Solid Freeform Fabrication 2023: Proceedings of the 34th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

DESIGN FOR INTERNAL LATTICE STRUCTURES WITH APPLICATION IN ADDITIVE MANUFACTURING

Donald Palomino[1], Ryan McClelland[2], Mike Grau[3], Ryan Watkins[4], Bingbing Li[1]

[1]Autonomy Research Center for STEAHM (ARCS), California State University Northridge, CA 91330
[2]Instrument Systems and Technology Division (ISTD), NASA Goddard Space Flight Center, Greenbelt, MD 20771
[3]Autodesk Inc, Novi, MI 94105
[4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Abstract

Internal lattice structures have the potential to significantly reduce the mass of an existing metal component, which is a desirable characteristic in the aerospace and automobile industries. However, there are still uncertainties on whether or not internal lattice structures can outperform a solid version of the same mass. Additionally, internal lattice structures can only be produced via additive manufacturing methods, bringing more challenges to resolve. To determine the viability of internal lattice structures, a study will be performed to compare its performance with solid, hollow, and mass penalty designs of equivalent masses using Autodesk Fusion 360. A performance baseline will be established by running multiple simulations on simple geometries to obtain the maximum displacement, first four modes, and first buckling mode. A generative design part, better known within NASA Goddard Space Flight Center as A15, will undergo the same simulations and have its results analyzed to determine feasibility.

Keywords: Metal Additive Manufacturing; Generative Design; Internal Lattice Structure

1. Introduction

CAD modeling is a fundamental component in contemporary engineering and requires both skill and experience from the designer. Replacing the need for hand drafting on light tables, it has greatly increased the efficiency of the design process. However, this process itself has remained largely stagnant since. As the complexity of projects scale with time, so too does design work required. This is especially evident in the aerospace industry where the stiffness-to-mass ratio of parts is one of the most critical parameters. One emerging technology to assist in this design phase is generative design.

Generative design allows for an engineer to create multiple, valid solutions to a design problem simultaneously and autonomously. This process can take what would take an experienced engineer weeks down to mere hours. To take advantage of this technology, a new methodology must be learned that contradicts the more traditional design process. However, the time invested into learning is more than made up in the increased productivity an engineer can achieve.

Lattice structures, although a technology applied only recently, has actually been prevalent on Earth for millions of years. Everywhere from the hexagonal shape of honeycombs to the Voronoi structure that forms our bones, lattices are an essential building block within nature. Following this example, there exists different types of lattices, each optimized towards specific goals. Mimicking this design in modern design problems can provide multiple advantages, although manufacturing such complex designs remains a pressing issue.

Internal lattice structures build upon this by adding a shell around the lattice, fully enclosing it. This has the potential to significantly increase the stiffness-to-mass ratio and buckling resistance for existing parts, yet is barely ever utilized in current industries because of a lack of research, education, and methods of validations for it. Additionally, they are fundamentally difficult to manufacture which further limits their use.

In this paper, a method to effectively design for internal lattice structures for additive manufacturing will be developed. This will be accomplished by utilizing Fusion 360 by Autodesk and nTopology, both CAD softwares with internal lattice structure capabilities. A baseline will be established by running simulations on a simple geometry of three different designs: solid, hollow, and internal lattice. Each of these designs will be approximately the same mass to effectively compare them under strict mass budget scenarios, similar to that seen in the aerospace industry. This design process will also be well documented to provide a template on design for internal lattice structures to supplement future engineers and designers in potential applications. Lastly, a method to validate them once additively manufactured will be created. To be practical, it is important that these validation methods do not damage or destroy the part after manufacturing, also known as NDE (nondestructive evaluation). Two methods will be looked into accomplishing this: using MRI (magnetic resonance imaging) and ultrasonic testing.

1.1. Current Status of Metal AM, Generative Design, and Internal Lattice Structures

1.1.1. Metal AM

Additive manufacturing (AM) grants incredible flexibility in manufacturing capabilities compared to traditional forms, like CNC machining. This process involves joining material, through various methods, together layer-by-layer to form one continuous part. Among its many advantages include reduction in material waste and logistics management[1], mass optimization of parts, and complex geometry such as lattice and corrugation[2]. However, each layer's stability is dependent on the prior layer. If there is too great a difference in the current layer profile compared with the prior layer, then the overhanging material could sag and ultimately lead to a print failure[3].

To remedy this common problem, support structure can be added to an existing part to ensure successful prints[4]. This is typically done autonomously by the 3D printing processing software, known as a slicer. Optimization of their ease of removal and reduction of material consumed is continuously being developed[5]. However, these support structures are only beneficial if they are able to be removed during post-processing. For internal lattice structures, this is not the case as the support material would be trapped inside without any method for removal. Therefore, a support-less AM method must be implemented to successfully print these complex structures[6]. Of the currently available options, two are the most applicable to this problem: powder bed fusion and direct energy deposition.

Powder bed fusion (PBF) is a process where a laser beam points in a preprogrammed path towards selected points of a flat bed of metal powder to fuse the material together. This is done either by full or partial melting, also known as selective laser melting (SLM) and selective laser sintering (SLS) respectively. To prevent oxidation of the metal and eliminate flammable gases like oxygen, the build chamber is vacuumed then filled with an inert gas[7]. This allows for a high XY resolution at the micron level, as well as having the capacity for very thin layer heights. Additionally, the powder bed acts as a support for the finished part, meaning no actual support structure is necessary. However, it does it come with its own challenges. This includes various imperfections during the manufacturing process, such as surface roughness due to irregular powder size, porosity due to unmelted areas[8], and perhaps most notoriously, trapped powder inside. This is perhaps the biggest limiting factor pertaining to internal lattice structures, as a majority of the complex geometry is enclosed in material. The conventional solution is adding a drain hole to the part to remove a majority of the powder, then heat treat is to sinter any residual powder left[9]. This is not as simple in the case of internal lattice structures, as enclosed cells are likely to form and prohibit ease of powder removal.

Direct energy deposition (DED) is a process that uses direct energy, typically in the form of a laser of electron beam, focused on a region to both melt the substrate and a deposited material onto the substrate, either a powder or wire. An important distinction between DED and PBF is the lack of a powder bed for DED, instead being more akin to a plasma welding machine. Similarly, it does not need support structures to produce complex shapes, but it has much poorer resolution and surface finish compared to PBF[10].

1.1.2. Generative Design

Generative Design (GD) is an iterative design process that uses artificial-intelligence based algorithms that involves a program that will generate a certain number of outputs that fulfill certain constraints. A designer is also involved in the process, selecting produced outputs or changing input values, ranges, and distribution. The designer does not necessarily have to be human; it can be an AI. The designer learns to refine the program with each iteration as their design goals become better defined over time[11].

This process can also be applied in great effect towards engineering application. Once a project's requirements have been properly identified, these can be input in a CAD software supporting GD, such as Fusion 360 by Autodesk. The outputs are designs that have been optimized for stiffness-to-mass ratio which is incredibly desirable in the aerospace industry. Typically, these results are organic in shape and require advanced manufacturing methods like 5-axis CNC machining and additive manufacturing, however it can be set to optimize its design for the relatively simpler 3-axis CNC machining[12]. This can significantly improve an engineer's productivity as GD allows them to design parts with a higher stiffness-to-mass ratio in hours, whereas the same part may have taken weeks or months of time if done traditionally. Additionally, adding manufacturing constraints increases the likelihood of a machine shop sending a quote, whereas a traditionally designed part may not receive any quotes at all due to difficulty of manufacturing[13].

1.1.3. Internal Lattice Structures

Lattice structures, although a technology applied only recently, has actually been prevalent on Earth for millions of years. Everywhere from the hexagonal shape of honeycombs to the Voronoi structure that forms our bones, lattices are an essential building block within nature. Following this example, there exists different types of lattices, each specializing in a specific function such as mechanical, thermal, or even storage[14]. Mimicking this design in modern design problems can provide multiple advantages, although manufacturing such complex designs remains a pressing issue.

Internal lattice structures build upon this by adding a shell around the lattice, fully enclosing it. This has the potential to increase the stiffness-to-mass ratio, buckling resistance, and add vibration and noise dampening[15]. However, their complex geometry makes them difficult to manufacture, even with additive manufacturing. Multiple variables like printer resolution, material, and support structures can influence the success of these prints[16]. Additionally, internal lattice structures are difficult to model and simulate, severely limiting their methods for validation prior to manufacturing[17].

2. Methodology

2.1. CAD Software & Design

Fusion 360 by Autodesk is the CAD software used as it offers a suite of workspaces including modeling, generative design, and simulation. A beta feature called Alpha Centauri will be used to create internal lattices from inputted designs. Firstly, the Design Workspace is used to create two simple geometries: a straight cylinder and a curved cylinder. This is to set a baseline of reference for more advanced models to be compared to. From this, four unique designs are applied: solid, hollow, internal lattice, and internal lattice with mass penalty. The first three designs are of the same mass for a fair comparison. This is done by first making the internal lattice design, then adjusting the diameter and shell thickness for the solid and hollow designs respectively until they reach the same mass as the former. The internal lattice with mass penalty features the same shell thickness as the hollow design, which is thicker than its equivalent mass internal lattice design. Once all four designs have been created for each simple geometry, it is run through a series of simulations to compare their performance against each other.

2.2. Internal Lattice Structure

To design for internal lattice structures using Alpha Centauri, a solid body and internal volume body must first be created. The solid body is simply the model created from the Design Workspace. To produce the internal volume body, the solid body is copied and internally shelled. Then the shell body is subtracted from the copy to produce an internal volume representative of the defined shell thickness. These two bodies are inputted into Alpha Centauri, as well as the lattice type, cell size, and pipe diameter. There are 15 unique lattice types available, however as of the time of this writing, it is not possible for a user to create their own unit cell. Cell size represents the size of the unit cell, and the pipe diameter is the thickness of the lattice struts. After processing these parameters, an internal lattice structure is produced and is ready to be simulated on.

2.3. Generative Design

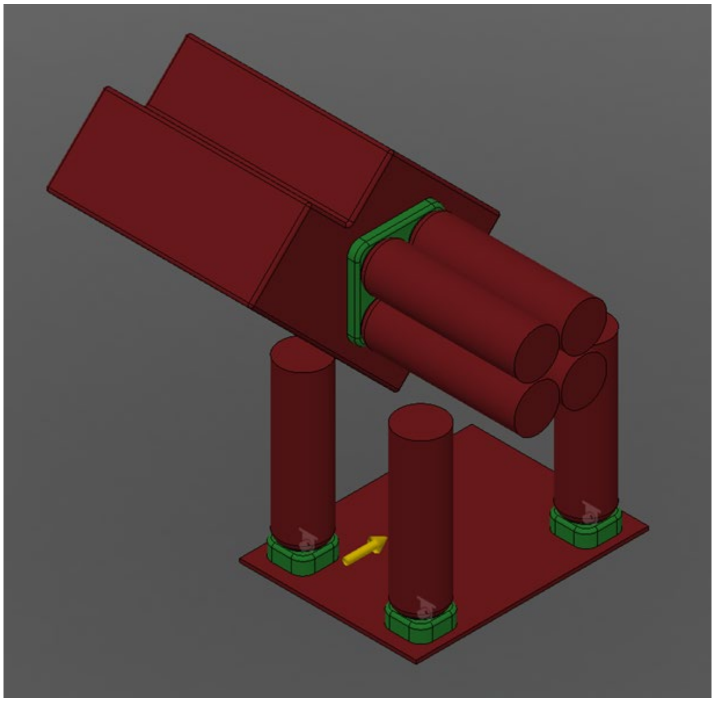

Figure 1: Setup for generative design with preserve geometries (green bodies) and obstacle geometries (red bodies)

Once a baseline has been established with simple geometry, more advanced models will be developed using the Design and Generative Design Workspaces. The first step in doing so is setting up a design space consisting of bodies to later be defined as preserve and obstacle geometries in the Design Workspace. Unlike conventional part design, generative design only requires bodies that will be used as preserve or obstacle geometrics. Therefore, a starting design is not required. Once all bodies are created within the Design workspace, the rest of the setup process will continue in the Generative Design Workspace.

Multiple inputs and parameters must be defined in the Generative Design workspace before a study can be successfully conducted. First is assigning the bodies made in the Design workspace as preserve or obstacle geometries. As their name implies, preserve geometries are assigned to bodies to incorporate them in the final shape of the design, while obstacle geometries are assigned to bodies to represent spaces for the design to avoid. These geometries are assigned within the Generative Design workspace once the bodies in the Design workspace are finished. **Figure 1** shows the preserve geometries assigned to the bodies representing the three bottom mounting pads and the large instrument interface at the top. **Figure 1** also shows the obstacle geometry blocking material from generating in the instrument mounting location, the spacecraft face, and the bolt interfaces.

Once all of the preserve and obstacle geometries have been assigned, design conditions including structural constraints and loads are defined. Structural constraints are to apply fixes, pins, or frictionless constraints to a geometry. In **Figure 1** three pin icons can be seen on the bottom three mounting pads, indicating a pinned structural constraint. A pin is used instead of a fixed constraint as it is more accurate to how the part will be installed in the real-world using machine bolts. Point masses are defined according to the center of gravity and mass of the part they represent, in this case being an optical instrument. These point masses must experience a G-load which is also applied according to the application. As these structures will undergo various G-loads during launch, this is also a more accurate way of modeling instead of subjecting faces to forces.

Design criteria, such as design objectives, manufacturing method, and materials are also defined. Design objectives allow for the generative design study to prioritize minimizing mass or maximizing stiffness, as well as the factor of safety. Next is the manufacturing method, of which the following can be selected: unrestricted, additive, milling, 2-axis cutting, and die-casting. Finally, the material that the part will be manufactured from must be defined. While multiple materials can be selected to produce different results of their respective materials, Generative Design cannot apply these materials into a single result simultaneously.

To give more volume for internal latticing to occur, an effort is made to alter these parameters to force generative design to produce designs that are thicker and with no holes or struts. The most effective way to do so was found to be setting the manufacturing method to 3-axis milling, increasing the drill size diameter to 0.5 [in], and greatly increasing the target mass beyond the mission specification. Because of the larger drill size and the limitation of 3-axes, generative design produces parts that would normally be manufacturable given these constraints, resulting in non-complex bodies with generous filets. The high target mass allows the generative design to produce parts with ample thickness and volume. Double, triple, and quadruple the initial target mass will be used to generate the thicker A15 brackets.

Once all of the results have been generated, filters are applied to select the stiffest parts, and to select the parts with the highest mass for hollow and latticed parts. These are then exported as part files where their organic body can be modified to make thin areas thicker and avoid self-intersecting geometry, a major obstacle in the workflow to producing internal lattice structures.

2.4. Avoiding Self-Intersecting Geometry

Perhaps the most time-consuming challenge in producing internal lattice structures are the self-intersecting geometries that are produced in Fusion 360. This is due to the simulation's inability to properly mesh the design if these are present. The software does not currently have a tool or feature that automatically resolves them, instead any corrections necessary must be done manually. It has been found that almost all self-intersecting geometry occurs where material generated closest to the bolt interface preserve geometries, as the material surrounding the obstacle geometry is thin and overlaps with each other when thickening the organic body.

The above steps in Section 3.4. to producing parts through generative design helps to reduce self-intersecting geometries, however they will likely still appear even with preventative steps. To remedy these occurrences, the following, additional steps should be taken. Firstly is to grab the organic body near the bolt interfaces and pull the faces apart to prevent overlaps from developing once it is thickened. This has to be done while making sure that the organic still overlaps the preserve geometry, otherwise a combine failure will occur instead. Even after this step, it is still likely that self-intersecting geometries will develop, so a last step to solve this is to use the section analysis tool and comb through the design to find them. Once found, an arbitrary shape should be made that covers up the region of self-intersection. Using a series of combine tools, this shape will fill in the self-intersecting geometry similar to filling in a cavity in a tooth. Once all of the self-intersecting geometries have been resolved, the part will properly mesh, and simulations can occur as normal.

2.5. Simulation

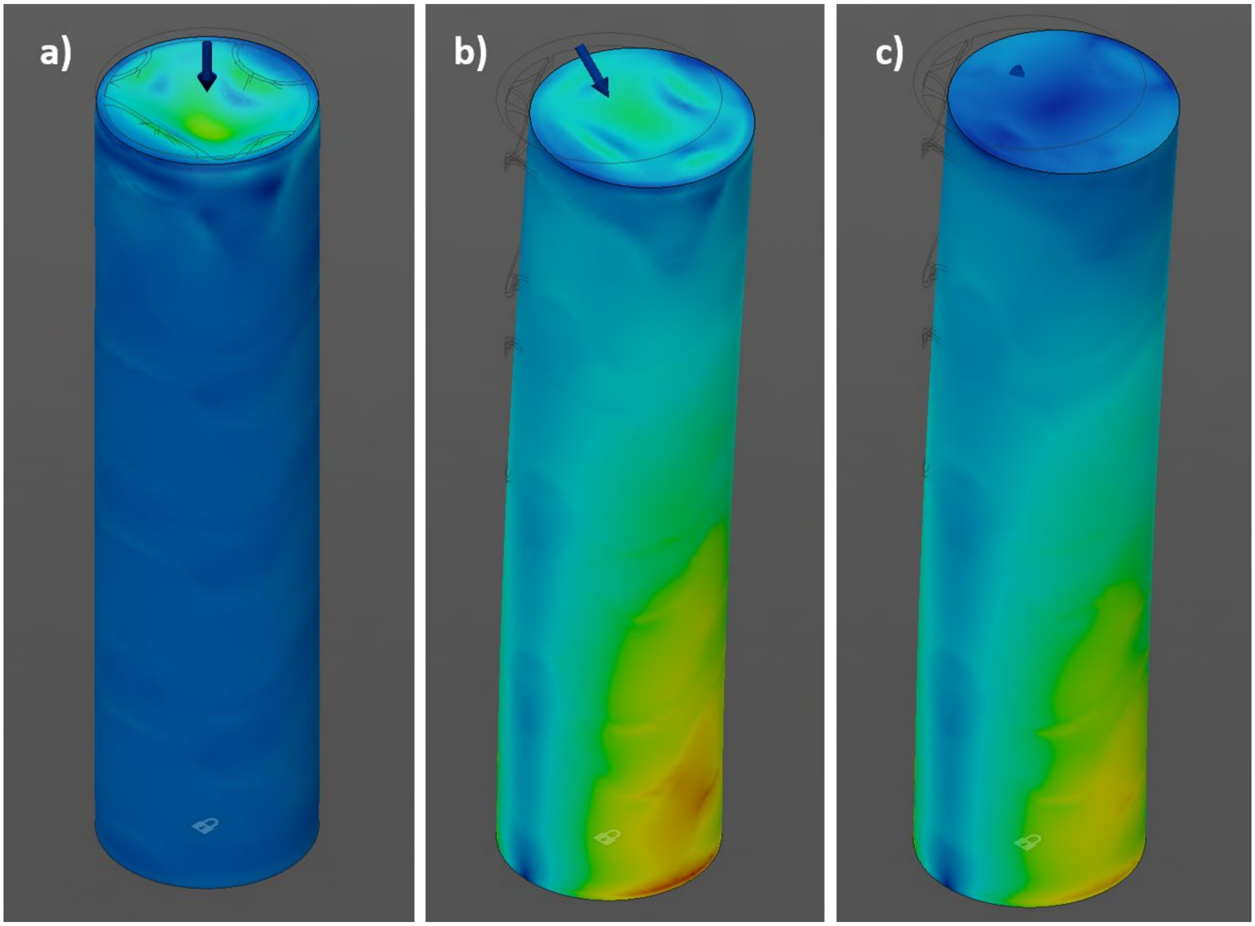

Figure 2: Static Stress Simulation of Lattice Straight Cylinder with Load Applied Relative to Perpendicular of Top Surface: **a)** 0 [deg], **b)** 45 [deg], **c)** 90 [deg]

After the parts produced using generative design have been modified appropriately and all self-intersecting geometries have been resolved, they can be brought to the Simulation Workspace. From here, three simulations are conducted to acquire the necessary data of the part to assess their performance: a Modal Frequency simulation for the first four modes, a Static Stress simulation for the maximum displacement and stress, and a Buckling simulation for the first buckling mode. An example of the static stress simulation for the lattice straight cylinder is shown in **Figure 2** where blue regions represent areas of low stress and red regions represent areas of high stress. Each simulation was set up by fixing the bottom face and applying a 100 [N] load to the top face. This load starts perpendicular to the applied face at 0 [deg], then is incremented by 15 [deg] until reaching 90 [deg], parallel to the applied face. The resultant deformation in each subfigure is adjusted to better show the effect of the applied force.

For A15 brackets, Fusion 360 can automatically take the setup parameters used for generative design to populate the necessary inputs for conducting simulations. The same three aforementioned simulations are run. The only major difference is the inclusion of steel bolts in the top instrument interface to best represent realistic conditions. Otherwise, these holes may collapse on themselves, which is incorrect as the steel bolts would prevent this.

3. Results

3.1. Simple Geometry Results

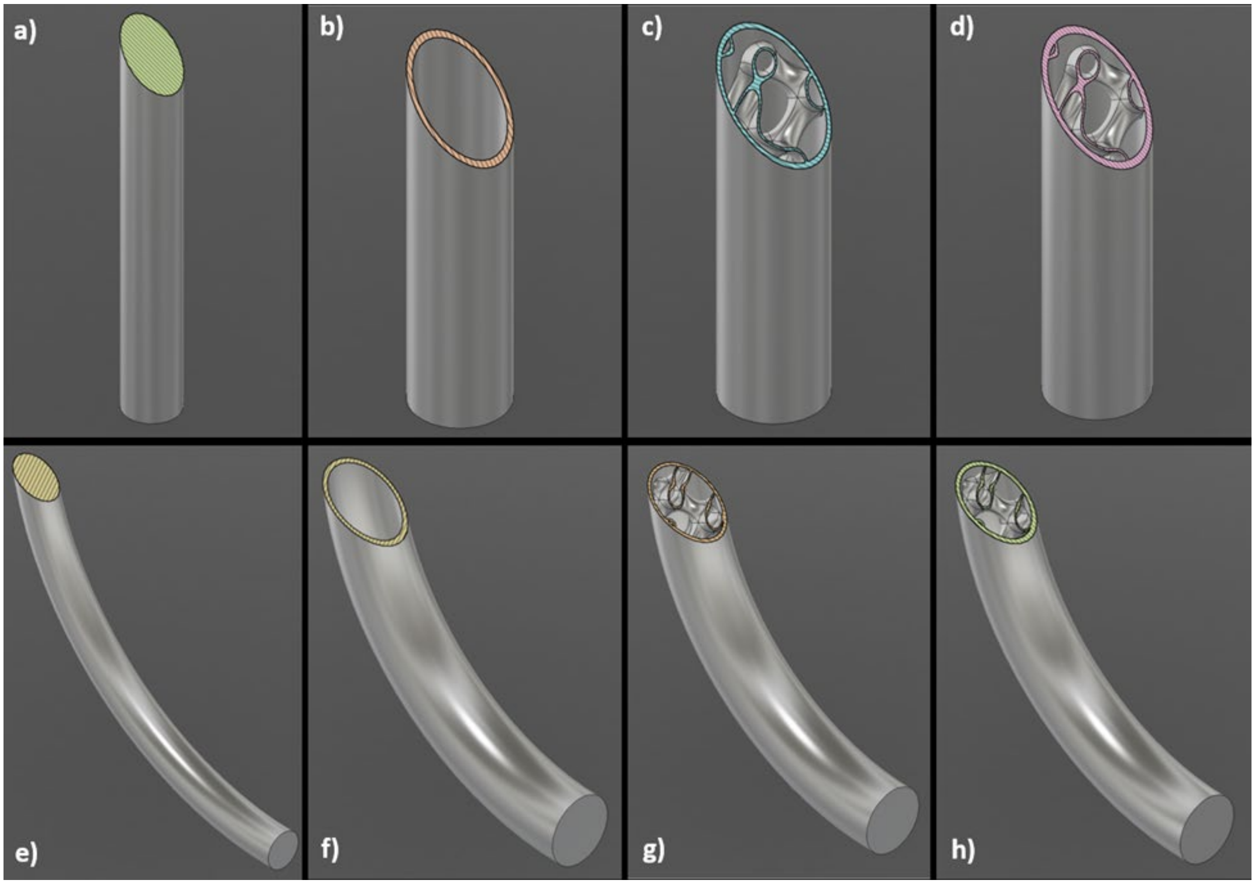

Figure 5: a) Solid Straight Cylinder, **b)** Hollow Straight Cylinder, **c)** Lattice Straight Cylinder, **d)** Lattice Straight Cylinder with Mass Penalty, **e)** Solid Curved Cylinder, **f)** Hollow Curved Cylinder, **g)** Lattice Curved Cylinder, **h)** Lattice Curved Cylinder with Mass Penalty

In total, eight simple geometries were designed using Fusion 360 as shown in **Figure 5**. These represent three different designs for testing: solid, hollow, and internal lattice. Each design for their respective cylinder was made to be approximately the same mass to ensure a fair comparison. Therefore, while the length for each cylinder remained as 100 [mm], their diameters and shell thicknesses vary where applicable. A fourth model called internal lattice with mass penalty was also made to provide results for an internal lattice cylinder with the same shell thickness as the hollow cylinder. This is because the shell thickness of the internal lattice cylinder is slightly less than that of the hollow one to reach similar masses. The unit cell of the lattice was 25 [mm], the beam diameter was 5 [mm], and the beam thickness was 0.5 [mm]. Due to current limitations with Alpha Centauri, these were the parameters that produced the most consistent results. Smaller parameters would result in errors.

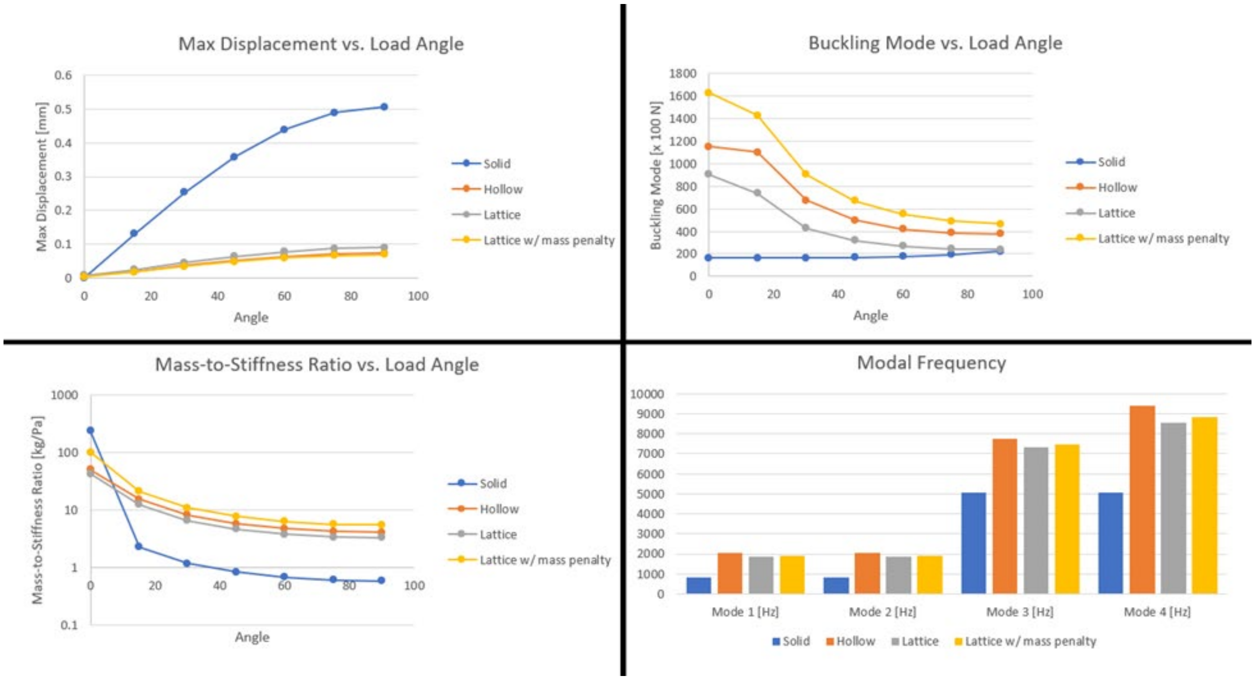

Figure 6: Performance Results of Straight Cylinder

After finishing the simulations, the results are graphed against each other to compare the solid, hollow, internal lattice, and internal lattice with mass penalty variations. From this, four graphs are produced as shown in **Figure 6**. The maximum displacement at 90 [deg] of the solid variation compared to the internal lattice with mass penalty variation is 86.5% more. All four variations are considerably resistant to buckling based on the applied loads. The stiffness-to-mass ratio at 90 [deg] of the solid variation compared to the internal lattice with mass penalty variation is 836.04% more. For the first modal frequency of the solid variation compared to the hollow variation is 140.3% more.

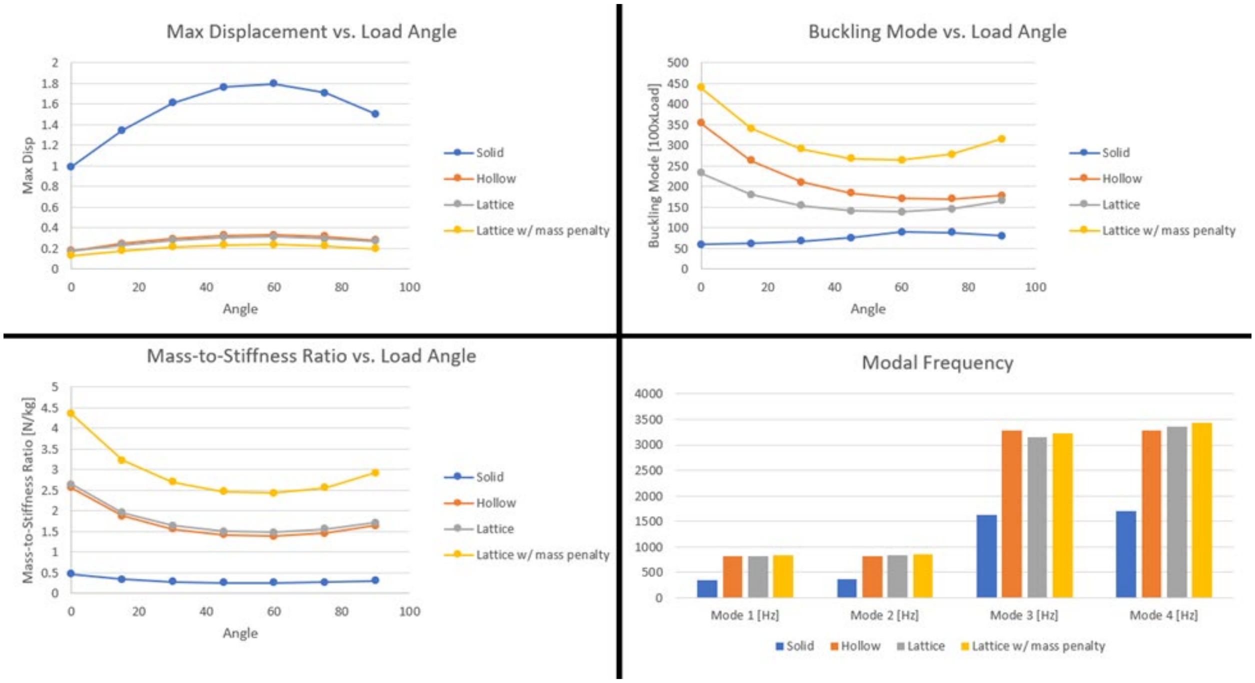

Figure 7: Performance Results of Curved Cylinder

Similar results and trends as the straight cylinder are shown for the curved cylinder in **Figure 7**. The maximum displacement at 90 [deg] of the solid variation compared to the internal lattice with mass penalty variation is 86.8% more. All four variations are considerably resistant to buckling based on the applied loads. The stiffness-to-mass ratio at 90 [deg] of the solid variation compared to the internal lattice with mass penalty variation is 856.1% more. For the first modal frequency of the solid variation compared to the internal lattice with mass penalty variation is 139.6% more.

3.2. Unit Cell Results

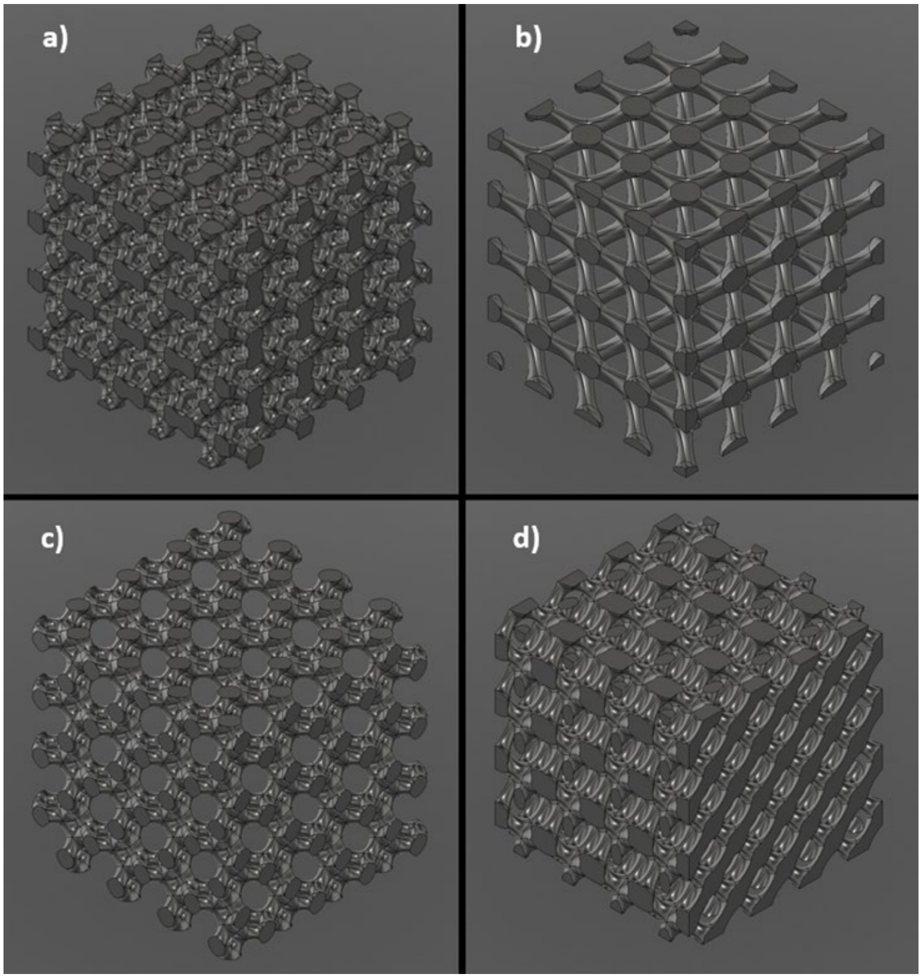

Figure 8: Unit Cell Lattices **a)** Pyritohedron, **b)** Dualtx, **c)** Vin Tiles, **d)** Softbox

As one of the purposes of this paper is to determine the most optimal design for internal lattice structures, another series of simulations were run on curved cylinders with different lattice structures as shown in **Figure 8**. Different unit cells may afford better performance despite having the same shell thickness and body. Also, some may be easier to produce via additive manufacturing than others. For example larger overhang angles, measured from the horizon, are beneficial towards successful, un-supported prints.

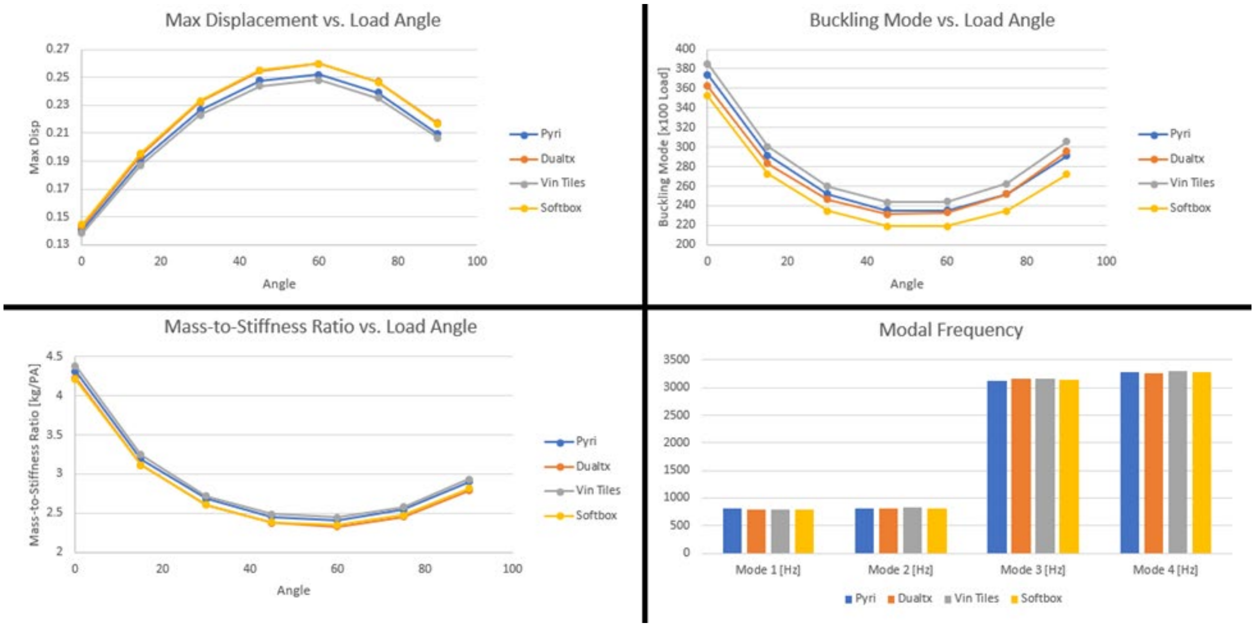

Figure 9: Performance Results of Curved Cylinders with Different Lattice Structures

Using the four, unit cells in **Figure 8** with the internal lattice with mass penalty curved cylinder design, the resulting graphs in **Figure 9** are produced. Since the shell thickness and body is the same with the four cases, the results are very similar to one another. For maximum displacement, the Softbox lattice experiences 4.93% more displacement than the Vin Tiles at 90 [deg]. Similarly, Vin Tiles perform marginally better than the other lattice types for buckling mode and stiffness-to-mass ratio. Vin Tiles also performed best for Modes 2 and 4, but overall the differences in modes were slim with only a 1.81% difference between the Pyritohedron and DualTX designs for Mode 1.

3.3. A15 Results

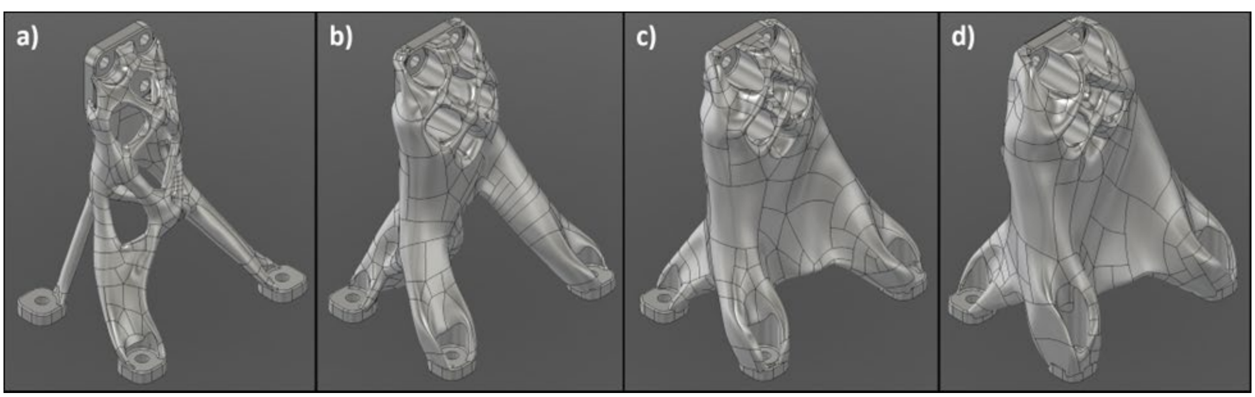

Figure 10: A15 Variations **a)** Solid, **b)** 400g Target Mass, **c)** 600g Target Mass, **d)** 800g Target Mass

Once the baseline has been established with the results obtained from the simple geometry designs, the same series of versions and simulations are done to the A15 bracket, as shown in **Figure 10**. To ensure sufficient internal volume for hollowing and latticing to occur, the A15 is set up to be thick and without thin beams, unlike **Figure 10a)**. Both hollow and internal lattice structures are formed from **Figure 10b)**, **c)**. and **d)**.

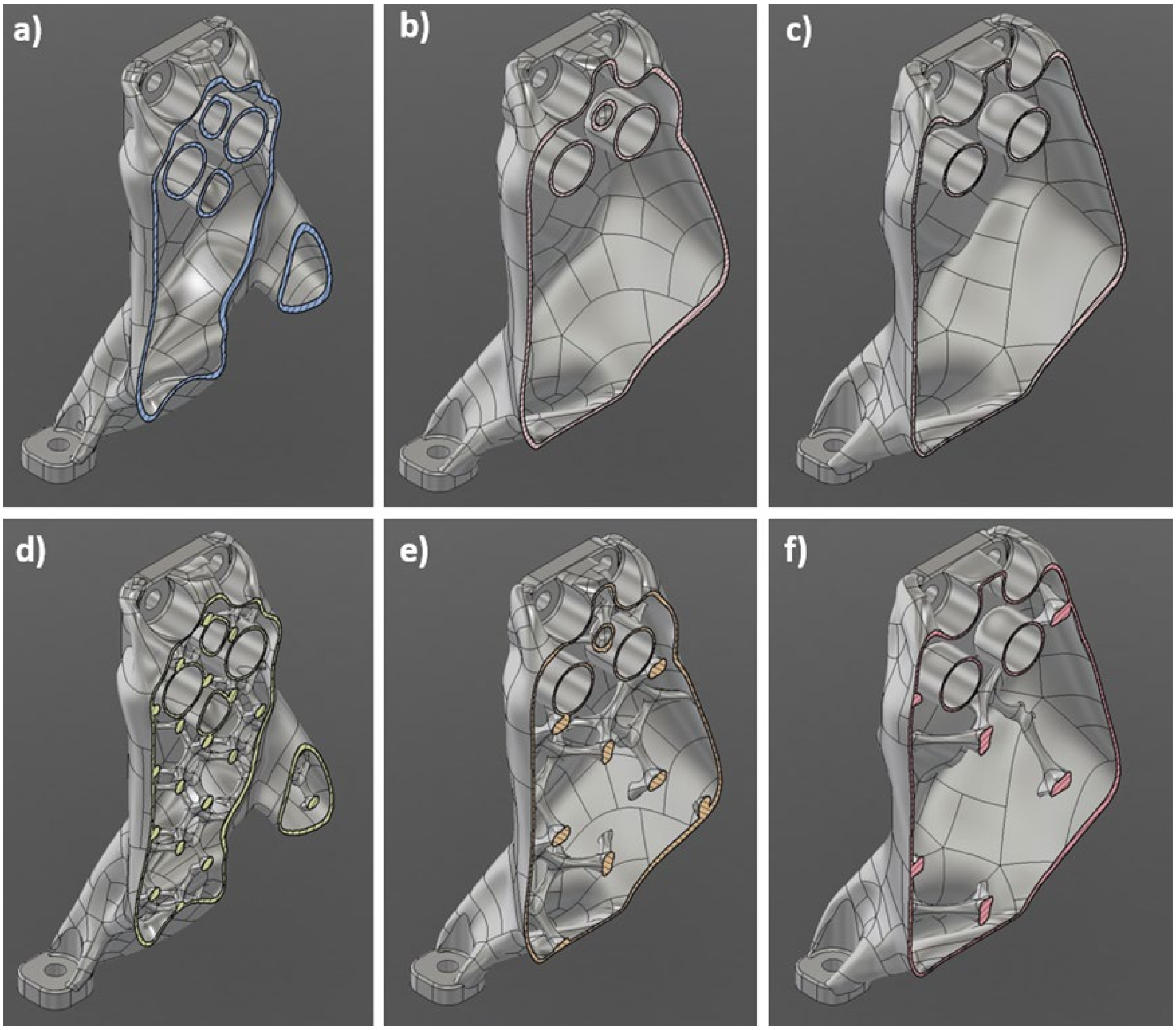

Figure 11: Internal Lattice vs. Hollow: **a)** Internal Lattice from 400g Target Mass, **b)** Internal Lattice from 600g Target Mass, **c)** Internal Lattice from 800g Target Mass, **d)** Hollow from 400g Target Mass, **e)** Hollow from 600g Target Mass, **f)** Hollow from 800g Target Mass

A section view of the thicker A15 versions for both hollow and internal lattice structures are shown in **Figure 11**. To ensure all variations are approximately the same mass, the hollow variations have a shell thickness of 1.5 [mm], 1.3 [mm], and 1.1 [mm] respectively to **Figure 11a)**, **b)** and **c)**. For the internal lattice variations, all three's shell thickness is 1 [mm] with an appropriate lattice density to match the mass of the solid variation.

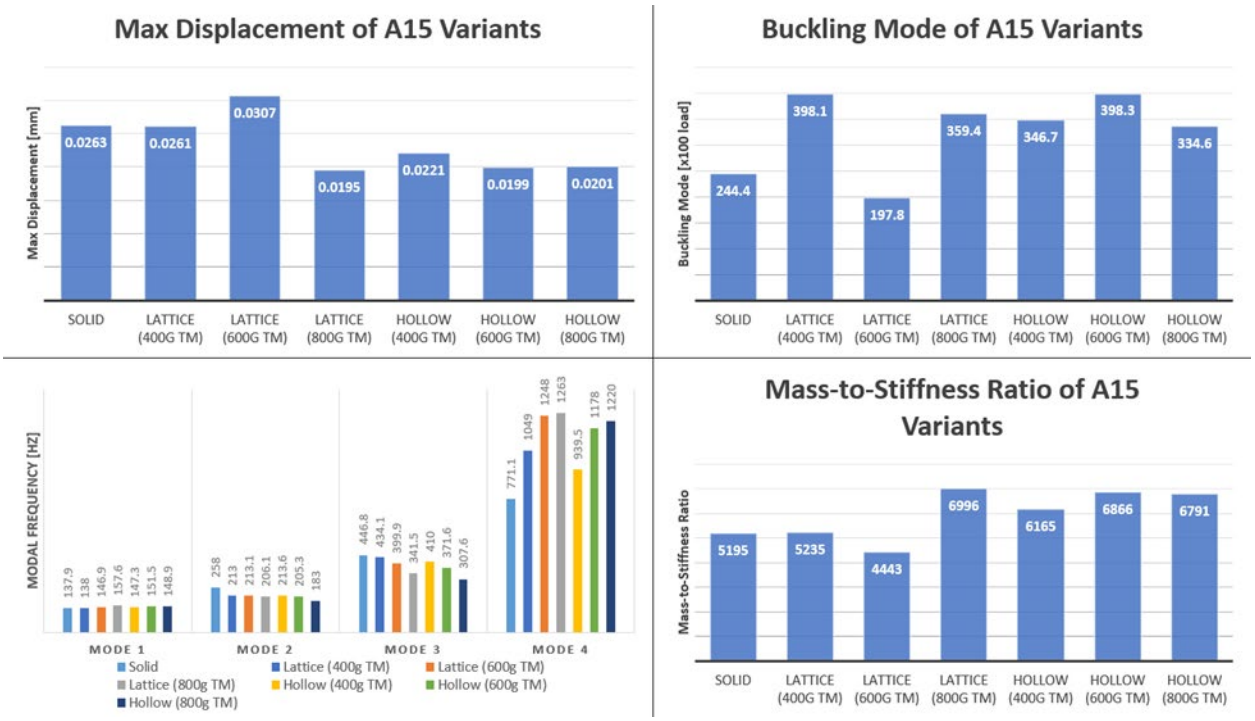

Figure 12: Performance Results of Solid, Hollow, and Internal Lattice A15 Variants

Using the same three simulations in Fusion 360 used for the simple geometries (static stress, modal frequency, and structural buckling), the performance of the solid, hollow, and internal lattice variants of A15 were obtained, as shown in **Figure 12**. The average maximum displacement of the internal lattice and hollow A15 variants is 0.0254 [mm] and 0.0207 [mm] respectively, an 18.5% decrease. The average first modal frequency of the internal lattice and hollow A15 variants is 147.5 [Hz] and 149.2 [Hz] respectively, a 1.2% increase.

4. Discussion

4.1. Simple Geometry

The simple geometry forms a baseline to observe resultant patterns from the data. As seen in **Figure 6** for the results of a straight cylinder, the maximum displacement, stiffness-to-mass ratio, and first modal frequency of the hollow and internal lattice variants are overall considerably better than the solid variant, with the hollow and lattice variants showing closely related trends. The hollow variant produced 30.0% less displacement, 19.4% greater stiffness-to-mass ratio, and 9.4% greater first modal frequency compared to the lattice variant. When compared to the lattice with mass penalty variant, these results change with the hollow variant having 5.7% more displacement, 34.3% lesser stiffness-to-mass ratio, and 7.1% greater first modal frequency. This shows that the hollow variant is overall the better performing design for the simple hollow cylinder.

Figure 7 shows the results for a simple curved cylinder. Similar to the results obtained from the straight cylinder, the maximum displacement and first modal frequency of the hollow and internal lattice variants are overall considerably better than the solid variant, with the hollow and lattice variants showing closely related trends. However, the stiffness-to-mass ratio of the lattice with mass penalty variant is noticeably better compared to the hollow and lattice variants. The hollow variant has an 81.5% greater stiffness-to-mass ratio compared to the solid variant, but the lattice with mass penalty variant has a further 77.3% increase in stiffness-to-mass ratio. However, the hollow variant has only a 3.7% advantage over the lattice variant. As the lattice with mass penalty variant is the same as the lattice variant but with a greater shell thickness, this increase in stiffness-to-mass ratio may be attributed more due to the shell thickness rather than the internal lattice structure. Putting it aside, the hollow and lattice variant behave very similarly across the board.

4.2. Unit Cell

One of the biggest advantages in additive manufacturing is free complexity, which is where the manufacturing cost per piece does not increase relative to increase in geometric complexity[18]. This gives merit to determining the best performing unit cell for the internal lattice structure. Based on the results shown in **Figure 9**, this was found to be the Vin Tiles unit cell as it consistently had the lowest maximum displacement and a high first modal frequency. Although it only yielded less than 5% better properties compared to the worst performing unit cell, the free complexity afforded by additive manufacturing makes this small improvement worth the effort.

4.3. A15

As one of the major issues with producing internal lattice structures and hollow designs in Fusion 360 is the generation of self-intersecting geometries, three different A15 brackets were made based on increasing target masses inputted during generative design. Additionally, the three hollow variants based on these generative design results were made with slightly increased shell thicknesses to approximate the mass of the solid and lattice variants. Based on the results shown in **Figure 12**, there does not seem to be a clear trend forming between the hollow or lattice triplets. The 400 [g] and 600 [g] target mass lattice variants perform worse than the solid A15, but the 800 [g] target mass variant performs 25.9% better than the solid variant. This sudden increase in performance may be due to the wider diameter of the A15 due to the high initial target mass. An example of this can be found in nature through the baobab tree in Africa which features an incredibly wide trunk diameter with a very low inner density. It was found that increasing trunk diameter directly increases its strength against buckling[19]. Similarly, the 600 [g] and 800 [g] target mass hollow variants perform best in their group. This may be explained by the wider diameter compared to the solid and 400 [g] target mass hollow variant. However, when looking at the first modal frequency of all seven A15 variants, there is only a 14.3% difference between the worst performing variant, solid, and the best performing one, 800 [g] target mass lattice. While this is indeed an improvement, it may not be considerable enough to justify the additional time necessary towards producing such a design, at least considering the current methodology. Lastly is the stiffness-to-mass ratio, from which the 800 [g] target mass lattice variant and hollow group has the highest ratio. However, as seen in **Figure 11**, there is very little infill at all in the 800 [g] target mass lattice variant. This suggests that a high stiffness-to-mass ratio is more dependent on the diameter width, similar to a baobab tree. Therefore, internal lattice structures do not offer a significant enough advantage over solid designs to offset the associated risks and difficulties of additive manufacturing. However, hollow designs may have the potential to outperform solid designs if the diameter width and shell thickness are optimized. To this point, it can be seen with the solid A15 variant that it closely resembles a hollow structure. The center of the part is completely void of material, with the outer geometries seemingly wrapping around it. These outer geometries likely show the maximum load paths that the part experiences. All of the empty spaces in between them can be thought of as zero thickness walls. As these spaces in the center of the part and between the outer geometries do not experience high loads or stresses, no material is required to support the structure. This shows that the generative design process converges on hollow designs as the most optimal stiffness-to-mass parts.

4.3.1. Wider Diameter A15 Variants

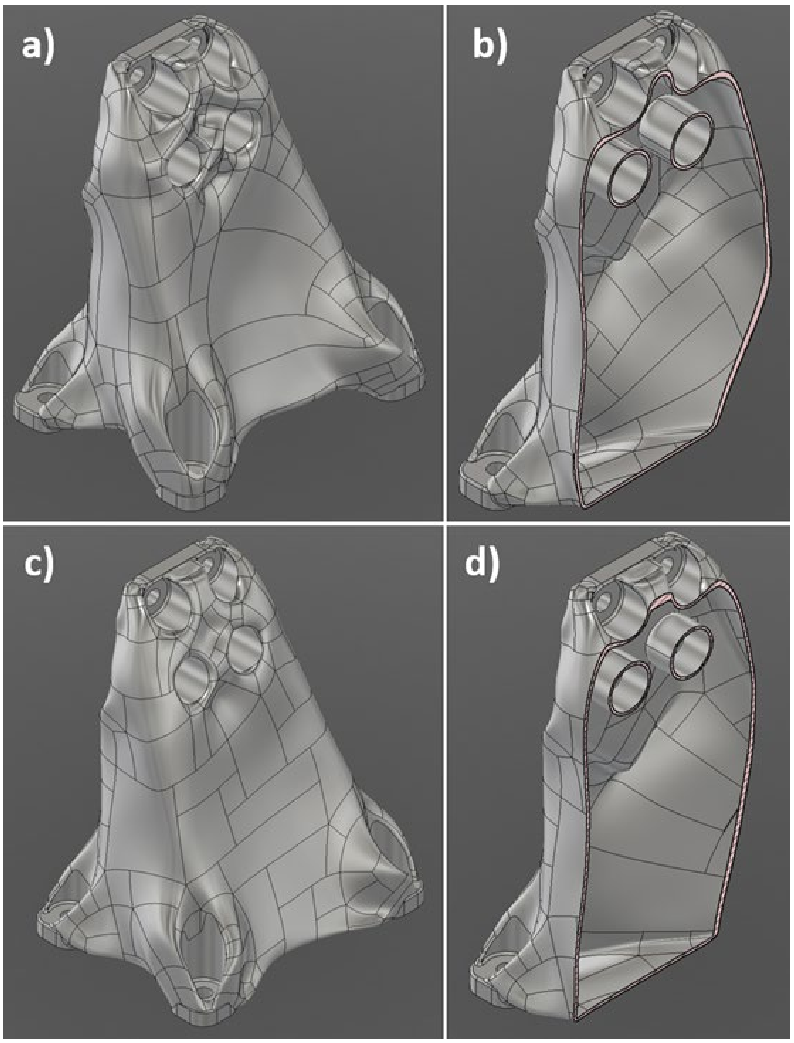

Figure 13: Wider Diameter A15 Variants: **a)** Hollow (2kg TM), **b)** Section View, **c)** Hollow ("Brick"), **d)** Section View

Based on the new hypothesis that hollow structures with a wide diameter will result in stiffer parts, two new designs were produced using generative design. As seen in **Figure 13a)** and **b)**, these parts were produced by inputting a target mass of 2 [kg] and taking an early iteration from generative design respectively. By adjusting the shell thickness, both parts are approximately 140 [g] like the other A15 variants. The results of these two variants are listed below in Table 1 to contrast with the already established variants. It should be noted that due to the high volume that these parts have, proper care should be taken to ensure that there is sufficient space in their installation location.

4.4. Verification

Table 1: Performance Results of Solid, Hollow, and Internal Lattice A15 Variants

Version	Mass [g]	Max Displacement [mm]	Mode 1 [Hz]	Mode 2 [Hz]	Mode 3 [Hz]	Mode 4 [Hz]	Mass-to-Stiffness Ratio
Solid	139	0.0263	137.9	258	446.8	771.1	5195
Lattice (400g TM)	141	0.0261	138	213	434.1	1049	5235
Lattice (600g TM)	141	0.0307	146.9	213.1	399.9	1248	4443
Lattice (800g TM)	144	0.0195	157.6	206.1	341.5	1263	6996
Hollow (400g TM)	139	0.0221	147.3	213.6	410	939.5	6165
Hollow (600g TM)	139	0.0199	151.5	205.3	371.6	1178	6866
Hollow (800g TM)	139	0.0201	148.9	183	307.6	1220	6791
Hollow (2kg TM)	136	0.0198	148.3	175	279.6	1533	6904
Hollow ("Brick")	138	0.0174	154.6	170.6	273.7	1664	7841

As seen in **Table 1** above, there is a general trend where generative design results with higher target masses leads tend to lead to lower maximum displacements, higher modal frequencies, and higher stiffness-to-mass ratios. This supports the hypothesis that wider diameters in hollow structures result in higher stiffness. The best of these results comes from the "brick" hollow variant which was obtained by rolling back the iterations of a generative design result to reveal a design that was as thick as possible. Conversely, parts with a lower target mass during generative design resulted in higher maximum displacements, lower modal frequencies, and lower stiffness-to-mass ratios. Therefore, it can be stated that wider diameters directly correlate to higher stiffness for hollow structures. Additionally, internal lattice structures do not offer greater stiffness compared to hollow designs.

5. Conclusion

Despite recent advancements in software and additive manufacturing technologies allowing for the modeling, simulation, and fabrication of internal lattice structures, the A15 case study does not yet offer a clear advantage compared to contemporary designs. While this may not be universally indicative of all applications, it does point to this conclusion for similarly behaving parts used in the aerospace industry. Parts produced from generative design have flexibility in being optimized for 3-axis & 5-axis CNC machining and additive manufacturing, however, internal lattice structures can only be produced via the latter. With this comes additive manufacturing's restrictions in build volume, non-homogeneous material, and difficulty in validation. Similar to internal lattice structures, hollow structures can only be produced by additive manufacturing, however they are much easier to model, simulate, and post-process. Both hollow and internal lattice structures require drain holes to remove excess powder after printing, however, it is more difficult to remove said powder from the latter than the former. Fusion 360 is not able to automate internal lattice structures, requiring more time to be expended by the designer or engineer to develop. Lastly, based on the simulation results of the multiple A15 variants, internal lattice structures do not offer significantly better performance compared to the much more feasible hollow structure. Therefore, if additive manufacturing is an option, efforts should be directed toward producing hollow structure to achieve the highest stiffness-to-mass parts with minimal work needed.

For future work, efforts should be diverted toward shell thickness optimization and increasing diameter width of the part. The results of this paper have shown that diameter width is one of the driving variables in decreasing maximum displacement, which is one of the most important performance metrics considered for aerospace applications. Additionally, by optimizing shell thickness, more material can be dedicated to high stress areas while conserving material in areas of low stress. This could both save powder usage and further minimize mass. Additionally, another path of research worth considering is variable density hollow structures. This takes inspiration from naturally occurring hollow structures like bamboo and baobab trees, both of which increase fiber density towards their outer edge where stresses are the highest[19 20]. Optimizing the density of sintered metal powder in the structure could further increase stiffness in conjunction with shell thickness optimization.

References

[1] Khajavi, Siavash H., et al. "Additive Manufacturing in the Spare Parts Supply Chain." Computers in Industry, vol. 65, no. 1, 2014, pp. 50–63., https://doi.org/10.1016/j.compind.2013.07.008.

[2] Abureden, Ghaith A., et al. "Exploring Potential Benefits of Additive Manufacturing in Creating Corrugated Web Steel Beams." Journal of Constructional Steel Research, vol. 187, 2021, p. 106975., https://doi.org/10.1016/j.jcsr.2021.106975.

[3] Jiang, Jingchao, et al. "Support Structures for Additive Manufacturing: A Review." Journal of Manufacturing and Materials Processing, vol. 2, no. 4, 2018, p. 64., https://doi.org/10.3390/jmmp2040064.

[4] Jin, Yu-an, et al. "Support Generation for Additive Manufacturing Based on Sliced Data." The International Journal of Advanced Manufacturing Technology, vol. 80, no. 9-12, 2015, pp. 2041–2052., https://doi.org/10.1007/s00170-015-7190-3.

[5] Strano, G., et al. "A New Approach to the Design and Optimisation of Support Structures in Additive Manufacturing." The International Journal of Advanced Manufacturing Technology, vol. 66, no. 9-12, 2012, pp. 1247–1254., https://doi.org/10.1007/s00170-012-4403-x.

[6] Kumar, Ajeet, et al. "Design and Additive Manufacturing of Closed Cells from Supportless Lattice Structure." Additive Manufacturing, vol. 33, 2020, p. 101168., https://doi.org/10.1016/j.addma.2020.101168.

[7] Sun, S., et al. "Powder Bed Fusion Processes." Laser Additive Manufacturing, 2017, pp. 55–77., https://doi.org/10.1016/b978-0-08-100433-3.00002-6.

[8] Vrána, Radek, et al. "Contour Laser Strategy and Its Benefits for Lattice Structure Manufacturing by Selective Laser Melting Technology." Journal of Manufacturing Processes, vol. 74, 2022, pp. 640–657., https://doi.org/10.1016/j.jmapro.2021.12.006.

[9] Hunter, Luke W., et al. "Assessment of Trapped Powder Removal and Inspection Strategies for Powder Bed Fusion Techniques." The International Journal of Advanced Manufacturing Technology, vol. 106, no. 9-10, 2020, pp. 4521–4532., https://doi.org/10.1007/s00170-020-04930-w.

[10] Gibson, Ian, et al. "Directed Energy Deposition Processes." Additive Manufacturing Technologies, 2015, pp. 245–268., https://doi.org/10.1007/978-1-4939-2113-3_10.

[11] Barbieri, Loris, and Maurizio Muzzupappa. "Performance-Driven Engineering Design Approaches Based on Generative Design and Topology Optimization Tools: A Comparative Study." Applied Sciences, vol. 12, no. 4, 2022, p. 2106., https://doi.org/10.3390/app12042106.

[12] Logozzo, Paula, et al. "Generative Design for Additive Manufacturing of Satellite Optical Tracker Mount." Solid Freeform Fabrication Symposium. 2022, p. 2081.

[13] McClelland, Ryan S. “Generative Design and Digital Manufacturing: Using AI and Robots to Build Lightweight Instrument Structures.” Current Developments in Lens Design and Optical Engineering XXIII, 2022, https://doi.org/10.1117/12.2646476.

[14] Sun, S., et al. “Powder Bed Fusion Processes.” Laser Additive Manufacturing, 2017, pp. 55–77., https://doi.org/10.1016/b978-0-08-100433-3.00002-6.

[15] Vrána, Radek, et al. “Contour Laser Strategy and Its Benefits for Lattice Structure Manufacturing by Selective Laser Melting Technology.” Journal of Manufacturing Processes, vol. 74, 2022, pp. 640–657., https://doi.org/10.1016/j.jmapro.2021.12.006.

[16] Hunter, Luke W., et al. “Assessment of Trapped Powder Removal and Inspection Strategies for Powder Bed Fusion Techniques.” The International Journal of Advanced Manufacturing Technology, vol. 106, no. 9-10, 2020, pp. 4521–4532., https://doi.org/10.1007/s00170-020-04930-w.

[17] Gibson, Ian, et al. “Directed Energy Deposition Processes.” Additive Manufacturing Technologies, 2015, pp. 245–268., https://doi.org/10.1007/978-1-4939-2113-3_10.

[18] Kirchheim, Andreas, et al. “Why Education and Training in the Field of Additive Manufacturing Is a Necessity.” Industrializing Additive Manufacturing - Proceedings of Additive Manufacturing in Products and Applications - AMPA2017, 2017, pp. 329–336., https://doi.org/10.1007/978-3-319-66866-6_31.

[19] Fournier, M., et al. “Integrative Biomechanics for Tree Ecology: Beyond Wood Density and Strength.” Journal of Experimental Botany, vol. 64, no. 15, 2013, pp. 4793–4815., https://doi.org/10.1093/jxb/ert279.

[20] Sato, Motohiro, et al. “Bamboo-Inspired Optimal Design for Functionally Graded Hollow Cylinders.” PLOS ONE, vol. 12, no. 5, 2017, https://doi.org/10.1371/journal.pone.0175029.