2018 ASEE ANNUAL CONFERENCE & EXPOSITION
JUNE 24–27, 2018
SALT PALACE CONVENTION CENTER
SALT LAKE CITY, UT

Paper ID #22774

Analyzing the Composite 3-D Printer Frame for Rigidity

Mr. Jonathan Mark Holman, University of Pittsburgh at Johnstown

Jonathan Holman is currently a student at the University of Pittsburgh at Johnstown, majoring in Mechanical Engineering. He founded a club devoted to researching and learning about the Additive Manufacturing process through hands-on projects at UPJ. He spends lots of time working with various FDM (Fused Deposition Modeling) 3D printers. Ranging from professional systems, to RepRap style kit printers, he works on all of them. When he isn't working on 3D printers, Jonathan is learning more about them through research projects, and experiments, ranging from testing materials for strength, to experimenting with new ways to implement design and process techniques for Additive Manufacturing. He is currently engaged in numerous projects in the field of Additive Manufacturing covering a range of topics.

Dr. Tumkor Serdar, University of Pittsburgh at Johnstown

Serdar Tumkor is an Assistant Professor of Mechanical Engineering at the University of Pittsburgh at Johnstown. Dr. Tumkor has more than 20 years of experience in education, having taught at Stevens Institute of Technology and Istanbul Technical University. His engineering experience includes design, manufacturing, and product development. He has been lecturing Manufacturing Processes, Machine Design, Engineering Design, and Computer Aided Technical Drawing courses.

Analyzing the Composite 3D Printer Frame for Rigidity

Abstract

Additive Manufacturing offers a wide variety of options when it comes to the construction of a part. Different infill patterns, infill densities, varying shell thickness, and different materials all have different effects on the final strength of a functional 3D printed part. This paper studies the benefits of using a fused deposition modeling (FDM) process to print a part completely hollow and fill the completed hollow shell with epoxy resin to create a solid component. FDM is also known as fused filament fabrication (FFF). Often times, large functional FDM parts can take quite a long time to complete printing due to high strength setting requirements. Hollow parts can print much faster than parts with infill, then be filled with an epoxy resin to create a solid part in much less time. When cured, the resin filled components will produce a stronger and more rigid finished product than a printing the part with comparable print settings. To illustrate this, a 3D printer frame was designed, analyzed with an FEM simulation and fabricated.

Keywords

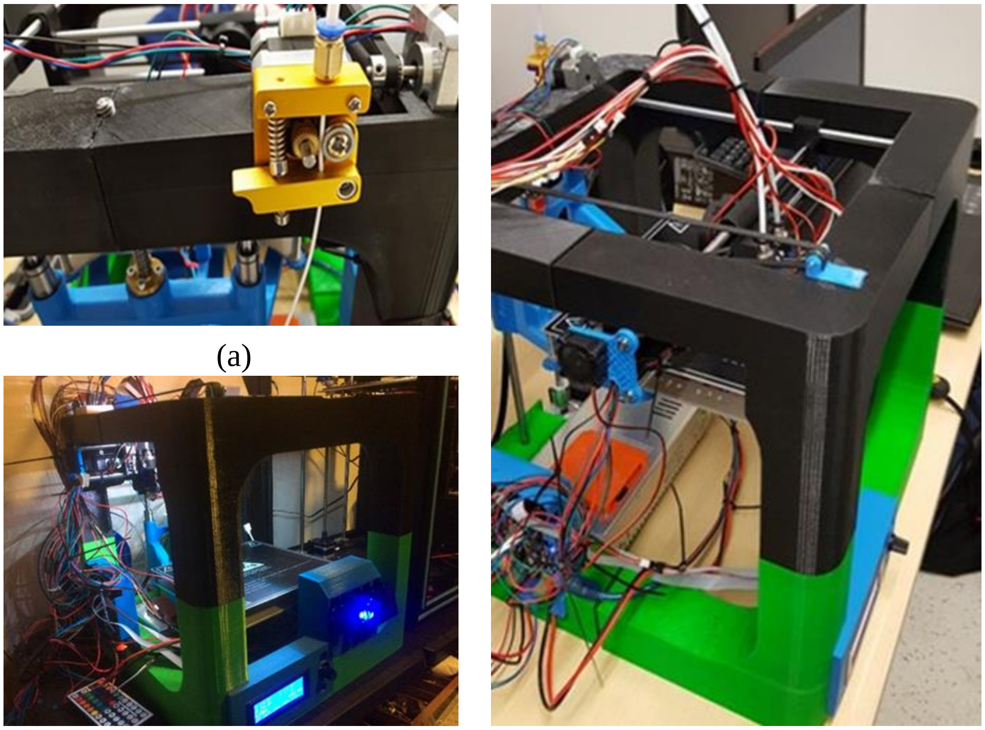
3D Printer, 3D printing, fused filament fabrication, FEM simulation, composite frame.

Introduction

Additive Manufacturing is constantly expanding as a manufacturing technique for parts that serve a function, rather than just rapid prototyping and modeling. There are many different methods to use to additively manufacture a part [1]. One of the holdbacks of additive manufacturing processes is that they can be time-consuming. Particularly, Fused Deposition Modeling (FDM) machines can take hours [2], or days to complete a large load-bearing part, just because the part requires a sizeable amount of plastic to complete a higher percentage infill component with additional perimeters around the part to achieve strong enough mechanical properties for the part to sustain the loads required [3],[4]. Some solutions have been faster machines, that can extrude material quicker at the cost of print quality, multi-extruder systems that have multiple extruders that all work on the same part in unison [5], or larger diameter nozzles that cause a loss of print quality and dimensional accuracy due to a reduction in the number of layers, or perimeters used in a print. A better solution is to print large parts with 0% infill[6], then fill the resulting internal cavity with fiber and resin to create a composite solid. This is applicable to additively manufacturing frame structures, or larger parts that will bear heavier loads. This design idea came about from the need for a dual extruder printer. The original concept was to design, and 3D print the frame for a 3D printer. A few of the issues of the design process were excessive print times. The original estimates for print times were roughly 67 hours, even with minimal strength settings. The idea came about that we could print frames hollow to reduce print times and fill the completed parts with resin to replace infill structures. Advantages to a 3D printed composite part that is filled with fiber & resin include withstanding a higher load force, ability to be fabricated in a shorter time and made stronger than the same part with 15% infill. A variety of resins can be used as a filler, depending on the application. This paper will take a detailed look at specifically epoxy resin for use in composite frames[7]. Epoxy resin is often used as an adhesive, or in composite structures like carbon fiber, or fiberglass. Epoxy can quickly be cured with a curing agent, heat [8], or UV light [9]. Curing times may vary depending on which curing agent is used to cure the resin. This specific type of resin has a wide variety of variants, from fiberglass filled, to nanocomposites [10]. In this study, time and material consumptions are estimated by the slicer data and stresses are analyzed using a Finite Element Model (FEM). The validation plan of the frame structure is to first, print both a 15% infill, and hollow frame parts to compare print times, and resulting quality [11]. Then fill the hollow frame part with epoxy and allow to cure. After curing is complete, a flexural test can be conducted on the frame sections to verify the difference in deflection between fill parameters.

Design of a 3D Printer Frame

A basic 3D printer was designed with the objective of making a maker printer. The frame of the printer was designed to experiment the reliability of the surface quality of the products. This printer design consists of eight corner components, linked together to create a cube with a cross-sectional area of $50mm^2$. All printer components, such as stepper motors, and linear rods are inserted into this cube structure, post-printing (Figure 1).



(a)

(b)

(c)

Figure 1 3D Printed printer frame (a) left extruder feeding filament (b) printing another frame, (c) motion system for the printing head

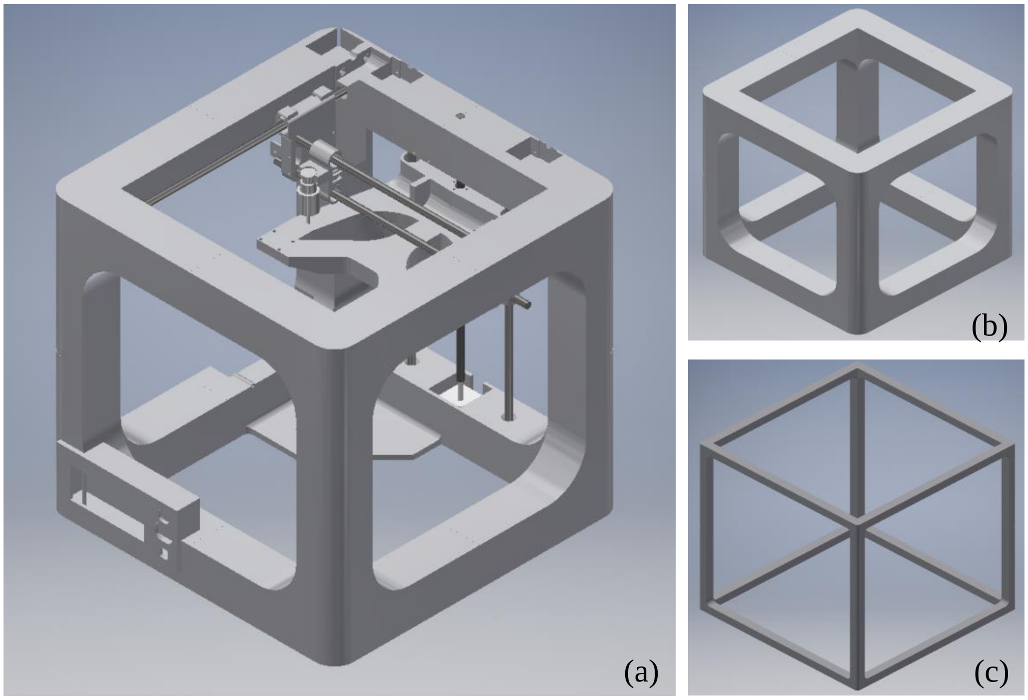


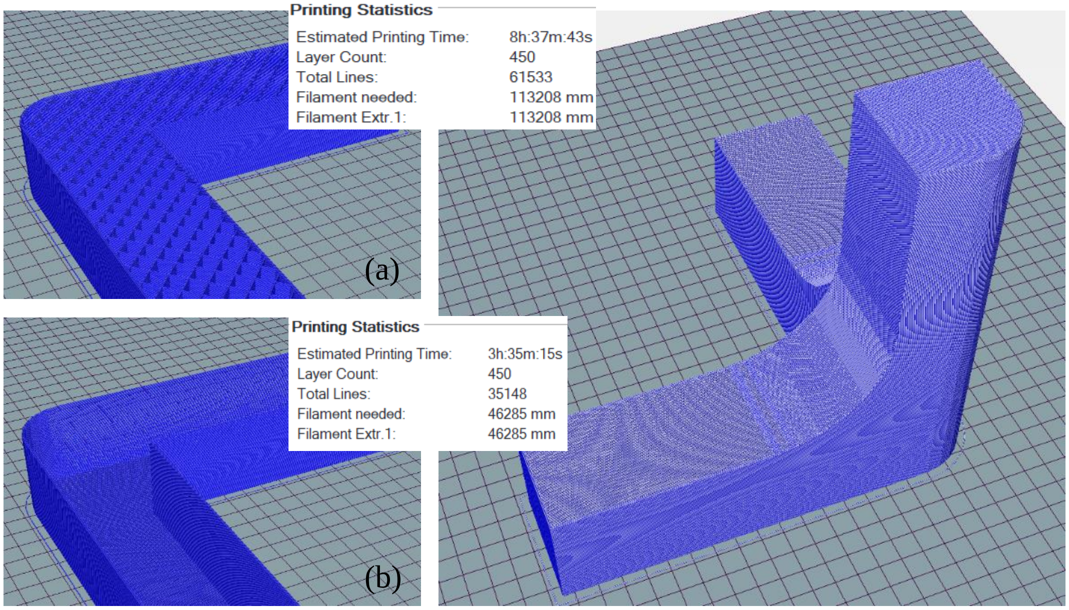
Figure 2 3D Printer frame assembly models for simulations a) Master assembly file b) Small (40x40 cm) frame c) Large (110x110 cm) frame

An equivalent CAD model (Figure 2) was designed for simulation, to better illustrate the differences in composite structures. This analog has the same simple design and construction of the completed machine but has no mounts, or other attachment points to provide a clearer illustration of the effects of changing the internal composition of the cube structure itself.

The sets of simulations were carried out at both scales, at all thee configurations, 15% of the internal volume is taken up by infill patterns, without any infill structure, and with an epoxy resin taking up the volume that infill patterns would be taking up if the part was printed solid.

Printing Time and Material Estimations

The frame structures were sliced in Repetier-Host for 60mm/s printing-speed with a 0.6mm nozzle at 0.4mm layer height with 2 perimeters and 3 solid top/bottom layers, providing an overall shell thickness of 1.2mm. The slicer estimates more than 8 hours and 113 m filament to print a 40x40cm frame with 15% infill while without any infill the print time and material are reduced by ~40%. (Figure 3)



Printing Statistics

Estimated Printing Time:	8h:37m:43s
Layer Count:	450
Total Lines:	61533
Filament needed:	113208 mm
Filament Extr.1:	113208 mm

Printing Statistics

Estimated Printing Time:	3h:35m:15s
Layer Count:	450
Total Lines:	35148
Filament needed:	46285 mm
Filament Extr.1:	46285 mm

Figure 3 Slicer estimates and printing statistics of 40x40cm frame parts a) 15% infill slice with printing statistics b) 0% infill slice with

Two sets of frames are designed and analyzed. Printing time and material consumptions are given in Table 1 for each frame size and fill settings.

Table 1 Analyzed frames and estimation of printing time and material

Frame Size	Infill Density & Pattern	Print Time	Filament [m]
Small Frame (40cm x 40cm)	100% Linear	30h 49m 20s	492.6
	15% Linear	8h 37m 43s	113.0
	0%	3h 35m 15s	46.0
Large Frame (110cm x 110cm)	100% Linear	100h 44m 39s	1610.9
	15% Linear	26h 55m 25s	354.8
	0%	11h 29m 52s	146.8

The slicer estimates a decrease in time and material consumption by 42%. By filling the hollow printed frame with an epoxy composite material, an increase in process speed and mechanical properties are expected as well.

Production of Composite Parts

Composite FDM parts can be designed as shells in CAD software or designed as a solid part and printed hollow by modifying infill settings in the slicer software. Production of shells to be filled requires a machine that is capable of handling higher flowrates for larger diameter nozzles while maintaining a consistent enough extrusion to provide for a watertight part, to retain the resin. Part models require two holes, an input hole, and an air escape hole positioned at the top of the part. These holes can either be modeled into the part directly or simply drilled or punched in the top or bottom of a part post-printing.

FEM Analysis of the Frame Structure

The objective of the analysis is to examine the deformations and stresses of the printer frame that affect the print quality and reliability of the printer. Expected deflections in the frame structure should be lower than the tolerances of the product. Large deflections of the frame will decrease the quality and dimensional accuracy of the printed parts. A structural analysis has been done for the 3D printed frames before experimenting. Each set of simulation consisted of four results, comparing maximum deflection accumulated on the top level of the frame structure when the printer is changing directions rapidly. One simulation will test the frame as it were if was to be printed with an infill of only 15% with a 0.6mm nozzle. The second simulation tests the frame structures with no infill. The third simulation tests the frame that has been filled with Epoxy resin.

The simulations were carried out on frame sizes of 40cm x 40cm x 40cm and 110cm x 110cm x 110cm. The Infill structure is also modeled to see the effects of different infill conditions to the frame structure (Figure 4).

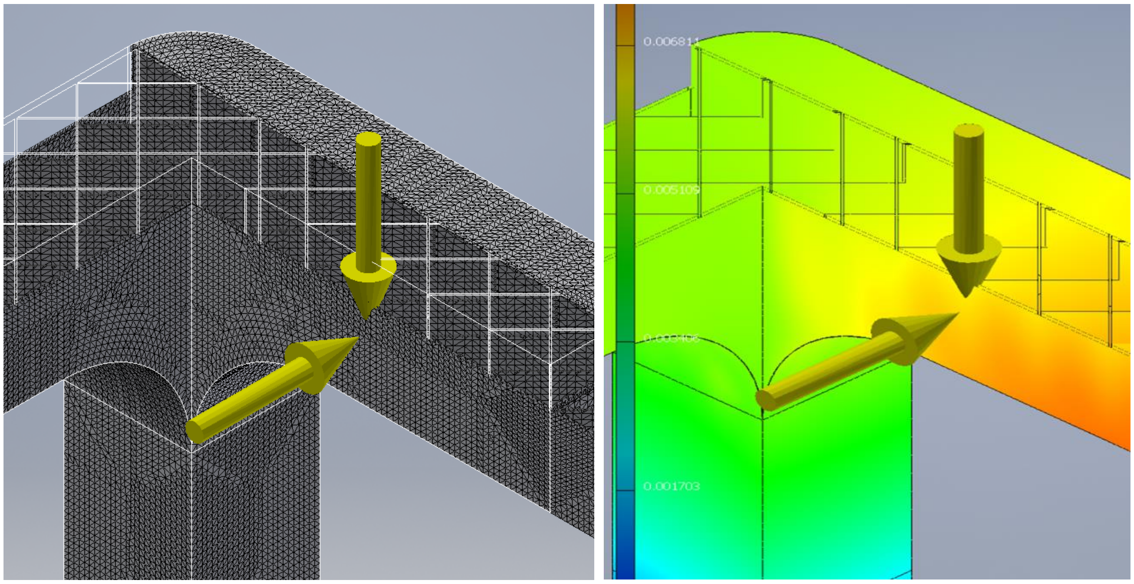


Figure 4 Mesh view of the internal structure

The loading boundary conditions were derived from the weight of the extruder head assembly and its motions on the slider rails. The weight of the complete assembly with the carriage is 785g. The assumption is that a sudden change of direction with an acceleration of 2500 mm/s^2 will cause a reaction force F_z in the z-direction addition to the weight F_y applied to the frame in the y-direction (Figure 5).

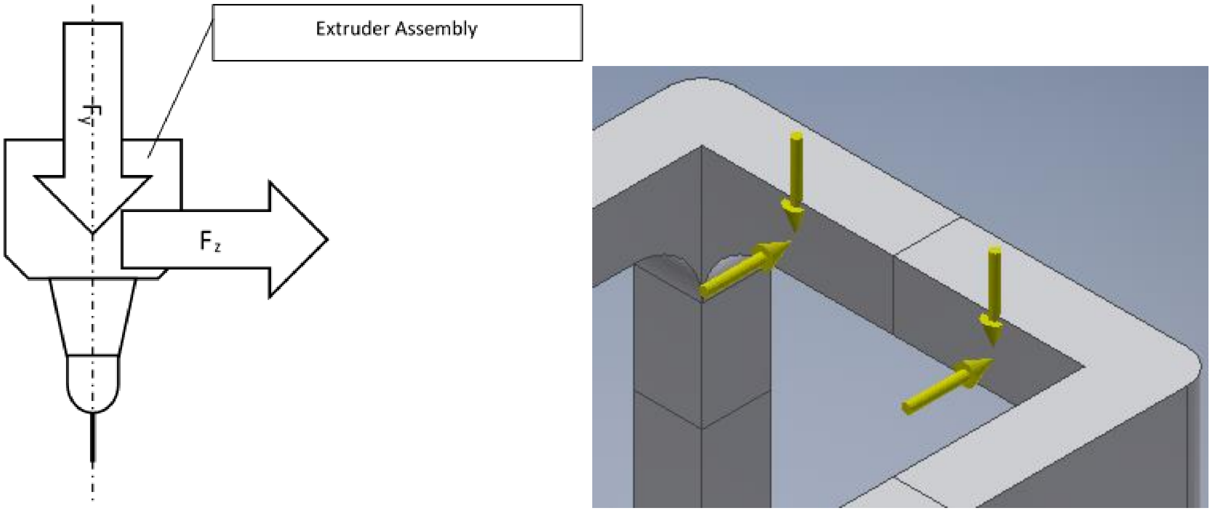


Figure 5 Forces applied to the frame

According to Newton's second law, a reaction force of F_z = 1.96 N is calculated while the extruder head assembly is changing the direction.

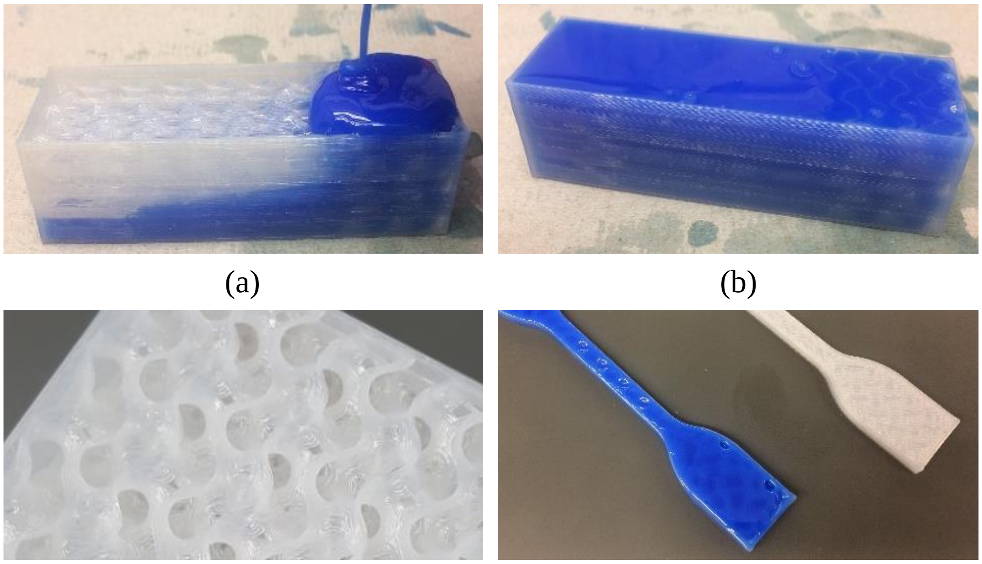
The stress distribution (Figure 7) and the maximum deformation (Figure 8) of the beam cross-section where the force is applied to the frame are examined. The maximum deflections and stresses calculated by the FEM simulations of the different infill densities in cross-section are listed in (Table 2).

Table 2 Maximum deflection and stress for different infill parameters

Infill density & Material	Max. Deflection [mm]		Stress [MPa]			Safety factor
	Z	Y	Von Mises	ZZ	YZ	
100% Infill ABS	0.0024	0.0004	0.007	0.006	0.002	15
15% Infill ABS	0.0085	0.0059	0.077	0.076	0.024	15
0% Infill Epoxy Composite	0.0010	0.0004	0.087	0.084	0.013	15

Additional Composite Infill Options

Different infill structures have been designed that will help the composite filling process. One of the structures is the gyroid infill pattern. A gyroid lattice is an infill option in the slicer Slic3r. This infill structure generates a structure with curves and holes that allows fluids to easily flow around the lattice inside the 3D printed part. Even very viscous fluids can flow and fill the part if the infill density correctly selected (Figure 6). In this study, a high impact polystyrene (HIPS) slurry has also been used in an attempt to fill the frame structures to absorb vibrations from printer motion, and stepper operation.



(a) (b)

(c) (d)

Figure 6 (a-b) High impact polystyrene (HIPS) slurry filling process (c-d) gyroid infill test specimen before and after the filling of the HIPS matrix.

HIPS slurry is the result of dissolving HIPS in D-Limonene. Over time if left in the open air in a container, this saturated solution of HIPS in D-Limonene will thicken into a viscous fluid as the limonene evaporates. This slurry will harden given enough time, and heat if needed. This combination of HIPS slurry and gyroid infill pattern will allow for reusing an otherwise wasted residue of support material into a useful component in stronger 3D prints.

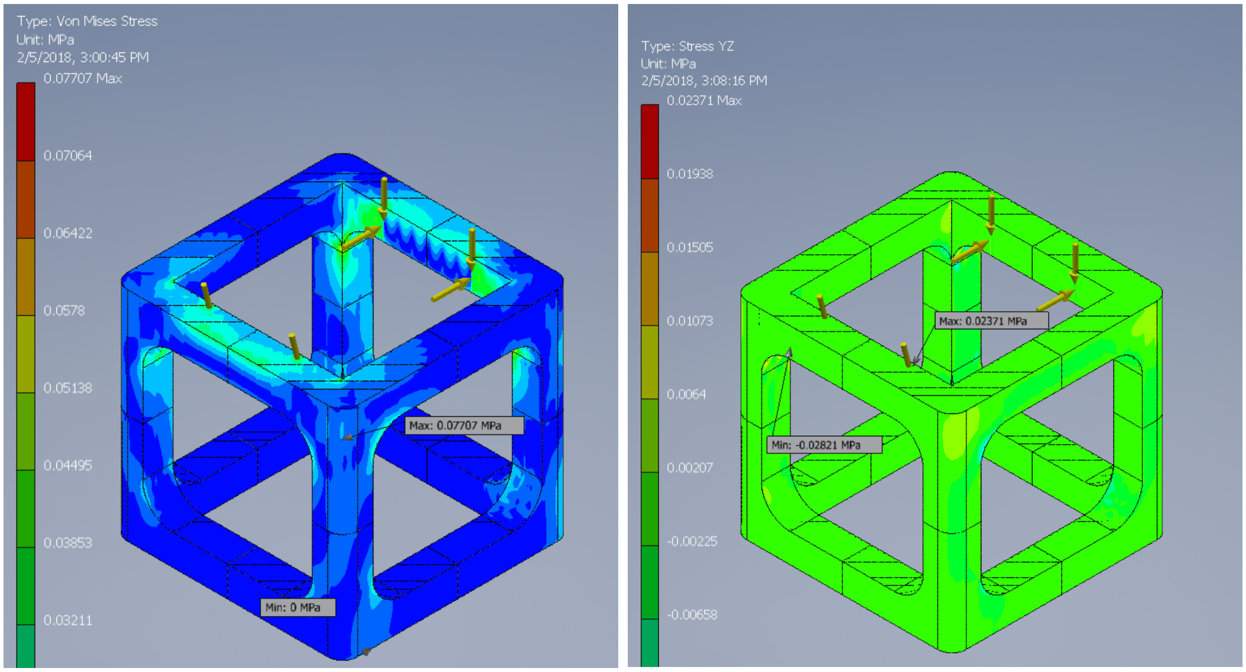


Figure 7 Stress Distributions

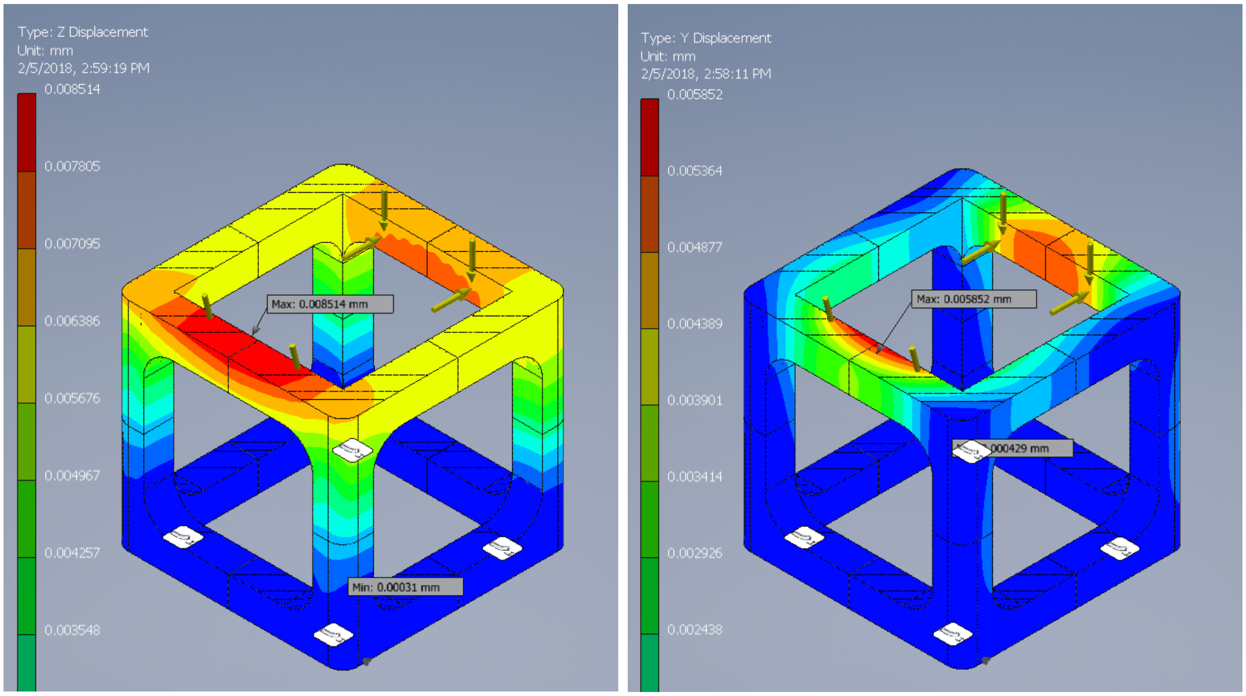


Figure 8 Deformations in Z- and Y- directions

Conclusion

A frame for a 3D printer is redesigned for composite material and additively manufactured. The hollow cross-section of the frame has been enforced by injecting the epoxy fiber composite. Composite FDM machine frames have several distinct advantages over entirely printed frames. Completely hollow parts print much faster than parts with infill and use much less print material. As a result, a hollow frame structure can be printed in half the time, using much less material than what would be required for similar frames with infill. The hollow shells can be filled with a thermosetting epoxy, and cured, to make a more rigid frame than printing the entire structure. On average, printing hollow shells of printer frame components took 60% less time to print, and saved on average 40% more print material than printing with 15% infill. If the tests were to be re-run, different frame co-polymers would be chosen such as PLA or PETG. Different frame designs would also be used, such as with a circular frame shape, or triangular cross sections. The ratio of shell thickness to the volume and shape of the hollow for epoxy resin will be analyzed in a further study. The gyroid infill is another parameter that will be examined in further detail for use in composite parts, as opposed to printing a part hollow.

References

[1] B. P. Conner, G. P. Manogharan, A. N. Martof, L. M. Rodomsky, C. M Rodomsky, D. C. Jordan, & J. W. Limperos, (2014). Making sense of 3-D printing: Creating a map of additive manufacturing products and services. Additive Manufacturing, 1, pp.64-76.

[2] M. K. Niaki, & F. Nonino, (2018). Selection and Implementation of Additive Manufacturing. In The Management of Additive Manufacturing, Springer, Cham, pp. 193-220

[3] I. Jasiuk, D. W. Abueidda, C. Kozuch, S. Pang, F. Y. Su, & J. McKittrick, (2018). An Overview on Additive Manufacturing of Polymers. JOM, pp.1-9.

[4] M. Martin-Gallego, V. Yuste-Sanchez, R. Sanchez-Hidalgo, R. Verdejo, & M. A. Lopez-Manchado (2018). Epoxy Nanocomposites filled with Carbon Nanoparticles. The Chemical Record, 18, pp.1-13.

[5] Y. Wang, Z. Gu, L. Song, T. Li, H. Cui and F. C. M. Lau, "Speeding up 3D Printing Using Multi-Head Slicing Algorithms," 2017 5th International Conference on Enterprise Systems (ES), Beijing, 2017, pp. 99-106.

[6] M. S. Alsoufi, & A. E. Elsayed (2018). Quantitative analysis of 0% infill density surface profile of printed part fabricated by personal FDM 3D printer. International Journal of Engineering & Technology, 7(1), pp.44-52.

[7] M. Yourdkhani, W. Liu, S. Baril-Gosselin, F. Robitaille, & P. Hubert (2018). Carbon nanotube-reinforced carbon fibre-epoxy composites manufactured by resin film infusion. *Composites Science and Technology*.

[8] P. R. Wilson, A. F. Cinar, M. Mostafavi, & J. Meredith (2018). Temperature driven failure of carbon epoxy composites–A quantitative full-field study. Composites Science and Technology, 155, pp.33-40.

[9] Sangermano, M., D'Anna, A., Marro, C., Klikovits, N., & Liska, R. (2018). UV-activated frontal polymerization of glass fibre reinforced epoxy composites. *Composites Part B: Engineering*, *143*, pp.168-171.

[10] L. Yue, A. Maiorana, F. Khelifa, A. Patel, J. M. Raquez, L. Bonnaud, & I. Manas-Zloczower (2018). Surface-modified cellulose nanocrystals for biobased epoxy nanocomposites. *Polymer*, *134*, pp.155-162.

[11] H. C. Kim (2018). Mechanical Properties Assessment and Reliability Verification for FDM 3D Printed Products, Ms. Thesis. Graduate School of UNIST.