Increasing Material Efficiency of Additive Manufacturing through Lattice Infill Pattern

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(**Received** 22 March 2019; **Accepted** 27 June 2019; **Published on line** 1 June 2020)

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DOI: 10.5875/ausmt.v10i1.2140

Abstract: Fused Deposition Modelling (FDM) is one of the widely utilized technology of low-cost 3D Printing. It uses plastic filament as material for Additive Manufacturing. To lessen the amount of filament consumption of the prints, modification of the infill patterns was conducted. This study focuses on the introduction of new infill pattern – the lattice infill to increase material efficiency of 3D prints, compared to conventional infill patterns. Benchmark designs such as the grid and cubic infill pattern were first created by the 3D printer slicing software. The proposed lattice infill design was created using a CAD software and rendered as STL file for compatibility with the slicing software. The three infill patterns were simulated in the slicing software to measure approximate product weight and the proposed design is simulated in an engineering simulation software to determine the stress performance and displacement when an external force is introduced. Results showed that the new infill pattern saves material up to 61.3% compared to conventional infill patterns. In effect, it increased the amount of prints produced per spool by 2.5 times. It is also found out that the lattice infill pattern print can resist to up to 1.6kN of compressive load prior to breaking.

Keywords: Additive manufacturing; Infill; Lattice.

Introduction

Additive Manufacturing (AM), also known as 3D printing, creates physical three dimensional objects from virtual computer aided design through successive addition of material without using any particular tooling. This is in contrast to conventional subtractive manufacturing which creates 3D structure by material removal. Additive manufacturing has the advantage in rapid prototyping and manufacturing, production of spare parts, small volume and very complex work pieces. It allows the rapid creation of sustainable objects and has been utilized to fabricate lightweight parts to save cost, speed, quality and impact [1].

Moreover, additive manufacturing has been using infill patterns as weight reduction of the print. It is made by using cellular materials with a regular and periodic microstructure [2]. The term infill refers to the interior structure of an object that is printed. The infill often has a regular structure, which is selected by the user in the slicing software along with a specific volume percentage. The infill pattern and volume percentage significantly influence the printing process as well as physical properties of the printed object. While a higher volume percentage leads to a more resistant print, it also consumes more material and prolongs the print time [3]. Among several types of infill, the grid (also called rectangular) infill pattern is the most common and general purpose pattern being used by designers [4].

Fused Deposition Modeling (FDM) meanwhile, is one of the most productive technology typically used in low-cost 3D printers. In this method, a plastic filament is pushed through a heated extrusion nozzle melting. This is done as soon the software processes an STL or CAD (computer-aided design) file, then mathematically slicing and orienting the model generating GCODEs, and finally running the generated GCODEs through the printer before printing begins [5]. This method contrasts another widely known AM method, the SLA (stereolithography) process which is characterized by printing layer by layer using photo-polymerizable liquid resin through ultraviolet light [6].

FDM printers primarily use two specific plastics, namely Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). However, one challenging factor of using FDM technology is the costly price of the plastic filament. This filament material is being inflated in the market by providing a huge markup over the cost of the plastic pellets used in making such filaments [7]. These filaments are available the market in terms of spools, which weighs approximately a kilogram each.

The amount of plastic filament consumption plays a huge effect on the over-all cost of producing a print. Likewise, the type of infill design influences the filament consumption of the print. With that, a need for conceptualizing a pattern that will require less filament material arises; which in effect will lessen the cost needed for a print and increase the number of prints in a single spool.

Researchers from Huazhong University in China conducted a study that utilizes the concept of Topology optimization, specifically the Level Set Method (LSM) [8]. Topology optimization is a design process wherein it determines the optimum balance between weight reduction and structural integrity. The objective of the study was to present a multiscale topology optimization method capable of providing the optimal shell layout and infill pattern by defining the parameters for shell thickness and infill density. The researchers used beams and trusses as their experimental design for the optimization. Simulating the method on the experimental designs, it was concluded that the method was effective for both 2D and 3D models. While this method provides a mathematical model for concurrent optimization of the shell and infill, the approach focused on the microstructure of the infill. This sets the limit for method's application only for compliance minimization.

A new approach in combining structural and optimization techniques is presented in the study of Wu, et.al in 2018 [3] wherein the infill pattern used is based from the structure of the bone. The basis of this study is the Wolff's law [9] which states that that bone grows and remodels in response to the forces that are placed upon it. As a result of this natural adaptation, micro-structures of trabecular bone are aligned along the principal stress directions. The resulting composition is lightweight, resistant, robust with respect to force variations, and damage-tolerant [10, 11]. This makes the optimized interior structures an ideal candidate for application-specific infill in additive manufacturing. While this approach is effective in lessening the object weight, the resulting infill lacks uniformity of pattern around its shell. This is because as the volume limit is being decreased, porosity in the infill region surrounding the shell is increased. While it is applicable to slender shapes like bones, challenge of sturdiness can be ascertained once used on shorter or equidistant shapes.

This paper presents a new and innovative infill pattern design that will increase material efficiency of additive manufacturing using FDM technology and offers permissible rigidity like that of a typical print. Validations are utilized to measure its effectivity while simulations are employed to determine the strength of the proposed design.

Infill Design Development Concept

The term ''lattice" in mathematics usually refers to a group of points whose positions follow a predefined pattern. Based on the pattern, a network that represents the connections of points can be obtained [12].

In the past decade, with the advances in innovative constructional technologies and high-strength materials, the steel lattice structure has been increasingly incorporated in the construction practice of high-rise and spatial steel structures such as power transmission towers and long-span.

In a separate research [13], the lattice girder was introduced to overcome the weakness of H-shaped steel ribs, and its geometric characteristics significantly reduce the possibility of an internal gap. The flexural stiffness and strength of lattice girders have been studied via analytical and experimental methods, and its structural benefits were widely recognized.

A new design for infill pattern is proposed in this paper called the lattice pattern which aims to save material consumption in 3D printing. The design is called lattice since the structure mainly focuses on the edges of a cube forming a lattice-like pattern inside the model

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(Figure 1). This concept was engendered by the design concept of steel structures, whereas a typical steel structure design would consist of a combination of columns, beams, and girders subjected to compressive loads in hundreds of metric tons while it can be considerably hollow inside. Likewise, since steel structures serve as the skeletal system of a structure, the lattice pattern will similarly serve as the skeletal framework of the model.

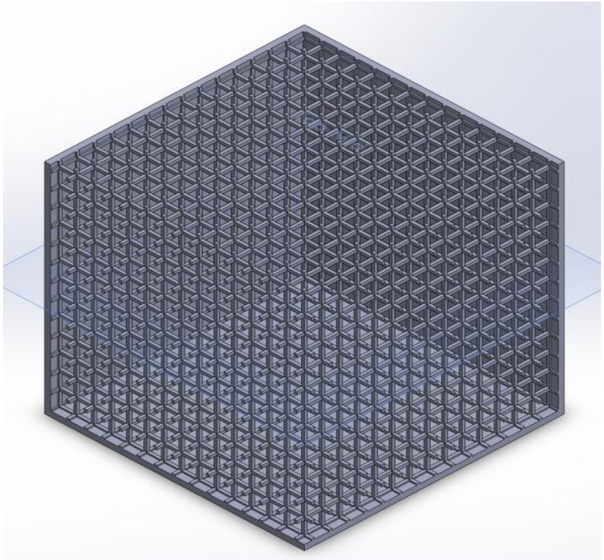


Figure 1. Zoom-out view of the lattice pattern.

Printer slicer softwares like Cura® introduce a number of pre-loaded infill patterns where designers choose. Some of which are: Grid, which is a grid shaped infill with lines in both diagonal directions on each layer; Lines, which creates grid shaped infill but printing in one diagonal direction per layer; Triangles which creates a triangular shaped infill pattern; Cubic, which is a 3D infill of tilted cubes; Tetrahedral, which comprises of 3D infill pyramid shapes; Zig Zag which is also a grid shaped infill but printing continuously in one diagonal direction; and many others [14]. But all of these built-in pattern designs are printed horizontally by layers on top of each other thus creating vertical faces, which in effect consumes a lot of plastic material to construct.

Meanwhile, the studied lattice pattern being used in construction industry for their steel structures do not require vertical faces, while still maintaining the pattern's rigidity.

Figure 2 (Lattice Infill Pattern) details the steel structure used in the construction industry which is used as an inspiration for the proposed lattice infill structure. It is noticeable that the adopted design was slightly altered by making the beams consisted in profile, with even spaces and supporting beams removed as a requirement for an easy layer slicing. This structural-like pattern was used to function as the infill pattern for 3D printing.

Methodology

Figure 3 detailed the methodology used in conducting this research. It focused on three parts: two design phases, two simulation phases and one evaluation phase.

The design phase consisted of two components: defining of benchmark infill pattern parameters and designing of proposed infill pattern. For consistency and due to its simplicity, all patterns are designed to make a 100mm x 100mm x 100mm cube print. ABS filament is

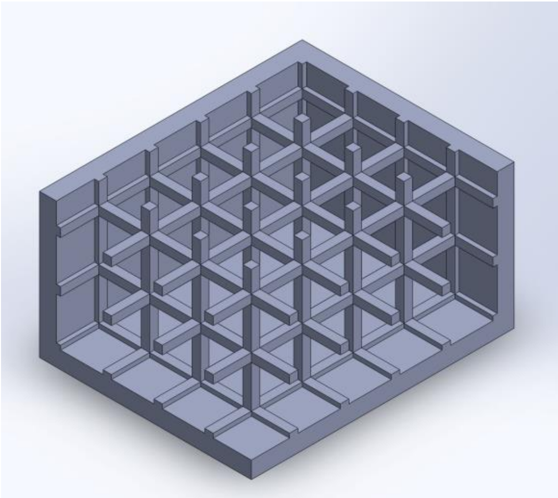


Figure 2. Lattice Infill Pattern.

used as material for 3D printing as it is one of the most commonly used filaments by users.

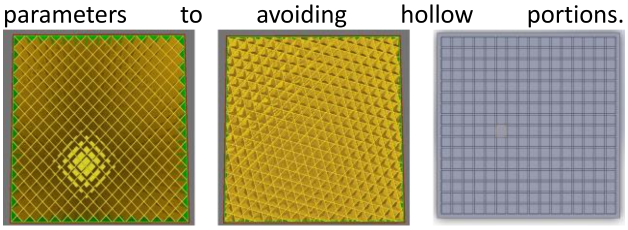
The study is initiated by defining benchmark parameters allowing the researchers to compare and analyze the obtained data and performance of the proposed design with respect to the reference data sheet. The researchers decided to use the grid infill pattern to serve as the benchmark infill pattern, since this is commonly used by 3D Printer users. The cubic infill pattern is also utilized in this study for additional validation. Parameters are set to 5 mm infill line distance with 250 microns of layer thickness for the infill, and a shell thickness of 2mm for the cube surfaces. Testing and simulation of both benchmark and proposed using Lulzbot Cura® printer slicing software.

Figure 4 presented the zoom-in view of both the grid (a) and cubic (b) infill patterns. Differences of the two is difficult to ascertain at a glance, but noticeable on the edges. Uneven triangles are seen on the edges of cubic pattern model, while equilateral ones are surrounding the grid pattern model. This is due to the design of the cubic pattern, wherein it utilizes tilted cubes.

Meanwhile the design of proposed lattice infill pattern is constructed using Solidworks® 3D design software. The researchers used an infill layer thickness of 1 mm and the same infill line distance parameters that of benchmark designs. The lattice infill assumed a layer thickness of 1mm due to slicer limitations of it being unable to print solid parts less than 0.75mm. After designing, the proposed design is then exported as an STL file extension for compatibility with Cura® software. Figure 3c illustrated the top view of lattice infill design. As compared to the other models, the proposed design is composed of squares drawn perpendicular to the edges, unlike the other two, which were drawn diagonally to their respective edges.

The simulation phase meanwhile, is composed of two components: the printing simulation and the impact force simulation.

Printing simulation is done using Lulzbot Cura® printer slicing software. Since the two benchmark patterns were originally created using the same software, no further configuration was needed. Meanwhile, since the proposed lattice infill design was created and exported from another software, a 0% infill configuration to Cura® Slicer software was needed. This is done to remove any infill influences since the design accounts for the other parameters to avoiding hollow portions.



(a) (b) (c)

Figure 4. Top view of grid (a) and cubic (b) patterns as benchmark infill models to the proposed lattice infill design (c).

Moreover, impact force simulation was done using Solidworks® Engineering Simulation & 3D Design Software. This is to determine the contribution of the infill to the durability of the model. As per the technical data sheet [15], ABS can withstand up to 139N of impact force. Hence, the simulation began by subjecting the model to 139N compressive load. The load was applied on one side, while the opposite side served as a fixed point. Since the design model is uniform in shape, it is assumed that the exhibited behavior of compressive load tests is the same all throughout. Additional simulations are done with relevant increments of compressive loads until the model is near breaking point. This simulation is done only on the proposed lattice design so as to determine if the model can exhibit the same performance as determined by the technical data sheet and by how much it can resist up to near breaking point.

Evaluation commenced after simulations. The formula below was used to determine the number of prints per spool each models can considering their respective weight:

$$N_{prints} = \frac{W_{spool}}{W_{model}} \quad (1)$$

where N_{prints} denotes the estimated number of prints per spool each design model can produce, W_{spool} pertains to the weight of a spool of filament, which is approximately 1 kilogram, and W_{model} is the weight of the product of each models acquired from the slicer software. The measurement is used to determine if increasing material efficiency is enough to yield to additional prints.

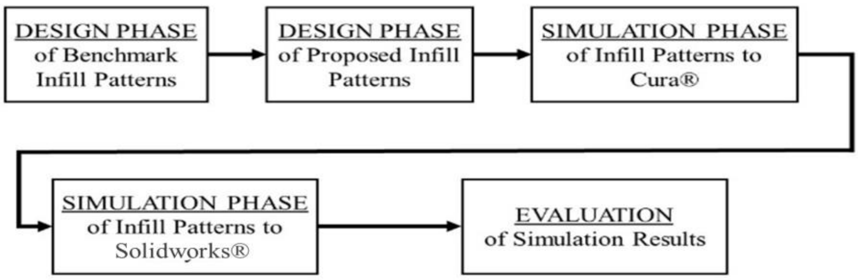


Figure 3. Flow chart of the research methodology

Meanwhile, the gathered data for weight of each design is also used to compute efficiency in terms of the percentage of materials saved with respect to the benchmark model using the formula below,

$$\%materials\ saved = \left(1 - \frac{W_{proposed}}{W_{benchmark}}\right) x100 \quad (2)$$

where $W_{proposed}$ is the weight of the lattice infill pattern design and $W_{benchmark}$ is the weight of the benchmark infill pattern design.

Results from compressive force simulation were evaluated in terms of the ratio between the experienced maximum pressure on a simulated compressive load over ABS standard stress capacity from Makerbot of 1100psi (or 7584 KPa). The standard (STD) stress capacity data is used in this study since the STD stress capacity is defined in [16] as the printed output possessing a standard resolution with infill influences, which is this study is all about. This to determine about how much percentage the model is near breaking point. The proponents utilized this data from Makerbot's Technical Datasheet [16] as the baseline data since the company is a well-known manufacturer of quality filaments used in FDM printing.

Results

Grid Infill Performance

The data from printing simulation of grid infill pattern served as the benchmark of the study. The grid infill pattern, as shown in the Figure 5, marked yellow, would consume around 298g of material as mentioned in the slicer software outlined in red. The standard weight of one spool of filament is 1kg, though there are variations as made by manufacturer. For the sake of comparison, the researchers use the 1kg as the baseline. With this information, around 3 cubes can be printed with the given specification.

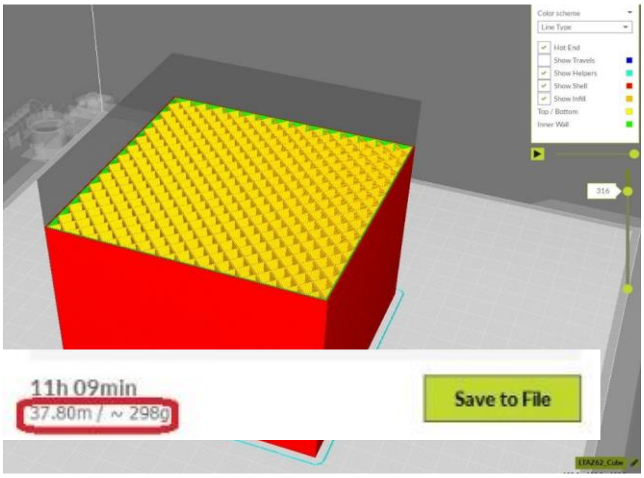


Figure 5 Grid Infill Pattern Results.

Cubic Infill Performance

The cubic infill pattern is used in this design as additional benchmark model since this pattern is also starting to gain popularity for novelty purposes. The cubic infill pattern as show in Figure 6, marked yellow, consumed around 416g of material; which leads to a maximum of 2 prints of cube per 1kg of spool. This infill pattern shows that it needs 39.5% more material than the grid pattern.

Note that the Cubic Infill Pattern can be made efficient by manipulating infill line distance, so that it can obtain the same efficiency as compared to the grid pattern. The same can be concluded with the proposed design to achieve better efficiency. For consistency, the researchers defined the infill line distance of 5mm for all patterns for comparison.

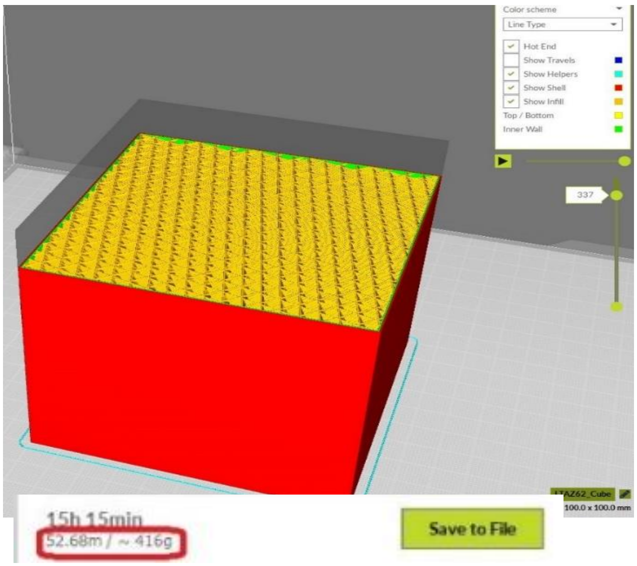


Figure 6. Cubic Infill Pattern Results.

Lattice Infill Performance

The lattice infill pattern is the proposed design of this paper. The lattice pattern would consume 198g of material to print a cube. In effect, this result allows 5 cubes to be printed with 1 kg spool. This pattern saves up to 33.5% of material consumption compared to the grid pattern and 52.4% material consumption compared to the cubic pattern.

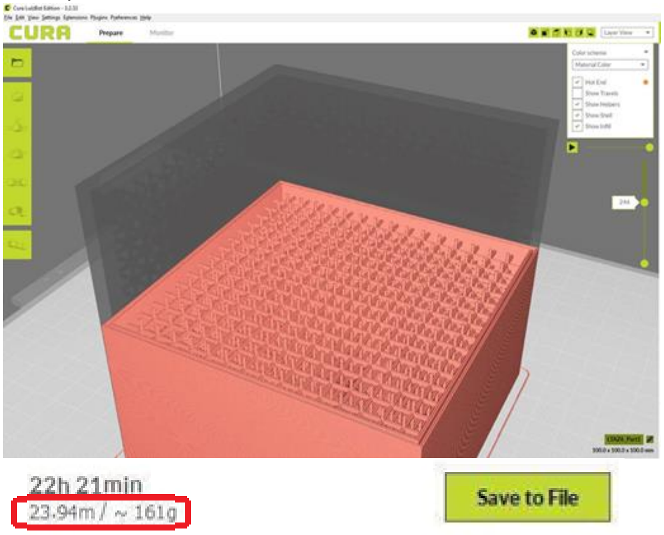


Figure 7. Lattice Infill Pattern Results.

Stress Simulation Analysis

Table 1 shows the complete results gained from this simulation. At 139N, the model is subjected to a pressure of 559 kPa which is 7% of the allowable pressure of the material specification with a displacement 0.018mm. Load Stress and Displacement Analysis at 139N are illustrated in Figures 8 and 11 respectively. The colors indicate the amount of pressure or displacement is experienced in the area, Figure 8 shows a color of blue around the cube, suggesting that the blue sections are experiencing an average of 47 kPa. Meanwhile, Figure 11 shows a variety of colors suggesting that a particular section is experiencing varying displacements. The blue section around the edges of the top surface is experiencing a displacement between 1.508 µm to 3.015 µm, the green area is experiencing an average displacement of 9.045 µm, and in the center marked as red is experiencing an average displacement of 0.018 mm. The simulation also determined that a maximum pressure of 7572 kPa is experienced by the model, which is significantly close to the standard stress capacity dictated by Marketbot, upon an application of a compressive load of 1.6kN. This suggests that the lattice infill design is capable of holding up to 1.6 kN or a mass up to 163 kg prior to breaking. The Load Stress and Displacement Analysis for 1.620kN load are illustrated in Figures 9 and 10 respectively. Figure 10 suggests that the cube is experiencing a maximum displacement of 0.212 mm at the red area.

Table 1. Stress Performance Analysis

Compressive Force Load (N)	*Max Pressure Experienced in Model (kPa)*	*Makerbot STD Stress Capacity (kPa)*	*Percentage Experience Pressure over Max Pressure*	*Displace-ment (mm)*
139	559	7584	7%	0.018
150	604	7584	8%	0.0194
200	805	7584	11%	0.0259
500	2320	7584	31%	0.065
1000	4640	7584	61%	0.13
1632	7572	7584	100%	0.212

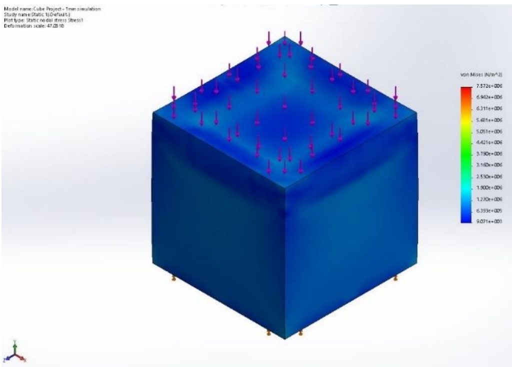


Figure 8. 139N Load Stress Analysis.

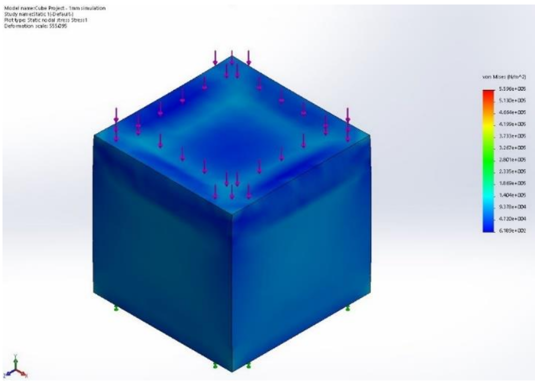


Figure 9. 1.620kN Load Stress Analysis.

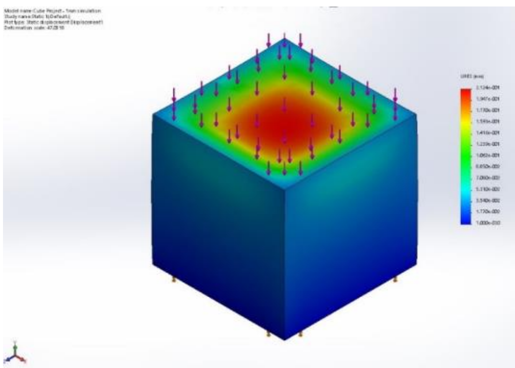


Figure 10. 1.620kN Load Displacement Analysis.

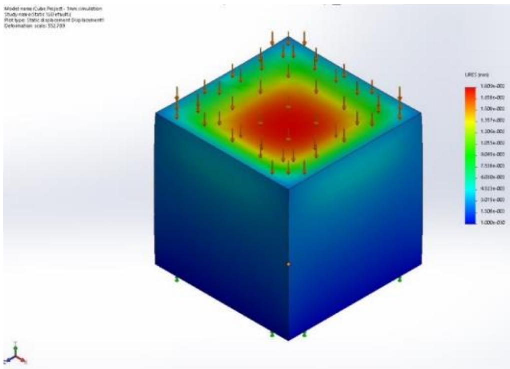


Figure 11. 139N Load Load Displacement Analysis.

Printing simulation results

One of the features of Lulzbot Cura® is the estimation of the material consumption and printing time displayed in the software's graphic user interface (GUI) after the simulation. These data were acquired, tabulated. Moreover, the data for number of prints was computed using Formula (1) detailed in the methodology.

Table 2. Summary of printing simulation results

Infill Pattern	***Material Consumed***	***Estimated Printing Time***	***Number of Printable cubes based on 1kg spool***
Grid	298g	11h 09min	3
Cubic	416g	15h 15min	2
Lattice	161g	22h 21min	6

Table 2 summarizes the results of printing simulation. The data is further evaluated in the succeeding subsection.

Evaluation

Table 1 shows the data on various applied compressive force loads and the respective maximum experienced pressure of the model which were obtained from the simulation. This was done to determine how much force and mass can the model withstand with respect to the pressure it develops in the model. The obtained pressure values which were compared to the STD stress capacity showed that the model can withstand 1.6 kN. This can be interpreted that the model can withstand a mass up to 163 kg or 359 lb_{mass} prior to breaking.

Table 2 and Figure 12 both detailed the comparison of two benchmark infill pattern designs and the proposed design in terms of material consumption and duration of print. The grid and cubic infill patterns weighs heavier than that of the proposed design. In effect, the proposed design can produce more prints than the two benchmark designs as detailed in Table 2 and Figure 13.

Using Equation 2 of the methodology, it is computed that the Lattice infill pattern can save up to 45.97% of material as compared to the grid, and 61.3% of material as compared to the cubic. Both data exceed the research objective of 25% reduction of material consumption.

While the data proves that there is practicality in the proposed infill design, it is also noticeable that the lattice infill has longer printing time than the other two. The lattice infill needs at least extra seven hours of printing as compared to that of the benchmark infill patterns.

The lengthy printing time of the proposed design is mainly due to the need for multiple passes in achieving the required thickness of the infill. The nozzle diameter is one main factor for printing the infill. The process of printing the infill of a model is through a single pass per layer from point A to point B. With those considerations, the printing time of the infill is faster than the outer shell of the model since the outer shell would require multiple passes before shifting to the next layer. The layer width of the infill will always follow the specified layer thickness up to a maximum of the nozzle diameter, and the standard nozzle diameter is between 0.4 mm to 0.5 mm. The lattice infill assumed a layer thickness of 1mm due to slicer limitations of it being unable to print solid parts less than 0.75mm. The slicer treated the 1mm infill layer thickness specified in the design as a solid part, requiring it to have multiple passes to fulfill the required thickness before shifting to another layer resulting to a longer printing time as compared to a regular infill pattern.

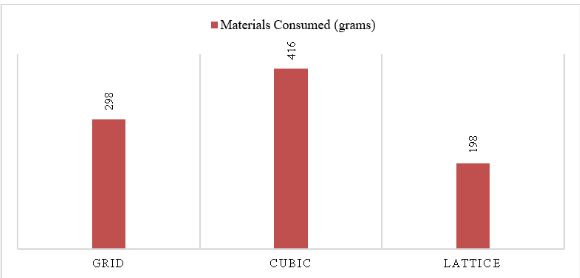


Figure 12. Materials Consumed (in grams).

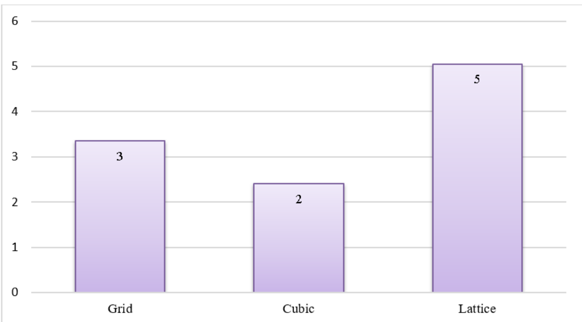


Figure 13. Number of Printable Cubes based on 1kg Spool.

Conclusion

This paper described a new designed lattice infill pattern that effectively increased the material efficiency of additive manufacturing. The lattice infill pattern is designed using Solidworks® and rendered using STL file extension and is reconstructed together with the pattern's shell using Cura®. Cubic and Grid infill designs which are designated as benchmark where the proposed design is compared to, is created using Cura®.

The proposed design saves from 45.9-61.3% of the material consumption compared to benchmark infill patterns. Weight is used as reference of consumption comparison deduced in the simulation of designs to Cura®.

The lattice infill design subjected to benchmark parameters can withstand up to 1.6 kN of compressive load or 163 kg prior to breaking when the proposed design infill pattern is applied. The data was acquired and analyzed through simulations of the design to Solidworks® and comparing it to the reference datasheet of ABS material given by Makerbot.

Moreover, the proponents recommend further research on the efficiency of material consumption which also considers the total printing time needed by the proposed infill design, and possible optimization solutions to at least make it on par to the time consumption of the benchmark infill patterns utilized in the study.

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