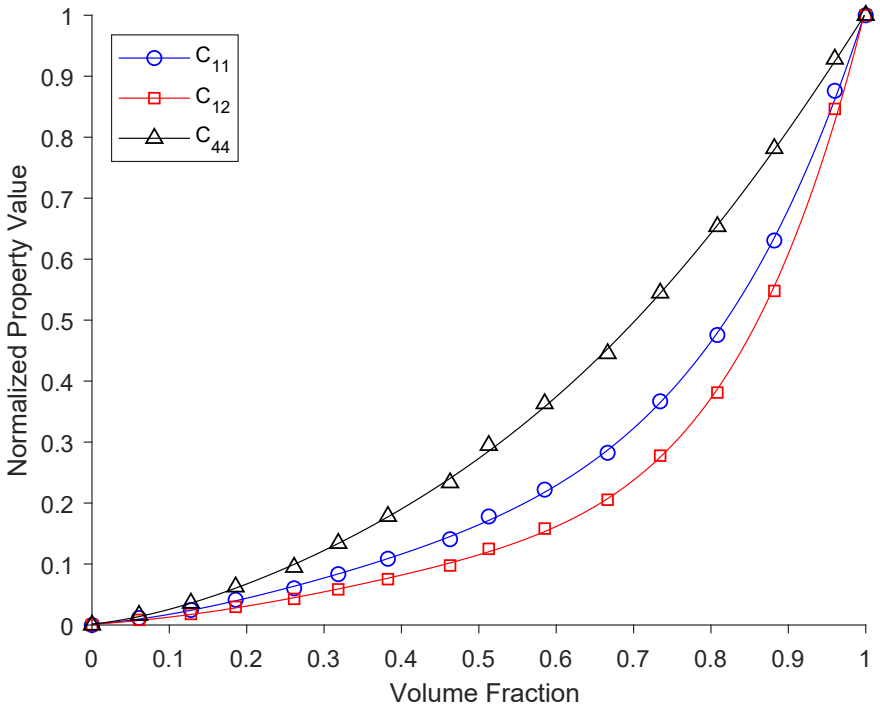


Figure 6: Relationship between homogenized properties of the TPSf Gyroid lattice and volume fraction

3.11 Lattice Cell Verification

We homogenize the lattice as a linear elastic anisotropic material using an in-house code based on methods of Tan et al. [9]. This homogenization routine provides relationships between the normalized components of the stiffness matrix and the VF of the lattice, and results for the TPSf Gyroid lattice can be seen in Fig. 6. The properties of the homogenized material can be compared to the lattice level requirements that fall within the lattice domain, as outlined in the lattice verification plan (see Section 3.6). The normalized Young's modulus surface of the homogenized lattice cell is shown in Fig. 5c. As the lattice is uniform, from the lattice level requirements and lattice domain, we have the same requirements for each cell of the lattice, namely, that it should be 2.3% of the bulk material response.

3.12 Lattice Integration

The TPSf Gyroid lattice was modeled monolithically in nTopology Platform, requiring no integration of the cells with one another. As the lattice is uniformly distributed within the lattice domain, there are no transitions between cells that could produce discontinuities requiring smoothing.

3.13 Component Integration

The lattice structure can now be united with the solid regions of the component domain (see Fig. 7a). At the intersections of the lattice and solid, we apply a 2 mm radius to reduce poten-

tial stress concentrations at the transition. Future work should investigate stress cracking at the interface between the solid regions and the lattice structure.

This design now undergoes V&V as specified in the planning stage (see Section 3.3), the first step of which is applying FEA on the completed model with the lattice incorporated. Depending on the model complexity and required fidelity, this evaluation can be performed using either a mesh of the lattice itself or by replacing it with a homogenized solid with properties based on Section 3.11. In this application, we mesh the lattice, and Fig. 7b shows the von Mises stress in the component. Using the yield stress from Table 1, we find that the minimum Factor of Safety is 3.3 which exceeds the required Factor of Safety of 1.5. This design represents a 49.3% reduction in mass compared to the original, non-lattice design.

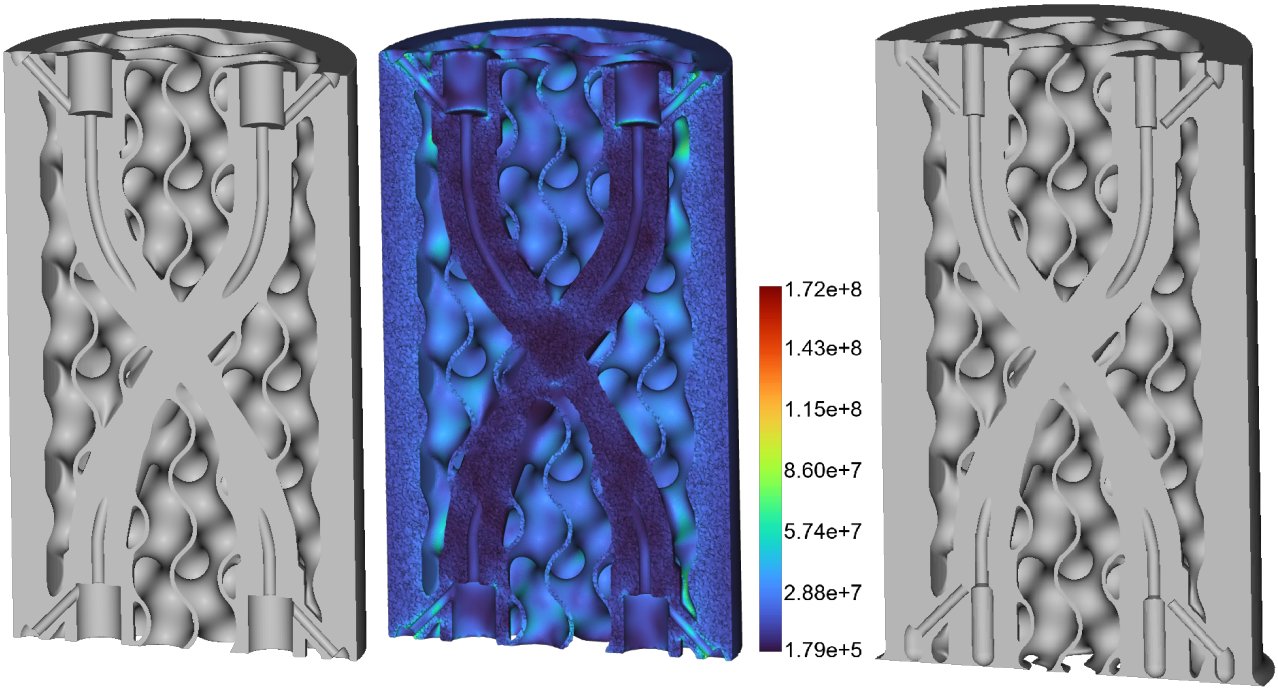


Figure 7: Cross-sectional views of (a) proposed design with lattice structure integrated, (b) resulting von Mises stress from FEA (in Pascals), and (c) the proposed model to be printed

With the design successfully passing the FEA validation, we can now generate a model for manufacturing. Our model must also consider the manufacturability of the solid regions, ensuring that they are self-supporting or have sufficient support from either the lattice or from additional support structures. In this example, there are no such issues. To prepare the model, we apply machining offsets to the exterior cylindrical surface, to the four fluid ports, and to the two end faces of the cylinder. We add a larger offset (5 mm) between the component and the build plate to allow for component removal using wire electrical discharge machining. In addition, we add a radius at the interface with the build plate to reduce potential for crack formation caused by residual stresses produced during the LPBF process [52]. We add 45° chamfers on the horizontal overhangs of the fluid ports to eliminate the need for support material on those features. Figure 7c shows this

proposed build plan. Prior to manufacturing, simulation of the manufacturing process can be used to predict deformation and stresses occurring during the process [53, 54, 55]. This can be used to quantify the deformation and determine if it is acceptable (i.e. that machining allowances are sufficient to account for the distortion and that recoater interference is not predicted [55]).

After manufacturing, NDE and pressure testing should be performed to allow for finalization of the design, that will be integrated into the upper level assembly from which the component requirements were derived.

4 DISCUSSION

For the application of the model in Section 3, Kantareddy et al. [46] did not specify the maximum stress, (or minimum FOS) in their finalized design that was produced, simply that it was below the allowable stress. We can compare the weight savings of the two designs, to show that the design developed here has 6.9% greater savings. This, however, is a function of the factor of safety which was just over twice the limit; further savings can still be achieved. Allowing the framework to determine the solid domain and allowing for non-uniform material distribution (as well as other properties of the lattice structure) within the lattice domain would offer the potential for better material utilization, further reducing weight and (possibly) cost.

To effectively apply the Vee model, a large database of known lattice structure properties covering impacts of cell size, VF (or other definition of material content), and material is needed. This database would directly inform the Unit Cell Exploration and Lattice Cell Definition steps of the Vee Sections 2.8 and 2.9. This could further include cell aspect ratio, cell shape, and material grading within the cell. The generation of this database would require a vast design of experiments (DOE) to be conducted either using FEA or a comprehensive experimental campaign for each unit cell considered. The scale of this data collection motivates an open-sourced and collaborative effort to produce consistent data across different efforts.

As additional lattice data becomes available in different materials, the requirements for the material to be known prior to starting the Lattice Vee is likely to change, allowing for the unit cell exploration and lattice cell definition steps to expand to encompass material selection driven by the lattice level requirements.

5 CONCLUSION AND FUTURE WORK

Lattice structures offer many benefits for AM including reducing the weight of components. However, the design of lattices is complex and typically considered in a bubble, separate from broader engineering design. We present the Lattice Vee Framework that we propose to close this gap. The framework takes in the component requirements and uses them to inform unit cell selection through requirement flow down that parallels the System Vee. The Lattice Vee offers the ability to bring the design of lattice structures into requirement-driven engineering without limiting the design freedom that lattices afford and enabling wider adoption in engineering design. We then demonstrate the steps of the Lattice Vee through the design, integration, and testing of a component

with a uniform lattice. This example highlights the efficacy of the framework as well the current limitations and future work needed for wide adoption.

Further development pertaining to this framework is ongoing and includes integration of a tool chain to produce a streamlined implementation of the Lattice Vee, lattice testing, and development of more quantitative case studies to demonstrate capabilities of the framework that include utilization of different techniques for defining the lattice structure incorporating optimization and non-uniform lattices. The framework is expected to continue to evolve alongside additive manufacturing design techniques and become more refined through application of the process with case studies and dissemination of engineering data alongside those studies. We will also explore the application of homogenization, which has been shown to predict the properties of uniform lattices, to non-uniform lattices with different homogenized properties within each cell of the lattice based on the cells unique geometry.

To reduce the computational load during manufacturability analysis and homogenization (Sections 2.10 and 2.11), we propose testing a representative set of cells rather then each individual cell of the lattice. For a uniform lattice, all cells are the same and a single cell can be characterized. For a non-uniform lattice, each cell can be unique requiring characterization of each cell individually. For representative cells to be used, clustering of cells must be explored based on similarity metrics. This clustering of cells and selection of representative cells for manufacturability analysis and homogenization has not yet been explored. Computational expense, while verifying the performance of lattice cells, could be further reduced by applying machine learning techniques to estimate the properties of lattice cells thereby removing the need to perform homogenization while validating the lattice [56]. This would likely require a training set of data for each lattice topology. This also motivates the data collection effort discussed in Section 4.

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