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Effect of infill on tensile and flexural strength of 3D printed PLA parts

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Abstract. Development in open source three-dimensional (3D) printing has generated interest for creating low-cost customised objects; in both personal and commercial. In the 3D printing process, the quality and cost of the objects produced are normally influenced by the processing parameter. One of the parameter is infill patterns. Infill patterns can be used to reduce material usage and printing time. Various infill patterns are available in the 3D printing software. Four different infill patterns were used to evaluate the mechanical properties of fabricated parts. Open source 3D printer was used to print five PLA specimens for each different infill pattern. Tensile and 3-point bending tests were performed on the printed parts in order to determine the tensile and flexural strength. The mechanical strength of printed parts is influence by different infill patterns. The results obtained indicated that Rectilinear pattern has the highest tensile and flexural strength. The average tensile strength of Rectilinear is 19.1 MPa with average modulus elasticity of 10.51 GPa, whereas the average flexural strength of Rectilinear is 24.4 MPa with average tangent modulus elasticity of 0.359 GPa.

1. Introduction

Additive Manufacturing (AM) technology is utilized in making physical objects from three-dimensional (3D) models generated by computer-aided design (CAD) software. In the late 1980's the method or technology of fused deposition modeling (FDM) was invented and expanded by S.Scott Crump and was commercialized in 1990. After the patent expiration of FDM innovation, a vast open-source advancement group was formed and both businesses and DIY variations using FDM for 3D printing showed up [1]. RepRap, a short form for Replicating Rapid Prototyping, is a kind of 3D printer that was developed after the patent of FDM expired and released with concept of open free software license. RepRap 3D printer basically able to print out different type of pattern fills of the internal structure of the printed part and it will generate different of mechanical properties.

However, the printed pattern fills characteristics of the internal structure of the printed parts is not fully defined and studied yet. It is desirable to include others parameters to support its printing process such as control of temperature and internal supporting structure.

2. Methodology

In order to test the specimen's mechanical properties, a series of samples is required to be built with different infill patterns. The test specimens were design using CATIA V5R20 computer-aided design (CAD) software to ASTM D638-14 and ASTM D790-10 for tensile and bending test. The geometrical dog-bone and rectangular bar test specimen model were representation as solid model in CATIA. The solid CAD models were saved in Standard Triangular Language (STL) file format which is the file format that can be read by 3D printer. STL file format interpret the external closed surfaces from solid CAD model and divide the model into slices for printing purpose. However, some general adjustments are required of the STL file such that it is correct in size, position, and orientation for test specimen printing[2]. The adjustments were made using Slic3r software. The G-code file was decoded by the Pronterface software and printing time was estimated, the designed specimen were shown in the software. After confirming the proper printing setup, the printer can start printing. Polylactic Acid (PLA) filament was used as obtained from supplier to print the specimens.The selected PLA was extruded from the heated nozzle and build the specimen layer by layer from bottom until the top according to the coordinate as generated in the G code until the specimen is completely formed as drawn in the CAD file. Six specimens are printed for each infill pattern from dog-bone shape and rectangular bar shape respectively.

2.1. Printing Setup

Slic3r was also used to setup the printing parameter in term of material usage, temperature, nozzle movement speed, nozzle flow rate and the machine stability besides infill patterns. The dimensional accuracy and surface roughness of the specimens can be influence by these parameters. Set of testing specimens were produced selected infill patterns of rectilinear, concentric, honeycomb and hilbert curve. The Slic3r software then generates G-code from the STL files with the setup parameters. Open-source 3D printing machine based on REPRAP 3D Printer used this G-code to print 3D specimens

2.2. Tensile and Flexural Test

The mechanical behaviour for a particular part is the reaction of the material to a mechanical stress. The deformation causes from the applied force of a component relying on the direction of the applied force and the size of the component design or mechanical properties [2]. The mechanical properties of printed part from PLA such as tensile strength and flexural strength were determined according to American Society for Testing and Materials (ASTM) standard.

Tensile testing of the specimens was performed on a Universal Testing Machine (UTM) by using the crosshead testing rate of 5mm/min. In order to obtained the tensile properties of the testing specimens [4] accurately, the printed specimens was prepared based on the designed dimensional according to the ASTM D638-14. There were at least five dumbbell or dog-bone shape specimens have to be tested for each of the type of infill pattern so that results will be more precise [5].

Flexural testing of the specimens was performed on a Shimadzu Universal Testing Machine using a particular crosshead testing rate of 1.28 mm/min. In order to identify the flexural properties of the testing specimens, the printed specimens was prepared based on the designed dimensional according to the ASTM D790-10. There were at least five rectangular bar shape specimens have to be tested for each of the type of infill pattern.

The drawing file was input and the details parameters such as drawing dimension and geometry design. In this tensile properties testing would focus on determining the tensile strength, elongation and modulus of elasticity or Young's Modulus as well as respectively standard deviation of the printed part with four different types infill patterns. The tensile testing was conducted on those specimens with setup the crosshead speed of 5mm/min and applied force of 100kN. All the specimens were designed according to the ASTM D638-14 in category of Type I specimen.

3. Results and discussion

3.1. Comparison of Stress-strain Among Infill Patterns

Figure 1 show the details scattered plot for different infill patterns which showed that the Rectilinear infill pattern contains highest tensile strength compared to Concentric, Honeycomb and Hilbertcurve. While for Hilbertcurve infill pattern was lowest tensile strength or can be classified as weakest in tensile strength among these four types of infill patterns. The difference of tensile strength between Rectilinear and Hilbertcurve was 14.93 MPa. This implies that Rectilinear can withstand extra 78.17% of load compare to Hilbertcurve before going to rupture.

From the results of maximum strain showed that Rectilinear and HoneyComb are highest and closed to each other which contribute 3.45% and 3.66% respectively. The difference of maximum strain between both of these infill patterns was 0.21%. Hence, this indicate that the force distribution among the intra bonding of HoneyComb available to flow much more fluent and less concentrate in the linkage chain as a result it yields a slightly higher strain of extra 6.09% than Rectilinear.

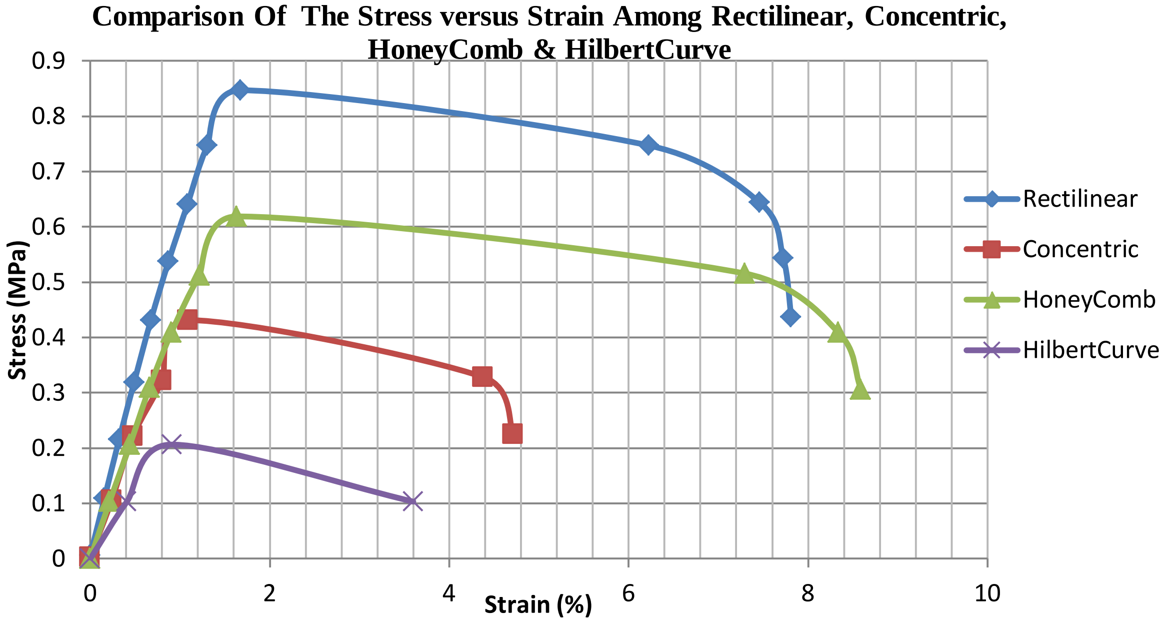

Figure 1. Scattered plot of infill patterns

Modulus of Elasticity among these four types of infill pattern was obtained by plotted a slope in the elastic region of the graph and identified that Rectilinear infill pattern was highest which achieved 10.51 GPa, where Concentric was 7.34 GPa, HoneyComb was 6.92 GPa and HilbertCurve was 3.27 GPa which is the weakest among these four infill patterns. The difference of modulus of elasticity among the strongest and weakest was 7.24 GPa and this possible to indicate that the different infill patterns have a considerable influence on strength and modulus tensile properties of the material.

It is possible to conclude that the Rectilinear infill pattern overall contains the strongest tensile mechanical properties among the four different type infill pattern. Although, the HoneyComb infill pattern attain a slightly higher 0.21% of maximum strain, this is possible due to fabrication of printed part where the excess material extruded from the nozzle and causes the orientation of the molecule chains which decreases the elongation characteristics of the infill pattern [5]. In Table 1 is the summary of tensile properties for those infill patterns have been tabulated.

Table 1. Summarize Of Tensile Properties against the Infill Patterns

	Infill Pattern			
Tensile Properties	Rectilinear	Concentric	HoneyComb	HilbertCurve
Young's Modulus, E (GPa)	10.51	7.34	6.92	3.27
Tensile Strength, σ (MPa)	19.1	10.1	13.2	4.17
Maximum Force, F (kN)	0.799	0.463	0.611	0.207
Maximum Strain, ε (%)	3.45	2.48	3.66	1.74

3.2. Comparison of Infill Patterns

The data showed the details scattered plot, Figure 2 showed that the Rectilinear infill pattern contains the highest flexural properties compared to concentric, honeycomb and hilbertcurve. While for hilbertcurve infill pattern was lowest flexural properties or can be classified as weakest in flexural properties among these four types of infill patterns. The difference of flexural strength between Rectilinear and Hilbertcurve was 14.7 MPa. This implies that Rectilinear can withstand extra 14.7 MPa of maximum flexural stress compare to Hilbertcurve before going to rupture. Tangent modulus of elasticity among these four types of infill pattern was obtained by plotted a slope in the elastic region of the load-deflection curve with specific formula calculation and identified that Rectilinear infill pattern was highest which achieved 0.359 GPa, where Concentric was 0.263 GPa, HoneyComb was 0.287 GPa and HilbertCurve was 0.236 GPa which is the weakest among these four infill patterns. The difference of modulus of elasticity among the strongest and weakest was 0.123 GPa.

Although, the flexural strain showed that HilbertCurve was 0.068% higher than the other three infill patterns, but overall Rectilinear was indicated that better results than Concentric, HoneyComb and HilbertCurve regardless whether it is for tangent modulus of elasticity, flexural stress, flexural strength and maximum force as shown in Table 2.

It is possible to conclude that the Rectilinear infill pattern overall contains the strongest flexural mechanical properties among the four different type infill patterns. However, HilbertCurve considered its flexural properties are advance in term of flexural strain. Hence, it is possible to indicate that the different infill patterns have a considerable influence on strength and modulus of flexural properties of the material. In Table 2 is the summary of flexural properties for the infill patterns.

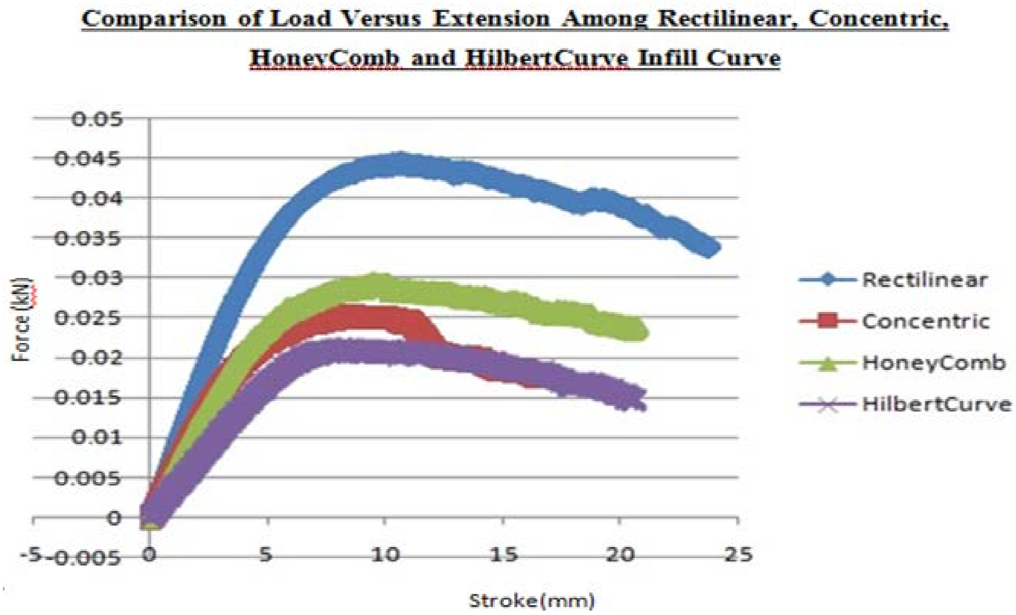

Figure 2. Load versus extension of infill patterns

Table 2. Summarize of Flexural Properties against the Infill Patterns

Properties	Infill Pattern Rectilinear	Concentric	HoneyComb	HilbertCurve
Tangent Modulus of Elasticity, E_B (GPa)	0.359	0.263	0.287	0.236
Flexural Stress, σ_{fB} (MPa)	24.4	12.8	14.5	10.6
Flexural Strength,	24.4	12.5	14.0	9.7

σ_{fM} (MPa)				
Maximum Force, P (kN)	0.042	0.025	0.030	0.020
Flexural Strain, ε_f (%)	0.056	0.054	0.061	0.068

3.3. Comparison of Mechanical Properties of Infill Patterns

The best modulus of elasticity was plotted in graph as shown in Figure 3 below. It can be observed that Rectilinear infill pattern was highest whereas HilbertCurve infill pattern was lowest in term of tensile and flexural test as well. Meanwhile, the best strength graph was plotted as shown in Figure 4 below. Obviously we able to define that Rectilinear infill pattern consist of highest strength while HilbertCurve was lowest in both tensile and flexural test as well.

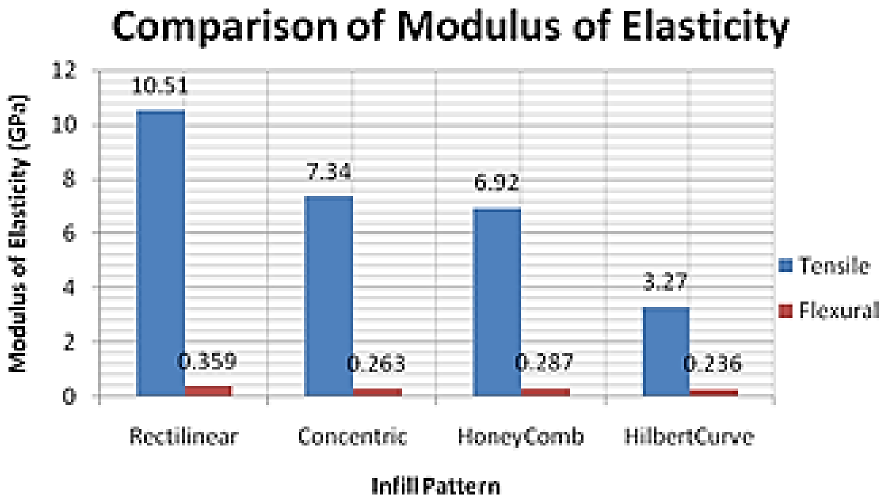

Figure 3. Modulus of elasticity in different infill

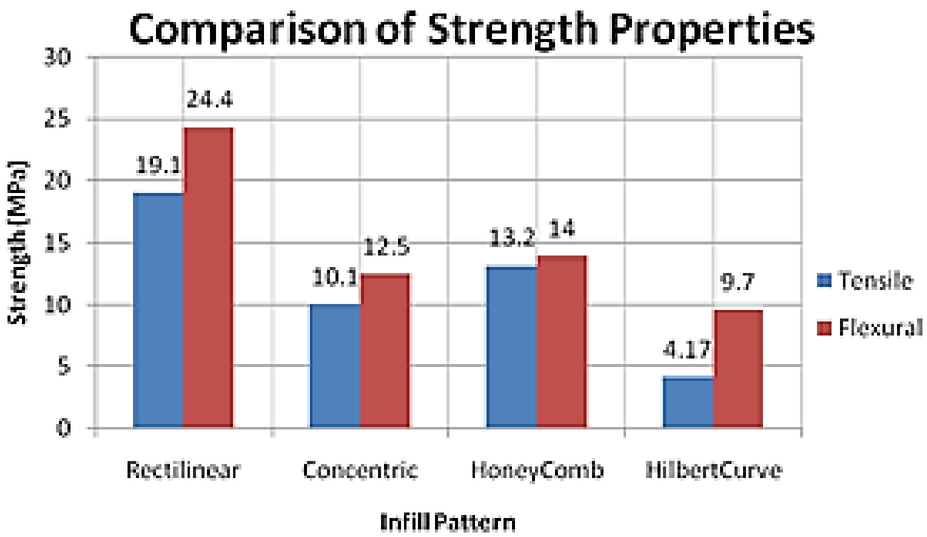

Figure 4. Strength in different infill

4. Conclusion

Experimental testing was conducted in order to identify the mechanical properties of 3D printed part that printing by RepRap 3D printer meanwhile to select the desired infill pattern. There are some conclusions found out from this research. Firstly, the setting of the parameters of the RepRap 3D

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printer such as density, nozzle temperature and movement speed and stability of the machine as well was important, this can be affect the printing quality of the specimen and causes the deviation towards the testing results.

Secondly, from the experimental testing results showed that the specimens generated with different infill pattern was given different prominence results, therefore can be concluded that the mechanical strength properties was depend on the given infill pattern that printed by RepRap 3D printer.

Thirdly, throughout the experimental testing results, Rectilinear infill pattern was achieved the best results among the four different type of infill patterns such as Rectilinear, Concentric, HoneyComb and HilbertCurve.

Fourthly, in comparison with computer simulation and experimental testing results showed that the tensile analysis was as expected achieved the same outcome with experimental testing results, where flexural analysis was beyond expectation and showed that HoneyComb as strongest strength, therefore computer simulation was only as a reference since we unable exactly duplicate whichever parameters, conditions, or influences into the virtual simulation software, consequence produce the divergent results.

Fifthly, from the results of experimental testing results compare with manufacture's bulk material datasheet showed that the strength of printed part was weaker compare to original bulk material, this is possible to conclude that the bulk material after undergone heated and melted was definitely changed its properties.

5. Acknowledgment

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