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Development of Guidelines for Support Structure Design and Placement in Metal Additive Manufacturing

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DEVELOPMENT OF GUIDELINES FOR SUPPORT STRUCTURE DESIGN AND PLACEMENT IN METAL ADDITIVE MANUFACTURING

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by
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ABSTRACT

Support structures used in metal additive manufacturing (AM) have traditionally been used to overcome process limitations. A new approach explored in this study used novel design and placement of support structures to reduce part deformation. First, a case study was conducted with a simple production part at a major OEM. Changing the support structures used in the print reduced the average deformation by up to 21% and the maximum deformation by up to 24%. Once this opportunity for customized support structure design was established, interviews with AM engineers were used to identify the most common challenge features that would benefit from support design: bottom surface, hole, roof, and overhang. Supports were designed for these features using a mechanical analysis, print simulation, and test print. The advanced support strategies showed multiple levels of success, with the bottom surface showing up to a 6% reduction in maximum deformation, the overhang experiencing up to a 11.21% reduction in average deformation, the hole reducing average deformation by up to 24.59%, and the roof showing up to a 32.10% reduction in average deformation. Guidelines with a geometry definition, support design envelope, and example support solution were created for each of the four challenge geometries and used to support a crank plate containing the four geometries. In print simulations of the crank plate, the varied advanced supports reduced maximum part deformation by 14.6% compared to the constant baselines supports. Finally, a general method for generating AM guidelines was created.

DEDICATION

This thesis is dedicated to my grandfather, Jean-Claude Golion. His engineering projects and achievements fueled my wonderment as a child and pushed me to chase my own as I grew older. His pride in my work was always the motivator I needed and is what I will continue to carry with me throughout my career.

ACKNOWLEDGEMENT

I would like to thank my advisors Dr. Joshua D. Summers and Dr. Garrett J. Pataky as well as my committee member Dr. Geetha Chimata for their guidance during this research. They have provided professional and personal development by encouraging me to discover things for myself for which I am always thankful for after the fact. They have made me a better engineer and researcher and I look forward to continuing to mature with them. I would also like to thank the members of the CEDAR lab for their input and advice and the FRAME lab for welcoming me and being so generous with their help. Finally, my collaborators at the OEM gave their time, knowledge, and resources to this research, for which I am incredibly thankful.

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ADDITIVE MANUFACTURING: THE FUTURE OF MANUFACTURING?

Additive Manufacturing (AM), the umbrella term covering many different technologies and approaches, uses computer instructions to additively place material in a layer-by-layer fashion [1–4]. This young manufacturing process, first explored in the 1960's thanks to the advances in computers, resins, and lasers of the 1940's, 50's and 60's, respectively, has grown to a $12.8 billion industry in 2020 [3,5,6]. Over the past ten years, the average growth has been 27.4% annually [3,5,6]. The opportunities created by AM, such as design freedoms, mass customization, material possibilities, and part consolidation, have fueled this growth that has branched into many different subsets [5].

The broad class of AM can be characterized into seven classifications: vat photopolymerization, material jetting, binder jetting, fused filament fabrication, sheet lamination, direct energy deposition, and powder bed fusion [7]. There are variances in the energy sources, raw materials, and deposition strategies [4]. Vat photopolymerization was among the first explored and utilizes photo-sensitive resins to selectively solidify geometries at different layer heights through lasers or flashes of light at specific wavelengths [8,9]. Material jetting is similar to a common office paper printer and deposits drops of material onto a print bed [10–12]. Conversely, binder jetting lays drops of a binding agent onto a bed of powder material to bind each layer [13–15]. Fused filament fabrication (FFF) is the most common consumer technology, feeding spools of material through a hot end, comparable to a hot-glue gun, onto a build plate [16–18]. Sheet lamination bonds thin sheets of material together, similar to laminating sheets of paper, to get to a final or near-final shape [19–21]. Direct energy deposition holds both the material and energy source together to deposit onto a build plate or piece [22–25]. Finally, powder bed fusion (PBF) hosts industrial processes such as selective laser sintering or direct metal laser melting (DMLM). In PBF, a layer of powder is laid on the build plate and an energy source such as an electron beam or high-powered laser selectively sinters or melts that layer to the one below it [26–28]. While these processes vary slightly, they hold the common theme of adding material instead of subtracting material from a raw stock and doing it as a highly digital process.

AM requires 3-dimensional data. This could be generated through the use of a computer-aided design software package or through a 3D-scanning solution [29–31]. The file is then fed through a "slicer" software that prepares the part geometry for printing [32]. This may include fixing any errors in the file such as being non-manifold, cleaning up noise, or generating necessary modifications such as support structures that are critical to ensuring a successful print. The geometry, with any accompanying modifications or supports, is converted into 2-dimensional slices that the machine will follow for each layer, gradually moving up the z-axis to create a part [31,33,34]. This allows for complex geometries to be created that would be challenging or impossible to make using other manufacturing methods and is the driving factor behind AM development.

1.1 Direct Metal Laser Melting

Of the previously described AM processes, the PBF subgroup is one that is popular in industrial applications [19]. Selective laser melting (SLM) is an approach within PBF shown in Figure 1.1 that uses a laser to fully melt the powder at each layer [35]. Increasingly powerful lasers have enabled a wide material library including metals, ceramics, and composites [36,37]. These lasers enable a part to reach up to 99.9% relative density, allowing AM parts to begin to rival the more isotropic characteristics of cast parts [35]. Within SLM is direct metal laser melting; SLM of metal powders. This is the process of interest for this research and a commercially available, multi-laser, high-volume option is used with process parameters deemed out of scope and held constant.

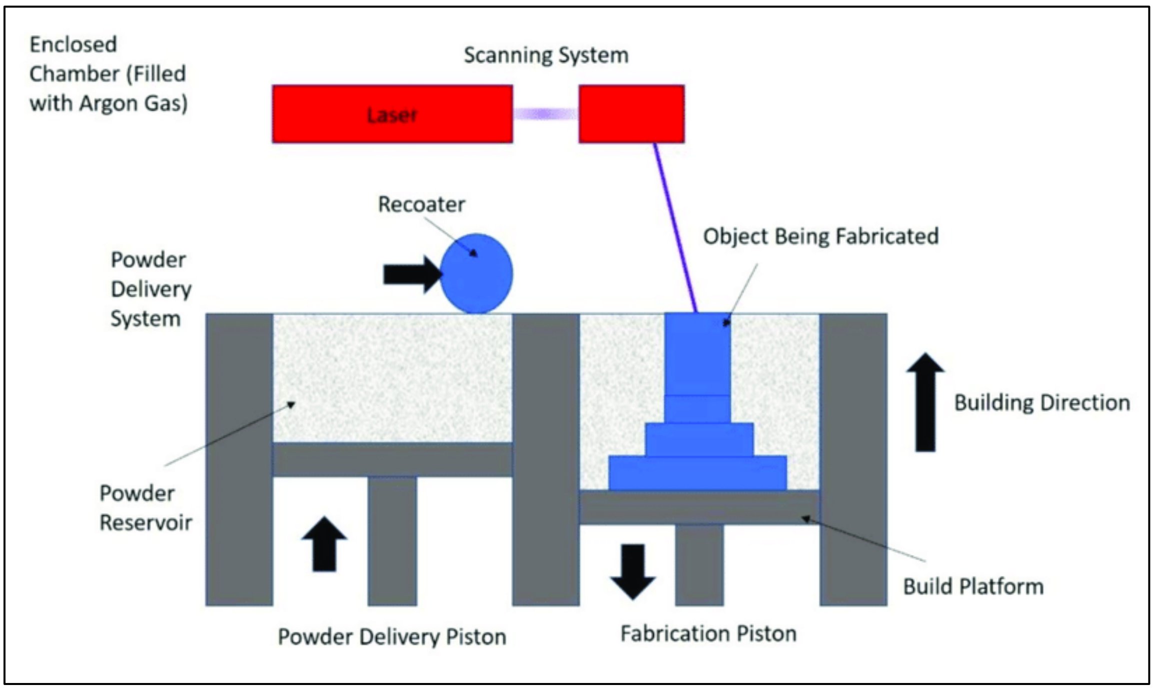


Figure 1.1: Visual description of the DMLM process, a subset of PBF. [38]

DMLM is often used with nickel-based superalloys such as Haynes 282, Inconel 718, Waspaloy, and MAR M-247 due to their desirable properties in high-temperature applications [39–41]. This family of materials is mechanically and chemically stable at the high operating windows often found in aerospace and power-generation applications and offers favorable strength, creep, fatigue, oxidation, and corrosion properties [41,42]. Their continued development is crucial to these industries and unlocks performance that is impossible with other materials. However, the material properties are out of scope for this research and the same nickel-based super alloy is used throughout.

1.2 Benefits of Additive Manufacturing

Many of the capabilities of AM would be too lengthy, expensive, or completely impossible with a traditional manufacturing approach such as injection molding or machining. Some appealing advantages include less tooling, more complexity, quicker turnaround, reduced inventory, and part consolidation [43]. A major cost of traditional manufacturing processes is in the tooling. Subtractive approaches go through many consumables such as cutting heads and fluids, and in forming, molds are costly in time and capital to create. AM enables complex internal geometries that would be difficult or impossible to obtain in molding or machining because of undercuts or lack of tool head access, all with little-to-no wasted material [44]. With no need for molds or custom tooling, it is much faster to generate new geometries and it does not have the same need for large quantity batches to amortize costs. This allows for another advantage: customization [45]. Parts can be made unique with small modifications of g-code as opposed to needing a new mold [46]. AM also requires fewer highly trained operators as it is a digital process that does not need the same skilled labor as welding or machining [47,48]. The ability to consolidate multiple parts into one monolithic component also proves significant to companies like GE aviation as evidenced when they were able to reduce the twenty components of a fuel nozzle into one, reducing weight by 25% and improving durability by a factor of five [49]. Reducing the number of parts in an assembly improve the process all the way up and down stream including less parts to model and stock in inventory and fewer assembly steps and failure opportunities.

Domestically, government agencies recognize the importance of AM for its potential to increase American global competitiveness in advanced manufacturing by reducing costs and increasing product performance [50]. AM is key to the application of the new advanced materials being developed in parallel [50]. The American Society of Mechanical Engineers (ASME) details different concerns that AM can alleviate. In a report on global supply chains, they call for the American government to “maintain or establish domestic capabilities and rapidly scalable manufacturing capacities” [51]. With low labor costs being a major reason for companies offshoring, a manufacturing process that is highly digital instead of labor intensive, such as AM, is conducive to this target [51]. The flexibility and development speed afforded by AM also addresses their recommendation for the federal government to “invest in research and development aimed at creation of transformative advanced manufacturing technologies that will enable rapid scale-up of manufacturing capacities of critical goods to meet domestic needs in times of a national emergency” [51]. Finally, the Massachusetts Institute of Technology’s “Work of the Future” task force claims AM “could be the most disruptive manufacturing technology on the horizon” because of not only the design space it opens up for designers but because of the impact it can have both up- and down-stream from the manufacturing facility. By allowing a fully digital experience from design to purchase to delivery, the traditional product lifecycle model is upended [52].

1.3 Weaknesses of Additive Manufacturing

While full of innovative benefits, the additive family of processes still comes with limitations. Modern CAD modeling was developed around the traditional subtractive methods of manufacturing [5]. It is not optimized for the freeform possibilities of AM. Models are also used as the direct instructions for the machine and therefore must be of great detail and fidelity [5]. AM part characteristics further depend largely on print parameters. For example, the orientation of the part within the build chamber will influence its surface finish, anisotropic material properties, and need for support structures, among other factors [5,53]. Beyond the actual part, machines still have a relatively small build volume and, although continuously improving, a high cost. Once an expensive machine is purchased, print times are still high and the machines use large amounts of energy and expensive raw materials. The material library is expanding but remains smaller than the traditional manufacturing options, as raw stock input must be a powder, filament, or special sheet [5,54–57]. The parts will often also require post-processing, adding finishing costs through more machines and labor hours [5].

More broadly, two larger challenges faced by AM are reliability and repeatability [50]. AM processes are much younger compared to their traditional counterparts and as such, work is still being done to standardize and certify parts [58]. Major sources of variation in PBF include: the properties of the powder, the characteristics of the laser, and the diverse post-processing operations [59]. The quality of the powder, including the shape and uniformity, affects the density and thermal conductivity of each layer as well as the laser's penetration depth [59,60]. The laser's energy density influences both strength and elongation of the parts [59,61,62]. Stress relief post-processing steps such as hot isostatic pressing are often used, but have been shown to introduce variations in elongation that does not present in as-built counterparts [59,63]. All of these sources often point to the challenge of residual stress in parts, especially in DMLM. The full melting of the powder is an energy intensive process and the part geometry affects the cooling of the part. As the laser heats an area of the powder, the surrounding area experiences thermal expansion and compresses. As the part cools and shrinks following solidification, it then experiences a tensile state. Variables such as the build chamber temperature or thick/thin transitions in the part geometry keep the resulting part mass in compression with a surrounding shell of tension, shown in Figure 1.2 [64]. This often leads to costly part deformation and cracking.

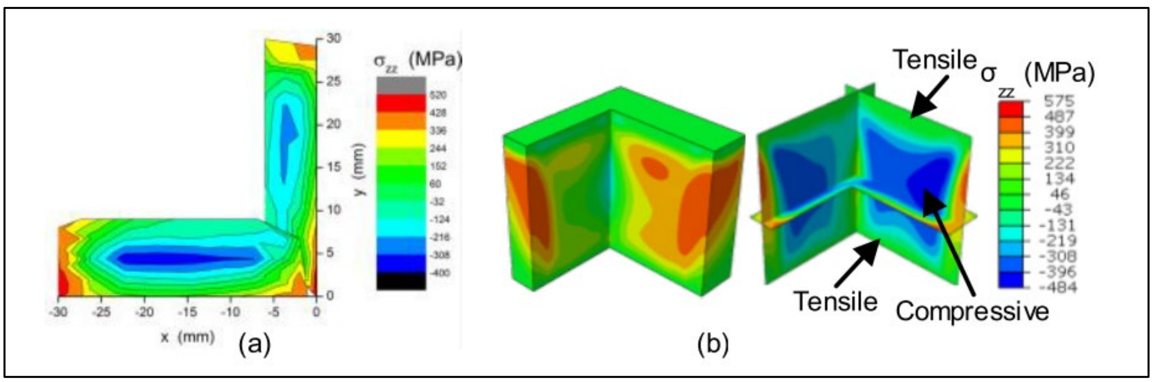


Figure 1.2: Example of residual stress in a SLM part. a) cross section of the part showing the tensile exterior and compressive interior, as measured. b) corresponding simulation of residual stress. [64]

1.4 Design for Additive Manufacturing

Designers working with processes such as DMLM must remember to account for the opportunities and threats described above. Designers are constrained by restrictive guidelines and enabled by opportunistic guidelines [65]. The former comes from limitations of the process and the latter is based on the unique abilities.

1.4.1 Restrictive Guidelines in Design for Additive Manufacturing

Restrictive guidelines are derived from the weaknesses or limitations of AM. These can address cost improvements as well as general work arounds for the inherent requirements of a layer-based process [66–68]. It is important to reduce the waste associated with each print, but it is especially crucial to prevent failed prints.

Restrictive guidelines have also been developed to optimize mathematical approaches to minimize the support structures required to have a successful print. The supports are traditionally sacrificial structures not part of the component geometry and thus do not add value to the end product [69]. They simply serve as intermediate structures necessary for printing certain features in specific orientations. As such, they require material, energy, and time and traditionally have been minimized to further drive down AM costs [68]. This can be extended to include considerations on ease of removal and therefore post-processing costs [70].

Parts that are deformed can sometimes be repaired, but this adds time, labor, and increased performance variability. Further restrictions can include specifics such as minimum wall thickness, maximum overhang length, and smallest hole diameter, as found experimentally to prevent unsatisfactory prints [71,72]. Some researchers create something resembling an instruction manual for their machines. These discuss specific ratios and process parameters setting the limits for successful prints that they have found through bracketing and iteration, such as the steepest angle a part face can be printed without supports before failing. [73,74]. A further restrictive guideline for designers is based on the PBF processes being similar to welding and creating thermal concentrations leading to residual stresses [75]. Authors also offer solutions, tested experimentally, for designers to implement to reduce the stresses that usually lead to deformation such as topology optimizations to manage stress [76]. However, restrictive guidelines concentrate on the limitations of AM and are only one type of guideline.

1.4.2 Opportunistic Guidelines in Design for Additive Manufacturing

Opportunistic approaches to guidelines look at the unique opportunities available in the AM process and seek to inform designers of the best way to leverage them. This is often done *post factum* once the researchers have successfully used AM in a novel way and now seek to share. This can be in the hope of moving away from design fixation of using only the traditional subtractive manufacturing processes and encouraging designers to keep AM in their design toolbox [77]. These tools are not meant to alter the design process but instead are helpful guidelines to be implemented whenever the designers need them [78,79]. For example, topology optimization often generates structures too complex for the traditional subtractive manufacturing methods. AM has become a large test bed for these complicated structures, with researchers showing demonstration studies and examples of successful implementations of topology optimization, offering best-practices and lessons-learned to take advantage of the geometries that are now able to be manufactured by AM [80–83]. Other researchers have sought to keep the engineer in the loop by providing approaches to meso-structure design using verified guidelines instead of optimization [84,85]. The challenge of deformation in DMLM can be addressed with some of the capabilities afforded by these sorts of structures.

1.4.3 Motivation: Leveraging Support Structures to Reduce Part Deformation

From the previously discussed approaches to design for AM, a gap can be identified. The two guideline types are presented in mostly a mutually exclusive fashion as two paths. In painting the restrictions as burdens that exist until the process and parameters improve, they are left alone by designers as hard rules. However, the design freedoms and opportunities afforded by AM could be used to address the restrictive concerns of support structures and residual stress. For example, this is just starting to be explored by using geometries such as lattices, impossible to create through other means, to act as heat sinks during the build [76]. However, there is much more work to be done leveraging the opportunistic to alleviate the restrictive.

One of the advantages of AM is the ability to customize parts without the need to amortize mold costs over large production runs. With that capability, parts are able to be uniquely altered for their print success. Support structures are a prime example of this. They are traditionally used to aid the process in depositing material. Because of the layer-by-layer nature, each layer needs something below it to be deposited onto as shown in Figure 1.3. Some geometries, such as overhangs, bridges, and holes, need support structures to fill the void and allow a layer to be deposited [68]. As such, each part's geometry, print orientation, and even specific print technology can require unique support structures. Traditionally, support material is placed based on known parameter limits. For example, a maximum allowable overhang ratio can be experimentally determined to then know the minimum allowable support spacing to successfully print the overhang feature [86]. For SLM, a minimum surface orientation of 45˚ has been identified experimentally [71]. This allows manufacturers to further reduce the challenges associated with increased support structures, including the added finishing steps, material, and time, among other wastes [87].

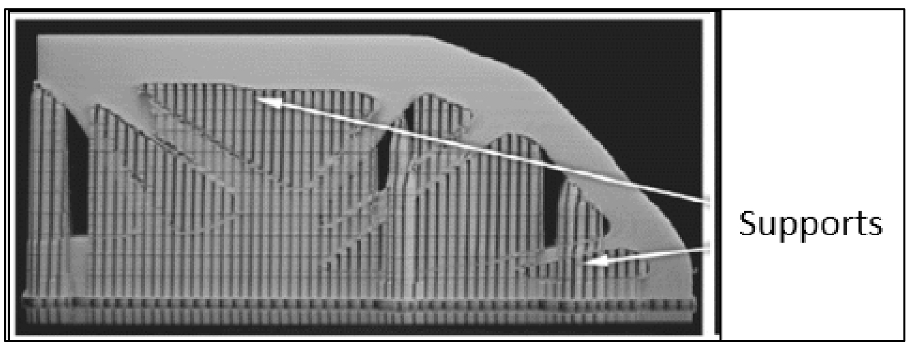


Figure 1.3: This part is shown with the support structures necessary to help the machine deposit material over gaps apparent behind the vertical supports. [88]

Instead, it is proposed to take customized support structures, traditionally sacrificial components of AM restricted by the process, and leverage them to address the process weaknesses. This takes the opportunistic to alleviate the restrictive. Support structures, which already will be required, can have their geometry varied to improve a part's deformation post-print. This uses support structures beyond their original intent and employs them in a novel manner. Based on results of this application, guidelines for support structure design based on key part features can be developed for AM engineers and designers involved in the AM process.

The resulting guidelines will be able to direct the creation of support structures in a more systematic and informed way. In a manufacturing context, a part that is out of design tolerance would cause the engineer to seek stronger supports to create a successful print, at the expense of added material and post-processing time to remove the supports. However, a part that is already successfully printing in tolerance may cause the engineer to seek to minimize support volume. The guidelines culminating from this research are not created as "one size fits all" solutions. Rather, the intersection of deformation prevention, material use, and removability is explored to create resources for engineers to create more successful parts based on their unique needs.

Chapter Two

PRELIMINARY STUDY: CASE STUDY ON INDUSTRIALIZED PROCESS AT OEM

A case study was first conducted to confirm if there was a connection between the support structures used in a part and that part's post-print deformation. While manufacturers attempt to lessen waste by reducing things like support structures, the larger issue is that of failed prints because of the stress concentrations that are not addressed. In powder-bed fusion processes (utilizing powder material and an energy source such as a laser or electron beam) that behave similarly to welding, the temperature changes and exotic materials present challenges such as residual stresses that often lead to part deformation [89]. DMLM introduces a higher amount of build and residual stress because it fully melts the metal, unlike sintering processes. This can cause a variety of challenges in the print as different regions of a part in production face large temperature gradients [35,89]. These can lead to stress concentrations that develop into deformation or even shifts that lift the part from the build plate and collide with the machine's re-coater. However, the ability to have the increased part density of up to 99.9% through melting keeps the DMLM process appealing enough to continue to develop [35].

There exist many variables to consider in DMLM printing from the gas flow in the chamber to scan patterns of the laser. Values such as these are often set by the manufacturer, but research is being conducted on optimization of these variables [90]. Instead, the process can be treated at as a black box model. The prepared print file that holds the geometry to be printed is one input, with the various print parameters being the second. These combine in the black box to output the print result as it appears on the build plate. The print parameters are deemed out of scope, and the geometry of the prepared file becomes the input of interest of this research.

2.1 Case Study

Case studies have been previously successful and have been validated for use in design research [91–95]. They focus on describing a real, specific case [96]. They are especially useful when the context cannot be disassociated from the phenomenon, such as in the case of this preliminary work. Here, the workflow of an ordinary AM part is followed at a major energy OEM and the results, while expected to be tied to the specific situation, are still applicable in a broader design and manufacturing environment as relevant lessons learned.

2.1.1 Description of OEM and Current Process

The study of the part occurred at a major energy OEM that designs and manufactures products from components to power generation systems and assemblies for worldwide markets. The tools used in the study are commercially available, enterprise solutions occasionally with customizations. The case study explored how the OEM designs support structures for DMLM part printing in a typical scenario at their manufacturing validation facility. This industry site creates production prototypes and manufacturing plans that are validated before being pushed to a larger AM facility. The parts produced range from tooling to parts of larger subsystems and are on a production scale in the thousands per year. Broadly, there is a five-step process model shown in Figure 2.1: (1)

Model Generation, (2) Additive Validation, (3) Additive Preparation, (4) Additive Manufacturing, and (5) Post Processing. This process model was derived from a series of informal interviews with engineers at the OEM over the course of almost year. First, the model was drafted with a design engineer over weekly meetings spanning five months. The model was then revised with and confirmed by three AM engineers over the next three months.

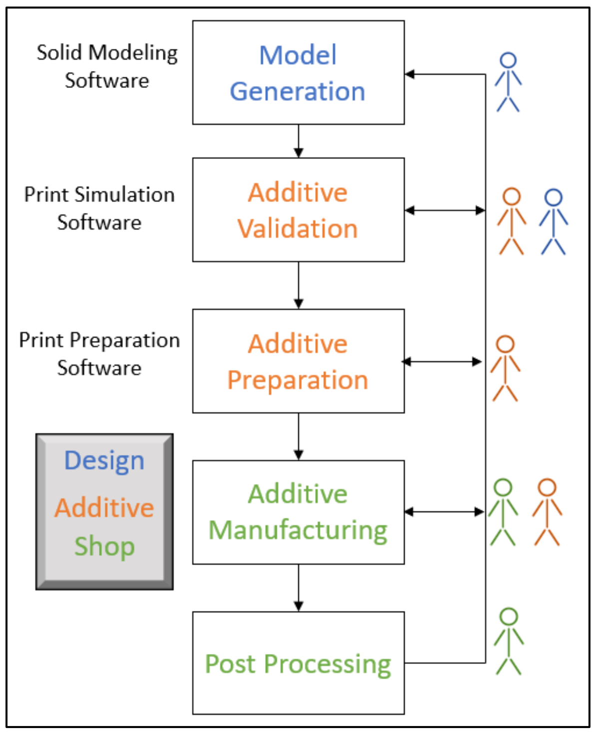


Figure 2.1: The OEM's process model for additively manufactured parts. The primary team is shown closest to the arrows, with the secondary next to them.

Model Generation involves solid modeling of a geometry for print. This is usually performed by various teams in the company that design a part and expect it to be additively manufactured. They design the part internally to their team before communicating to a team of AM engineers their part geometry and design goals.

This moves into Additive Validation where the printability of the geometry is evaluated. The AM team, composed of engineers on site at the production validation facility, reviews the design and intent with the design team. This is based on restrictive guideline considerations previously discussed, specific to the intended DMLM machine, material, and application. Decisions are made on geometric features the AM team predict to be a challenge in production. This spans from minor tweaks to part redesigns that can vary from five days to forty days of iteration.

Once predicted to be successful, the part moves into Additive Preparation, where the appropriate orienting, supporting, and slicing occurs over three to seven days. These decisions are made by the AM team still in communication with the design team to decide what will satisfy the design requirements encompassing functionality, time, and cost.

The output is sent to the machine for printing that takes one to five days, which upon successful print then goes through various post-processing stages as dictated by the design requirements by a shop team of technicians on-site at the validation facility. Depending on these necessities, the post-processing can take five to forty days. The machines used are direct metal laser melting printers from a commercial company with modifications done by the OEM. The post-processing available for these parts includes support removal, surface treatment, heat treatment, and non-destructive testing. Some post-processing portions are done internally by the OEM while others are contracted out to vendors depending on time, cost, and need.

Much iteration is expected in this process as requirements change and feedback is communicated between the three teams (design, additive, and shop), as highlighted by the arrows in Figure 2.1. The individuals representing each of the teams might change between the steps. For instance, one design individual might be focused on model generation while a second design team member might be working with the additive team representative during the additive validation step.

The OEM uses three main software packages in the additive process model. A commercial solid modeling solution is used to generate the part and create an STL file in the Model Generation phase. The second tool is a customized commercial AM simulation software used to simulate the print of the part and make decisions in the Additive Validation phase. Finally, an AM specific tool that allows for preparation, analysis, and modification of the STL as well as support generation is used in Additive Preparation.

2.1.2 Exploration Study

Once the AM process of the OEM was established, a part was selected to produce via DMLM. An exploration study was conducted to investigate the effects of different support strategies on the part's deformation. This study also delved into support removal at different stages in the part's manufacturing timeline.

2.1.2.1 Support Strategy Design

For the test part, a simple geometry shown in Figure 2.2 was chosen and held constant to test different support structures. This shape was oriented as an A-frame and featured varying thicknesses with fillets between them. The commercial solid modeling solution was used to generate the part and then create the STL file shown in Figure 2.2.

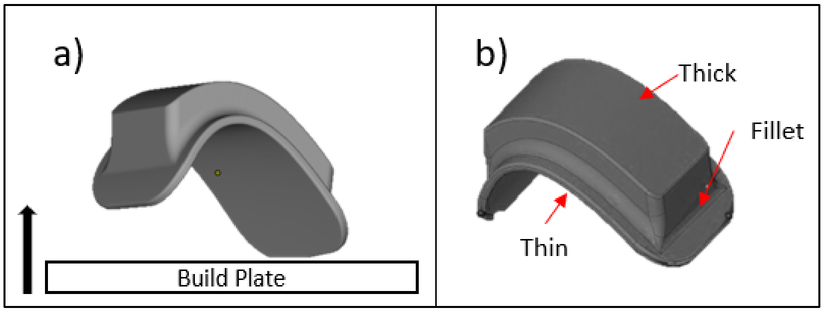


Figure 2.2: The test part in its print orientation. a) The black arrow signifies the build direction relative to the build plate. b) The red arrows show the regions of change in the geometry.

Next, the print simulation software was used to analyze the print of the part and its anticipated deformation. Two support strategies were identified in connection with the predicted deformation regions from the simulation software: strengthening and releasing. The strengthening strategy was used to strengthen the regions of highest anticipated deformation by increasing the support grouping density. This bracing would stiffen the print and prevent the part from moving, yielding an end geometry that was truer to the original STL file and CAD model. The strengthening strategy is shown in Figure 2.3. The releasing strategy was based on the opposite idea: allowing the relaxation. To combat the high stresses of the DMLM process, the regions of anticipated deformation should be allowed to naturally relax as needed with a less-dense support grouping while the other remaining regions would have the higher density support grouping.

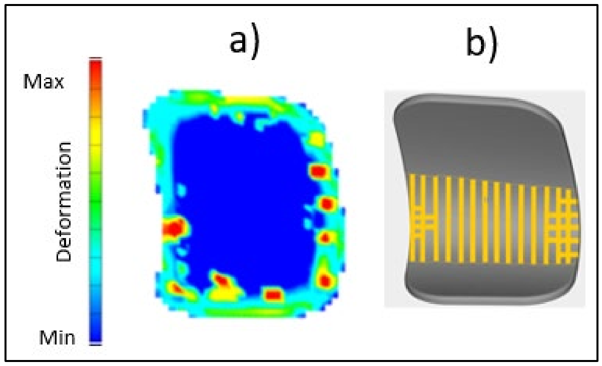


Figure 2.3: Comparison between the print simulation results and the supports modeled from the simulation results. a) The color scale shows regions of deformation. b) The supports modeled with the strengthening strategy.

In the print preparation software, the baseline supports were added based on process restrictions found experimentally by the OEM based on variables such as material, process, and machine, as is found similarly in the literature [86]. The attachment point to the part was made into a toothed connection to more easily remove the supports in the post-processing stage of the workflow. This decision was made based on a manufacturability consideration. The three strategies, including the baseline approach, are shown in Figure 2.4. The results of the simulation runs were used to determine the placement of the varied density supports in the print preparation software.

Figure 2.4: The three strategies viewed from the bottom showing the differing support structures in yellow.

Once the models were ready for print, they were sliced in the print preparation software and the resulting files sent to the machines for print. The parts were printed via DMLM from a nickel-based super alloy on the same machine. The machine is a commercially available, multi-laser, high-volume option.

An experimental plan was developed to further compare the effects of keeping supports on through the post-processing steps. The two variables of interest were the support strategy and the presence of support structures during post-processing. This would allow a better understanding of when in the process to remove the supports to minimize part deformation. Their serialization is shown in Table 2.1.

Table 2.1: Matrix of test prints with their associated variables.

Support Strategy	Part S/N	Supports During Post-Processing
Baseline	A1	X
	A2	-
Strengthen	B1	X
	B2	-
Release	C1	X
	C2	-

The parts were printed and post-processed in accordance with a serial number approach. The three support strategies each were given two prints:

- one with supports on through the post-processing (#1) and
- one with supports off through the post-processing (#2).

For example, A2 had supports removed after the print while A1 did not. The parts each went through print, surface treatment, heat treatment, and non-destructive testing. These steps are shown in order in Figure 2.5. Post-processing steps like surface treatments are shown to improve operational characteristics without altering the geometry of the part [97].

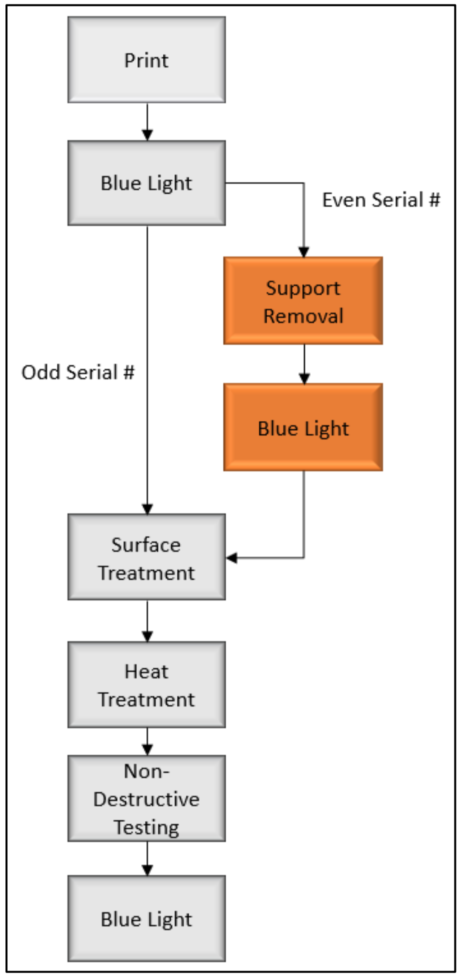


Figure 2.5: Flow chart of possible post-processing steps. Parts with an even serial number diverted to support removal and an intermediary scan before completing the rest of the post-processing steps.

At multiple stages, blue light scanning was employed to compare the part to its original part file and measure the deformation at four common locations across the part shown in Figure 2.6. These values were used for average and maximum calculations.

When a part needed supports removed, the baseline support strategy parts were able to be removed by hand tools, while the other two strategies required electrical discharge machining.

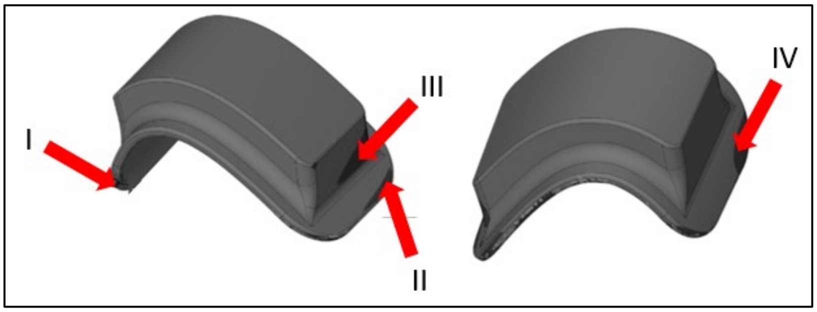


Figure 2.6: Blue light scan of common measurement points. These four points were compared to the original CAD model and the resulting deviation amounts were used in calculations.

2.1.2.2 Support Strategy Effects and Outcomes

The first result in the data is in the difference between the average deformation of the control baseline with constant supports kept on through processing, A1, and the strategized strengthen and release approaches (B and C). Figure 2.7 shows that there is a 16% reduction in average deformation between control (A1) and the strengthening parts (B) and a 16% reduction in maximum deformation. With respect to the control (A1) and the releasing parts (C), there was a 21% reduction in average deformation and a 24% reduction in maximum deformation. Full measurement data can be found in Appendix A: Case Study.

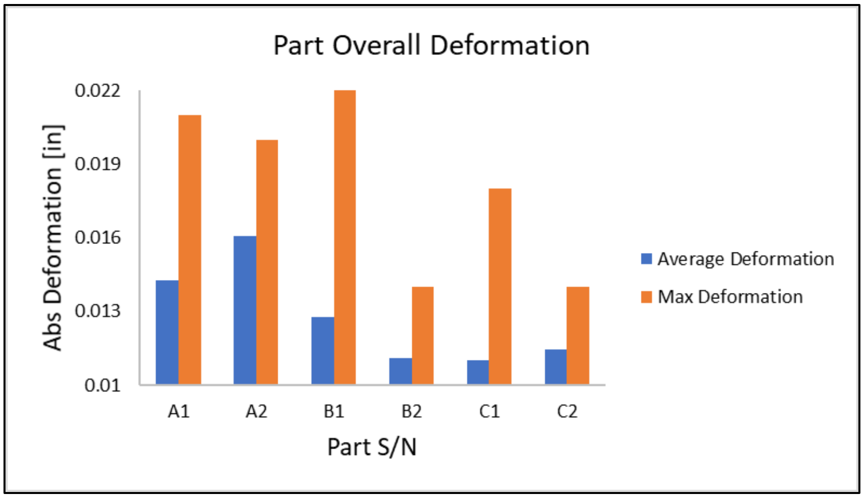


Figure 2.7: Part Overall Deformation. The strategized supports (B and C) have lower average and average of maximum deformation than the baseline (A).

This data showed that the supports used in the prints affected the overall part deformation. In this case, the strategized supports, B and C, both yielded less deformation in the part than the conventional control approach, A1. The releasing approach, C, was the most effective at preventing deformation and yielded a part that was truer to the original CAD geometry.

The second takeaway from the data was the effect of keeping support structures on through post-processing operations. The baseline approach (A) and the releasing strategy (C) both show in Figure 2.7 that keeping supports on through post-processing stages prevented average part deformation. The supported control baseline (A1) saw a 13% increase in average deformation when the supports were removed (A2). The supported release strategy (C1) saw a 4% increase in average deformation when the supports were removed (C2). However, the strengthening strategy (B1) average deformation decreased 13% when removing the supports (B2). This decrease in deformation by removing the support structures before post-processing was also shown in the maximum deformation values. Across all three strategies, the maximum deformation was less when the supports were removed (the even serial number). In total, four out of the six comparisons showed less deformation when the supports were removed before the post-processing steps.

The biggest consideration in the traditional application of support structures in metal AM is the added material use from the supports. Because of the cost of the metal powder and added print time, support volume is the target of minimization. Here, the volume of the supports was also used to compare the deformation values of each strategy. Table 2.2 shows the volume of support material used in each part in comparison with the associated average and maximum deformation values.

Table 2.2: Comparison of support volume and corresponding deformation

Strategy	**Support Volume** in^3	**Tot Avg Deformation** in	**Max Deformation** in	**Max Deformation Location**
A1	0.217	0.014	0.021	IV
A2	0.217	0.016	0.020	II
B1	0.312	0.013	0.022	I
B2	0.312	0.011	0.014	I
C1	0.353	0.011	0.018	I, IV
C2	0.353	0.011	0.014	I, II

Depending on the application and tolerance requirements of the part, AM engineers must consider the tradeoff between material use and deformation. If a goal of AM is to reduce cost, this can be done by fewer failed prints – defined either by complete print failures or parts that are out of design tolerance. As such, it is up to the engineers to decide between lesser support volume but higher deformation and hoping to be in tolerance or extra material used in the supports but less deformation and a higher chance of being in tolerance. This consideration is displayed in Table 2.2 where the C2 strategy, releasing strategy and supports removed in post-processing, had the lowest amounts of average and maximum deformation but a 63% increase in support volume compared to the baseline. This tradeoff between added material in the supports and the acceptable part deformation is at the discretion of the designers and engineers based on design specifications and allowable post-processing steps. More labor and tools used in the support removal process lead to increased cost, another compromise to be considered.

The blue light scans addressed the common measuring points shown in Figure 2.6. After the processing steps, the location of the maximum deformation was as displayed in Table 2.2. It is shown that the support strategy not only affected the amount of maximum deformation experienced by the parts, but it also moved that deformation location around the part.

Overall, in comparing the maximum deformation results, the releasing strategy yielded smaller values than the baseline and the strengthening strategies. In terms of support structure presence in post-processing, the removal of the structures before surface treatment, heat treatment, and non-destructive testing yielded less maximum deformation than keeping the structures on. This led to combination C2, the releasing strategy with supports removed, being the strategy of choice for maximum deformation reduction in this part, even with the highest support volume.

While supports are traditionally used as a bypass to process limitations as described earlier, the data presented offers that supports used in prints have a different impact than their original purpose. The key observation was not the success of the C2 combination in reducing deformation in this specific part geometry. Instead, support structures actually affected the part's overall deformation in the print process, the part's resistance to deformation during post-processing operations, and the location of maximum deformation rather than simply helping the printer build on top of a vacancy in the part geometry. Support structures are tools that should not be automatically applied in a consistent pattern. Rather, the support structure and therefore the support strategy should be customized to each part and geometry. Using tools such as the print simulation software enables designers and engineers to make informed and intentional decisions on the approach to supporting the part. Support structures are a way forward to alleviate DMLM process restrictions.

2.1.2.3 Notes on the Support Exploration Study

In this case study the support grouping density and therefore total support material volume were altered while the thickness, support shape, and specific attachment parameters were held constant. However, in changing the grouping density, supports were added along the longitudinal direction to create the strategized approaches rather than changing the latitudinal density. The orientation of these perpendicular supports could also have played a role in the improved deformation performance of the part.

Some parts were printed and processed not in accordance with the model laid forth in Figure 2.5 but still maintaining the case study support strategies. In this batch, no surface treatment occurred before the heat treatment. All of these parts developed cracks near locations II and IV shown in Figure 2.6 with the exception of one that only cracked in one location. The cracks sites are near the regions of highest deformation on the part. The simulation software also predicted these regions to be concentrations of stress during the build process. The variation in support strategies did not change the presence of the crack. While the deformation was investigated in this case study, the link between cracks and support strategies needs to be further explored.

2.2 Next Steps Identified

The work in this preliminary study was based around DMLM, a nickel-based alloy, and the part geometry presented. The support strategies were uniquely designed and applied for these parameters. However, the larger observations stand: support structures influenced the deformation behavior of the part both post-print and through each of the post-processing stages, key challenges faced by DMLM.

To apply custom support structures to parts, a nomenclature for the features of the part must first be derived. Defining what constitutes a part feature is already challenging and sometimes subjective with the nuances of language. This is further exacerbated by the different print orientations possible in AM. In one orientation a print may have an overhang but rotated 90-degrees it does not. There are many ontologies developed with AM in mind but there lacks a wide standard [76,98–100]. In Figure 2.1 it is shown that the five steps in the process model are divided between three teams. Without a robust standardized nomenclature, the communication between teams will suffer and details will be lost by the time the part has completed all of its process steps.

Once a standard is decided on to describe the part, an exploration into the relationship between part features and support structures in DMLM prints can occur. How to adapt supports with intent for individual part feature success is an open question. Applying customized support structures to parts will yield similar results to the reduced deformation quantified in this case study. Broadly, this preliminary study demonstrated the need for exploring the opportunities afforded by AM to alleviate restrictions on geometry no matter the process or material.

Chapter Three

CHALLENGE REGION IDENTIFICATION: AN INTERVIEW STUDY

To identify geometries that would benefit from having a customized support structure developed for them, interviews were conducted with stakeholders in the AM process. The interviews included presenting a variety of sample parts and having the interviewee identify features they believed to be of concern if the part were to be printed. Based on the results of the interview, the most common features were identified and given a relevant name that would be logical to the greatest number of users. The interviews were developed to last one hour. This included 5-minute introductions, 45 minutes of analysis, and 10 minutes for an exit survey.

The population consisted of eight AM engineers, two design engineers, and two shop technicians at the energy OEM. Because the goal of the work was to develop guidelines for AM engineers, most of the interviewees fell in this category. However, it was still crucial to maintain some interviewees located upstream and downstream in the process for better context. These interviewees are shown in Table 3.1. AM engineers support additively manufactured part production from cradle to grave. Design engineers can be from a variety of teams and work with AM as a possible tool to achieve their design needs. Technicians work in the production stages of AM, ensuring proper machine functionality and perform any supporting duties around the completion of the part.

Table 3.1: Population of challenge feature interviews

Identifier	Role	Job % Pertaining to AM
7O	AM Engineer	100
1M	AM Engineer	100
8C	AM Engineer	75
4F	AM Engineer	100
0M	AM Engineer	100
7N	AM Engineer	100
8P	Technician	100
3P	Design Engineer	50
3S	Design Engineer	60
0V	AM Engineer	100
5I	AM Engineer	100
2S	Technician	100

The interviews were conducted remotely through a consumer tele-communication app. First, this virtualized interview approach was critical as the interviews spanned 2020-2021, overlapping with the COVID-19 pandemic. Further, this was selected because of the ability to screen share during meetings and screen record for future reference and analysis. At the start of the session, the interviewee was given a link to a shared folder in a cloud-based file-sharing service. They were granted access to STL files and an associated guided notes document for each test geometry. In the parent folder was also a guiding document that included any information on necessary software, generating an anonymizing identifier, consent, analysis instructions, assumptions, and a link to a post-analysis survey. This document was read to the interviewee who, upon agreeing with the instructions, downloaded the two sub-folders of part files and notes documents. They were then asked to share their screen on the call while opening each part in parallel with its corresponding guided notes document and completing as much analysis as possible in the allotted time frame. With ten minutes remaining, the interviewer regained control of screen sharing and opened the link to the post-interview survey, where they read the questions to the interviewee and had them answer. At the end of the session, they were asked to upload their completed guided notes documents back into the cloud folder to complete the interview.

3.1 Interview Setup

Some key steps occurred in the five-minute introduction using the instructional documents. A 6-digit identifier was created for each interviewee that was generated using the last two digits of their birth year, their mother's maiden initials, and their state or country of birth. This was done to anonymize the documents created while still being able to connect the call recordings, guided notes documents, and post-interview survey. It also allowed for a unique identifier that the interviewees could recreate in future interviews. In a secondary capacity, it served to relax the interviewee and remind them that this was in no way a review of their performance or efficacy at their job. Next, the introduction listed the assumptions that the interviewee should carry with them as they assessed the geometries. The orientation of the part was to be as presented. This was to keep the interviewee from considering how they would orient the part and instead completely concentrate on features and geometry of the part. It also kept those geometries and features constant as some regions in one orientation are no longer challenging when printed in another orientation (e.g. holes or overhangs). The scale of the part was to be as described in each notes document and set by the STL file. Each part was to be fully dense, as the scope of the work was to only look at external challenge features and nothing internal. Therefore, assuming the part to be fully dense would prevent those kinds of considerations. The material of the print was assumed to be a nickel-based alloy printed in DMLM. The selection of the material and process was made because this combination creates interesting challenges in print and it was what the interviewees were most knowledgeable about [101,102]. To keep the interviewee concentrated on just the part geometry presented, the final two assumptions were that the loading of the part while in use was accounted for in the design and that the post-processing would be industry standard and considerations like surface finish should not be dealt with at this time.

3.2 Part Analysis

Once the introductory phase was complete, the interview began. The interviewee was presented with sets of STL part files and guided notes documents. A sample of one these parts is shown in Figure 3.1. Some were taken from online repositories while others were derived from production parts, such as brackets and other hardware.

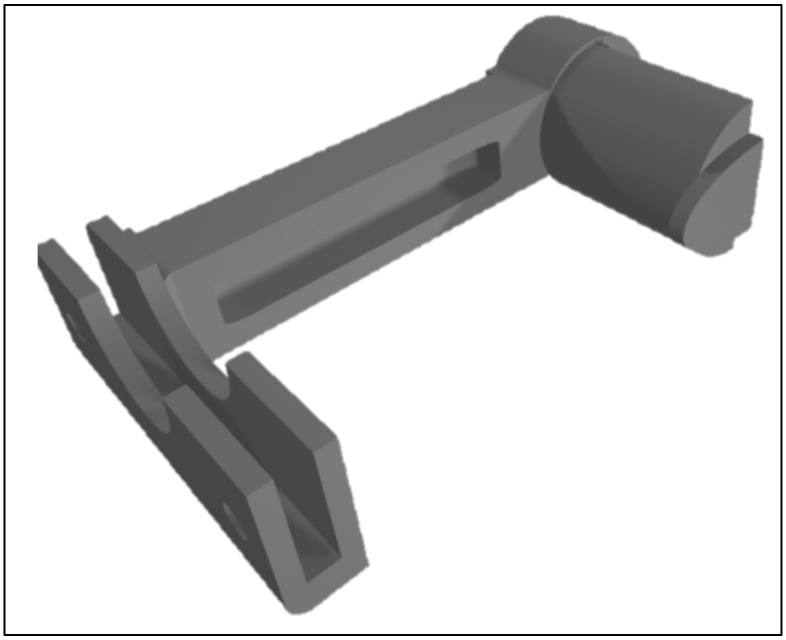


Figure 3.1: Sample part from an online repository used in interviews to identify challenge features.

The documents had space for their user identifier, the geometry serial number, and the scale of the part. Each document had two images of the associated part which were used to drag circles onto key features of the part that interviewees anticipated being challenging to print. For each of the circles, they were asked to name the challenge feature, assign a criticality level on a one to ten scale, and describe any extra considerations they had. Once all of the features were identified, the document asked what would guide the support strategy for this part, further narrowing to what the interviewee considered to be the most important considerations. The final question on the document served as a blanket question and allowed for the interviewee to mention any extra information they would have liked to know prior to printing. The interviewee was given the ability to edit and complete this document themselves so that they could refine without pressure on their rankings of the most important issues, as this was the point of interest of this portion of the research. This document was completed for as many of the parts as could fit in the allotted time.

3.3 Exit Survey

The final portion of the interview included the online exit survey. This was completed by the interviewer while screensharing with the interviewee to get consistent language and formatting in the answers. The first question in the survey was the identifier of the interviewee to anonymously tie the survey to the analyses. Next, a process model of the AM part flow was presented. They interviewee was asked where their work fit in to the process model shown in Figure 3.2, with the ability to click on multiple steps in the process. During the interview, the figure had only blue shapes and solid arrows. The model shown was an elaboration of the one shown in Figure 2.1 to better see where interviewees fit specifically. They were also given the opportunity to give feedback on the accuracy of the process model. The fourth question asked what percentage of their job related to AM. The final two questions asked to list the software and tools they used with AM and their confidence level, training, and years of experience with each.

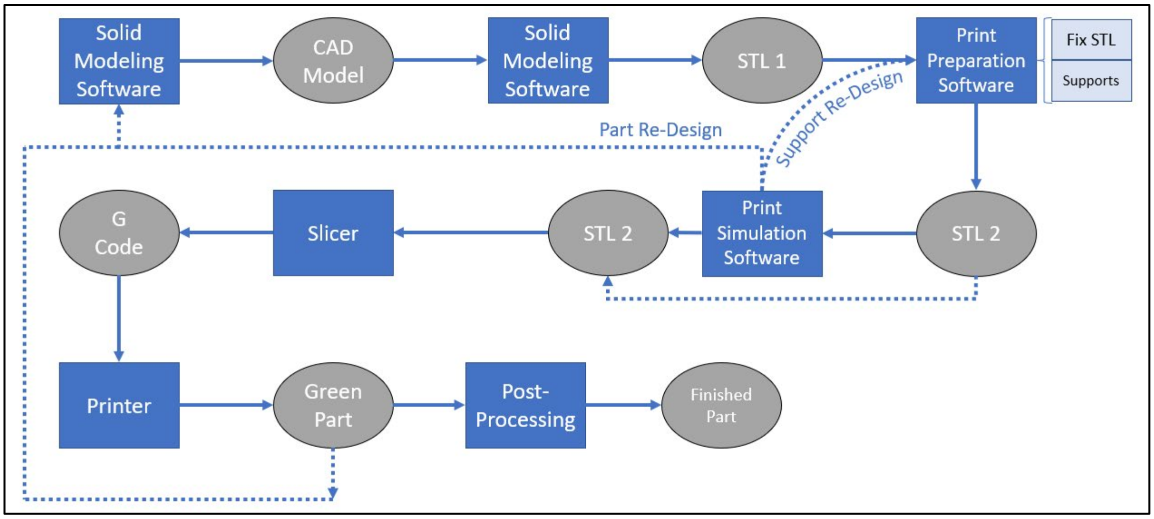
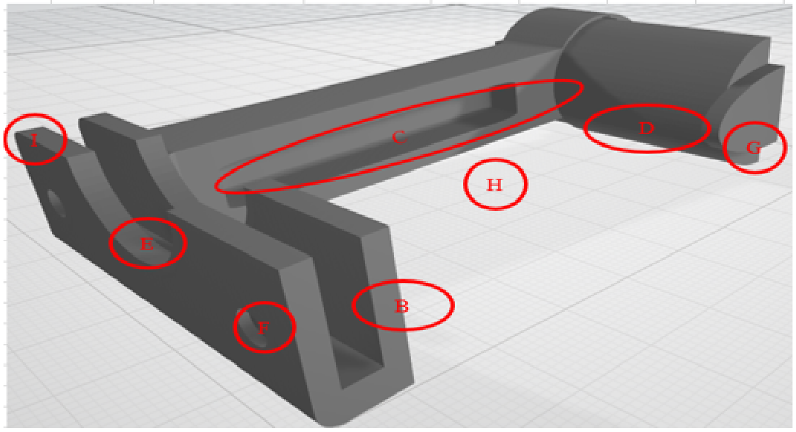


Figure 3.2: Detailed process model of AM at the OEM that allows interviewees to better show where they work. Blue squares are tools and grey ovals are the intermediary inputs and outputs.

3.4 Analysis of Interviews

To identify the key challenge features within the geometries presented to the interviewees, the interviews were used to list every challenge feature identified for each geometry. Then, the occurrences of each were counted. Based on the rates, the top features were identified for each geometry and characterized generally. One of the geometries is shown in Figure 3.3.



Area	Times Referenced	Description	Identification
A	6	Keyway	55%
B	8	Sharp Edges	73%
C	11	Pocket	100%
D	6	Downskin	55%
E	1	Bottom surfaces	9%
F	8	Hole	73%
G	6	Unsupported	55%
H	5	Plate attachment	45%
I	1	Distortion/Pull	9%
I	1	Thin	9%
-	2	STL Quality	18%
	11		

Top 3	Pocket
	Sharp Edges
	Holes

Figure 3.3: Top challenge feature identification for one of the geometries used in the interviews.

Overall, the top three challenges of each geometry were taken to compare across geometries. They were given temporary, general names to complete the analysis. The most occurrences, in descending order and with general names, were holes, sharp edges, connection to build plate, overhangs, and pockets. These are shown in Figure 3.4.

Top Problems					
Geometry A	Geometry C	Geometry D	Geometry H	Geometry I	Geometry K
Area C	Area D	Area D	Area D	Area A	Area D
Area E	Area E	Area A	Area A	Area E	Area E
Area D	Area B	Area C	Area B	Area B	Area B

Pocket	Holes	Holes	Holes	Overhang	Holes
Sharp Edges	Sharp Edges	Overhangs	Overhangs	Sharp Edges	Sharp Edges
Holes	Connect to BP	Pocket	Connect to BP	Connect to BP	Connect to BP

Problem	Occurrences
Overhang	3
Holes	5
Sharp Edges	4
Connect to BP	4
Pocket	2
Bridging	1

Figure 3.4: Tabulation of overall occurrences of challenge features, given temporary identifiers.

To develop an intuitive naming scheme for them, the interviews were again leveraged. Using the guided interview notes documents that had each interviewee's name for each challenge feature, the frequency of each identifier word was counted. Therefore, each challenge feature was named based on the most occurring nomenclature. This yielded the five features of:

1) bottom surface,
2) overhang,
3) roof,
4) hole, and
5) sharp edge.

These five features were characterized largely with the number of sides that were connecting the top and bottom of the feature as well as whether the feature was within the part or above the build plate. Because this research explores the use of support structures, the “Sharp Edge” challenge feature was deemed out of scope because it was not immediately addressable with support structures.

Chapter Four

GUIDELINE DEVELOPMENT

Guidelines have been used extensively as tools for engineers and designers to improve their parts and assemblies. They are used to replace tribal knowledge and informal best-practices with more robust, tested solutions [84,103]. Design guidelines have been validated as tools that provide recommendations to designers across different levels of detail [104,105].

4.1 Metrics of Success

By identifying which combinations of part geometries and support structures improve part deformation, recommendations on support design can be made to AM engineers and other key stakeholders. While these guidelines need to be effective in reducing part deformation, real-world use dictates that they must also make business sense. For example, an extreme solution would be to fill in the challenge features completely with material, then machine or otherwise remove material to achieve the targeted part geometry. As such, more than just part deformation reduction should be targeted. Two additional metrics were considered: support volume and support removability. If the volume of the support is minimized, then material use and print time are also reduced – both beneficial to the manufacturer. The removability of the supports from the part is also crucial. One of the appeals of AM is the reduction of labor in favor of a digital approach. Producing parts that then require extensive manual labor or machining negates this advantage and should be avoided. The success of the support structures was therefore measured in deformation amount, support volume, and support removability.

4.2 Challenge Geometry Modeling

Based on the four challenge features identified during the interviews, testable versions were modeled to be lightweight in simulation and prints while still remaining representative. These are shown in Figure 4.1.

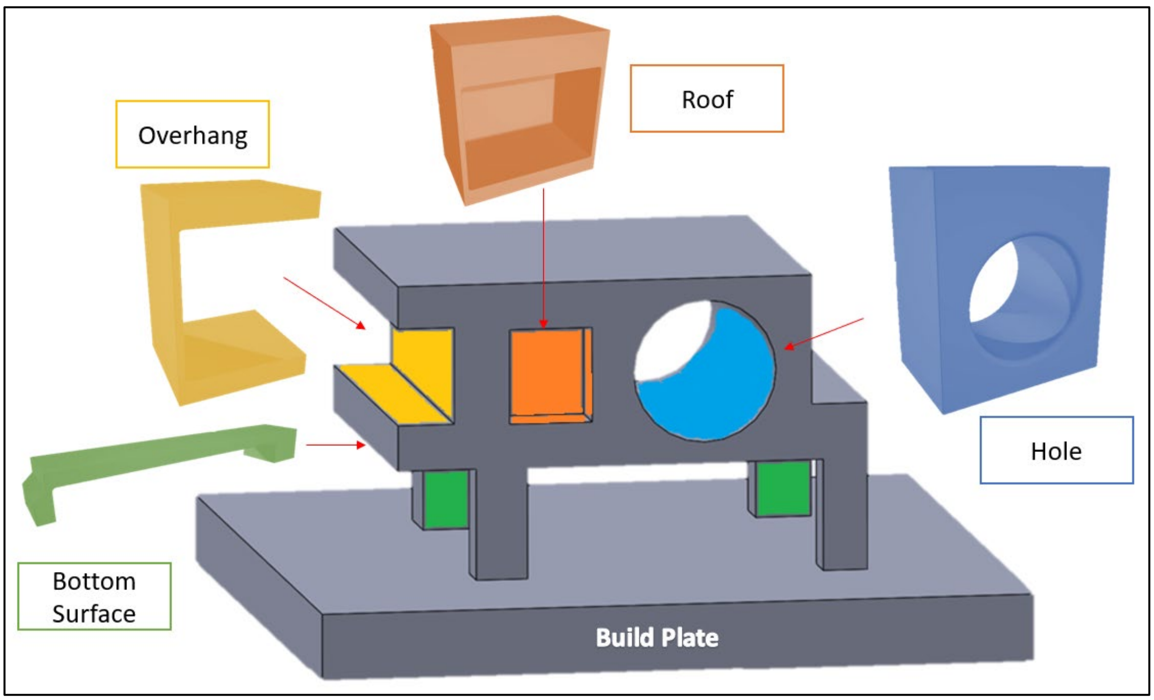


Figure 4.1: Challenge features and their derived challenge geometries.

First, the bottom surface was explored. This was characterized as requiring part-to-plate supports and having two stress concentration points (90-degree corners) with two open sides. The roof needed part-to-part supports and had four concentration bends making a rectangle, with three enclosed sides. The overhang also required part-to-part supports and featured two concentration points but with only one vertical side. Finally, the hole necessitated part-to-part supports but with a circular shape (no stress concentration points) completely through the body. These are shown in Figure 4.2. The overall size of the geometries was selected to facilitate simulation and print times. Key ratios and thicknesses were decided through simulations to prompt the most amount of deformation possible as well as to remain representative of real-world parts even while isolating the geometries.

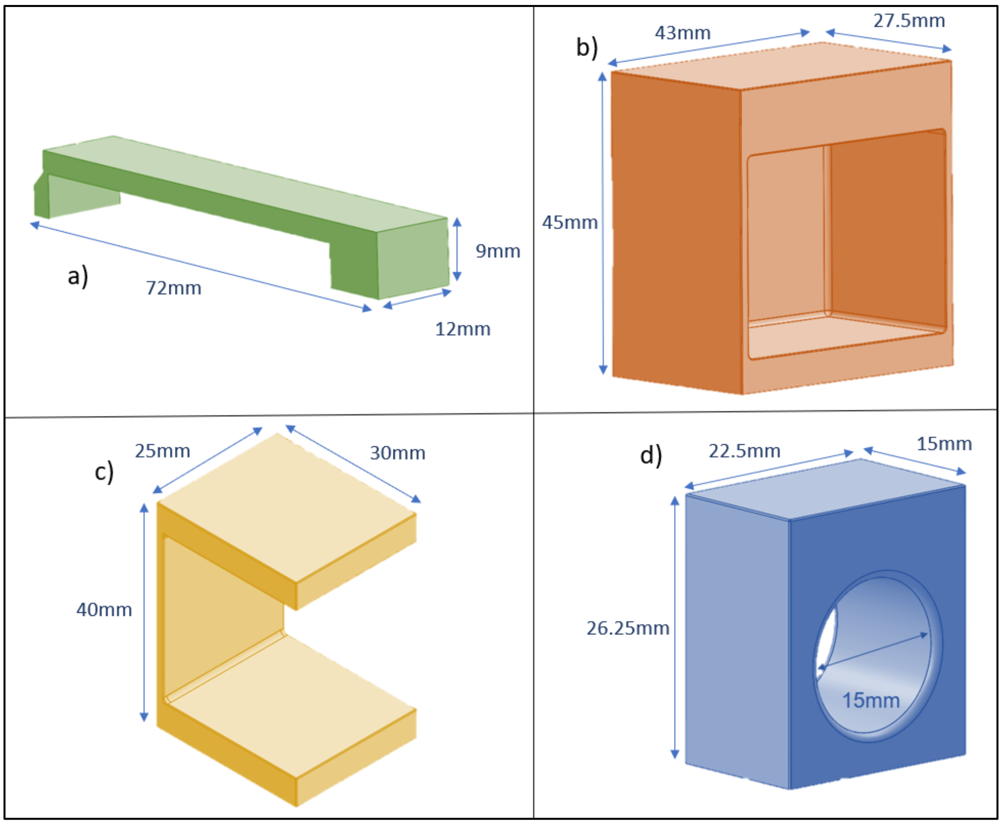


Figure 4.2: Challenge geometries and their sizes. a) is the bottom surface, b) is the roof, c) is the overhang, and d) is the hole.

4.3 <u>Baseline Support Creation</u>

First, baseline supports for each geometry were modeled. Using the current approach to support structure design, they were designed to address process restrictions while ensuring minimal material use and maximum ease of removal. This resulted in thin plates with toothed attachments to the parts. The length of each plate and the toothed vertical ends were chosen for their ease of removability, while their spacing was decided based on machine limits. These baseline supports are shown for each of the challenge geometries in Figure 4.3. Each baseline print was simulated using the same print simulation software as presented in the case study and also printed with the same machines and material as before. The simulation software discussed later in Section 4.4.1 aligned with the deformation behavior of the physically printed parts and was leveraged in the rest of this research. The baseline prints are shown in Figure 4.4.

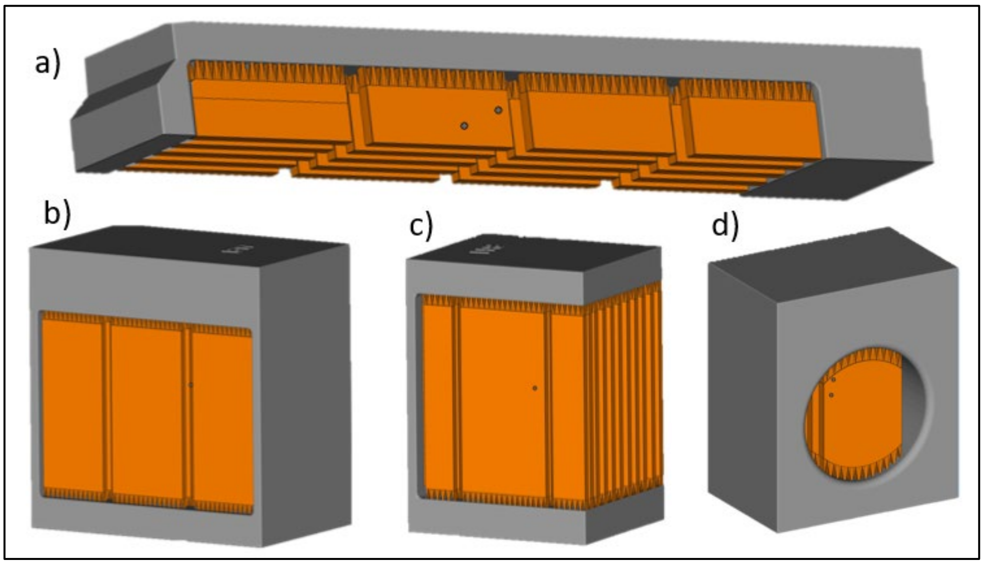


Figure 4.3: Baseline supports are shown in orange for each geometry in grey. a) is the bottom surface, b) is the roof, c) is the overhang, and d) is the hole.

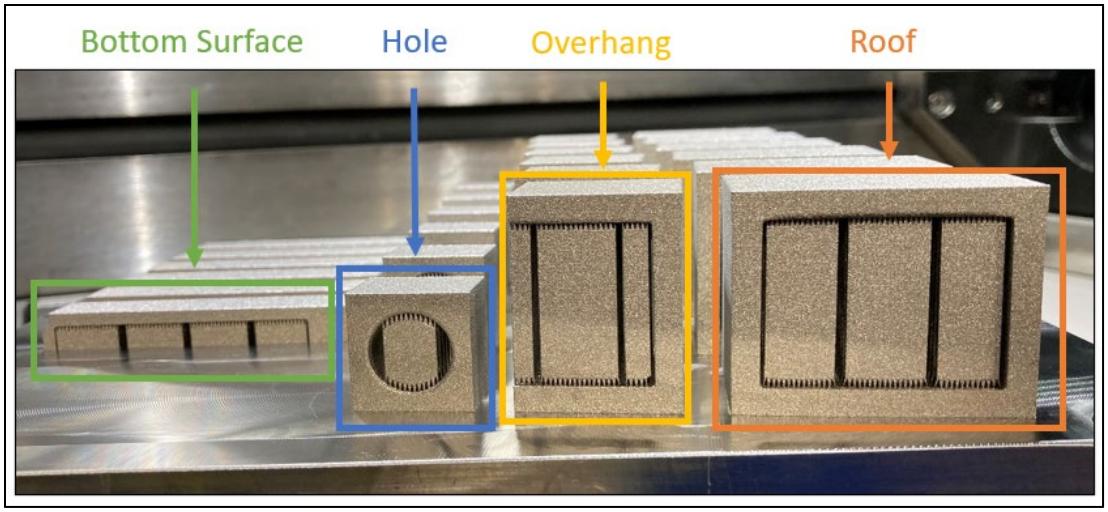


Figure 4.4: Baseline prints still attached to build plate.

4.4 Support Design Process

To better understand how the challenge geometries would behave during the print, a combination of print simulation and simplified mechanics analysis was completed. Using these results, supports could be designed that would directly address each geometry's needs rather than using a uniformly placed structure across all of them.

4.4.1 Print Simulation

The same print simulation software as in the case study was used as in the development of the advanced supports. This software simulates the print layer-by-layer and outputs a variety of results, including stress and deformation. The stress analysis was important to understand the presence of any stress concentrations in the geometries and whether they manifested as compressive or tensile. Secondly, the deformation analysis proved useful in seeing where each challenge geometry was facing challenges in the metric of success. These results, such as the one shown in Figure 4.5, aided in understanding the behavior of the parts during and after prints and then creating simplified 2-dimensional diagrams to further gain clarification on the mechanics behind the part deformation.

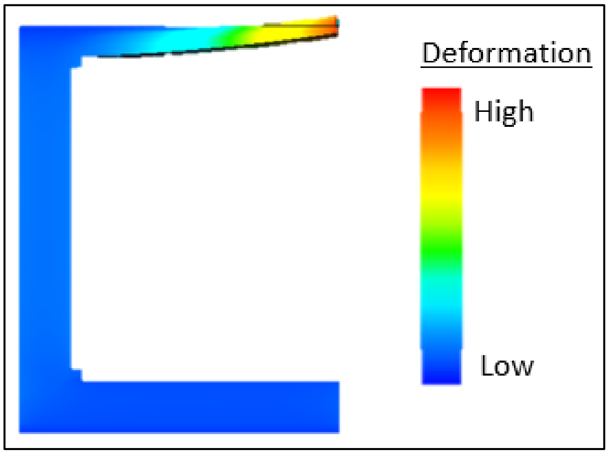


Figure 4.5: Deformation simulation results of an unsupported overhang geometry.

To ensure the accuracy of the simulations, parts were printed and scanned using blue light to compare. The simulation parameters were the same as the print parameters and the comparisons are shown below with the scans on the left and the simulations on the right. The deformations measured from the printed part showed similar intensities and locations as those predicted by the simulations. These regions are circled in red. This verified the software as an accurate tool to simulate the prints and gain both a qualitative and an acceptable quantitative understanding of part behavior.

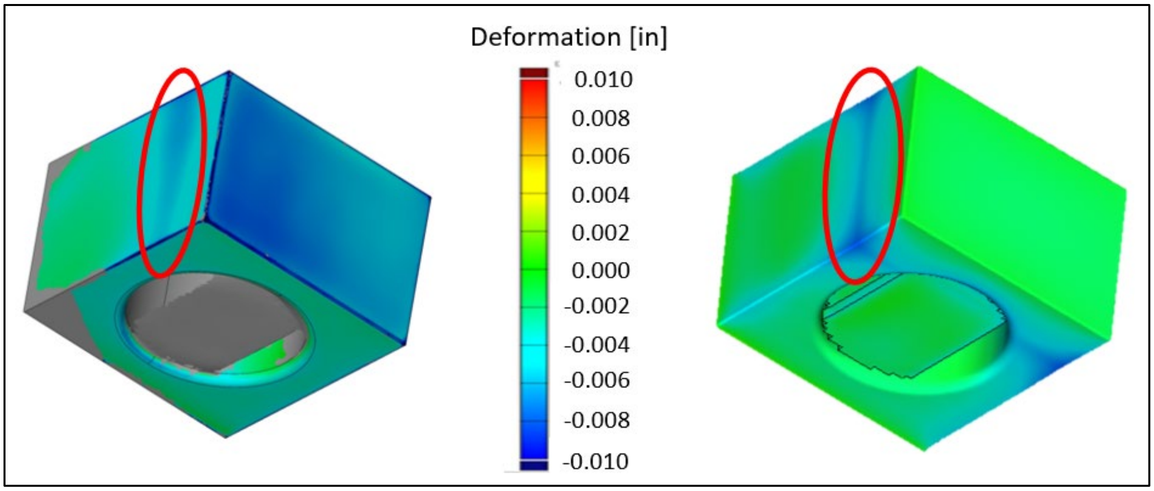


Figure 4.6: Comparison between real print (left) and simulation (right) of the supported hole geometry. Similarities are circled in red.

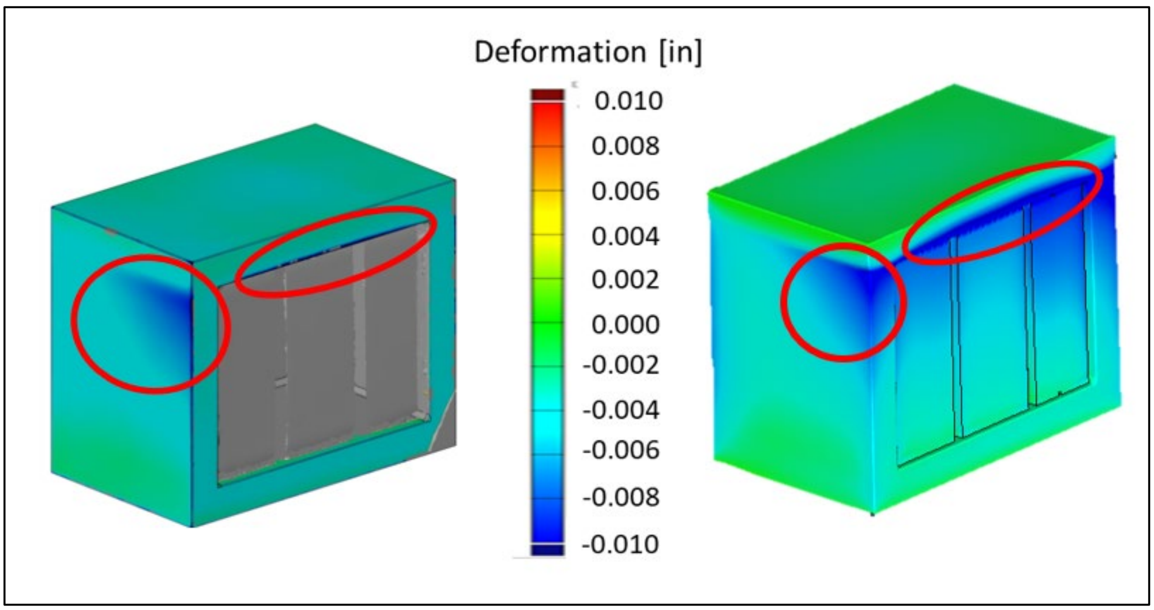


Figure 4.7: Comparison between real print (left) and simulation (right) of the supported roof geometry. Similarities are circled in red.

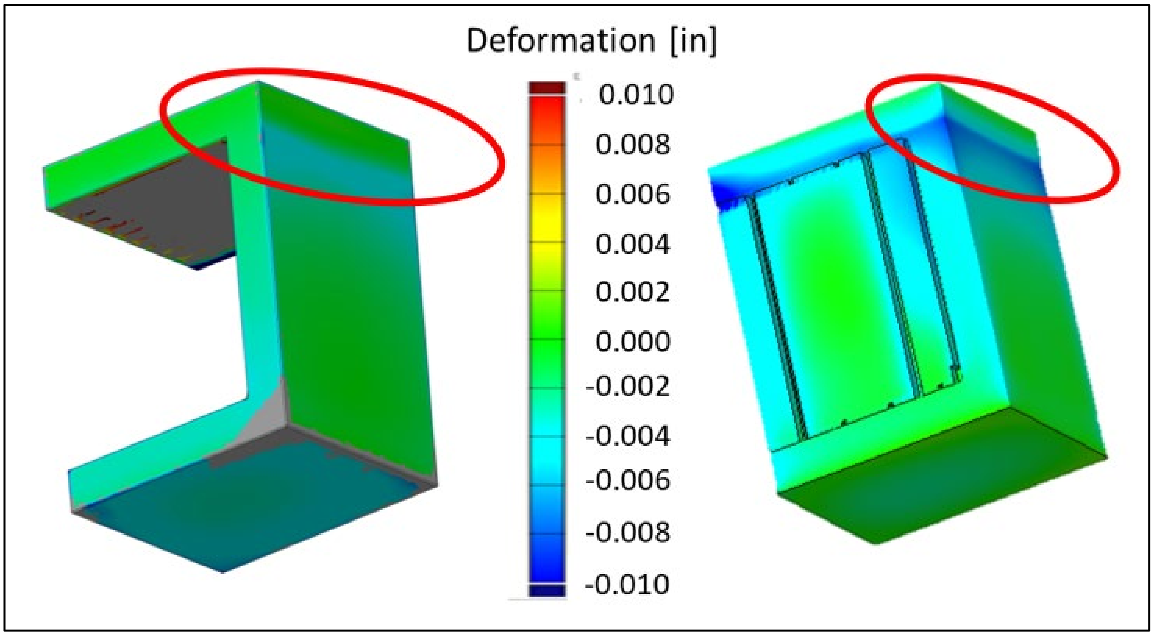


Figure 4.8: Comparison between real print (left) and simulation (right) of the supported overhang geometry. Similarities are circled in red.

4.4.2 Mechanical Analysis

The print simulations complemented a basic, simplified mechanics analysis to better recognize the effects of support structures on the internal shear, bending, and normal stresses in each geometry. For example, removing the top beam of the overhang geometry and isolating it in 2D yielded a free-body diagram shown in Figure 4.9. *N* and *M* represented the reactionary normal force and bending moment where the beam was cut at the red dotted line and *L* characterized the length of the beam.

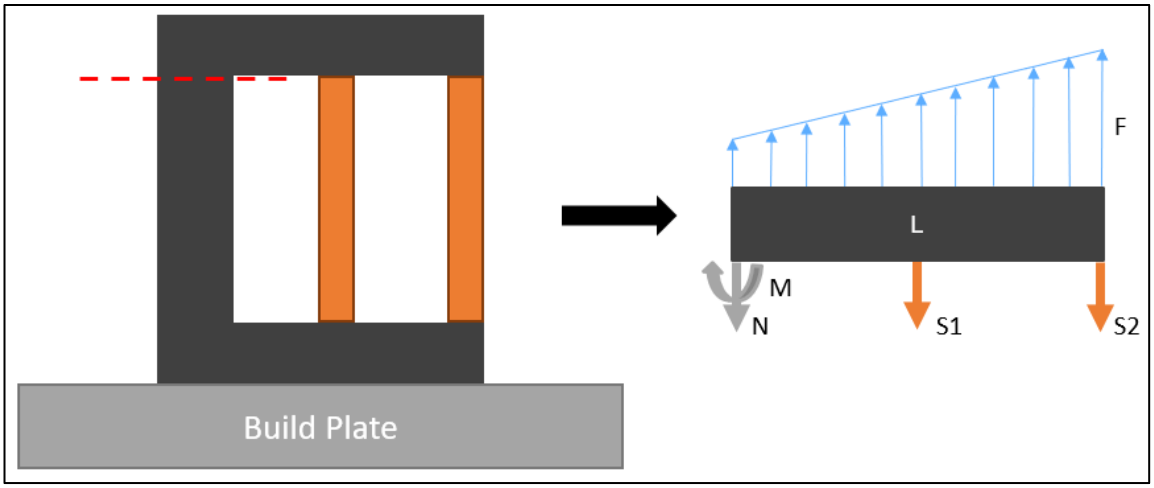


Figure 4.9: Simplified representation of overhang challenge geometry to understand effects of support placement. The example part on the left is cut at the red dotted line to create a simplified version for analysis.

Using this, Equations 4.1 and 4.2 showed that the horizontal placement of the *S1* and *S2* values (support reactions) along the beam did not affect the value of *N* because they have no *L* term. However, when looking at the value for *M* in Equations 4.3 and 4.4, it is reduced the further away from it the *S* values are (as *L* is maximized).

$$\downarrow \Sigma F_y = N + S_1 + S_2 - \frac{1}{2}FL = 0 \tag{4.1}$$

$$N = \frac{1}{2}FL - S_1 - S_2 \tag{4.2}$$

$$\circlearrowleft \Sigma M = M + \frac{1}{2}LS_1 + LS_2 - \left(\frac{2}{3}L\right)\left(\frac{1}{2}FL\right) = 0 \tag{4.3}$$

$$M = \frac{1}{3}FL^2 - \frac{1}{2}S_1L - S_2L \tag{4.4}$$

Similarly, the challenge geometry for the hole was simplified to a hole in uniaxial tension (Kirsch's solution). Qualitatively, Figure 4.10 shows that the regions of most importance to offer support to are the 0/180-degree range in tension and the 90/270-degree range in compression. Also, the 40/60-degree range does not experience a significant amount of stress compared the previous two zones, as illustrated in Equation 4.5. This analysis was a simplified, 2-dimensional representation of the challenge faced in print and was used as guidance in conjunction with the print simulations to gain a better understanding of the geometry behaviors and the effects of support placement.

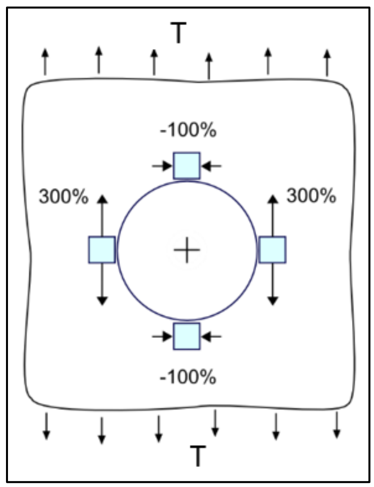


Figure 4.10: Hole in infinite plane in tension. [106]

$$\sigma_\theta = \frac{T}{2}\left(1+\frac{a^2}{r^2}\right) - \frac{T}{2}\left(1+\frac{3a^4}{r^4}\right)\cos(2\theta) \tag{4.5}$$

4.4.3 Geometry Design Envelopes

Based on the analysis approaches described above, each challenge geometry was given a design envelope to address both the mechanical needs as well as the DMLM process limits. A mechanical need was something like addressing tension, while a process limit was something like a need to support a resulting 45-degree slope that the machine was unable to print. The mechanical need superseded the process need, as it supported both movement and the process. The process need only supported the process. An analogy would be for the mechanical need to be load bearing, while the process limit would not. This analogy is shown in Figure 4.11, with the movement to address shown in blue arrows, the non-load bearing zone in green, and the crucial load-bearing zone in red.

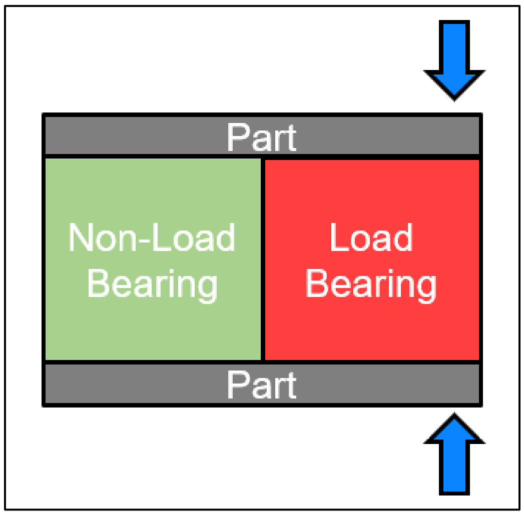


Figure 4.11: Example design envelope analogy with anticipated movement shown in blue, non-load bearing zone in green, and crucial load bearing zone in red.

4.4.3.1 Bottom Surface

The first geometry, the bottom surface, was expected to bow with the middle portion putting supports in compression while the sides closest to the vertical walls put the supports in tension. This led to needing mechanically driven supports along the entire length of the part, as is shown in Figure 4.12.

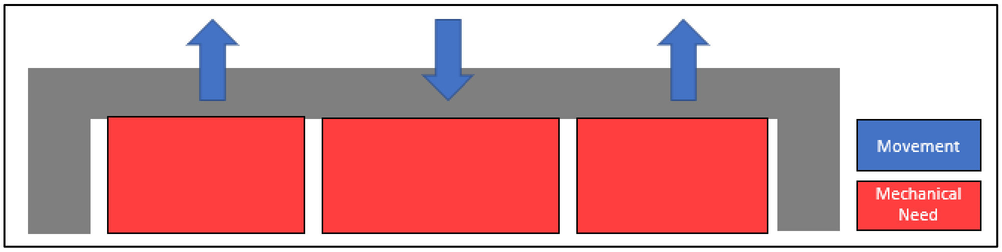


Figure 4.12: Bottom surface design envelope viewed from the side, with anticipated movement shown with blue arrows.

4.4.3.2 Roof

The roof faced movement in two directions. First, the upper horizontal portion pulled up and created tension at the portion furthest from all three vertical walls, resulting in bending of the top member of the roof. Then, the two vertical walls bended inwards, providing compression. As such, mechanical-based supports to address the two movements are shown in red in Figure 4.13 with the resulting process limit needs shown in green. The red envelope was needed to prevent movement, while the green envelope was required because the DMLM process cannot print over "empty" space. The supports within the green zones were defined by parameters known to the manufacturer such as each machine's maximum bridging distance.

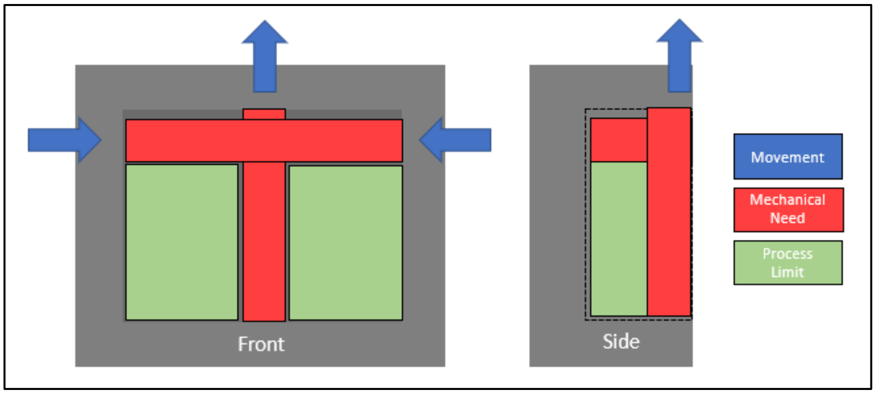


Figure 4.13: Roof design envelope viewed from the front and side, with anticipated movement shown with blue arrows.

4.4.3.3 Overhang

In the overhang challenge geometry, the region of most mechanical importance was furthest away from the vertical wall. The movement in this zone can be compared to a cantilever beam and created tension, as shown in red in Figure 4.14. The remaining region was dictated by the process limits shown in green.

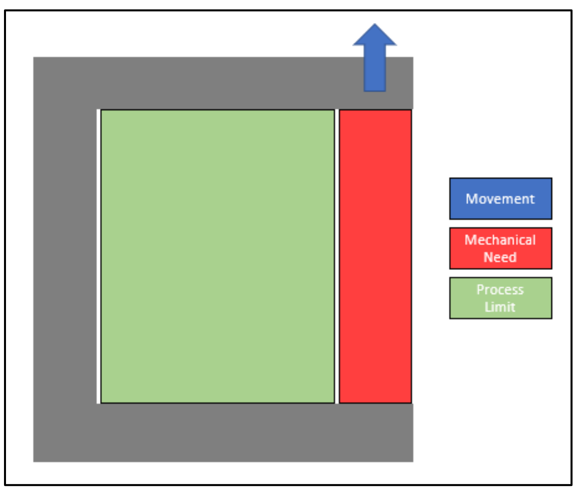


Figure 4.14: Overhang design envelope viewed from the side, with anticipated movement shown with blue arrows.

4.4.3.4 Hole

Finally, the hole geometry presented regions of both tension and compression. At 0° and 180° there was a tensile stress while the 90- and 270-degree zones faced compressive stress. These are shown in Figure 4.15. Similar to the overhang, this geometry also had a large volume to be managed by process limit supports.

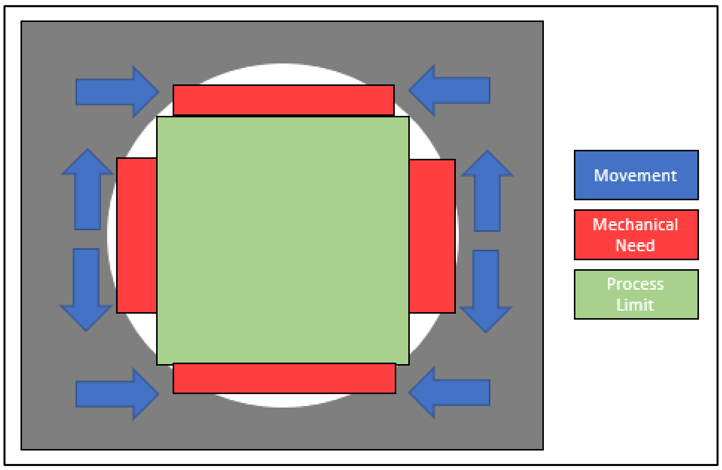


Figure 4.15: Hole design envelope viewed from the side, with anticipated movement shown with blue arrows.

4.5 <u>Description of Example Support Strategies</u>

The analysis previously described detailed the requisite for a balance between supports that are based on a mechanics need and ones that are based on a print process limit. These needs were also driven by the three metrics of success previously defined: reduction in deformation, minimized support volume, and ease of removability. These considerations led to the design of the supports described in the following sections.

4.5.1 Bottom Surface

First, the bottom surface challenge geometry's supports were modeled in accordance with the predefined design envelope. Two contrasting strategies were developed: plate-majority, and block-majority. The plate portion utilized plates similar to the baseline, but with a thicker center plate to further reduce any movement. The box portion used a checkerboard pattern of square cross-section columns. In the block approach, the columns were expected to be in tension while in the plate-majority version, they were anticipated to face compression as the challenge geometry bows. Both are shown from a top-down view in Figure 4.16.

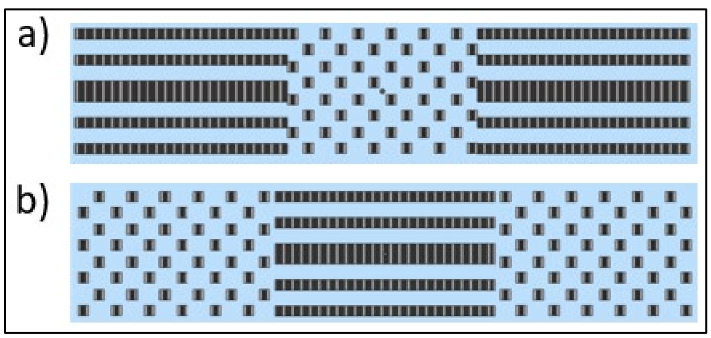


Figure 4.16: Bottom surface support strategies shown from above. a) shows plate while b) shows block. The two strategies show opposite ways of supporting the edges and middle of a bottom surface.

As expected, the two approaches yielded opposite results. The block strategy putting the columns in tension showed a 55.2% increase in maximum deformation from the baseline while the plate strategy with columns in compression reduced maximum deformation by 18.9%. However, blocks reduced support volume by 13.4% while plates increased support volume by 11.1%. The removability of both was expected to be the same and easier than the baseline supports.

4.5.2 Roof

The support strategies for the roof began with the “Y” and the beam configurations. First, the Y interfaced with the top corners of the roof then came down to the base at an angle defined by process limits. It was solid in the shape of a Y, with plates in the valley of the Y. The solid shape shown in Figure 4.17 kept the vertical walls from compressing inwards, while the plates in the valley kept the top vertical component of the roof from peeling upwards and addressed process limits. There were teeth at each part/support interface to aid with removability and the plating was designed to reduce material use in regions where the mechanics need was not as great.

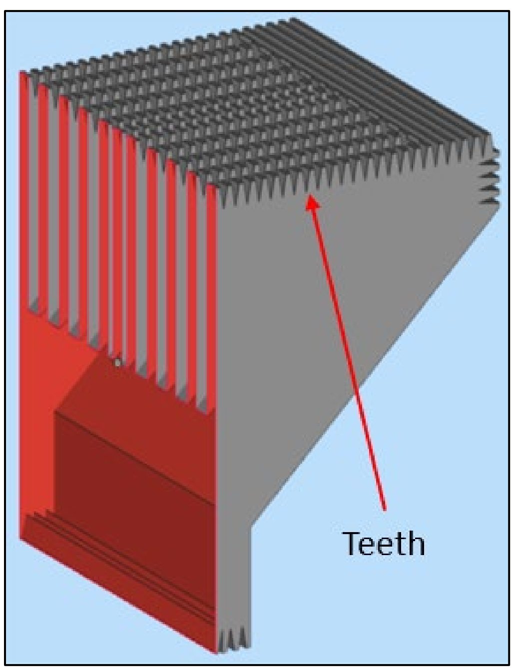


Figure 4.17: Y support cross-section for roof.

The second support approach for the roof, beam, addressed the vertical wall movement more directly with a solid bar across the top of the cavity as that was where the deformation was most prevalent. This bar was normal to the walls, unlike the Y that was around a 45-degree incline, and therefore completely addressed the deflection orthogonally instead of in one of two components. The beam utilized plates at an incline underneath the bar to minimize material use where movement prevention was not as crucial. Teeth were again used at all interfaces. The support cross-section is shown in Figure 4.18.

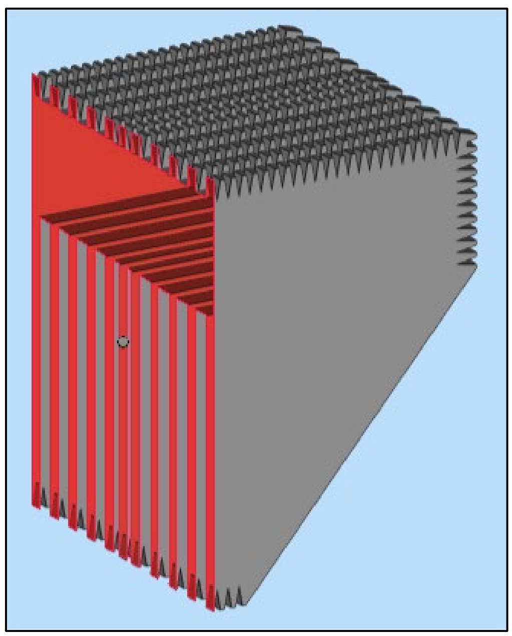


Figure 4.18: Beam support cross-section for roof.

These two strategies were further developed into three derivations. First, they were both fully plated to improve material use and removability. This was done because the solid sections in both the Y and beam proved to greatly increase support volume and make removal difficult. The geometry of the roof made it incapable of using electrical discharge machining to remove the supports, meaning costly time in a machine shop instead. Also, the beam was modeled with holes in the lower portion to further reduce material use. These derivations' cross-sections are shown below in Figure 4.19.

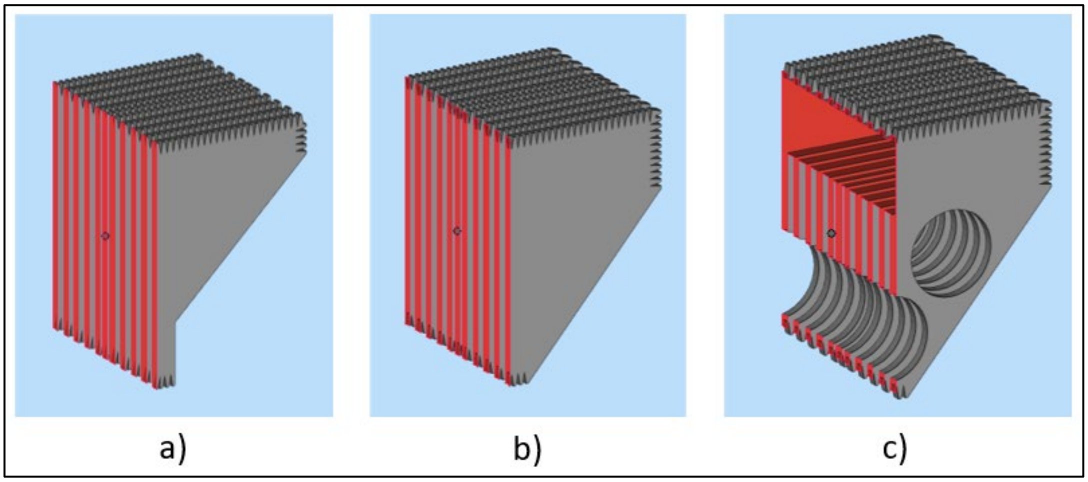


Figure 4.19: Derivations of the initial roof support strategies. a) and b) show the plated versions of Y and beam, respectively, while c) shows the solid beam with holes.

In comparing the simulations of the five roof supports, all saw reductions in deformation of at least 20%. The Y-Plate was the only support that used less material than the baseline, but both the Y-Plate and the Beam-Plate were expected to be as easy to remove as the baseline. The results are summarized below in Table 4.1, with Y-Plate showing the most improvement over the baseline. By plating the Y and Beam configurations, both the volume of the supports as well as the effect on deformation were reduced. Similarly, the beam configuration with holes in the region of process-based supports used less material and resulted in a smaller deformation reduction. All advanced support strategies reduced part deformation with varying amounts of material use in terms of support volume. The ratios for needed part deformation reduction versus material use are dictated by individual part design requirements and engineer discretion.

Table 4.1: Comparison of roof supports with improvements from the baseline highlighted in green and removability on a 3-point scale.

Support	Deformation Change	Volume Change	Removability
Baseline	-	-	☺ ☺ ☺
Y	-40.3%	+37.3%	☺
Y-Plate	-22.4%	-23.3%	☺ ☺ ☺
Beam	-37.3%	+52.4%	☺
Beam-Plate	-20.9%	+3.6%	☺ ☺ ☺
Beam-Hole	-28.4%	+23.9%	☺

4.5.3 Overhang

The overhang geometry was addressed with two options: boxed column and cylindrical column. On both, the half of the region closest to the vertical wall was deemed less critical to support based on the design envelope and designed on a process limit basis with minimal plates. The other half featured either box or circle cross-section columns. These columns were identical in volume, although the cylinder strategy had more columns than the box because of the minimum space required between columns by process limits.

Both are shown in Figure 4.20 and used toothed connections at both top and bottom interfaces with the part.

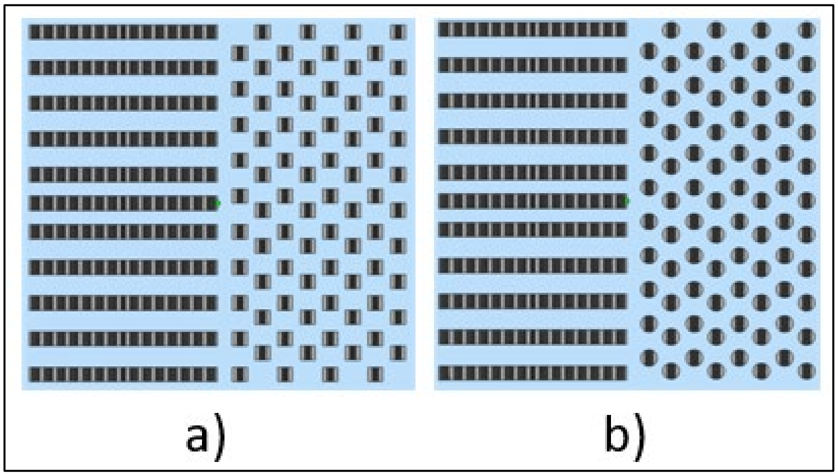


Figure 4.20: Overhang supports shown from above. a) is the box cross-section while b) is the cylinder cross-section.

The simulation results showed very similar findings between the two cross-section approaches. Both significantly improved deformation of the overhang with a small increase in support volume. The two strategies had a slightly easier removability than the baseline. The box experienced a 42.4% decrease in maximum deformation with a 9.5% increase in support volume while the cylinder saw a 41.9% maximum deformation decrease and 10.9% support volume increase. The use of circular versus boxed columns in the mechanical-need regions did not significantly change the amount that deformation was reduced by or the support volume. Both successfully reduced deformation for similar material use.

4.5.4 Hole

Finally, the hole was addressed through a box support strategy and a cross support strategy. Both placed solid supports preventing the tension and compression at the 0/180- and 90˚/270˚ regions, respectively. However, the inner region defined by process limits served as the main differentiating factor. The box used rectangular slots spaced by process limits for material reduction while the cross used a shape resembling a cross, as shown in Figure 4.21. Again, teeth were used at every interface with the part to help removability.

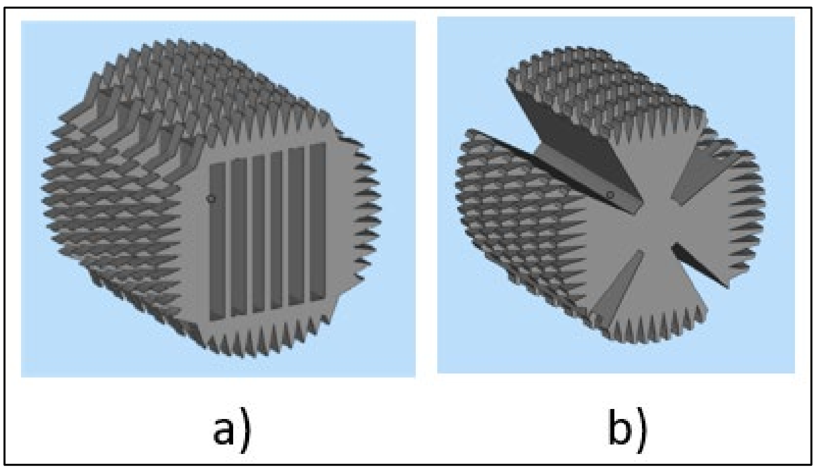


Figure 4.21: Supports for the hole. a) shows the box while b) shows the cross support strategy.

Both the box and cross saw reductions in deformation but increases in support volume and worse removability. The box reduced deformation by 14.3% but increased support volume by 51.5% while the cross reduced deformation by 17.9% but saw 96.4% more support volume. Both had worse removability than the baseline.

4.5.5 Performance Summary

In total, all of the support strategies shown in Figure 4.22 except the bottom surface block configuration reduced maximum deformation in simulations. Two of them decreased support volume and four improved removability as shown in Table 4.2. The most successful support strategy as defined by these metrics of success was the Y-Plate for the roof geometry as it reduced deformation and support volume while retaining the same removability as the baseline.

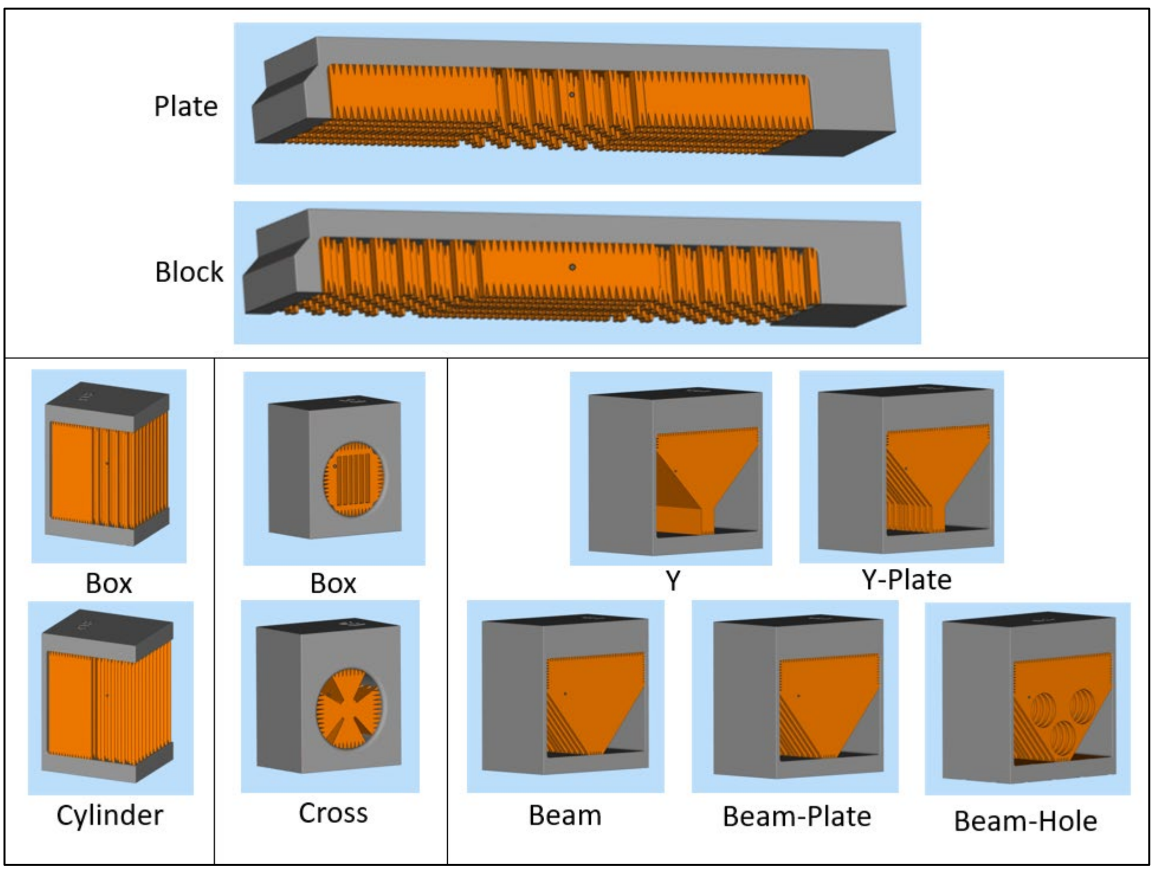


Figure 4.22: All of the support strategies.

Table 4.2: Summary of success metrics for each of the support strategy simulations.

Support	Max Deformation Change	Volume Change	Removability
Bottom Surface Baseline	-	-	☺ ☺
Bottom Surface Plated	-18.9%	+11.1%	☺ ☺ ☺
Bottom Surface Block	+55.2%	-13.4%	☺ ☺ ☺
Hole Baseline	-	-	☺ ☺ ☺
Hole Box	-14.3%	+51.5%	☺
Hole Cross	-17.9%	+96.4%	☺
Roof Baseline	-	-	☺ ☺ ☺
Roof Y	-40.3%	+37.3%	☺
Roof Y-Plate	-22.4%	-23.3%	☺ ☺ ☺
Roof Beam	-37.3%	+52.4%	☺
Roof Beam-Plate	-20.9%	+3.6%	☺ ☺ ☺
Roof Beam-Hole	-28.4%	+23.9%	☺
Overhang Baseline	-	-	☺ ☺
Overhang Box	-42.4%	+9.5%	☺ ☺ ☺
Overhang Cylinder	-41.9%	+10.9%	☺ ☺ ☺

Two of each part were printed to validate the findings beyond the simulation results. The parts were printed from a nickel-based super alloy on a commercial DMLM machine, Their layout on the plate and their serialization is shown in Figure 4.23.

Figure 4.23: Print layout of the challenge geometries.

Once printed, the bottom surface parts were partially cut with a wire EDM to measure curl with a vertical gauge as shown in Figure 4.24. Then, all parts were removed completely from the build plate and scanned with a blue light process to compare them to the original nominal CAD files. Multiple points were used on each part to compare maximum and average deformations on each geometry and the full table of values is presented in Appendix C: Part Simulation and Print Data.

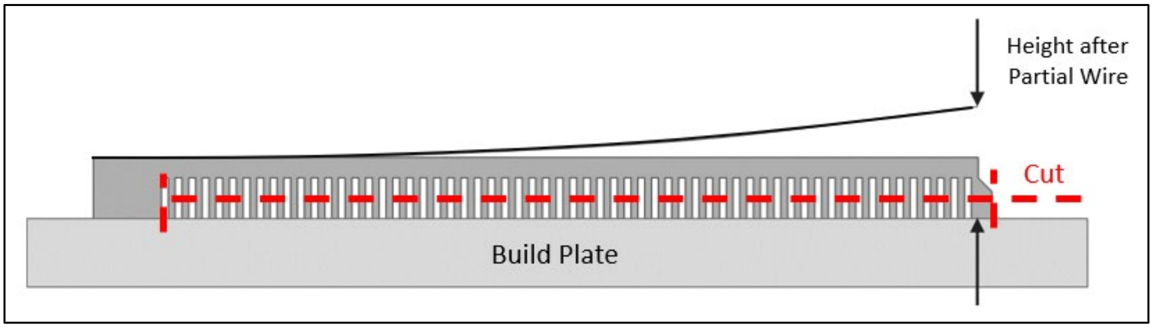


Figure 4.24: Measurement method for bottom surface geometry. The parts were cut horizontally along the red dotted line then had the deflected height measured.

The hole, overhang, and roof parts were first scanned and measured with the support still attached. They were measured across multiple locations on each face as well as in regions of most deformation to get a holistic representation of the deformation. One of the geometries, the roof, shows the seven measurement points and comparison between the baseline, beam, and Y supports in Figure 4.25.

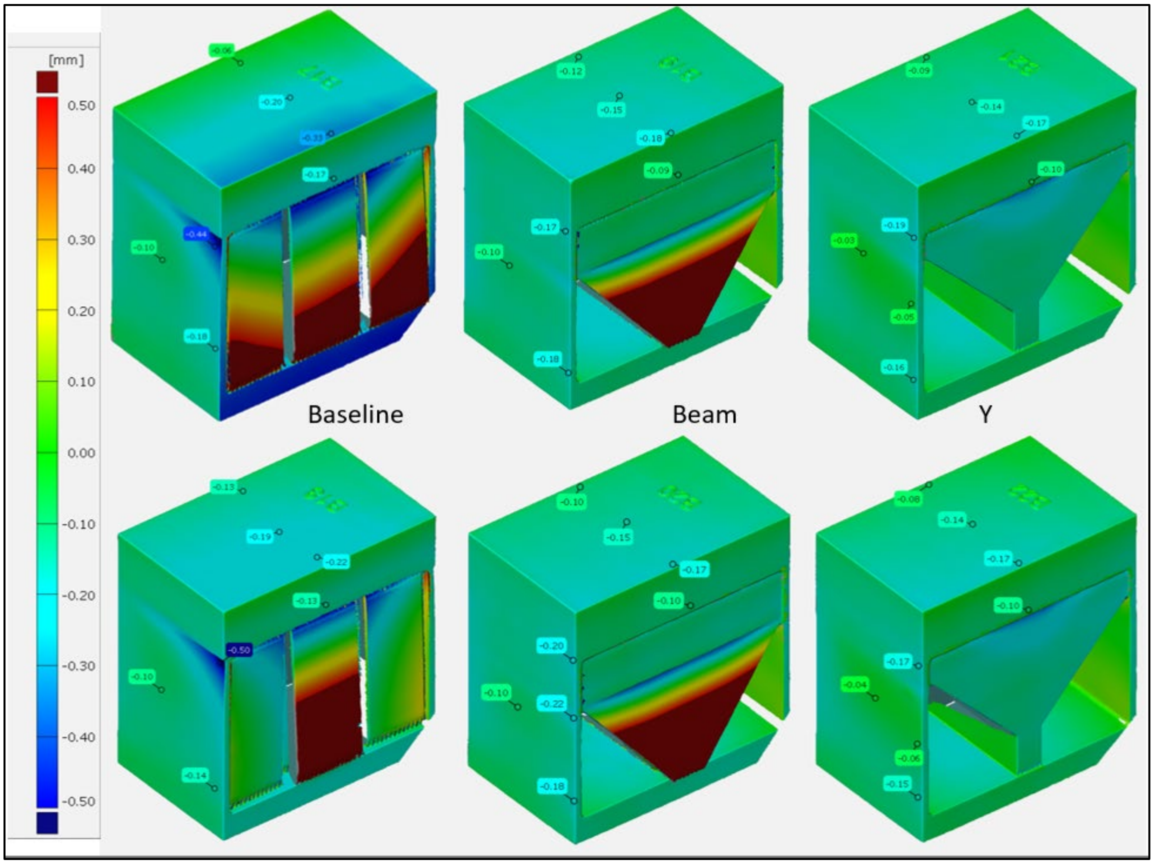


Figure 4.25: Deviation from the CAD model of the roof geometry.

All of the advanced supports showed improvements in average deformation compared to the baseline. Nine of the ten advanced supports reduced maximum deformation with only the box supports for the hole geometry measuring the same maximum deformation as the baseline. The maximum deformation improved by 63.83% in the case of the roof geometry's beam supports with hole and the average deformation improved by 48.10% in the same supports. The hole advanced supports improved maximum deformation by 3.45% and average deformation by 8.33%. In the overhang, the maximum deformation was reduced by 22.67% and the average deformation was reduced by 14.62%. The bottom surface was the least successful improvement, with a reduction in height after partial wire cut of only 0.95% and a reduction in maximum deformation by blue light measurement of 6.06%. As seen in Figure 4.25, some supports became detached during print and yielded deformation results that were higher. The use of interface attachments other than a toothed connection could prevent this in the future. However, the measurements used for the deformation calculations come only from points on the net part geometry, not the supports.

Table 4.3: Height measurements of bottom surface parts.

With Supports	**Height As Built** [mm]	**Height after Partial Wire** [mm]	**AVG** [mm]	**% change from baseline AVG**
Baseline	0.3500	0.4235	0.4230	
	0.3500	0.4225		
Plated	0.3505	0.4185	0.4190	-0.946%
	0.3495	0.4195		

Table 4.4: Measurements of blue light scanned parts with supports.

With Supports	Maximum [mm]	Average [mm]	Minimum [mm]	AVG of MAX [mm]	AVG of AVG [mm]	% change from baseline MAX	% change from baseline AVG
Hole Baseline	0.14	0.09	0.04	0.15	0.09	0.00%	0.00%
	0.15	0.09	0.04				
Hole Box	0.15	0.09	0.06	0.15	0.08	0.00%	-8.33%
	0.14	0.08	0.01				
Hole Cross	0.14	0.08	0.05	0.14	0.08	-3.45%	-7.41%
	0.14	0.08	0.05				
Overhang Baseline	0.36	0.18	0.03	0.38	0.18	0.00%	0.00%
	0.39	0.18	0.03				
Overhang Box	0.29	0.15	0.00	0.29	0.15	-22.67%	-14.62%
	0.29	0.16	0.01				
Overhang Cylinder	0.33	0.16	0.04	0.33	0.17	-12.00%	-7.91%
	0.33	0.17	0.03				
Roof Baseline	0.44	0.21	0.06	0.47	0.21	0.00%	0.00%
	0.50	0.20	0.10				
Roof Beam	0.18	0.14	0.09	0.19	0.14	-59.57%	-31.14%
	0.20	0.14	0.10				
Roof Y	0.19	0.13	0.03	0.18	0.12	-61.70%	-40.14%
	0.17	0.12	0.04				
Roof Beam-Hole	0.15	0.10	0.01	0.17	0.11	-63.83%	-48.10%
	0.19	0.11	0.01				
Roof Beam-Plate	0.19	0.13	0.08	0.19	0.12	-59.57%	-39.79%
	0.19	0.12	0.06				
Roof Y-Plate	0.20	0.11	0.05	0.20	0.12	-57.45%	-43.60%
	0.2	0.12	0.06				

Supports were removed from parts that allowed it and measured again in Table 4.5. The roof parts with beam, Y, beam-hole, and one beam-plate support were not able to be removed. This reflected the importance of the success metric of removability as even if those parts had completely reduced deformation to zero, they would still be unusable because the supports could not be removed. Similarly to the previous measurements, all advanced strategies measured reduced the average deformation of the parts. The maximum deformation was reduced by the implementation of advanced supports in all cases except the overhang with box supports. In the previous scan, there was no significant difference between the overhang box and cylinder improvements in part deformation. However, once the supports were removed, the cylinder supports reduced the average deformation by 11.21% and maximum deformation by 3.67% while the box supports reduced average deformation by 5.71% and increased maximum deformation by 11.93%. This separation of strategy performance once supports were removed was also shown in the roof's strategies of plated beam versus plated Y. The improvements were similar in the first scan, with the beam-plate reducing average deformation by 39.79% and maximum deformation by 59.57% and the Y-plate by 43.60% and 57.45%, respectively. After the second scan, the deformation reduction for the beam-plate was 13.65% for average and 49.49% for maximum while the Y-plate was 32.10% average reduction and 58.59% maximum reduction. After the first scan, the two strategies could have been expected to be used interchangeably and achieve similar results. However, the second scan showed the dominance of the overhang cylinder and roof Y-plate for their respective geometries. These changes reflect the varying levels of stress that different supports absorb from the part and lead to a future work on analyzing this ability and implementing it intentionally. The remaining roof parts did not show a similar differentiation in performance between the first and second scans.

Table 4.5: Measurements of blue light scanned parts without supports.

No Supports	Maximum [mm]	Average [mm]	Minimum [mm]	AVG of MAX [mm]	AVG of AVG [mm]	% change from baseline MAX	% change from baseline AVG
Hole Baseline	0.15	0.09	0.03	0.17	0.10	0.00%	0.00%
	0.18	0.12	0.03				
Hole Box	0.12	0.08	0.02	0.14	0.08	-15.15%	-24.59%
	0.16	0.08	0.04				
Hole Cross	0.12	0.08	0.04	0.13	0.08	-24.24%	-21.31%
	0.13	0.08	0.03				
Overhang Baseline	0.54	0.33	0.02	0.55	0.33	0.00%	0.00%
	0.55	0.32	0.04				
Overhang Box	0.62	0.31	0.00	0.61	0.31	11.93%	-5.71%
	0.60	0.31	0.01				
Overhang Cylinder	0.47	0.27	0.00	0.53	0.29	-3.67%	-11.21%
	0.58	0.30	0.02				
Roof Baseline	0.52	0.19	0.07	0.50	0.19	0.00%	0.00%
	0.47	0.20	0.09				
Roof Beam							
Roof Y							
Roof Beam-Hole							
Roof Beam-Plate	0.25	0.17	0.10	0.25	0.17	-49.49%	-13.65%
Roof Y-Plate	0.20	0.13	0.07	0.21	0.13	-58.59%	-32.10%
	0.21	0.14	0.04				

However, it should be remembered that success is not easily defined as design goals can change for each part. While the reduction in deformation and support volume may seem like obvious goals, some parts facing huge deformation may benefit from the support strategies that have more significant deformation reductions at the expense of more support volume or even post-processing and removal time. In many cases, a successful print even with more material and time used by more supports may be more worthwhile than a failure from being outside of tolerance or deformation causing a machine crash. As such, the results are presented as “tools in the toolbox” to designers and engineers. Ultimately, they hold the decision-making ability, but the information can be presented to them to make more informed, systematic decisions.

Chapter Five

GUIDELINES AND VALIDATION

Guidelines are commonly found in many areas of design [107–110]. Based on the findings detailed above, guidelines were created based on a modified version of the Unit Cell Design Guideline Development Method [103]. Modifications were made to a geometry and simulations demonstrated changes in behavior, so an if-then relation was created. If one of the challenge features was seen in a part, then the design envelope and suggested supports were presented. The general layout is shown in Figure 5.1 and the full guidelines for implementation and adoption can be found in Appendix B: Guidelines.

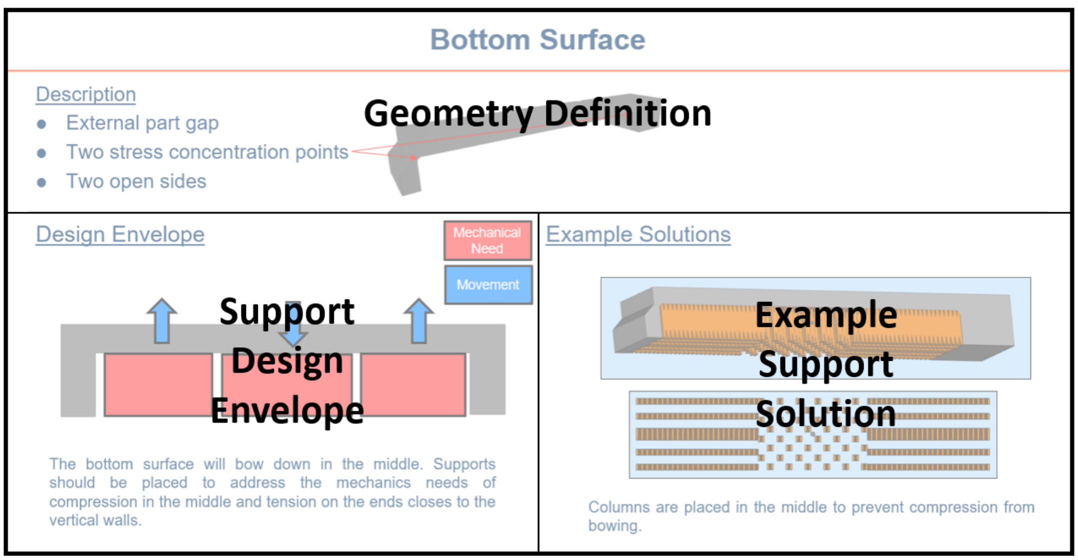


Figure 5.1: Layout of the support generation guidelines.

5.1 Support Strategy Guidelines for Key Challenge Features

Four challenge features were explored: the bottom surface, roof, overhang, and hole. Each was analyzed to determine a design envelope based on differing mechanical and process needs. Within these envelopes, example supports were applied that were shown to reduce part deformation. Figure 5.2 is the guideline for identifying a bottom surface and addressing the bowing of the feature. As an example, columns were used in the middle to prevent the sag and plates were used on either side to address the lift.

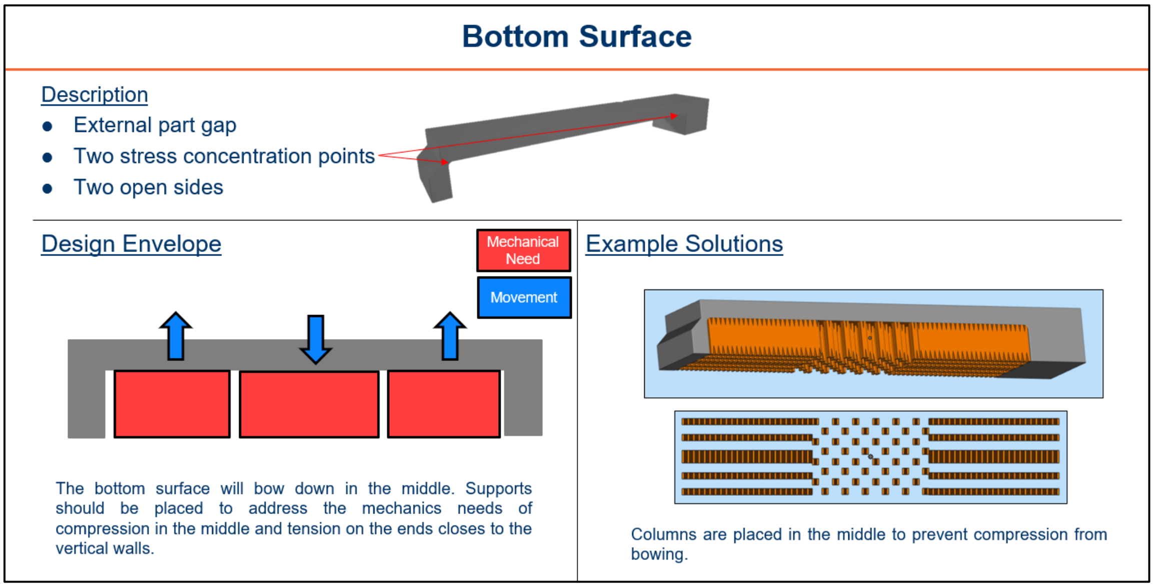


Figure 5.2: Support structure guideline for a bottom surface.

The roof is shown in Figure 5.3 with vertical wall compression and horizontal wall lift. The Y and beam support examples were shown.

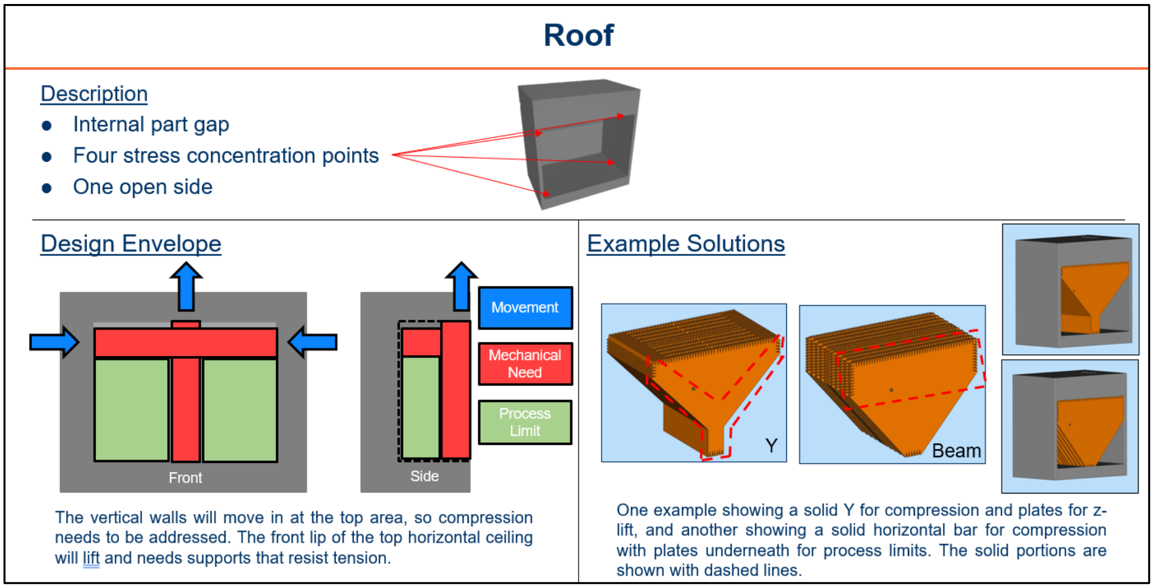


Figure 5.3: Support structure guideline for a roof.

Figure 5.4 helps to identify overhangs and the lift on the end of the upper surface that creates tension for supports. Circular columns were provided as an example to address this requirement. In the remaining region of the part defined by a process limit need, plates were used.

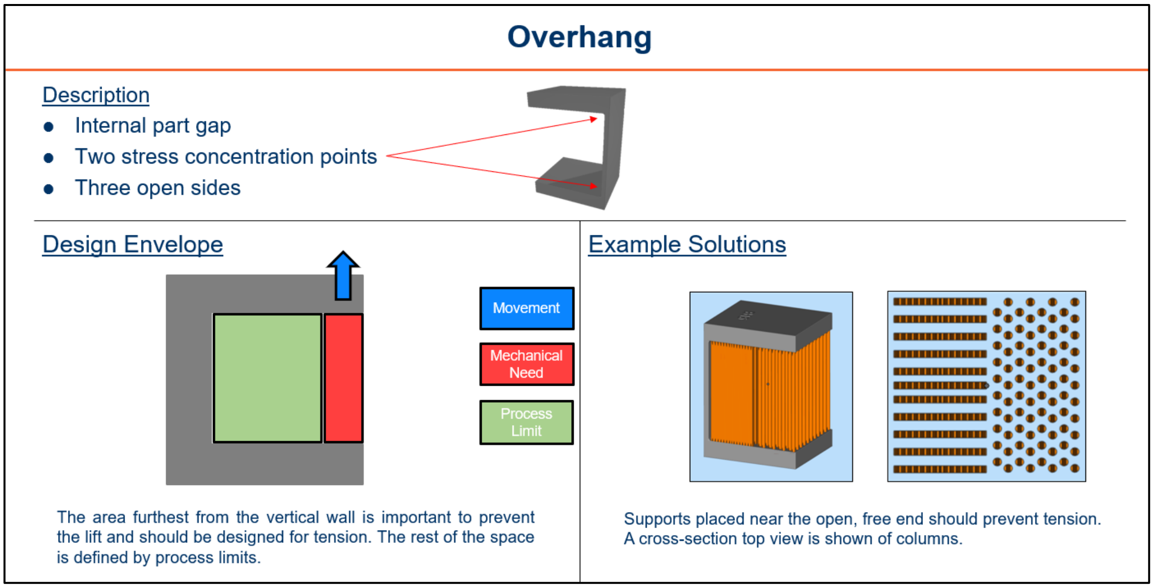


Figure 5.4: Support structure guideline for an overhang.

Finally, Figure 5.5 is the hole guideline that explains the vertical compression and horizontal tension that the example box and cross addressed. The box had the center portion removed to lessen material use and the cross was made empty at the 40˚ and 60˚ area for the same reason.

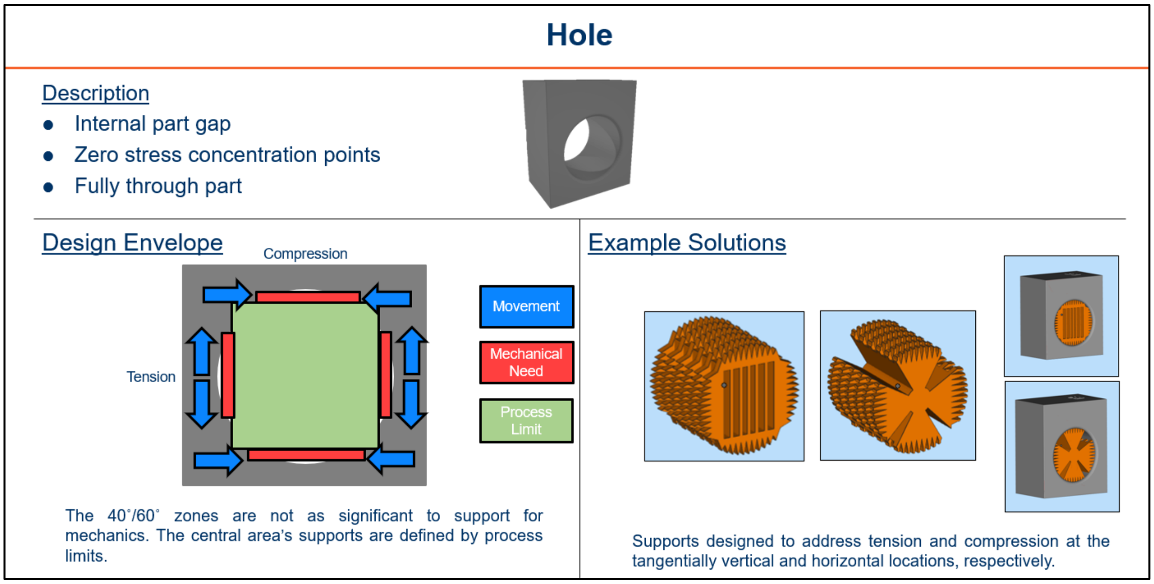


Figure 5.5: Support structure guideline for a hole.

A broader process to develop AM guidelines can be derived from these supporting guidelines. The ten steps are shown in Figure 5.6 and mirror the process of this research. This began with an observation of phenomenon. In this case, the initial case study showed that changing only support structures in a part affected the part's deformation. This found the basis to explore intentional support structure design in AM parts. The first interviews established the "if" of the if-then relationship in the guidelines by using AM engineers to identify the features of most challenge in prints. Those features were then turned into testable development geometries. This allowed for establishing a baseline that could be compared to in the largest step: simulation, analysis, and comparison. These results served in establishing the "then" portion of the if-then relationship and completing the guidelines. This transitioned into the final portions of the process discussed in the next sections: the guidelines were presented and tested with users as well as in real parts to validate their use.

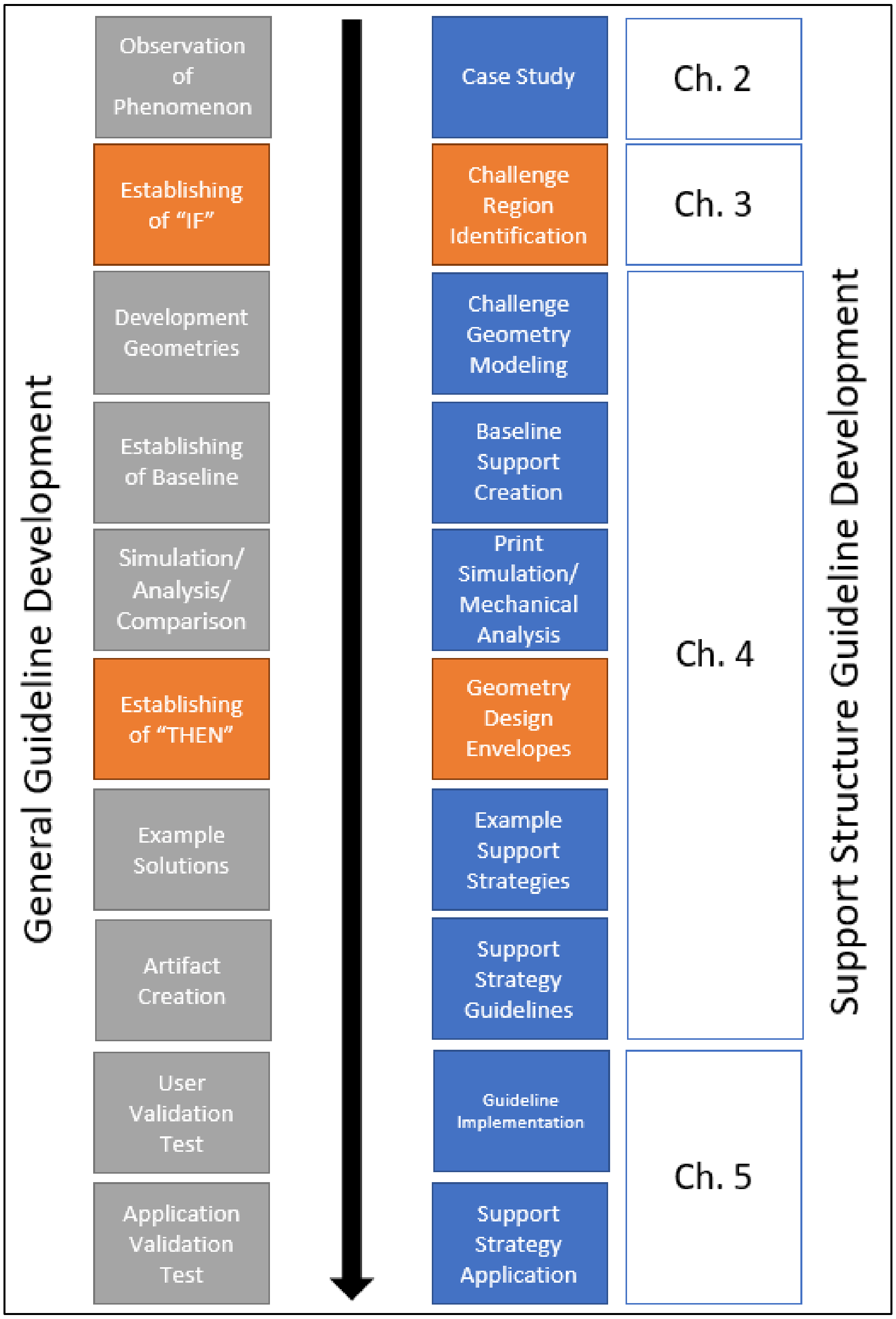


Figure 5.6: The general guideline development process shown in comparison to the way it was implemented here for support structures.

5.2 Guideline Implementation via Interviews

Another round of virtual interviews was conducted to validate that the results of the analyses and simulations could be clearly communicated to the stakeholders in the AM process. Five AM engineers from the same team as the previous interviewees and one graduate student studying the mechanics of AM materials were interviewed over thirty minutes. This included ten minutes of introduction, five minutes of part analysis for each of the three parts, then five minutes for a survey. These interviews were completed in a similar fashion to the first round – they were conducted remotely, and cloud-based file sharing was leveraged. However, the interview with the graduate student occurred in person.

In the first ten minutes they generated an anonymous identifier like in the first interviews. There was an introduction to the study, assumptions for the parts that were to be presented to them, and they were presented the guidelines shown in the figures of section 5.1. The assumptions included: the part was to be oriented as presented in the file, the scale was set by the STL file, the part was to be printed via DMLM from a nickel-based super alloy powder, the loading of the part was accounted for in the design, standard post-processing, and no considerations for surface finish. These assumptions were set so that the interviewee could fully concentrate on the analysis of interest: the geometry and layout of the support structures they would use. The interviewer-researcher then presented to them the guidelines for the four challenge features previously discussed. Once the introduction was complete, the interviewees were given three part files to analyze, shown in Figure 5.7. Part (a) was chosen for the presence of both overhangs and roofs. Overhangs and roofs were also prominent in part (b), but with difference width/depth ratios. Finally, a hole and overhang were present in part (c).

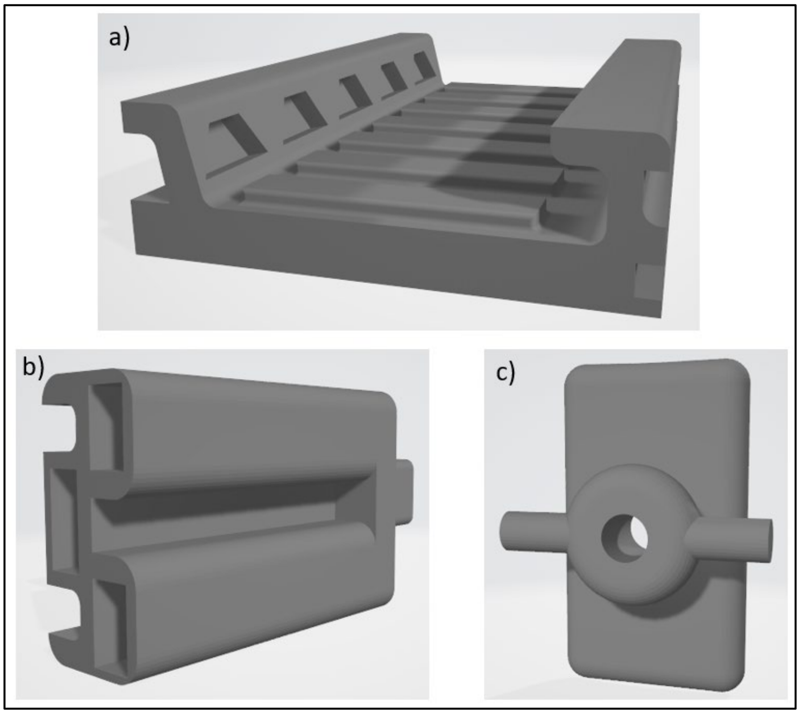


Figure 5.7: The three parts presented to interviewees to test the guideline use.

The interviewees were asked to describe or sketch where they would place supports on each part as well as the shape of the supports. The interviews were conducted to see if they could recognize the geometries shown in the guidelines when they were present on parts and if they could apply the concepts that the guidelines described in terms of design envelope and example supports.

After each interviewee finished analyzing the parts, they were asked to complete an exit survey. This directly asked them if they recognized on each part where they could apply the guidelines they had been presented earlier. It also allowed a space for them to offer any general comments on the guidelines.

Overall, the interviews yielded a variety of results. Starting from the bottom of Figure 5.8, all participants were able to recognize the challenge features from the guidelines on each geometry. This confirms the consistency of the challenge feature identification stage of the research, as the group that provided the data to find the features recognized the same features with a different user subgroup six months later. Each of the interviewees also understood the concept of a varied support layout and design within the same region on a part. In terms of application, this meant that they all described applying varied supports, but not always aligning with the example supports shown in each guideline. Participants modified the example supports to better fit the exact application, as the guidelines were made with simplified, general geometries. One participant showed interest in a modified hole support, saying they would use “Something like you described… and maybe slice them”. Finally, all showed implementation, with four articulating interest in adopting the guidelines in their future work with quotes such as “look forward to seeing that maybe adopted” and “I probably would have in the past have just done simple… but I do like the cross style you were showing so I would like to try and adopt that” and two replacing their supports with example supports during the interview saying “initially, I would think … but after seeing some of that presentation…” and “you had… I’d do those”.

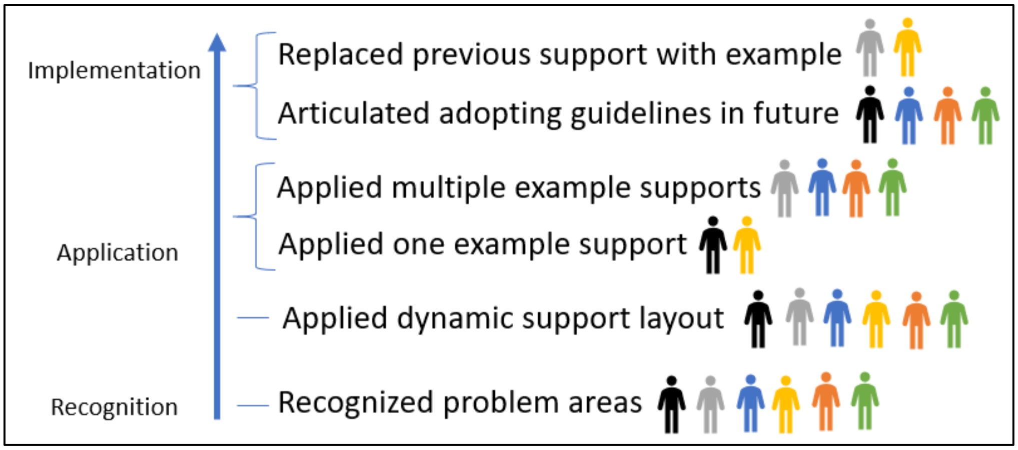


Figure 5.8: Results of interviews. The number of people next to each step shows how many interviewees the statements applies to. Each interviewee is represented as a different color figure.

The most common principle that the interviewees took from the guidelines was the concept of varying the support shapes and layout within the same region to better suit its needs. This demonstrated a shift in thinking about support structures and their role during prints, with one saying the guidelines "definitely made me think more about the possible tension and compression that the part was experiencing more so than I had done in the past". Participants also noted the novelty of supports interfacing with the part beyond at the top or bottom. This was most apparent in the example supports for the hole that attached at the 0-, 90-, 180-, and 270-degree marks rather than just vertically, saying ""typically… what I would have done… but after seeing yours I like that other design" about the hole support attachments. Their previous use of support structures involved a design space that only interfaced with the part vertically. Changing this design fixation served as a takeaway from the guidelines that participants carried with them for future support design. Finally, interviewees with less experience in metal AM relied more heavily and literally on the guidelines. These participants described simply taking the example supports and applying them directly to the example parts, demonstrating only an ability to follow the guideline instructions. Conversely, those with more experience applied the concepts of the guidelines, such as grading the supports or attachment points to the part, in conjunction with their best judgment for structures and removability. Novices leaned on the examples while experts started with the design envelopes. The intersection of experience and reliance on guidelines should be explored further as future work.

5.3 Support Strategy Application in Real Part

The support strategies and example supports were verified in isolated cases, with test parts being standalone versions of the identified challenge features. To validate them in an engineering or industrial context where the guidelines are meant to be used, the guidelines were used by the researcher on a crank plate that featured each of the challenge features of interest. This part is shown along with its main measurements in Figure 5.9.

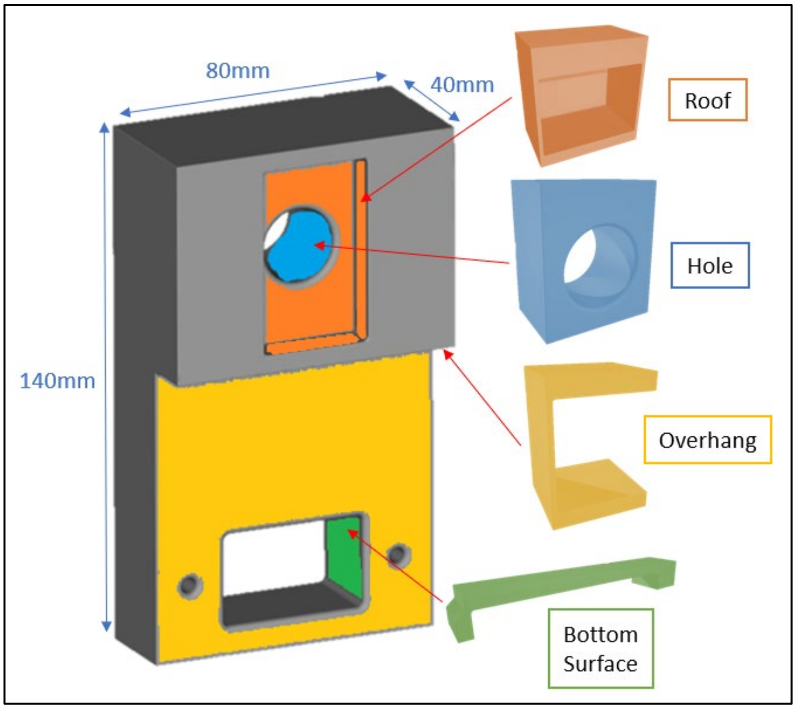


Figure 5.9: Demonstration part highlighting all of the combined challenge features.

The demonstration part was first supported with the same baseline supports as previously used in the research. These were uniformly distributed flat plates with teeth at part interfaces. Their design was centered around that of the traditional support role: minimizing material use as well as print and post-processing time. This contrasts with the advanced supports designed based on the support generation guidelines developed, as shown in Figure 5.10.

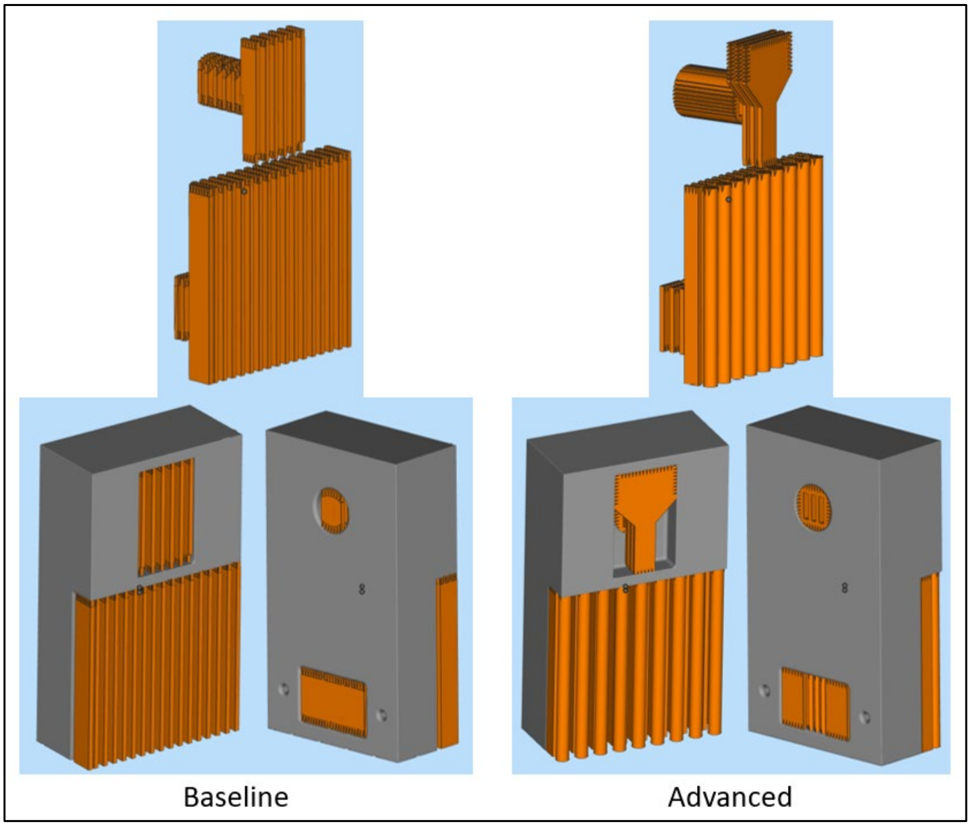


Figure 5.10: Baseline supports versus advanced supports for the demonstration part.

The advanced supports followed the information distributed in the guidelines and used many of the example supports. For the bottom surface, a plate-column-plate pattern was used to address the sagging resulting in alternating tension-compression-tension. The roof was supported by a plated Y to minimize material use and increase removability while still concentrating on the compression of the vertical walls and the tension of the top wall. The overhang dealt with the vertical tension caused by the part's movement by using columns at the free end and process-limit defined plates between the columns and the vertical wall. Finally, the hole interfaced with the part at the sides and top/bottom as described in the guidelines with slots in the center for less material use. All interfaces between part and support used teeth to facilitate removal of the supports in the case of a print. These supports are shown in isolated form below in Figure 5.11 and interacting with the part above in Figure 5.10.

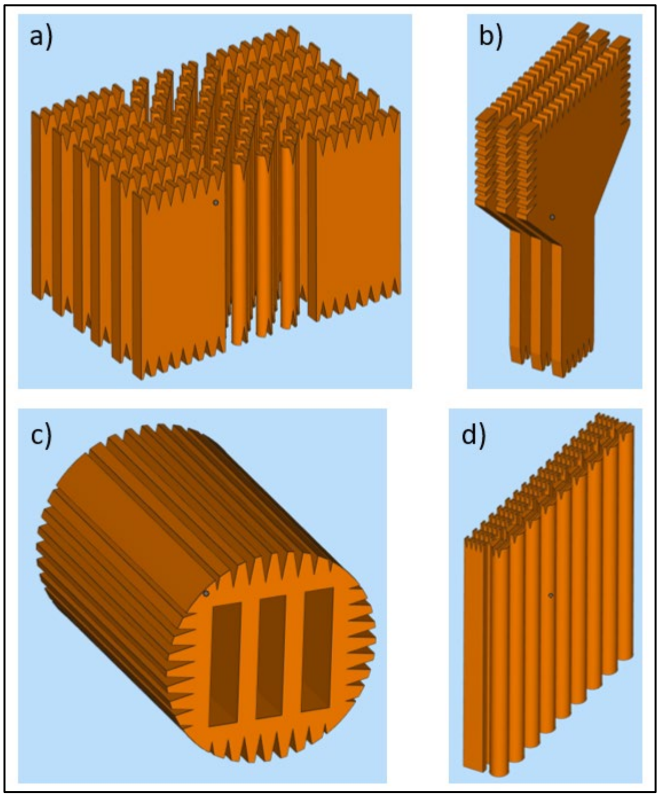


Figure 5.11: Advanced supports used in the demonstration part. a) addresses the bottom surface, b) is for the roof, c) addresses the hole, and d) is for the overhang.

The baseline supports resulted in a total volume of 52,290 mm^3 while the advanced supports used only 14.5% more material at 59,893 mm^3. In print simulations, the advanced supports had 14.6% less maximum deformation post-print after support removal. Isolating the directions yield -17.9%, +6.9%, and -19.9% changes in maximum deformation in the x-, y-, and z-directions, respectively. The results for total deformation are shown visually below in Figure 5.12. and the isolated directions in Appendix C: Part Simulation and Print Data.

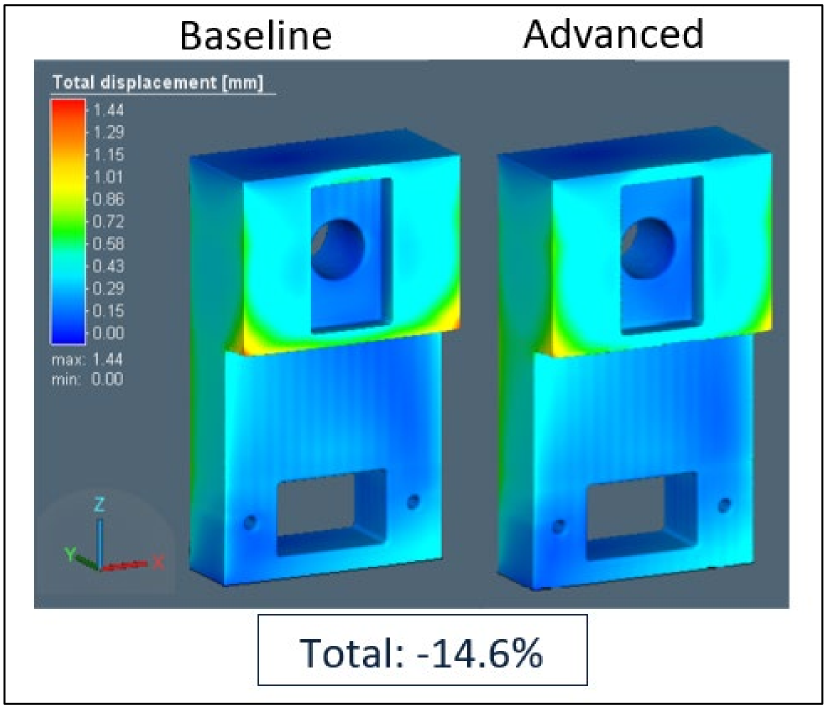


Figure 5.12: Deformation simulation comparison for total deformation.

The advanced supports that were applied based on the guidelines achieved a lower maximum deformation in total deformation, x-deformation, and z-deformation. These supports interface with the part in more directions than the baseline supports and were applied specifically to each region to address the unique concerns based on previous mechanical analyses, simulations, and prints. The information was packaged in straightforward guidelines ready for AM engineers to implement on their parts to achieve similar reductions in deformation as they see appropriate.

Chapter Six

CONCLUSIONS AND SIGNIFICANCE

The work presented addresses some of the challenges faced by metal AM such as part deformation. First, deformation was shown to be alleviated in a case study through changing the support structures of a production part. In the study, process parameters and part geometry were held constant while three different support strategies were applied. The parts were printed from a nickel-based super alloy on a commercial DMLM machine and in blue light scanning post-print, the advanced supports resulted in 21% less average deformation across the entire part and 24% less maximum deformation at localized regions compared to the baseline supports. Using supports to address part deformation is an unexplored area that allows AM designers and engineers to retain the necessary part geometries and change only part supports to print successfully. Reducing part deformation in the design phase minimizes the number of print-and-check iterations needed, further improving the design cycle time. A reduction in part deformation and eliminating part failure on the build plate keeps more AM parts within design tolerance, thus reducing the number of scrapped parts not meeting requirements. In addition, part deformations that are drastic enough to cause machine collisions and recoater tears further drive up AM costs. Being able to better control the part deformation serves to ensure more prints are successful.

Using interviews with industry professionals, the most common features that could benefit from intentional support design were identified: 1) bottom surface, 2) roof, 3) overhang, and 4) hole. Based on the features identified, testable geometries were modeled for simulations and prints.

For each challenge geometry, a mechanical analysis, simulations, print, and measurements were completed. Each geometry had at least two support strategies applied and evaluated for effect on part deformation, support volume, and support removability. These criteria represented more complete metrics to evaluate success of the supports in actual industry use. In summary, the challenge geometries all experienced decreases in average deformation, with the bottom surface reducing by 6.06% (maximum vertical deflection), the overhang by 11.21%, the hole by 24.59%, and the roof by 32.10%.

The validation of the supports in simulation and print led to the creation of guidelines on how to intentionally create support structures for the four features. Each guideline was defined with a one-page guiding document that included 1) and if condition to identify a feature, 2) the instructional steps to properly develop supports for the feature, and 3) examples of supports created from the steps. The instructions to create supports divided the support design space into portions with a mechanical need and portions with a process limit need, a novel differentiation in support design. The guidelines were presented to six engineers of varying experience to test their understanding and application of the guidelines. All interviewees applied multiple concepts of the guidelines, with some commenting on the novelty of ideas such as horizontal support attachment to the part rather than strictly vertical. The use of supports that interfaced beyond vertical attachment was a departure from institutional knowledge of support design that showed the novelty of the support design envelopes developed in this research. Representing this in guidelines ensured removing the dependence on tribal knowledge or informal best practices and replaced them with something more systematic and concrete.

The creation of guidelines supports the standardization of work and creates more consistent and less subjective work. With AM being a young process relative to other manufacturing methods, inexperienced engineers joining the field do not have the same amount of resources as available in more established manufacturing processes. The guidelines developed here help to fill the need for resources for young engineers as well as formally present new information to experienced engineers, as seen in the validation interviews. The overarching process of developing the guidelines also lends itself to broader use cases. As previously described, AM includes many materials, processes, and parameters to be changed and leveraged for different applications. Demonstrating a process to develop guidelines motivates future work that bases itself on this framework to build more guidelines. The structure presented in this study is flexible enough to address everything from broadening the support library to part orientation and more. This guideline development structure is not confined strictly to DMLM or nickel-based materials but instead lends itself for continued growth to parallel that of AM.

The advanced support structures were validated in a real part that combined all of the features identified and analyzed in the testable challenge geometries. This took the guidelines from isolated test cases to validating them in a real part as would be seen in industry application of the guidelines. The crank plate was modeled with baseline supports and advanced supports based on the guidelines. In simulations, the advanced supports reduced maximum deformation in the part by 14.6%. While the advanced supports used more material, the application and requirements of the tested crank plate would dictate whether material use or deformation was a driving factor in an AM engineer's support decision.

This work redefines support structures as design tools rather than the necessary waste they were considered as previously. Traditionally, supports were placed in a constant and consistent fashion as defined by process limits, with revisions being made to the part geometry to ensure a successful print. Instead, it is shown that support structure design is an active and intentional process that affects part deformation. The placement and shaping of supports are key parameters to a successful print. This is shown in defining supported regions as either mechanically driven or process limit driven and encouraging the application of a varied support layout within the same part region. Different features have different needs and should be supported as such. This work presents supports as a new tool to AM engineers that enables them to reduce part deformation without affecting the shape of the part that is already defined by design requirements.

Chapter Seven

FUTURE WORK

This thesis establishes the importance of support structures and suggests some new concepts for their use, including specific examples for four key challenge features. The first extension of this work is the application of the general guideline creation method. At the most similar level, more features need to be identified beyond the bottom surface, roof, overhang, and hole. Participants in the validation interview noted limits of the breadth of only four geometries. More guidelines that diversify the "if" statements identifying common features would increase the implementation of support structures to reduce part deformation in more features.

On a broader level, the guideline generation process developed in this thesis allows for guidelines to be created for different parameters beyond support structures. As discussed previously, AM's relative youth compared to more established manufacturing processes results in less resources for engineers to reference. This guideline generation process allows for guidelines to be developed for part orientation, print parameters, geometry ratios, and more. This is beneficial for both new engineers joining the field as well as experienced engineers to reference and understand novel concepts and applications, such as in the new implementation of support structures shown in this thesis.

The supports designed in these examples were developed to simply address anticipated deformation. Instead, a new class of supports could be explored – those with engineered compliance. A thorough understanding of how stress travels through a part during the build process could lead to the design of support structures that absorb the stress and deform in a predetermined way. This would alleviate stress induced deformation in parts by shifting the deformation to a more favorable region - in this case, the support structures. A similar phenomenon was observed in the change in part deformation before and after removing support structures, suggesting that some of the supports absorbed stress better than others. Some supports were even detached from the part after the print because the support had deformed so drastically. Channeling stress to supports that are designed with the intent of deforming predictably could prevent stress from deforming the part. The work in this thesis presents a novel implementation of support structures as a design tool rather than a sacrificial process requirement or by-product. Further investigating supports such as in the context of engineered compliance is a way forward to address the part deformation challenges in metal AM.

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APPENDICES

7.1 Appendix A: Case Study

The part used in the case study was scanned at multiple instances in its process flow. The first scan occurred after the parts were removed from the build plate. The second scan was only completed for even numbered parts as they had the supports removed while the odd numbered parts did not. However, all parts were scanned following heat treatment. Their deformation is shown in Table 7.1 and the photos of the part during print and at different stages of post processing are shown in Figure 7.1.

Table 7.1: Deformation of case study part

	Scan 1 - Print Supported [in]				**Scan 2 - Support Removed** [in]				**Scan 3 – HT** [in]			
S/N	**Location I**	**Location II**	**Location III**	**Location IV**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**
A1	0.012	0.013	0.013	0.015	x	x	x	x	0.014	0.01	0.016	0.021
A2	0.012	0.016	0.016	0.016	0.016	0.016	0.017	0.014	0.018	0.02	0.016	0.016
B1	0.011	0.011	0.008	0.013	x	x	x	x	0.022	0.006	0.011	0.02
B2	0.011	0.01	0.007	0.013	0.013	0.01	0.009	0.01	0.014	0.013	x	0.012
C1	x	0.009	0.007	0.010	x	x	x	x	0.018	0.005	0.010	0.018
C2	x	0.010	0.010	0.012	x	0.010	0.009	0.011	0.014	0.014	x	0.013

Figure 7.1: Parts during print and after removal from build-plate.

7.2 Appendix B: Guidelines

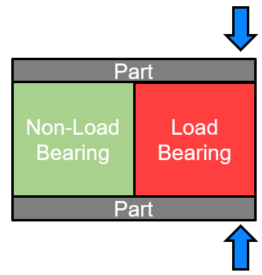
The guidelines, as to be presented to users, are shown below. An introductory slide has been added to supplement the four challenge feature guidelines in order to provide context on guidelines, layout, and formatting.

Introduction to Guidelines

- Guidelines are **tools** for engineers and designers to improve their parts and assemblies.
- The guidelines presented here are meant to reduce the deformation of DMLM parts through intentional support structure design.
- The uniform support structure strategy is replaced with a strategy based on mechanical analysis as well as print and simulation results to combat anticipated movement (blue)
- A geometry is presented and defined, and instructions are given on where to place supports that balance the mechanical need (red) with DMLM process limits (green).

Geometry Definition	
Support Design Envelope	Example Support Solution

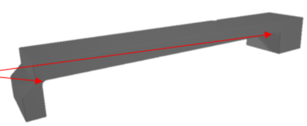
Design Envelope Analogy:
Red is load bearing
Green is non-load bearing



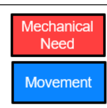
Bottom Surface

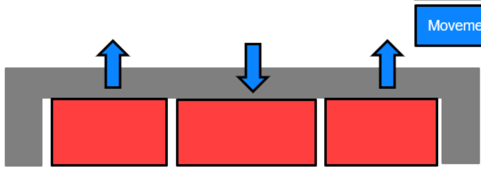
Description

- External part gap
- Two stress concentration points
- Two open sides



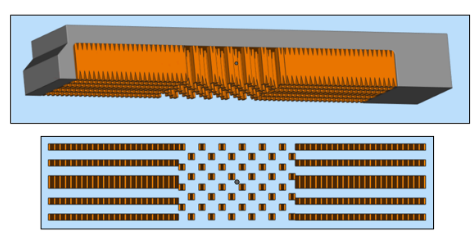
Design Envelope





The bottom surface will bow down in the middle. Supports should be placed to address the mechanics needs of compression in the middle and tension on the ends closes to the vertical walls.

Example Solutions

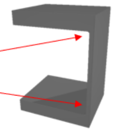


Columns are placed in the middle to prevent compression from bowing.

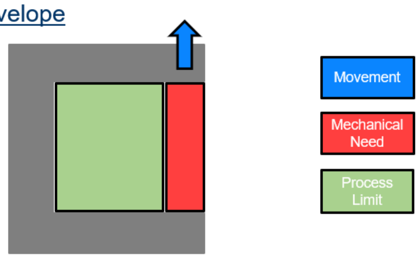
Overhang

Description

- Internal part gap
- Two stress concentration points
- Three open sides

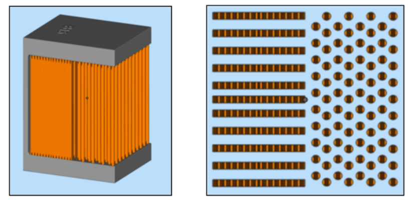


Design Envelope



The area furthest from the vertical wall is important to prevent the lift and should be designed for tension. The rest of the space is defined by process limits.

Example Solutions



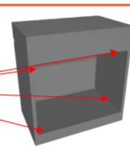
Supports placed near the open, free end should prevent tension. A cross-section top view is shown of columns.

CEDAR
LMORAND@G.CLEMSON.EDU
FRAME

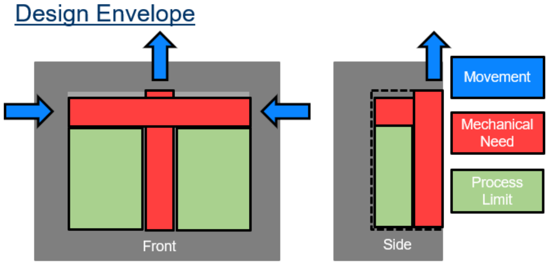
Roof

Description

- Internal part gap
- Four stress concentration points
- One open side

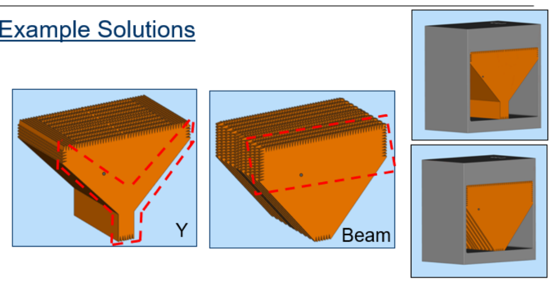


Design Envelope



The vertical walls will move in at the top area, so compression needs to be addressed. The front lip of the top horizontal ceiling will lift and needs supports that resist tension.

Example Solutions



One example showing a solid Y for compression and plates for z-lift, and another showing a solid horizontal bar for compression with plates underneath for process limits. The solid portions are shown with dashed lines.

CEDAR
LMORAND@G.CLEMSON.EDU
FRAME

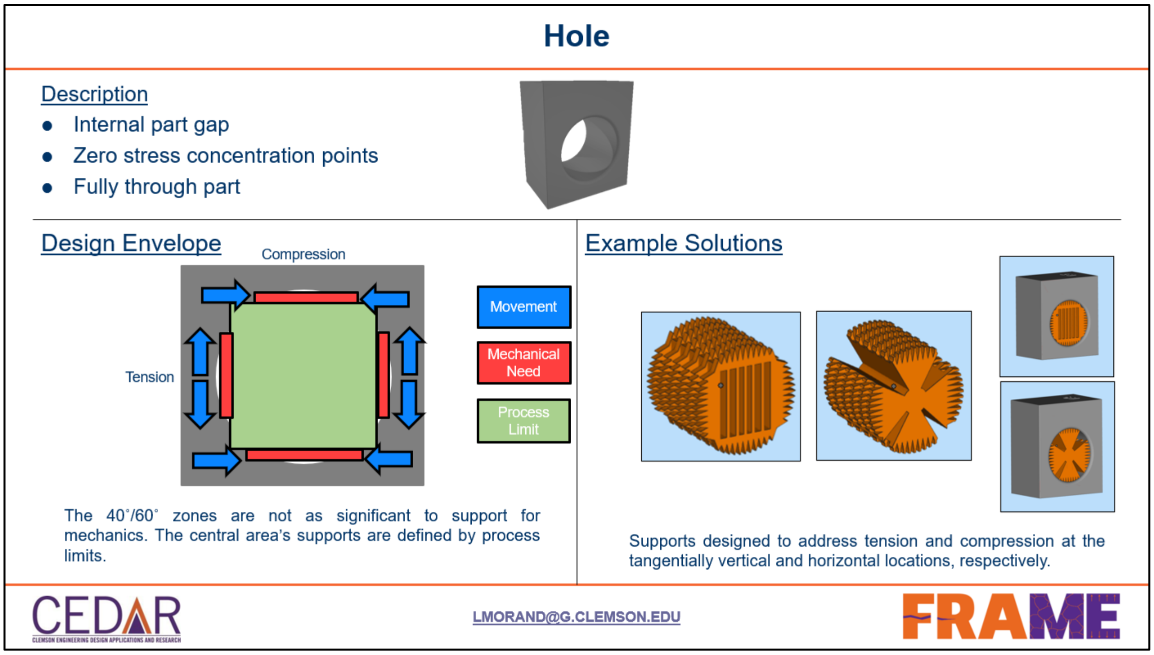


Figure 7.2: Guidelines for support structure design.

7.3 Appendix C: Part Simulation and Print Data

Each challenge geometry was scanned via blue light immediately after removal from the build plate and again after support removal if the supports were able to be removed. The locations for the data points used in average deformation calculations are shown for each geometry in Figure 7.3 and the values for each point are given in Table 7.2 for the first scan with supports and Table 7.3 for the second scan without supports.

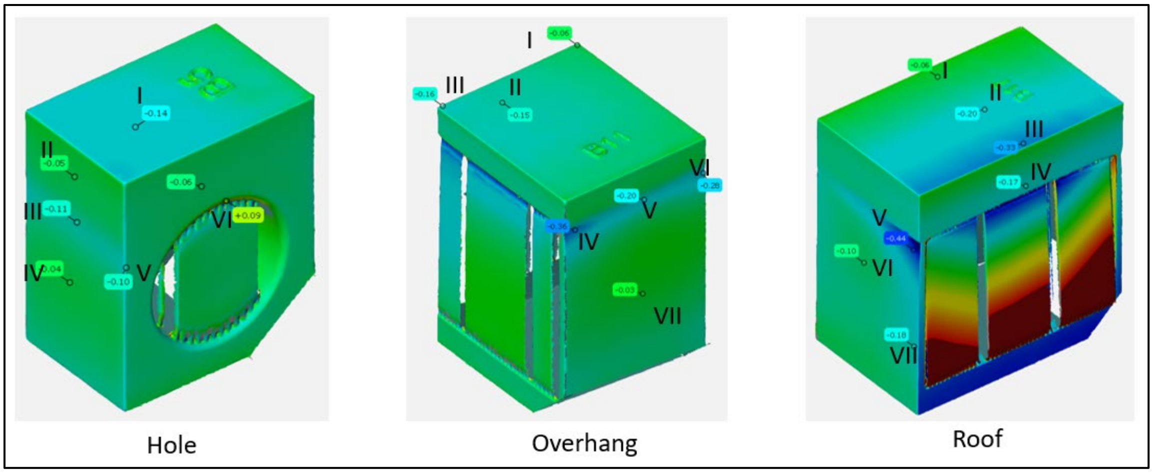


Figure 7.3: Measurement point locations for blue light scans.

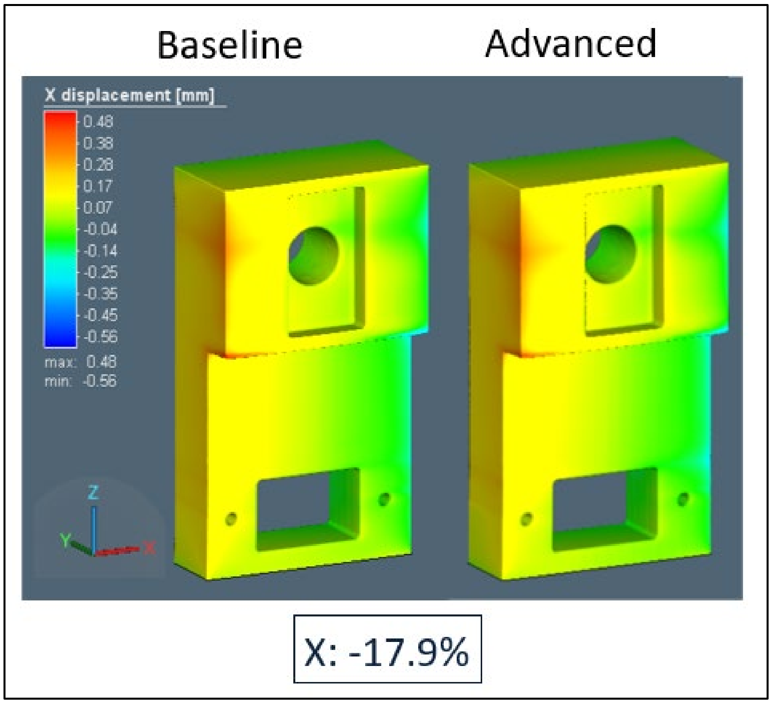
Table 7.2: Measurement points for parts with supports.

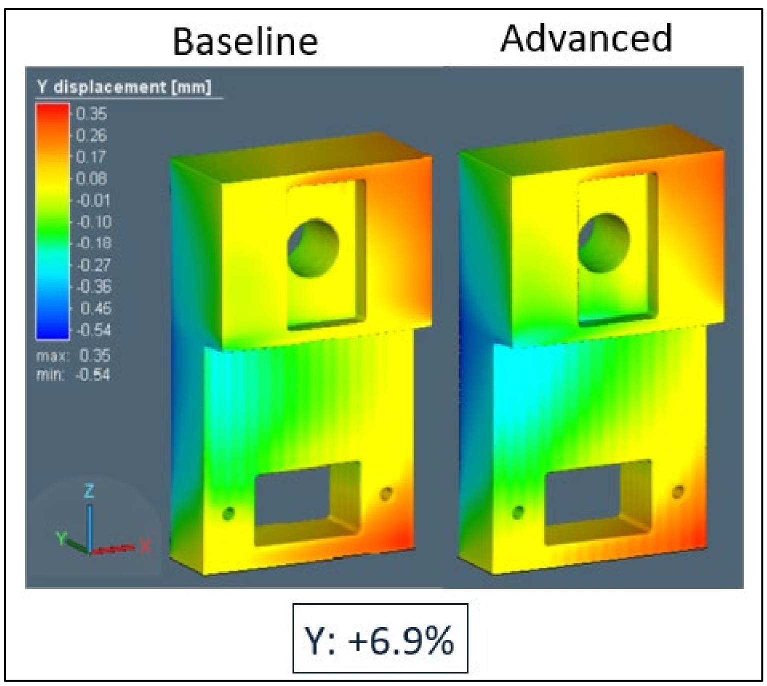
	[mm]												% change	% change
With Supports	Absolute Deformation							Maximum	Average	Minimum	Avg of MAX	Avg of AVG	from baseline MAX	from baseline AVG
Hole Baseline	0.14	0.05	0.11	0.04	0.10	0.09		0.14	0.09	0.04	0.15	0.09	0.00%	0.00%
	0.15	0.05	0.11	0.04	0.12	0.08		0.15	0.09	0.04				
Hole Box	0.15	0.06	0.10	0.07	0.09	0.07		0.15	0.09	0.06	0.15	0.08	0.00%	-8.33%
	0.14	0.05	0.01	0.06	0.11	0.08		0.14	0.08	0.01				
Hole Cross	0.14	0.05	0.06	0.06	0.12	0.07		0.14	0.08	0.05	0.14	0.08	-3.45%	-7.41%
	0.14	0.05	0.08	0.07	0.11	0.05		0.14	0.08	0.05				
Overhang Baseline	0.06	0.15	0.16	0.36	0.20	0.28	0.03	0.36	0.18	0.03	0.38	0.18	0.00%	0.00%
	0.05	0.16	0.15	0.39	0.23	0.28	0.03	0.39	0.18	0.03				
Overhang Box	0.07	0.18	0.11	0.29	0.17	0.24	0.00	0.29	0.15	0.00	0.29	0.15	-22.67%	-14.62%
	0.08	0.18	0.11	0.29	0.19	0.24	0.01	0.29	0.16	0.01				
Overhang Cylinder	0.08	0.18	0.10	0.33	0.20	0.22	0.04	0.33	0.16	0.04	0.33	0.17	-12.00%	-7.91%
	0.07	0.18	0.12	0.33	0.20	0.25	0.03	0.33	0.17	0.03				
Roof Baseline	0.06	0.20	0.33	0.17	0.44	0.10	0.18	0.44	0.21	0.06	0.47	0.21	0.00%	0.00%
	0.13	0.19	0.22	0.13	0.50	0.10	0.14	0.5	0.20	0.10				
Roof Beam	0.12	0.15	0.18	0.09	0.17	0.10	0.18	0.18	0.14	0.09	0.19	0.14	-59.57%	-31.14%
	0.10	0.15	0.17	0.10	0.20	0.10	0.18	0.2	0.14	0.10				
Roof Y	0.09	0.14	0.17	0.10	0.19	0.03	0.16	0.19	0.13	0.03	0.18	0.12	-61.70%	-40.14%
	0.08	0.14	0.17	0.10	0.17	0.04	0.15	0.17	0.12	0.04				
Roof Beam-Hole	0.13	0.15	0.11	0.09	0.15	0.01	0.09	0.15	0.10	0.01	0.17	0.11	-63.83%	-48.10%
	0.14	0.15	0.11	0.09	0.19	0.01	0.08	0.19	0.11	0.01				
Roof Beam-Plate	0.10	0.14	0.16	0.10	0.19	0.08	0.13	0.19	0.13	0.08	0.19	0.12	-59.57%	-39.79%
	0.09	0.14	0.15	0.08	0.19	0.06	0.13	0.19	0.12	0.06				
Roof Y-Plate	0.08	0.12	0.13	0.08	0.20	0.05	0.12	0.2	0.11	0.05	0.20	0.12	-57.45%	-43.60%
	0.10	0.13	0.14	0.10	0.20	0.06	0.12	0.2	0.12	0.06				

Table 7.3: Measurement points for parts without supports.

	[mm]												% change	% change
No Supports	Absolute Deformation							Maximum	Average	Minimum	Avg of MAX	Avg of AVG	from baseline MAX	from baseline AVG
Hole Baseline	0.15	0.04	0.09	0.03	0.12	0.10		0.15	0.09	0.03	0.17	0.10	0.00%	0.00%
	0.05	0.15	0.15	0.03	0.18	0.13		0.18	0.12	0.03				
Hole Box	0.11	0.05	0.10	0.07	0.12	0.02		0.12	0.08	0.02	0.14	0.08	-15.15%	-24.59%
	0.16	0.04	0.08	0.05	0.06	0.06		0.16	0.08	0.04				
Hole Cross	0.12	0.04	0.07	0.07	0.10	0.06		0.12	0.08	0.04	0.13	0.08	-24.24%	-21.31%
	0.05	0.10	0.10	0.03	0.13	0.09		0.13	0.08	0.03				
Overhang Baseline	0.54	0.10	0.46	0.43	0.32	0.41	0.02	0.54	0.33	0.02	0.55	0.33	0.00%	0.00%
	0.55	0.10	0.46	0.45	0.30	0.37	0.04	0.55	0.32	0.04				
Overhang Box	0.62	0.10	0.59	0.33	0.21	0.29	0.00	0.62	0.31	0.00	0.61	0.31	11.93%	-5.71%
	0.60	0.13	0.57	0.31	0.23	0.30	0.01	0.6	0.31	0.01				
Overhang Cylinder	0.43	0.08	0.47	0.35	0.26	0.33	0.00	0.47	0.27	0.00	0.53	0.29	-3.67%	-11.21%
	0.58	0.12	0.51	0.34	0.23	0.32	0.02	0.58	0.30	0.02				
Roof Baseline	0.07	0.13	0.17	0.16	0.52	0.11	0.15	0.52	0.19	0.07	0.50	0.19	0.00%	0.00%
	0.14	0.20	0.24	0.16	0.47	0.09	0.10	0.47	0.20	0.09				
Roof Beam														
Roof Y														
Roof Beam-Hole														
Roof Beam-Plate	0.17	0.23	0.25	0.14	0.15	0.13	0.10	0.25	0.17	0.10	0.25	0.17	-49.49%	-13.65%
Roof Y-Plate	0.11	0.17	0.20	0.09	0.16	0.08	0.07	0.2	0.13	0.07	0.21	0.13	-58.59%	-32.10%
	0.12	0.18	0.21	0.11	0.21	0.04	0.09	0.21	0.14	0.04				

The simulation results for the combination part were isolated in each direction. The results are shown in Figure 7.4.


Baseline
Advanced
X displacement [mm]
0.48
0.38
0.28
0.17
0.07
-0.04
-0.14
-0.25
-0.35
-0.45
-0.56
max: 0.48
min: -0.56
Z
Y
X
X: -17.9%


Baseline
Advanced
Y displacement [mm]
0.35
0.26
0.17
0.08
-0.01
-0.10
-0.18
-0.27
-0.36
0.45
-0.54
max: 0.35
min: -0.54
Z
Y
X
Y: +6.9%

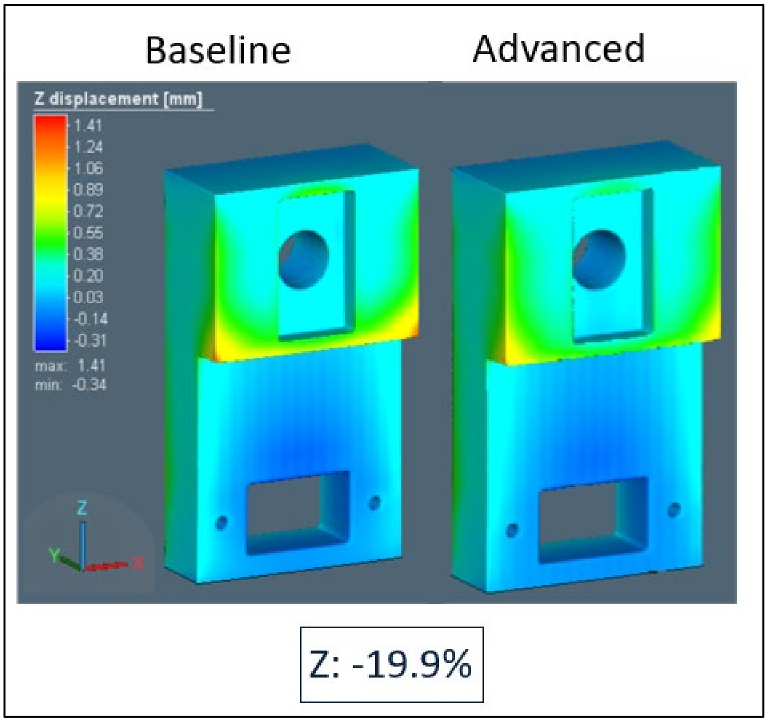


Figure 7.4: Deformation simulation results for the combination part in the x-, y-, and z-directions.