Manufacturability Analysis of Strut Lattice Design Using PLA-based Composite Material

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ABSTRACT

Additive Manufacturing (AM) revolutionizes conventional manufacturing in the aspect of design complexities. Currently, 3D printing lattice structure is gaining attention due to its lightweight properties. Unfortunately, studies on the characterization and mechanical properties of AM composite lattice are still limited due to the insufficient availability of design rules for the lattice-development. Therefore, this study aims to perform a manufacturability analysis of strut-lattice design, in assisting the development of design rules for Fused Deposition Modelling (FDM) technique. Four types of strut-lattice consisted of square, circle, triangle, and octagon strut were designed and fabricated using carbon fibre PLA (CF-PLA) and Wood-PLA. The fabricated strut-lattice was inspected, evaluated, and compared with Virgin PLA based on the pass and fail criteria. The result showed that all of the composite and Virgin PLA parts were successfully fabricated when the strut sizes higher than 2.00 mm. It is anticipated that this study provides a guide to develop a set of new design rules focusing on lightweight structures and bring inspiration to the development of a range of lightweight-high strength mechanical applications.

Keywords: *3D Printing, FDM, Lattice printing, CF-PLA, Wood-PLA,*

1.0 INTRODUCTION

Additive manufacturing (AM) is a revolutionary technology over the subtractive manufacturing process due to its efficiency of the process where complex parts can be fabricated using layer by layer techniques. It consists of four pillars of manufacturing complexities as compared to subtractive manufacturing which includes design complexity, functional complexity, hierarchical complexity, and material complexity [1]. Design complexity is the major advantage of AM because the process can produce complex structures without any additional tooling and cost for manufacturing [2]. Therefore, the complex parts such as lattice structure have been widely used in many research because it offers a lightweight design with high strength and efficiency [3]. The lattice structure is a type of cellular structure that is used widely in an application that requires a lightweight function, ranging from consumers, aerospace to the construction industry [4]. Recently, the use of lattice structures has become more prominently in the industry especially with the advancements in AM process to achieve four major goals which are, to reduce the amount of material used in the manufacturing process, reduce the amount of time taken to produce the product, reduce the amount of energy used in the manufacturing process and optimize the strength of the product with minimizing the weight of the product [5]. With the above-mentioned benefits of lattice structures, AM was often more preferred as a manufacturing alternative because it allows for the creation of structures with great accuracy and mechanical properties, especially when fabricated using a laser-based technique such as selective laser melting (SLM) [6]. Besides the SLM technique, another technique such as Fused Deposition Modelling (FDM) using material extrusion and continuous liquid interface to produce the lattice structure was also being discussed in the literature [4][7].

Previously, before AM was introduced, lattice structure was made using traditional manufacturing methods such as investment casting [8], 3D weaving [9] and traditional topological optimization that requires multiple post-processing techniques to be conducted [10]. Even though producing the lattice structures using the traditional method was time and material consumption, the lattice-quality produces was found better than the lattice produced using AM technique in terms of material stiffness and strength. The main reason for the significant loss of material stiffness and strength when using AM is its inherent process of additively layer manufacturing that leads to layer separations (delamination) which producing gaps and cause the printed part easily to be broken [11]. Especially when using material like poly-lactic acid (PLA), it increases the possibility of delamination and warping effects on the process. Therefore, recently, composite materials were introduced to solve the defects of printed parts especially on the aspect of mechanical strength [12]. The composite material is made up of reinforcement with particles to virgin polymers such as carbon fibre, wood fibres, and metal fibres to enhance the printed part strength and aesthetic appealing [13]. In addition to the AM-featured lightweight design in AM, Kessler et al. [14] has described that the product-oriented of lattice structure is made more difficult because the growing demand of lattice usage in industry is increasingly demanding. Therefore, in order to cater the demand, designers tend to do trial and error experiments before achieving the ideal results of their printed part because dealing with composite filament can be troublesome especially for inexperienced user. Consequently, higher material wastage was produced from the unsuccessful fabrications and consistently testing. Thus, in this study, the manufacturability of four composite-strut lattice designs (square, circle, triangle, and octagon strut) using carbon fibre PLA (CF-PLA) and Wood-PLA was investigated. The proposed procedure is useful for the assessment of composite lattice defects and deterioration analysis. The findings from this study are useful for the development of a design rule for lightweight structures, especially on lattice productions.

2.0 LATTICE PRINTING IN ADDITIVE MANUFACTURING

The design of multi-scale structures is one of the AM abilities that differ this technology from conventional manufacturing. The ability includes producing free-form surfaces and complex inner structures in high resolutions [15]. Due to these unique capabilities, building multi-scale range structures such as microscale, mesoscale, and microscale is even trivial. For example, building micro-scale objects with the production of micro and nano-scale feature is very challenging in some processes, but it is still a promising topic to discuss. It would even wider the uses of AM technology for the application such as sensors, biomedical, and scaffolds. According to Yunlong et al. [1], microscale design contains a feature size below 0.1mm, meanwhile, the mesoscale design contains a feature size between 0.1mm to 10.00mm. Lastly, a feature that is more than 10.00mm falls under macroscale design. Thus, for this study, the mesoscale design is adopted because the lattice feature size was designed in between the narrated size of the group. On a mesoscale design, lattice structure in general is widely discussed to achieve excellent performance and have multi-capabilities even while the weight is reduced. The study was also discussed by Gibson and Ashby [16] which they described that the lattice structures can provide good energy absorption characteristics and good thermal and acoustic insulation properties. However, previously, the lattice structure is almost impossible to manufacture especially when it involves the design like gyroid which have lots of curve and curvature. Some technology such as investment casting and 3D weaving was used to manufacture lattice, but the manufacturing cost was higher and the lead time to produce the structure took ages. Therefore, several alternatives were investigated to produce the lattice structure with a great combination of easy to manufacture and low-cost production using AM.

The earliest findings of lattice study in AM were investigated by Iyibilgin and Yigit [7] fabricated by FDM technique using standard polymers, Acrylonitrile Butadiene Styrene (ABS) filaments. Five different lattices such as honeycomb, square, diamond, triangle, and circle were designed with sparse and sparse-double dense builds. Compression testing was performed to find the strongest and best compression properties of lattice design among the five proposed structures. The results showed that the honeycomb design produced a compressive modulus of 286% higher than the sparse-double dense build and 579% higher than the sparse build. This was strongly supported by the finding from Davis et al. [4] where the strength of honeycomb lattice can be increased by increasing its wall thickness. The wall thickness varied by 0.35mm to 0.50mm. However, they performed the analysis using the continuous liquid interface production (CLIP) method. Varying the wall thickness means varying the strut of the lattice. Generally, a lattice contains a unit cell with strut, nodes, and beam. Strut is a very important feature in lattice because it determines the strength and manufacturability of successful lattice fabrication. The investigation of lattice strut geometry was investigated by Denzik [17] and it was found that the thicker strut produced a higher tensile strength value.

In FDM, the process to produce the lattice structure is tricky because the structures consist of thin walls, overhangs, bridges, and angles which lead to the bad quality of printed lattice. Therefore, to overcome this issue, the researcher investigates the influence of parameters of the FDM process on lattice structure using process parameter optimization [18]. For example, Dong et al. [18] performed the optimization approach using Taguchi methods to optimize the process parameter in product design through comprehensive experimental investigation. The experiment involves sixteen runs of experiments using the orthogonal array (L16). Three parameters include temperature, print speed, fan speed, and layer height to find optimum parameter combinations that have better compression testing. The signal-to-noise ratio (S/N) of thickness value was calculated by the lower-the better formula. The results showed the optimal parameter that contributed to the better quality of lattice printed parts were layer thickness (0.10 mm), fan speed (50%), and higher print speed (1200 mm/min). These results were also supported by the findings from Mazlan et al. [19] where it was found that the layer thickness also contributed to the higher compression force of the printed lattice. The findings of lattice structure fabricated using FDM were also discussed by Egan et al. [20] where the lattice structure with the dimension of 18.8 mm x 18.8 mm x 18.8 mm octagonal cross-section was fabricated using biocompatible material such as titanium [21]. Various layer thicknesses were used which consist of 0.4 mm, 0.6 mm, 0.8 mm and 1.00 mm for the parameter settings. The results showed that the stiffness of the lattice structure was increased when the layer thickness was increased. However, since the material used is biocompatible, therefore the printed lattice needs to be stored in the support materials. It was found that the stiffness of the lattice dropped over time which was caused by the water absorption or part deterioration.

Another study that used FDM to print the lattice structure was conducted by Ishak et al. [22]. The cubic lattice was designed with a 20 mm x 20 mm x 20 mm cube fabricated using PLA. Each unit cell is designed with a cube of 5 mm x 5mm x 5mm. For the experiments, the temperature of 220ºC was used and the printing speed was 15 mm/s. For this experiment, the researcher used a robot arm to produce the lattice to support the overhang parts. It was anticipated to see the results where the printed lattice was produced with a minimum stringing was found at the lattice. The lattice was fabricated using multi-direction by the assistant from the robot arm. To produce the printed part in a multi-plane platform, a custom G-code containing the toolpath motion was produced. The robotic parts controlled wrist angles of the nozzle, motion speed, volume of extrusion, and extrusion speed. Besides that, another example of a complex lattice structure that can be fabricated using FDM is the Gyroid structure. The gyroid is a perfect example of complex geometrical shapes which are nearly impossible to build using traditional manufacturing because it has a unique shape of the triply periodic minimal surfaces. However, when AM was introduced, the Gyroid can be manufactured using this method without additional cost and tooling needed. The compressive behaviour of 3D printed Gyroid was investigated by Maharjan et al.[23] where they designed the Schoen Gyroid type with different unit cell sizes and volume fractions to evaluate the manufacturability of the FDM 3D printing machine. Four different sizes of unit cells ranging from 6 mm to 12 mm and volume fractions of 14%, 20%, and 25% were investigated. All of the samples were built without the support and the results show that the smallest unit cell sizes of 6 mm and the highest volume fractions of 25% having the highest compressive strength among the samples tested.

Even though their many research conducted in fabricating the lattice structures using AM, there are still many issues related to its application involving lattice structures. These related issues are mainly due to the inherent process from the AM machine itself. The challenges include warping, shrinkage, elephant foot, low dimensional accuracy, low mechanical properties, and surface roughness, especially for the FDM technique. Due to the lack of research on the effects of process parameters on complex structures, there are no guidelines provided to obtain the optimal process parameters for FDM fabrication on the lattice structures. Therefore, it is essential to explore the relationship between the process parameters of FDM and the quality of lattice structures produced from this technology as well as to accommodate the development of design rules for AM.

3.0 METHODOLOGY

In this study, four types of strut-lattices; square strut, circle strut, octagonal strut and triangle strut, were designed. The designs were based on the preliminary observation of the cross-sectional area of the lattice structures. Each of the strut designs contains a shape that varies from one to another. Therefore, to compare the strut sizes for its manufacturability, their cross-sectional area and height were fixed. The experiment was conducted using a benchmark material of Virgin PLA to evaluate the composite-based material such as carbon fibre PLA (CF-PLA) and Wood-PLA. The pass or fail criteria were described to determine whether the fabricated struts produce are successful or not. The strut design developments, experimental setup, and pass or fail criteria will be described in the following sections.

3.1 Cad model development of strut lattices

Table 1 presents the summary of the CAD model and the incorporated strut features. Each of the strut lattices was constructed based on the respective strut measurements within the x, y and z-axis design. The four strut lattice designs were analysed involving the sizes of 0.50 mm, 1.00 mm, 1.50 mm, 2.00 mm, 2.50 mm, 3.00 mm, 3.50 mm, and 4.00 mm. On the other side, the height of the lattice was also assigned differently from 1.00 mm to 10.00 mm height. This is to observe the relationship between the effects on height and the quality of strut fabrication. The pass or fail features of each strut were firstly determined.

For example, the thin wall criteria for square struts. In the inspection, the thin wall was carefully examined followed by the other struts criteria. To compare the strut, the constant cross-sectional area was obtained and the formula on each of the strut designs was mathematically represented by the following equations as tabulated in Table 2. The guide represented a value of dimensions calculated using the cross-sectional area.

Table 1: Summary of CAD model and feature incorporated

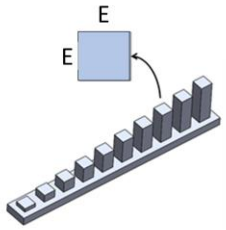
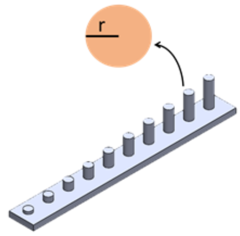
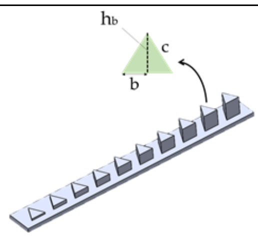
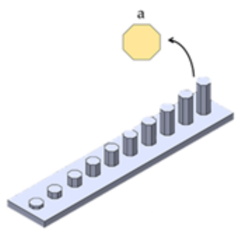
Strut feature	Square strut	Circle strut	Triangle strut	Octagon strut
CAD model				
Pass or fail features	Thin wall	Small hole diameter	Thin and sharp edges	Thin side and edges
Guide	Value of E	Value of *d*	Value of h_b and c	Value of a
Cross-sectional area (mm^2)	0.25-16.00	0.25-16.00	0.25-16.00	0.25-16.00

Table 2: Formula of cross-sectional area for every strut lattice design

Strut lattice design	Formula/ Equation	Descriptions
Square struts	$A=E\text{x}E$	E is length of the square side
Circle struts	$A=\pi r^2$	π is value of pi (~3.14) and r is value of radius
Triangle struts	$A=(h_b b)/2$	h_b is the value of height and b is the value of base.
Octagon struts	$A=2(1+\sqrt{2})\, a^2$	a is length of side of each octagon

3.2 Experimental setup

The fabrication and analysis process was conducted based on a sequence step as shown in a schematic diagram in Figure 1. The process starts with the development of a 3D CAD model. The CAD file was then converted to STL files and was prepared for the slicing process. In the slicing parameter, the process parameter was selected to obtain the optimal printed part quality. The process parameter optimization has been primarily obtained in the previous study [19]. After that, the parts were fabricated using a Prusa 3D printer machine. After the printed parts were ready, the inspection method was conducted using a microscopic analyzer for the pass or fail criteria evaluation.

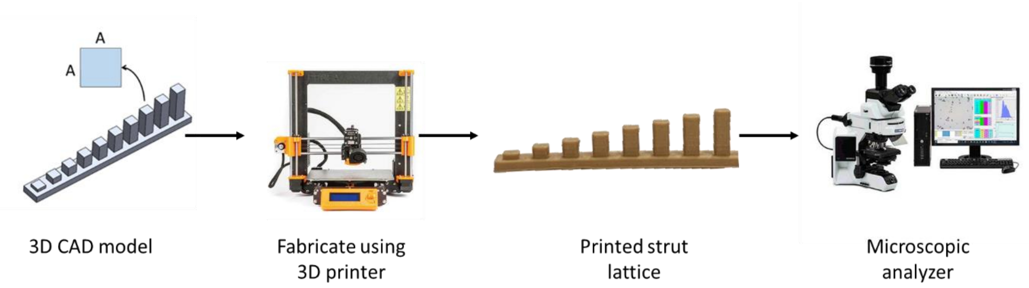


Figure 1: The fabrication process of strut lattice design and inspection

Table 3 summarizes the printing parameters for fabrication. The critical parameters were defined by layer thickness of 0.15 mm, an extruder speed of 60 mm/s, and also the temperature of 195ºC to ensure the consistency of extrusion. Since the evaluation was conducted using visual inspection, the infill density percentage used is only 20% to preserve the material consumptions. The fan used is 100% in speed to fully utilize the air circulation while printing the PLA-based materials. The visual inspection was conducted as a basic check to identify obvious damage at the printed part. The other main purpose of visual inspections is to verify that the printed strut is free of defects before the full 3D lattice was designed. Throughout this inspections, the pass or fail criteria was obtained as the basic guideline to design for 3D lattice and identify the existing and potential limitation of the design. In the previously reported study by Helou & Kara (2018), the strut was reported as a very crucial component in a 3D printed lattice. To date, there is only a single reported study of design rules for strut lattice using metal 3D printing [14]. In the study, a visual inspection was also conducted to identify the defects produces as the preliminary results. Therefore, to ensure the applicability of strut printing in the FDM technique, a visual inspection was also carried out. Table 2 presents the summary of the 3D CAD struts.

Table 3: Process parameter for strut lattice fabrications

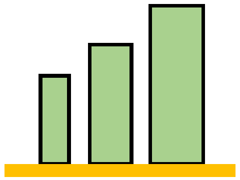
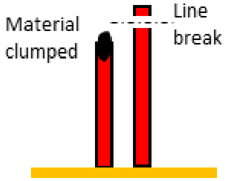
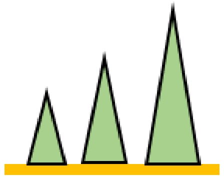
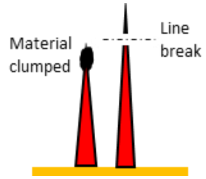
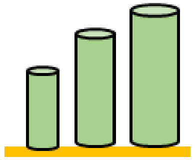
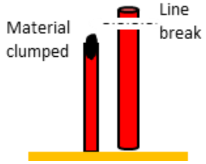
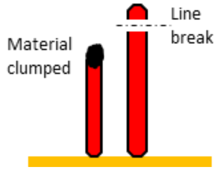
Parameters	Value
Layer thickness	0.15 mm
Extrusion temperature	195˚C
Printing speed	60 mm/s
Bed temperature	70 º
% infill	20%
Support structure	No
Brim generation	No
Fan	Yes/ 100%

3.3 Pass or fail criteria of the printed strut lattice

The schematic diagram in Table 4 represents the illustration or condition of fabricated parts if the parts undergo fail or successful fabrications. For fail criteria of square struts lattice design, it was observed that the geometry of the square does not properly develop because the shape does not represent square shapes. Some of the surfaces even undergo the discontinuities of layer adhesion showing a very poor layer adhere of surface finish. It can also be observed that the strut suffers from the stringing of materials. Meanwhile, for the pass criteria, the geometry realized can be clearly described and known. The surface quality is normal since the entire layer is properly developed showing the consistency of a good interlayer between the lines. It can also be seen that the square edges can be examined.

For the fail criteria of circle struts, it can be seen from the microscope that the top surfaces of the circle strut were clumped by the extruded materials, especially for the small surfaces strut. The clumped maybe happen because the extruded material does not fully solidify yet, however, the material is still extruding with the limited spaces available. The other observations include very poor layer adhesion and also poor stringing. Meanwhile, for the pass criteria, all the shapes are successfully fabricated with round underlined shapes perfectly. For triangle struts and octagon struts, the same observation for the fail criteria such as discontinuity and very poor layer adhesion was observed. For the pass criteria, all of the triangle struts and octagon struts were successfully fabricated with the sharp triangle shapes and perfect octagon shapes respectively.

Table 4: Summary of a pass and fail criteria for printed strut design

Criteria	Pass	Fail	Pass	Fail
	(i) Square strut		**(iii) Triangle strut**	
Schematic diagram				
Descriptions	Good layer adhesion and all the square edges is fabricated	Discontinuities layer adhesion and very poor stringing and clumped materials	Good layer adhesion and sharp triangle shape	Discontinuities layer adhesion and poor stringing with clumped of material
	(ii) Circle strut		**(iv) Octagon strut**	
Schematic diagram				
Descriptions	Good layer adhesion and round shape is properly developed with round underlined shape perfectly	Very poor layer adhesion and material clumped on upper area if the circle is too small	Good layer adhesion and octagon shape is properly developed with all edges form perfectly	Discontinuities layer adhesion and poor stringing with clumped of material

4.0 RESULTS AND DISCUSSION

The pass or fail criteria previously defined in Table 4 were used for better assessment and in evaluating the overall struts. The special focus on the observation was on the strut finishing and defects on surfaces. This test aims to evaluate the boundaries and influences of different strut geometries on the generation of struts in different sizes and heights. As a result, struts that passed for fabrications were defined according to the criteria and meet the requirements. The following sub-sections presented the results of an assessment and observation of fabricated struts.

4.1 Square strut

Table 5 presents the assessment of the pass and fail criteria for the square strut fabrication. The table consists of the cross-sectional value (mm^2), the value of A, and the PLA-based composite material assessed for each of the square struts. It can be observed from Table 5 that the square strut with a dimension higher than 2.00 mm (length of A) was considered as a pass for fabrication meanwhile, for dimensions below 2.00 mm, the strut fabrication was unsuccessful.

Table 5: Visual inspection for square strut design of PLA composite material

Cross-sectional area (mm^2)	Square strut A x A (mm)	Virgin PLA	CF-PLA	Wood-PLA
0.25	0.50	Fail	Fail	Fail
1.00	1.00	Fail	Fail	Fail
2.25	1.50	Fail	Fail	Fail
4.00	2.00	Pass	Pass	Pass
6.25	2.50	Pass	Pass	Pass
9.00	3.00	Pass	Pass	Pass
12.25	3.50	Pass	Pass	Pass
16.00	4.00	Pass	Pass	Pass

In FDM, the minimum feature size is mainly affected by the diameter of the print nozzle. The most common nozzle diameter is 0.40 mm, therefore, the smallest feature that can be printed is 0.50 mm. Many open-source 3D printers are allowed to swap out the nozzle using third-party upgrades and the smallest diameter that can be found in the market is 0.15 mm. However, it is important to keep in mind that the smaller features that can be fabricated using FDM are easier to deform by heat especially for the tall and thin parts such as towers. This structure often fails because the heat of the molten plastic and the nozzle causes the structure to soften and destroyed as shown in Figure 2. It can be observed that the small strut cannot be produced successfully and have defects. Furthermore, by increasing the height of the struts, more defects were observed. For example, on the strut fabrication with a height of 10.00 mm, the material was clumped together on the tips. Meanwhile, starting from the height of 6.00 mm, the shape is no longer becoming square, but more likely to become a circle shape. Generally, a printed strut with a tall and thin area is often failed because the heat of the molten plastic and nozzle causes the structures to soften. Since the area of the strut is smaller, thus, the existing layer is not able to solidify faster (and still soft), yet increasing the chances for the next layer to not adhere properly and clumped the materials together on the tips.

Therefore, to conclude, to produce the successful square strut for the lattice fabrication, designers are advised to use the feature-length higher than 2.00 mm as possible.

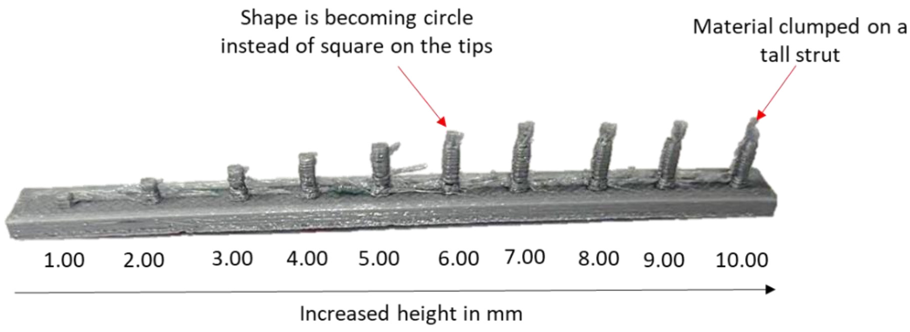


Figure 2: Printed struts with dimensions of A equal to 1.50 mm

4.2 Circle strut

Table 6 presents the assessment of the circle strut. It can be observed that the circle strut with a dimension higher than 1.129 mm (r) was successfully fabricated.

Table 6: Visual inspection for square strut design of PLA composite material

Cross-sectional area (mm^2)	Circle strut: *r* (mm)	Virgin PLA	CF-PLA	Wood-PLA
0.25	0.280	Fail	Fail	Fail
1.00	0.565	Fail	Fail	Fail
2.25	0.846	Fail	Fail	Fail
4.00	1.129	Pass	Pass	Pass
6.25	1.410	Pass	Pass	Pass
9.00	1.693	Pass	Pass	Pass
12.25	1.975	Pass	Pass	Pass
16.00	2.257	Pass	Pass	Pass

The circle strut was printed with a height between 1.00 mm to 10.00 mm. As the height of the circle strut increased, the shape looks exactly like a thin cylinder, especially when using the small diameter. In 3D printing, the thin cylinder or also known as vertical wire diameter is often manufactured using FDM for the assembly and alignment proposes, therefore, considering that these features are often functional, the size and the diameter of the vertical wire diameter is very necessary to ensure the printed parts can be produced accurately as per design. In this experiment, various circle diameters were tested according to their respective height. Figure 3 describes the printed part of the circle strut with a small radius (less than 1.00 mm). There are three comparisons on the fabricated strut in different diameter sizes. First, in Figure 3(a), when printing with a radius of 0.846 mm, as the height is increased, the curling effects is started to develop on the tips of diameter. Meanwhile, for Figure 3(b) and Figure 3(c), the circle strut was successfully developed with a very minimal string is observed. The radius for circle assigned for both diameters were 1.129 mm and 1.693 mm, respectively.

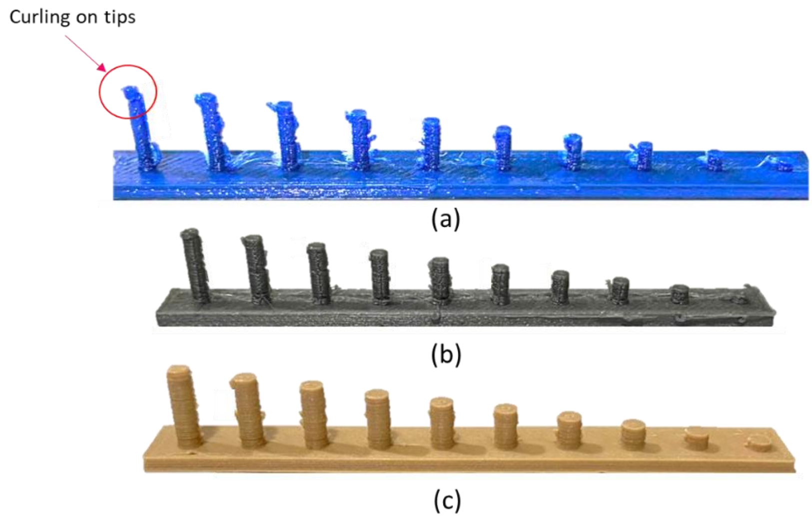


Figure 3: Printed square strut with various radius (a) 0.846; (b) 1.129 and (c) 1.693 mm

When fabricated using a smaller diameter or radius, the surface area is small. Therefore, the nozzle is concentrated into the area, which made the part difficult to harden due to the continuous extrusion from the melted materials results in curling effects. When the diameter's height is increased, it is advisable to not print the diameter with the small area because it could result in a weak connection between the layers which makes the part break and the worse scenario can happen such as detachment of parts from the platform. Figure 4 shows the scenario when the diameter is break due to the small surfaces area. Compared to the bigger diameter, the surface area is also larger which made the soften materials having an adequate time to solidify before the new layer was developed.

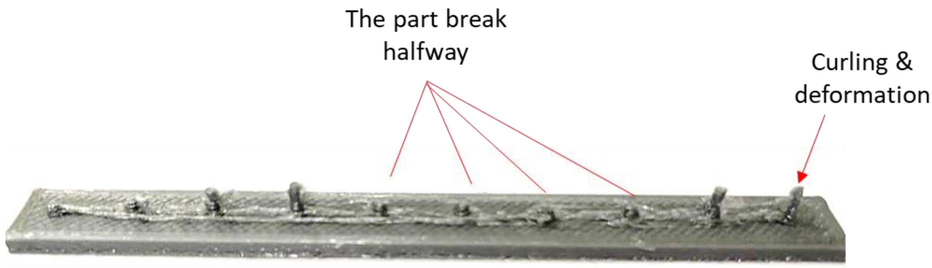


Figure 4: Example of unsuccessful circle strut fabrication

4.3 Triangle strut

Table 7 presents the visual inspection of the fabricated triangle strut. The Triangle strut was inspired by the cross-sectional area of the infill-mesh pattern which is a triangle in the slicing software. In an infill pattern, triangles design is a 2D mesh that is made of triangles in which this pattern has an inherent advantage in strength.

Table 7: Visual inspections of triangle struts design of PLA composite materials

Cross sectional area(mm^2)	Triangle strut	Virgin PLA	CF-PLA	Wood-PLA
0.25	1.00/ 0.50	Fail	Fail	Fail
1.00	2.00/1.00	Fail	Fail	Fail
2.25	3.00/1.50	Fail	Fail	Fail
4.00	4.00/2.00	Pass	Pass	Pass
6.25	5.00/2.50	Pass	Pass	Pass
9.00	6.00/3.00	Pass	Pass	Pass
12.25	7.00/3.50	Pass	Pass	Pass
16.00	8.00/4.00	Pass	Pass	Pass

In Table 7, the observation for the fail criteria such as geometry is indefinable, discontinuity and very poor layer adhesion are being observed on the triangle strut below 3.00 and 1.50 mm for the triangle base. Meanwhile, for the pass criteria, all of the triangle struts were successfully fabricated with the sharp triangle shapes is develop with a hint of a small wall. For triangle strut, the size of the triangle height (h_b), and the size of the triangle base (b) are very important to ensure the success of fabrications because the base determines the outer shell. It can be seen that the triangle will only pass when the base size is higher than 2.00 mm. Figure 5 explains why the base is an important factor for triangle successful fabrications. The example of size between the base of 1.50 mm and 2.00 mm was illustrated. When the model was sliced, it can be seen that the shell (distribute by the red colour) in Figure 5(b) conquer the surface area of the triangle. Therefore, the nozzle does not have enough spaces to distribute the heated materials on the designated area and led to the deformation of the parts as being discussed in the previous strut developments.

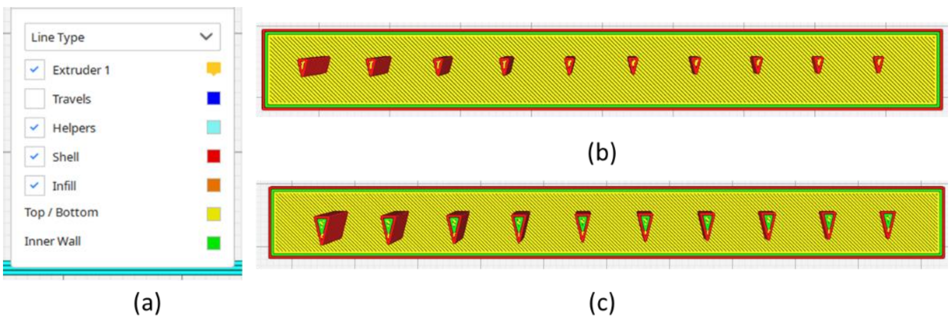


Figure 5: (a) Slicing indicator for parameter; (b) base 1.50 mm and (c) base 2.00 mm

4.4 Octagon strut

The Octagon strut was inspired by the honeycomb lattice structure in 3D. The honeycomb structure is the favourable infill pattern and lattice design to be further investigated by the researchers. As the name implies, the honeycomb structure is an appealing visual and this infill pattern is good for semi-fast prints that require a moderate strength and it does not consume too much material. Table 8 presents the visual inspections for the octagon strut. The table describes the criteria for octagon strut. The same observation for the fail criteria such as geometry is indefinable, discontinuity and very poor layer adhesion is being observed. For the pass criteria, all of the octagon struts were successfully fabricated with the good layer adhesion and all the octagon shape is properly developed with all the octagon edges form perfectly.

Table 8: Visual inspections of triangle strut design of PLA composite materials

Cross sectional area(mm^2)	Octagon strut:A= $2(1+\sqrt{2})\ a^2$ (mm)	Virgin PLA	CF-PLA	Wood-PLA
0.25	0.226	Fail	Fail	Fail
1.00	0.456	Fail	Fail	Fail
2.25	0.682	Fail	Fail	Fail
4.00	0.91	Fail	Fail	Fail
6.25	1.138	Pass	Pass	Pass
9.00	1.365	Pass	Pass	Pass
12.25	1.593	Pass	Pass	Pass
16.00	1.820	Pass	Pass	Pass

As being illustrated in Figure 6, there are few comparisons between the small strut size and bigger strut sizes when it was sliced. For Figure 6 (a), the strut size investigated is 0.456 mm which is lower than 1.00 mm, and the only shell was developed. Meanwhile, for the strut sizes of 0.691 mm, the sizes are slightly bigger so that the shell, inner wall, and the top-bottom can be designated in the slicing but with very minimal spaces. Still, the nozzle does not have enough space to properly develop the octagon edges. Therefore, instead of producing the octagon shape, it produces the circle shape as described in Figure 6 (b). At the end of the study, the summary of the basic design rule for strut lattice was tabulated in Table 9.

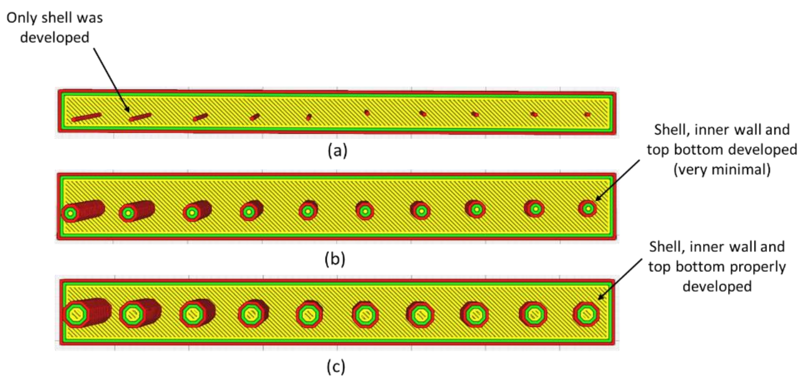
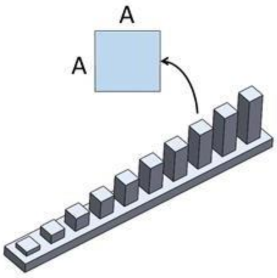
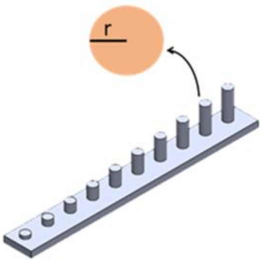
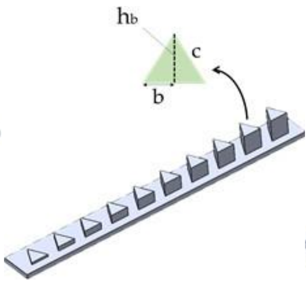
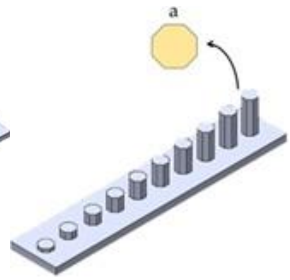


Figure 6: Octagon strut sliced in (a) 0.456 mm; (b) 0.91 mm and (c) 1.365 mm

In Table 9, for strut lattice design of square, the geometries can be successfully fabricated with the strut sizes higher than 2.00 mm, meanwhile for circle strut, the strut with radius more than 1.00 mm produce a good result with good layer adhesion. For triangle and octagon strut, the successful dimension to produce a good printed parts are more than 2.00 mm and more than 1.00 mm respectively. In general, the strut sizes produce lower than 2.00 mm having poor qualities such as layer discontinuities, poor stringing and curling on the tip of the struts. From the four design struts, the square and circle strut is easy to produce because the design is simple and does not contain the sharp edges as triangle and octagon struts. It was observed that some of the printed triangle and octagon strut was break in layers halfway of fabrications. Generally, compared to these three materials, struts lattice is at disadvantages when printing using Wood-PLA. There are three main reasons on why wood filament is at disadvantages when printing small features like struts. Firstly, the main cons when using Wood-PLA is prone to stringing. Secondly, the smaller nozzle can end up with partial clogs over time because wood fiber is larger than the carbon fiber. When the nozzle clogs, it results the poor interlayer adhesion that resulting crack, split and break between the layers at the fabricated struts. Thirdly, it was suggested that to use larger nozzle when printing with wood filament such as size of nozzle diameter of 0.60 mm and above to ensure the filaments is successfully extruded.

Table 9: Recommended design rules for composite strut lattice design

	Strut-lattice design			
Strut feature	**Square strut**	**Circle strut**	**Triangle strut**	**Octagon strut**
CAD model				
Guide	Value of A	Value of r	Value of h_b and b	Value of a
Virgin PLA	≥2.00 mm	≥1.00 mm	≥ 2.00 / 1.50 mm	≥1.00 mm
CF-PLA	≥2.50 mm	≥1.50 mm	≥ 2.00/ 1.50 mm	≥1.50mm
Wood-PLA	≥2.50 mm	≥1.50mm	≥ 2.00/ 1.50 mm	≥1.50 mm

5.0 CONCLUSIONS AND OUTLOOK

The study aims to perform a manufacturability analysis of composite-based strut lattice designs in assisting the development of basic design rules of a simple unit lattice cell; square strut, circle strut, octagon strut, and triangle strut. The main focus was on the evaluation of which geometry could be generated. All of the designed geometries were successfully fabricated with strut sizes higher than 2.00 mm, with good layer adhesion, geometry can be defined and all the strut designs were properly printed. Meanwhile, for the strut sizes lower than 2.00 mm, the geometry was not properly developed with discontinuities of layer adhesion and poor stringing. Compared to the four strut designs, it has been observed that the square and circle strut were easy to produce as compared to the triangle and octagon strut. Since the strut height varied from 1.00 mm to 10.00 mm, it can be seen that the smaller size of triangle and octagon strut were underdeveloped with the increased height due to the poor extrusion and poor adhesions. A few printed triangles and octagon struts were observed to be a break in layers halfway through fabrications. Further mechanical tests, such as compression tests should be provided using these four different strut designs. With the information obtained on the mechanical strength, the newly developed unit cells can then be produced for the individual lattice structures. The mechanical test includes, but not limited to tensile/compression test, fatigue test, three-point bending and torsion can also be carried out. These results will then determine the decision criteria for commercial user and can provide the 3D printer users with a specific design rules that can guide them with the technicality and manufacturability guideline specifies on the strut geometric and restrictions when printing with composite materials.

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