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EFFECT OF INTERNAL STRUCTURES ON COMPRESSIVE STRENGTH OF THE FDM PARTS

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Abstract: Fused deposition modeling (FDM) is one of the recently developed additive manufacturing techniques being used to build the industrial component structures in layer-by-layer from extruded filaments of molten thermoplastics. FDM technique is presently using for manufacturing the patterns for casting process, prototypes for functional and mechanical testing. The control parameters such as raster separation, filament flow rate, material depositing orientation, and extrusion temperatures are significantly effecting the mechanical properties of FDM parts. On this context, the present investigation is aimed to study the compressive strength, material usage and build time under varying the parameters: internal structure of matrix and internal density. The samples were fabricated with solid, hollow, rhombus, honeycomb and triangular internal structures with internal densities of 1 and 1.2 mm each. Finite element method simulation software ANSYS Workbench was used to model and predict the compressive strength of FDM structures and the results were compared with the values of experimental tests conducted on fabricated structures. Consequently, material usage and built time are also noted experimentally. The optimal structure for FDM parts was recommended through the results of experimental and numerical simulations.

Keywords: Internal structure, internal density, compressive strength, material usage, built time, Finite element analysis, Additive manufacturing, Fused Deposition Modelling.

1. Introduction

Additive manufacturing process is the advanced technology used to fabricate parts which are in complex nature. Fused deposition modeling (FDM) is one of the additive manufacturing process that builds parts layer by layer from extruded filaments of a semi-melted thermoplastic. The mechanical properties of parts depend mainly on variable factors such as the material's depositing orientation, filament's flow rate, raster's separation, and extrusion temperatures. Solid and shell are the two main FDM manufacturing strategies used indistinctively; however, there are applications where the solid build strategy may not be necessary and even problematic. Evidently, the mechanical properties of internal support material have not been defined in a full-fledged manner. Hence, it is desirable to include internal supporting structures with known properties and behavior, that will provide the support needed while balancing the amount of material used (both model and support). In FDM process containsnozzle which can movable in X and Y directions on to a substrate deposits thread of molten polymeric material. The temperature of the build material is increased slightly above the melting point temperature .So that it solidifies within a very short time (approximately 0.1 s) after extrusion and cold-welds to the previous layer as shown in Figure 1.

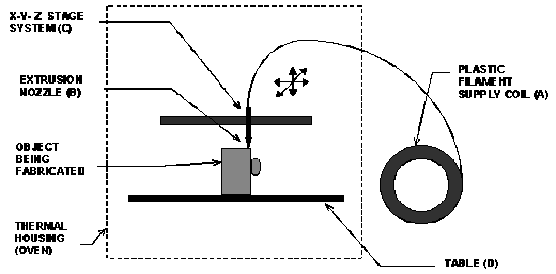


Figure 1. Schematic of the FDM machine

L.Villalpando [1] introduced internal structures which provide balance between strength and material usage. Physical testing was done on fabricated specimens. FEA simulation is also done and results were compared. FDM parts were further optimized by optimizing process parameters using genetic algorithm method. L.M Galantucci [2] aimed to improve surface finish of the fused deposition modeling parts. The mechanical properties of FDM prototypes treated with a solution of 90% di-methylketone and 10% water have been analyzed. Jose M.Arenas [3] proposed a novel method of construction by assembling parts with structural adhesive joints to redesign fused deposition modeling parts. Adhesives of five different families namely cyanoacrylate, polyurethane, epoxy, acrylic and silicone are analyzed. They showed that polyurethane as a better adhesive. M.Nikzad [4] developed new composite materials with iron filled particles in ABS (Acrylonitrile Butadiene Styrene) and copper filled particles in ABS for direct application in Fused Deposition Modeling rapid prototyping process. They showed that these materials have higher stiffness than pure polymeric material and also these materials can be applied in functional parts and direct rapid tooling.J.Martinez [5] applied finite element method (FEM) programs to FDM parts to analyze mechanical behavior and main manufacturing properties. By considering failure modes of composite laminate, different orientation configurations are analyzed. Sandeep Raut [6] investigated the effect of built orientation on the mechanical properties and total cost of the FDM parts. On fabricated test specimens tensile and bending test were conducted. Concluded that about y-axis at 0° built up orientation FDM parts has good tensile strength and minimum cost and about x-axis 0° parts has good flexural strength and medium cost.Ludmila Novakova [7] proposed different advanced materials that can be used in fused deposition modeling process. The materials include silicon nitrate, PZT, aluminum oxide, hydroxyapatite and stainless steel for a variety of structural, electro ceramic and bio ceramic applications. Sung-Hoon Ahn [8] characterized the ABS parts fabricated by FDM process. Using a Design of Experiment (DOE) approach, the process parameters of FDM, such as raster orientation, air gap, bead width, color, and model temperature were examined. Tensile and compressive strengths of specimens were measured and compared with injection molded parts. Samir kumar Panda [9] studied the effect of process parameters on mechanical properties like tensile, flexural and impact strength. Experiments were conducted using central composite design (CCD). Theoretical combination of parameter settings to achieve good strength simultaneously for all responses was suggested using bacterial foraging technique.

2. Problem Statement

To recommend optimum internal structure model for the FDM based parts based upon on high compressive strength, low material usage and less fabrication time by using experimental methods.

3. Problem Modeling

The internal structures are modeled using ANSYS Workbench 12. The dimensions of the outside shell are taken from the ASTM D-695-10 standards shown in Figure 2a. Basic elements are joined in a pattern to construct complex web-like structures. Once these internal structures are created, they are inserted into a shell case structure. Figure 2b and 2c shows typical view of the basic element and shell case structure.

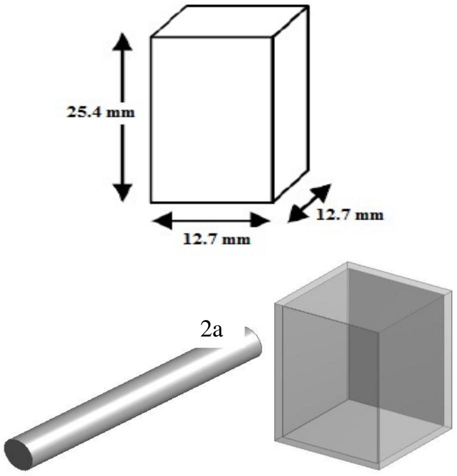


Figure 2. Parametric modelling of internal structures

Different types of inte 2b structures i.e., Triangle, Rhombus and honeycomb are considered in the present work which are shown in the Figure 3.These internal structures response are compared with hollow and solid cases.

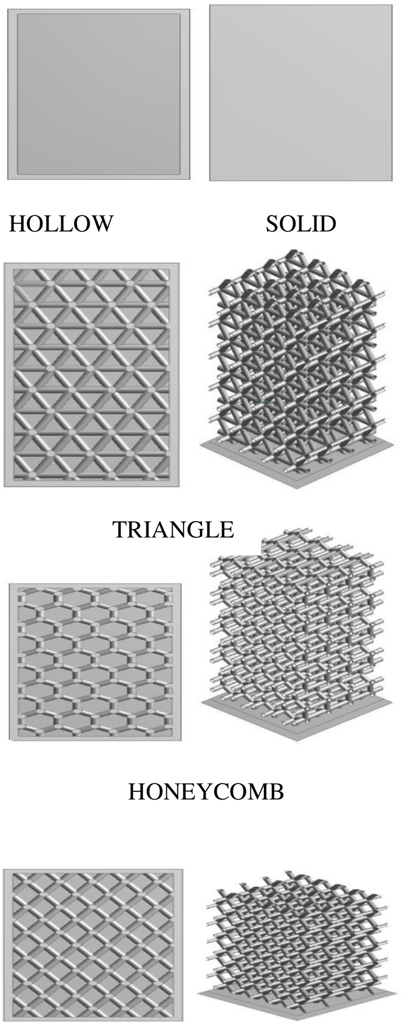


Figure 3. Different types of internal structures

These internal structures contain different types of internal densities which are listed in the Table 1.

Table 1. Internal densities

S.No	Name	Size (mm)
1	Loose	1
2	Compact	1.2

The internal densities of the internal structures are shown in the below Figure 4.

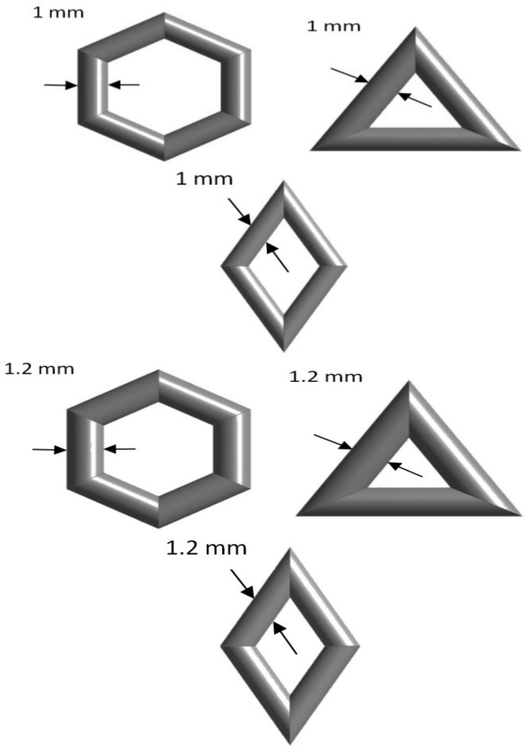


Figure 4. The internal densities of the internal structures

4. Finite Element Analysis

Analysis is done for all models with internal structures by varying the internal densities by using Ansys workbench. L.Villalpando [1] said that results from the finite element analysis are well matched with the experimental results performed on the compressive samples.

4.1. Loads and Boundary conditions

Load is given in the form of force as shown in Figure 5a. The magnitude of the force is varies between 500N to 20000N for all internal structure models with different internal densities. Fixed support is given to the bottom face of the object as shown in Figure 5b.

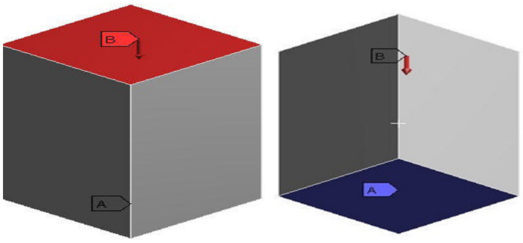
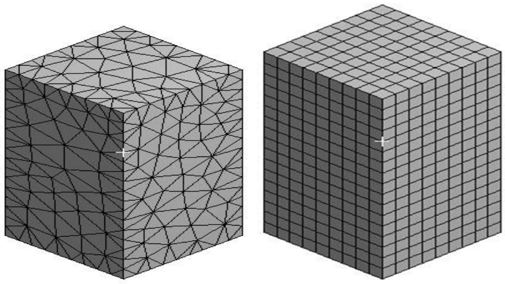


Figure 5a Figure 5b.

Figure 5. Loads and boundary conditions.

4.2 . Meshing

It is the process of converting geometric entities to the finite element entities [20]. 20 Node hexahedron elements are used for solid and hollow type internal structure. Higher order 10 Node tetrahedral elements used for triangle, honeycomb and rhombus internal structures. Fine mesh is carried out for the structures to get mesh convergence. The mesh of the internal structures is shown in the Figure 6.



Triangle, Honeycomb, Rhombus Hollow, Solid

Figure 6. Mesh of FDM specimens

The mesh characteristics for different internal structures are listed in the Table 2.

Table 2. Mesh characteristics of internal structures

Structure	Nodes	Elements
Hollow	3476	1733
Triangle	155017	87050
Honeycomb	156626	87269
Rhombus	113588	61358
Solid	6740	1377

4.3. Material Properties

ABS (Acrylonitrile Butadiene Styrene) Plus [1] is used as material for the analysis of the FDM parts. The material properties of the ABS material are listed in the Table 3.

Table 3. Mesh characteristics of internal structures

Density (kg/m^3)	Youngs Modulus (GPa)	Poisson's Ratio	Strength (MPa)
1040	2.22	0.35	65

4.4. Results & Discussions

FEA simulation is carried out for the all specimens with different internal structures and different densities. Load is applied in the form of force to a range between 500N to 2000N. Von-misses stresses are analyzed for all internal structures. Load is applied gradually to maximum compression yield point. Depending upon the Von-misses stresses, the breakage force is calculated and shown in the Figure 7.

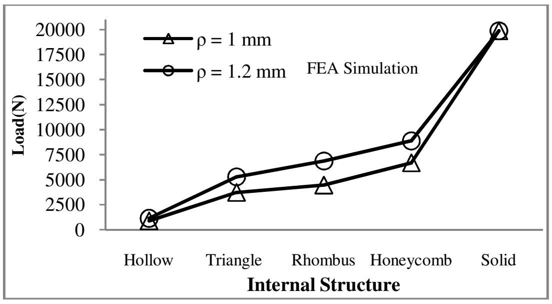
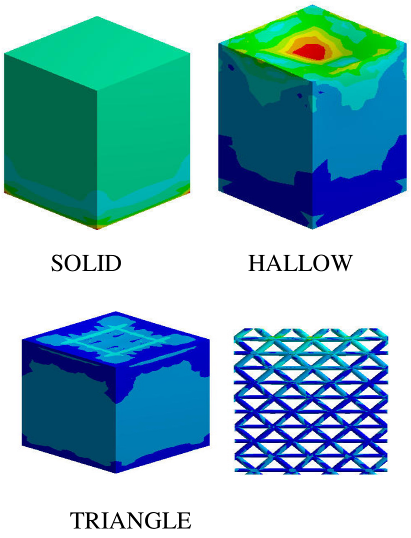


Figure 7. Failure load for different internal structures with different densities

From Figure 7,it is observed that honeycomb internal structure havingthe highest compressive strength followed by rhombus and triangle for both loose and compact densities.

Von mises stress contours of the different internal structures are shown in the Figure 8.



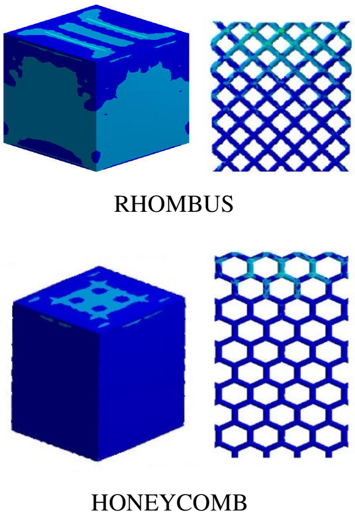


Figure 8. Von-misses Stress contours of the internal Structures

The von-misses stress contours produced in different internal structures are shown in Figure8.These 5 specimens are fabricated using FDM and they are experimentally tested and loading characteristics are noted.

5. Fabrication and Experimental Testing

5.1. Fabrication

A set of 5 different compression specimens were fabricated three times, and built using a Stratasys Mojo 3D printer with ABS material. In this process, through the nozzle a plastic material is extruded that traces the parts cross sectional geometry layer by layer. The build volume of this 3D printer is 127×127×127 mm^3 and the RP software used in this process is mojo print wizard. From this software we get build time and material usage. The RP machine and the work piece are shown in the Figure 9.

Figure 9. Work piece in a RP Machine

The obtained specimens with honeycomb, rhombus and triangle internal structures with supported material are shown in Figure 10.Supported material was removed by using post curing process.

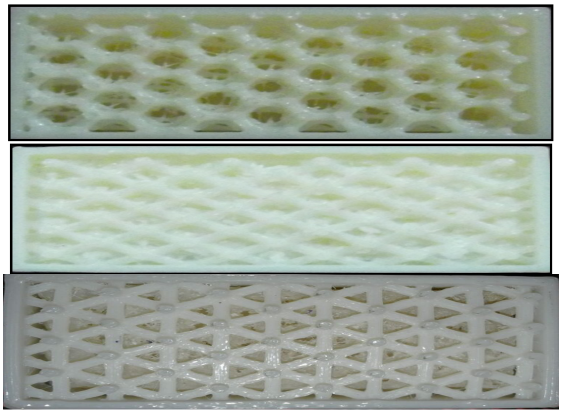


Figure 10. Internal Structures with supported material

Support material was removed using wave wash 55 support removal system. It contains ultrasonic heating chamber filled with amino based water solution maintained at temperature of 70 ˚F. The specimens are dipped into the solution for about 3hours. Due to this the support material is disintegrated in the tank. The post curing process setup is shown in Figure 11.

Figure 11. Post Curing process setup

After completing post curing process the fabricated structures are shown in the Figure 12.

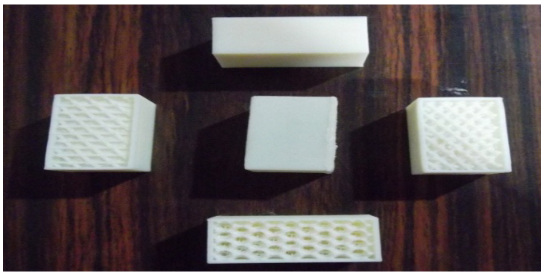


Figure 12. Internal structures after post curing process

From the RP machine, experimental values like build time & material usage are noted. Each model was fabricated thrice and average values were taken. Those values were plotted in a graph and shown in Figure 13.

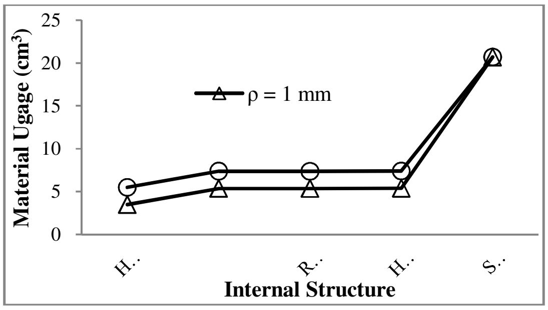


Figure 13. Material usage for fabrication (cm^3)

From figure 13 it is observed that there is no appreciate difference of material usage between triangle, rhombus and honeycomb internal structures. Solid has high material usage and hollow has low material usage compared to remaining structures.

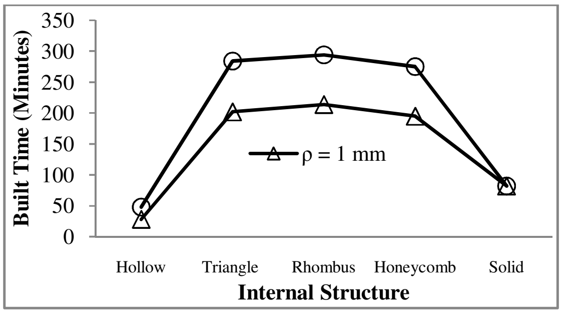


Figure 14. Build time for fabrication (Minutes)

Out of all internal structures, rhombus has the high build time and hollow has the low build time followed by solid and honeycomb. Honeycomb has less built time compared to rhombus and triangle.

5.2. Compression Test

Compression test is carried out for all specimens. For this a 40 ton universal testing machine (UTM) is used. The compression testing machine and specimen are shown in the Figure 15.

Figure 15. Compression test machine and specimen

The load is applied to the structures in axial direction. The resultant compressed specimens of different internal structures are shown in the Figure 16.

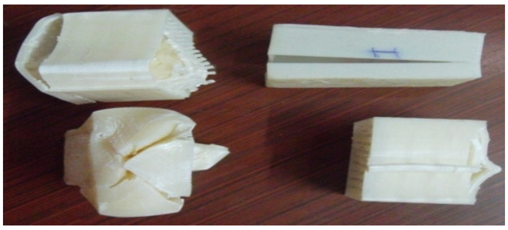


Figure 16. Compressed specimens

Figure 17 shows the loads at which internal structures are failed in compression test.

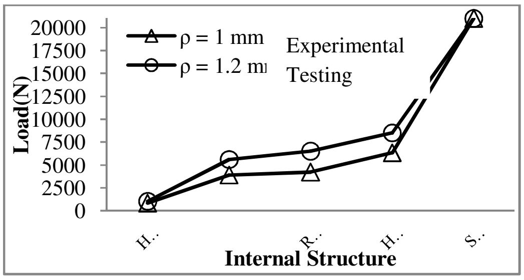


Figure 17. Failure Loads of internal structures

From Figure 17, out of all internal structures failure load is maximum for honeycomb structure followed by rhombus, and triangle for both internal densities. So it clearly indicates that honeycomb structure posses' highest compressive strength than all internal structures.

Figure 18 shows the comparison of the FEA and experimental results of compressive strength for 1 mm internal density specimens.

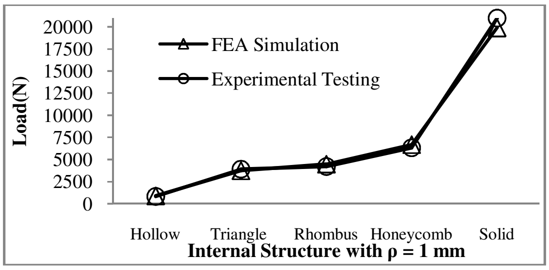


Figure 18. Comparision of failure loads between FEA Simulation and experimental Testing forρ= 1.

From Figure 18, it is observed that FEA results are nearly equal to the experimental results.

Figure 19 shows the comparison of the FEA and experimental results of compressive strength for 1.2 mm internal density specimens.

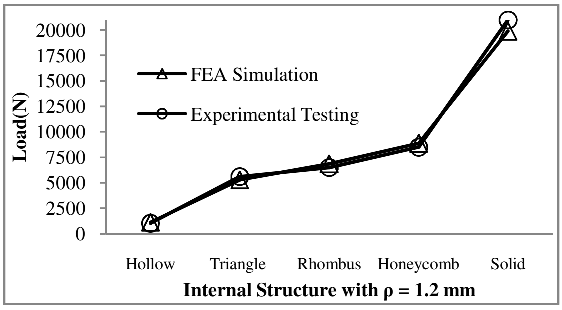


Figure 19. Comparision of failure loads between FEA Simulation and experimetal Testing forρ= 1.2.

From Figure 19, it is observed that FEA results are nearly equal to the experimental results.

Honeycomb has the high compressive strength than remaining structures except solid for both loose and compact densities.

6. Conclusions

From the above results, it can be observed that solid structure has high compressive strength and high material usage (weight). Hollow internal structure has less fabrication time, low compressive strength and less material usage. Material usage is approximately same for the remaining three internal structures (Triangle, Rhombus & Honeycomb) but honeycomb structure consumes less fabrication time and poses high compressive strength than that of the remaining three structures. From these observations, honeycomb internal structure is recommended wherever strength to weight ratio is required regard less of fabrication time. Solid internal structure is recommended wherever weight is not the critical factor.

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