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Expanding Material Property Space Maps with Functionally Graded materials for Large Scale Additive Manufacturing

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Abstract

Big Area Additive Manufacturing (BAAM) is a large scale extrusion-based print system that exceeds the throughput of conventional printers by five hundred times. In addition, BAAM uses pelletized feedstocks, which allows for site-specific definition of material composition and provides an unprecedented variety of material options. This study applies Ashby's concept of a material property space map to a variety of materials suitable for printing on BAAM. Ashby maps plot the performance of various materials across multiple parameters (such as strength, density, stiffness, etc) allowing for direct comparison of non-dimensional performance criteria. This study uses Ashby maps to identify opportunities for the use of functionally graded materials on BAAM to achieve structural performance not yet available with conventional printers and homogeneous materials.

Introduction

Additive manufacturing (AM), commonly called 3-D printing, is the process of creating a three-dimensional part with consecutive two-dimensional layers. The part is designed with computer aided design (CAD) software, and then divided into multiple layers through a virtual "slicing" software [1]. AM encompasses a variety of technologies, including selective laser sintering, stereo-lithography, and polymer extrusion [2]. One of the most common forms of 3-D printing is fused filament fabrication (FFF). In this process, filaments of thermoplastics, such as acrylonitrile butadiene styrene (ABS), are forced into a heating element, where it melts and flows through a die. A gantry system moves the deposition system in a plane, and deposits the material in a specified computer numerically controlled (CNC) path. This process is repeated for each 2-D layer. These FFF systems are typically restricted to flows rates of 70 grams per hour and build volumes around 0.125 cubic meters [3].

Large format additive manufacturing, such as Cincinnati Incorporated's Big Area Additive Manufacturing (BAAM), is an industrialized FFF system that creates parts 500 times faster than traditional FFF systems. BAAM has a build area of 2.5 (x-axis) meters by 6 meters (y-axis) with 2.5 meters of vertical height (z-axis). BAAM differs from traditional 3-D printers by depositing polymer beads with a diameter or 4 to 8mm, compared to 0.1 to 0.5mm. This larger die size allows deposition rates around 45 kilograms per hour. Whereas FFF uses a continuous filament, the BAAM system uses a custom, high-throughput single screw extruder to deposit pelletized feedstock that is common to the injection molding and extrusion industries. The advantage of pelletized thermoplastic feedstock is the wide variety of usable materials, such as commodity acrylonitrile butadiene styrene (ABS) or high performance polyphenylene sulfide (PPS), and the ability to add reinforcing fillers, like carbon fibers. Love et al demonstrates that adding carbon fibers to the feedstock increases strength, increases stiffness, and lowers the coefficient of thermal expansion [4]. In addition, pelletized thermoplastics are approximately five times cheaper than their continuous filament counterpart. The extruder on the BAAM is a custom, single screw extruder with six heating zones and one compressed air-fed hopper. The barrel is approximately 60 cm long, and has a 2.5 cm diameter screw designed for processing fiber filled polymers. The extruder has a maximum speed of 400 revolutions per minute (RPM) [5-7].

With a variety of polymer and filler combinations, Ashby material property space maps are needed to compare the performance of materials across multiple parameters. Duty [8] reports mechanical properties for BAAM printed parts. The authors show that when a flattening mechanism is used, the stiffness (Young's modulus) of a printed material can be equal to or greater than the reported values from injection molded reference. A BAAM specific material property space map has been created by using the injection molded reference values reported by Sabic [9], shown in Figure 1. Most of the materials group around the middle of the plot, leaving a large gap for potential improvement. Fleck et al identifies three ways to fill these holes in material property space [10-11]. One method is to control the architecture of the material by creating hybrids, such as composite reinforced materials, foams, and lattice structure. Using AM to create multifunctional structures with internal lattices are ongoing projects by other authors [12-14]. One method for exploring regions of the material property space map that is not directly mentioned by Fleck et al or AM focused authors is the use of a functionally graded material.

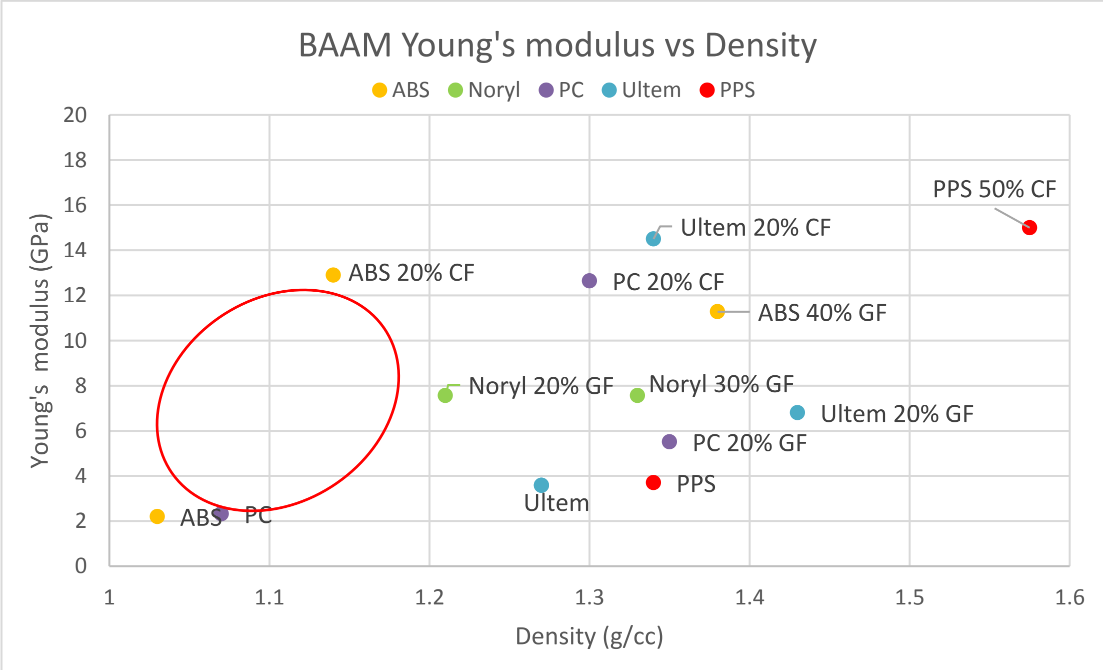


Figure 1. BAAM specific material property space map. The area circled in red identifies potentially accessible region with functionally graded materials

A functionally graded material (FGM) is an intentionally inhomogeneous hybrid, in which the constituents are gradually varied so that material properties of the hybrid continuously change over the geometry of the part to achieve a desired improvement in performance such as weight, mechanical properties, thermal properties, or cost [15]. In addition, varying the volume fraction of the constituents in a gradual manner reduces the likelihood of an interface failure [16]. One particular application of FGM is a sandwich panel, in which the structure grades from a high strength material at the face sheet to a low density material at the core. Traditional sandwich panels tend to fail from poor bonding mechanisms at the sharp transition between materials, but a FGM sandwich panel reduces the likelihood of interface failure [17]. The majority of FGM studies rely on simulations of mechanical or thermal behavior because manufacturing of FGMS is difficult. However, additive manufacturing allows design freedom over the geometry of a part and the pelletized feedstock of BAAM allows material to be easily blended and compositionally altered during a print. This study uses BAAM to manufacture functionally graded sandwich beams. An analysis is performed to quantify the cost and weight of the beams.

Experimental Procedure

FGM sandwich panels were manufactured using the most common BAAM materials. Twenty percent by weight carbon fiber-reinforced ABS (CF-ABS) was used as the face sheet material.

Unfilled acrylonitrile butadiene styrene (ABS) was chosen as the core material. Material properties for the two materials are shown in Table 1

Table 1. Material properties and cost for BAAM grade polymers

Material	Density (kg/m^3)	Young's Modulus (GPa)	Cost per Kg ($)
20% CF-ABS	1140	12.9	$11
Neat ABS	1040	2.02	$2 .2

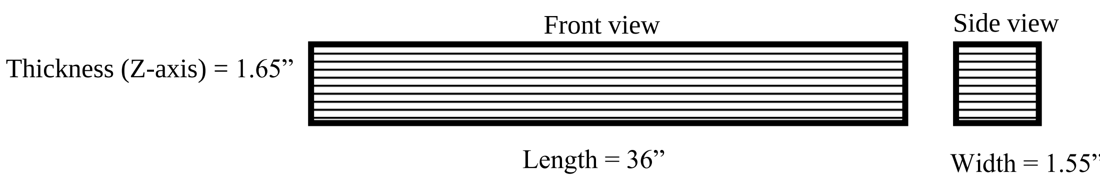


Figure 2. Geometry of beam

The beam geometry is shown in Figure 2. Since BAAM uses a layer thickness of 3.81mm, a beam with eleven layers (41.91 mm) was chosen. The FGM beam was created by first depositing a solid layer of CF-ABS to make the face sheet of the sandwich panel. Then, increasing amounts of ABS were mixed with CF-ABS and deposited in layers until a pure ABS core was achieved in the middle (layer 6). The process was then reversed to grade the beam composition from pure ABS at the core layer to CF-ABS at the top face sheet. The gradient pattern was created with the power law function

$$V = \left(\frac{2 * z}{h2 - h1}\right)^K$$

where V represents the volume fraction of ABS in a given layer numer, z. A K value of 1 results in a linear relationship between the volume fraction and layer number. A lower K value equates to a higher volume fraction of ABS throughout the part, as shown in Figure 3.

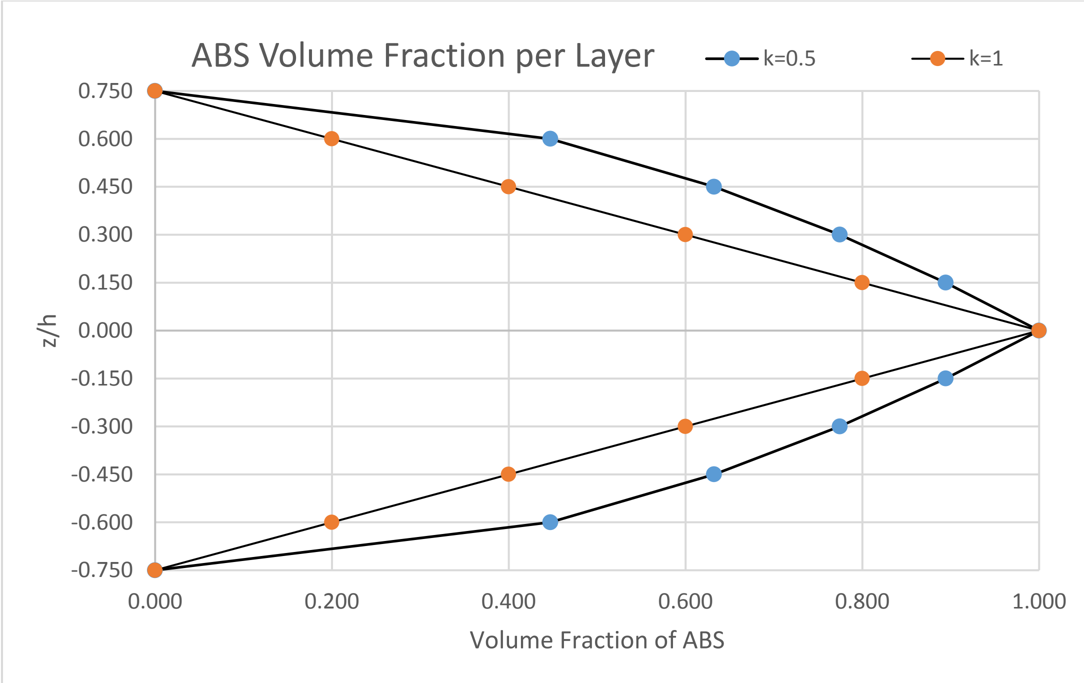


Figure 3. Volume percent of ABS in the FGM sandwich panel at each layer. Z/h represents distance from the neutral axis

Figure 3 is a traditional way of reporting the volume of fraction of material in a FGM. The variable z/h represents the distance of each layer from the neutral axis. Another method of representing the material content in each layer is shown in Figure 4. In Figure 4, it is clear that when K=0.5 (Power Law), there is more ABS in the transitions layers.

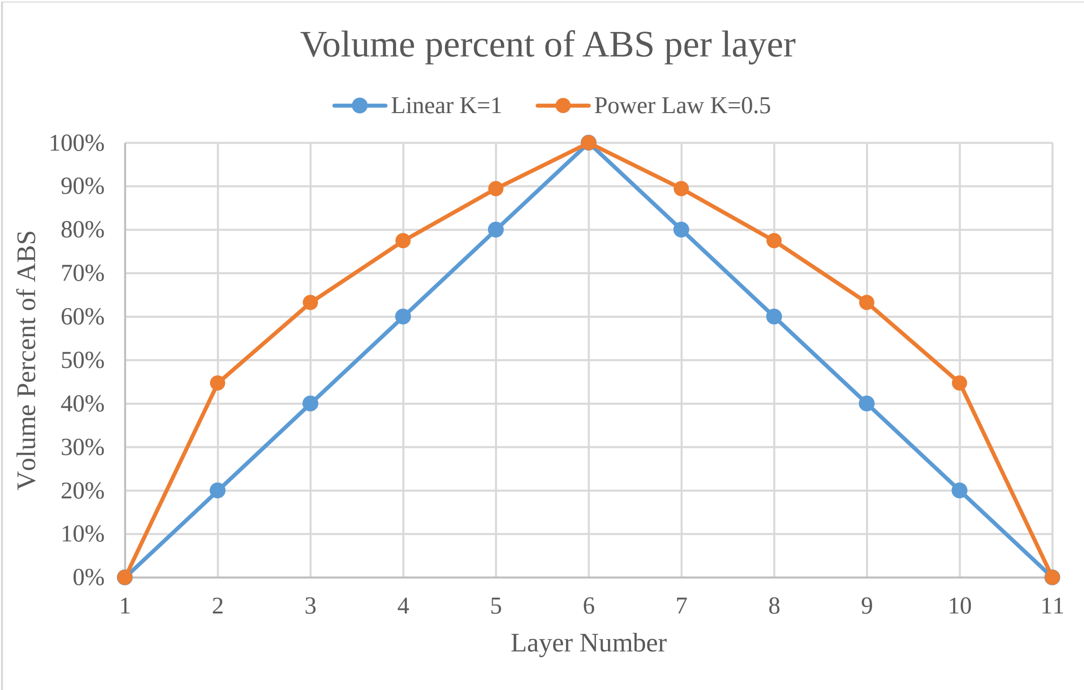


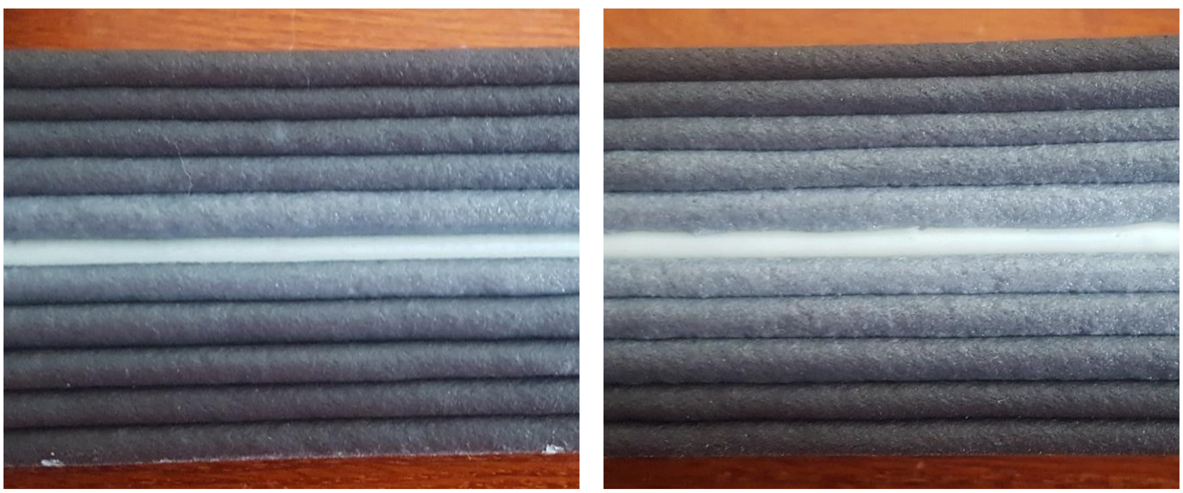
Figure 4. Graph representing the volume fraction in percent of ABS in each layer for both the Linear and Power Law variations

The amount of material needed for each layer was calculated by converting the volume percent from Figure 4 into weight percent. The material for each layer was pre-mixed in discrete batches (Figure 5). A CNC tool path of the beam from Figure 2 was created. The material for layer 1 was poured into the BAAM hopper and the print was started. After each layer, the print was paused. Material remaining in the extruder was purged into a waste bin. The next layer's material was added to the hopper, and was purged until steady state flow was achieved. The print was resumed, and the process was repeated for all layers. Thermal imaging was used to verify that the temperature of the previous layer remained above the glass transition temperature of ABS when the subsequent layer was deposited. Four beams were printed: One pure CF-ABS, one pure ABS, one Power Law FGM, and one Linear FGM.

Figure 5. Picture of the pre-mixed material for each layer. The white pellets are ABS, and the black pellets are CF-ABS

Results

The printed beams are shown in Figure 6. The black material is CF-ABS and the white material is ABS. The gradient is most visible in the Power Law variation because more ABS is present.



a) Linear FGM

b) Power Law FGM

Figure 6. Pictures of printed sandwich panel beams with functionally graded core

A cost and weight analysis of the beams were performed by first converting the known volume percent of ABS and CF-ABS of each layer into an actual print volume. Then, using the density values, the weight of ABS and CF-ABS in the specific layers were calculated. The price per kg of the ABS and CF-ABS were used to find the total cost of the beam. Figure 7 plots the cumulative material cost of each beam. The pure CF-ABS and pure ABS beams have a linear relationship between cost and layer because each layer uses the same weight of material, which directly correlates to cost. The two functionally graded beams have a non-linear relationship because increasing amounts of the cheaper material (ABS) are added. Both of the functionally graded beams show a large price decrease compared to the pure CF-ABS beam. Figure 8 applies the same cumulative analysis to the weight of each beam. In this figure, the difference in weight between the four beam types is inconsequential. Whereas the cost of ABS is 80% less than CF-ABS, the weight of ABS is only 9% less than CF-ABS.

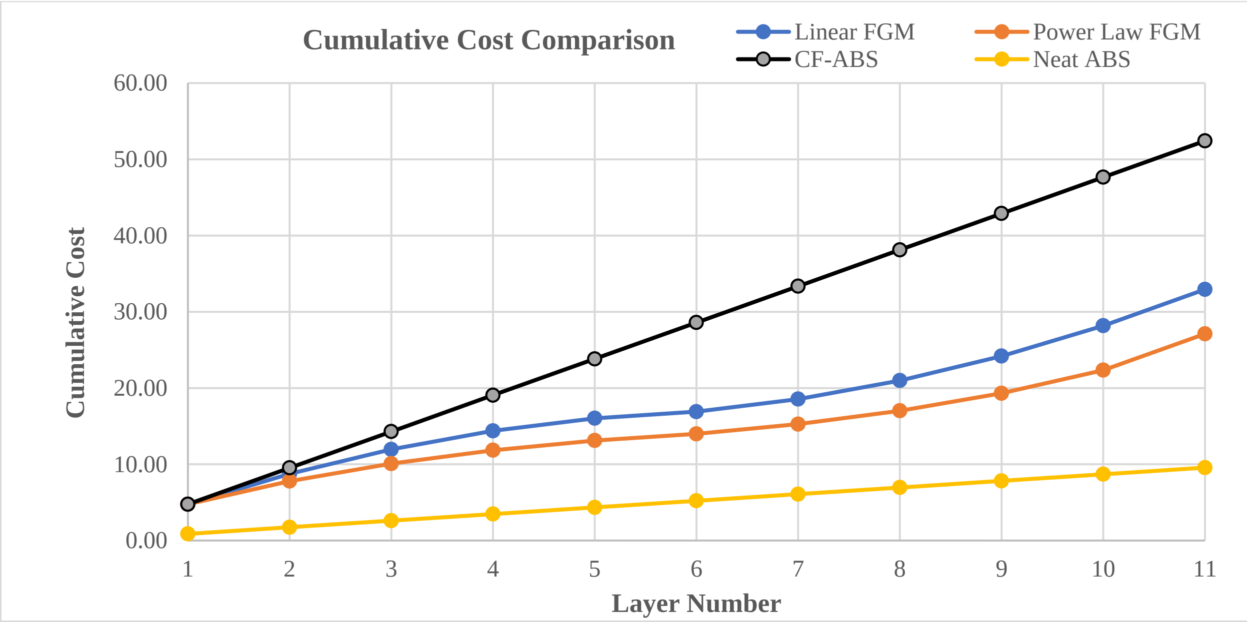


Figure 7. Material cost as a function of layer for all four variations

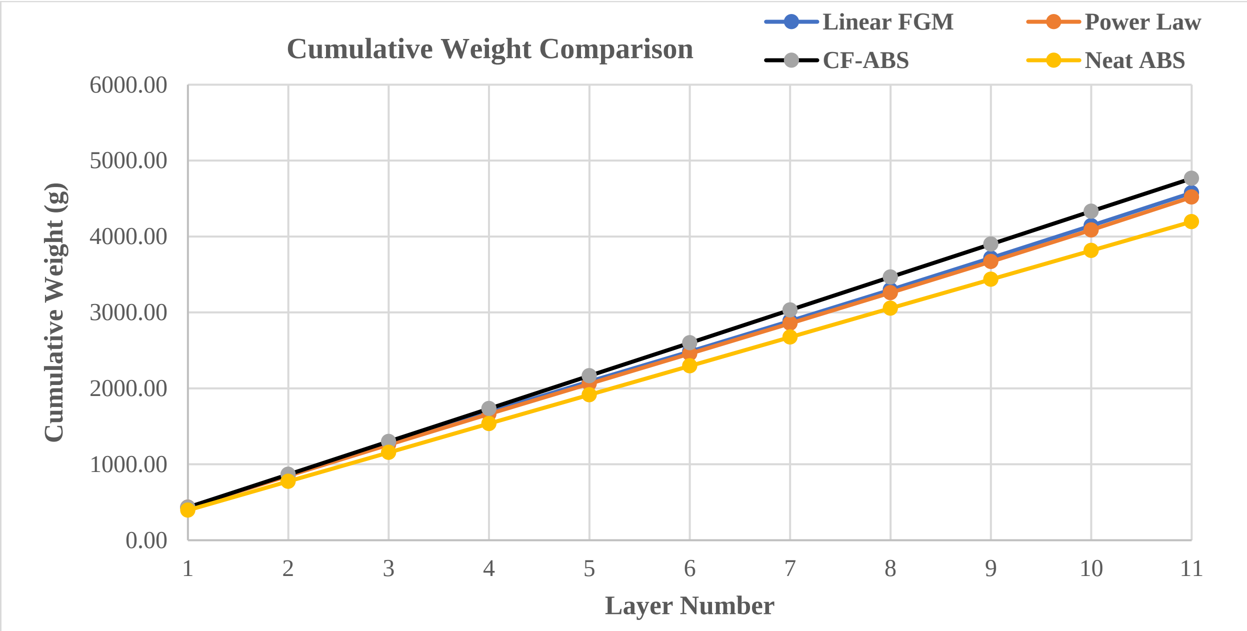


Figure 8. Beam weights as a function of layer count for all four variations

A comparison of weight and cost for each beam is shown in Table 2. Due to the similarity of densities in the chosen materials, the weight savings is small compared to the pure CF-ABS beam. However, the large discrepancy in price creates a large savings in cost compared to the CF-ABS beam.

Beam Type	Weight (kg)	Weight (lb)	Cost	Percent difference	
				Weight	Cost
CF-ABS	4.76	10.48	$ 52.42	-	-
Linear FGM	4.57	10.07	$ 32.94	4.0%	37.2%
Power Law FGM	4.51	9.94	$ 27.10	5.2%	48.3%
Neat ABS	4.34	9.56	$ 9.56	-	-

Conclusions

Big Area Additive Manufacturing is a large format fused deposition modeling style printer that uses pelletized feedstock to create parts faster than normal additive systems. In addition, the pelletized feedstock allows users to easily change materials between layers, which can be used to create a functionally graded material. Sandwich panels with functionally graded cores have shown to improve performance, but most publications are limited to simulations due to the difficulty in manufacturing FGM panels. This study demonstrated the manufacture of FGM sandwich panels with BAAM. A cost and weight analysis revealed that using a gradient core can reduce cost by 48% and weight by 5%. Future work will test the mechanical performance of the beams. Additional beams will also be printed and tested using a material with a larger weight discrepancy for the core.

Acknowledgements

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