Design the support structures for fused deposition modeling 3D printing

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Abstract

Fused deposition modeling (FDM) is one of the fastest growing three-dimensional (3D) technology and the extensively employed additive manufacturing process for producing prototypes and functional components in numerous engineering applications. Its widespread compliance can be attributed to its ability of building parts with complex geometry in reasonable time period. However, the fundamental drawback with FDM is the manufacturing of overhang structures. Therefore, the support structures are imperative and are most often utilized for 3D printing of overhanging surfaces to avert any failure especially when optimum orientation is ineffective. Certainly, this technique of providing support structures is not always adequate and several challenges can be associated with them, such as low printing efficiency, material wastage, higher time and material needs, post-processing requirements, likelihood of part damage, etc. As a result, this work carries out a study to determine the influence of different model interior fill and support structures on building time, material utilization in part as well as support structures, and overhang surface deformation. Additionally, this work has analyzed the deformation profile of the overhang surfaces. The primary objective in this study is the selection of appropriate setting or the strategy for efficacious and economical construction of overhang surfaces in FDM.

Keywords: Fused Deposition Modeling, Overhang Surfaces, Support structure, Deformation, 3D Comparison, 3D Printing

1 Introduction

The three dimensional (3D) printing also known as additive manufacturing (AM), layered manufacturing (LM), rapid prototyping (RP) or direct digital manufacturing (DDM), was initially introduced by 3D Systems in 1980s [1]. It can be identified as a manufacturing approach, where the physical parts are fabricated in a layer by layer fashion, directly from the computer-aided design (CAD) file. The 3D printing technology has been adopted passionately by the industries, academicians and research personnel, owing to its numerous benefits. The ability to produce complex geometries as well as its design flexibility are the primary advantages that can be associated with it. Moreover, its competence to manufacture unified products (i.e., assembled parts) cause considerable reduction in production time and manpower requirements [2]. It also does not require to maintain the inventory of spare parts as it can fabricate components whenever the demand arises. As a result of its diverse advantages, it possesses widespread applications in the areas of automobiles, aerospace, medicines, customized products, etc., [3].

3D printing, although, illustrates plentiful benefits, still there are challenges which needs to be overcome for its all-purpose acceptance in industrial set-up. One of the 3D printing limitations is the necessity of support structures in complex parts. Supports are generally introduced either in the form of vertical columns, or tree-like structures. The support structures have to be removed from the part to produce the final component, thus resulting in higher cost and material wastage [4, 5]. As a matter of fact, the fabrication in 3D printing begins from the lowest of the component and continues on in a layer by layer fashion to the top. Henceforth, the fabrication of complex features, especially, overhang structures in the absence of supports pose serious challenges, such as dimensional or geometrical inaccuracy, lower productivity, etc., [6]. The overhangs can be described as the down facing features, which need frame or construction to support their weight and to avoid overhang defects such as warping [7]. Certainly, the need to manufacture and then taking out the support material cause extensive material consumption, higher energy utilization, and a greater degree of manual post-processing, which of course neutralize many of its advantages [8]. According to Jiang et al. [5], the primary limitations of support structures can be summarized as follows.

- The prerequisite of manually eliminating the support inhibits the geometric freedom of the component as it emphasizes the importance of hand/tool accessibility.
- Support structure material is a wasted material and most often cannot be reutilized.
- Due to the generation of support structure, the fabrication time increases.
- Support structure may be destructive to the surface finish due to post-processing (support removal).

There is a significant economic requirement in minimizing the costs pertaining to support structures in 3D printing. To accomplish a balance between support utilization and performance of 3D printed parts, it is crucial to analyze the influence of supports on printed parts. There is a dearth of published works, which have investigated the support structures and optimized them for minimum material wastage, lower fabrication time, reduced energy cost, etc. Although, there are some papers which have been published with reference to support analysis, but majority of them are related to either optimizing the process parameters or obtaining the suitable build orientation for 3D printing. For example, Xu and Wong [9] studied the effect of part building direction on building cost, time and surface finish for various RP technologies, such as stereolithography (SL), selective laser sintering (SLS), and fusion deposition modeling (FDM) and laminated object manufacturing (LOM). Similarly, Cheng et al. [10] used a multiple objective-function method for determining the optimal orientation for SLA process. The maximization of the part accuracy and minimization of the building time were considered as the primary objectives. Moreover, to study the effects of AM process parameters on the mechanical properties of the produced part, Anoop Kumar Sood et al [11] used design of experiments (DOE). The different parameters considered were layer thickness, orientation, raster angle, raster width, air gap, etc. In one of their studies, Pandey et al [12] showed that the part deposition orientation significantly affects build time, support structure, dimensional accuracy, surface finish and cost of the prototype. The influence of the layer thickness, deposition style, support style and building orientation on the tensile strength, dimensional accuracy and surface roughness was investigated by Chung et al. [13]. The results showed that the building orientation had significant effect on the tensile strength and dimensional accuracy. Thrimurthulu et al. [14] employed genetic algorithm to obtain the optimum deposition orientation in order to improve the part surface finish and reduce build time. Moreover, Arjun et al. [15] proposed an approach for selecting a fabrication orientation in 3D printing and established a model to optimize support area, fabrication time and surface roughness. The proposed optimization model improved the fabrication efficiency of RP systems and reduced the cost.

To make 3D printing an environmental friendly and sustainable manufacturing technique in terms of fabrication time, material usage and cost, it is important to minimize the usage of supports. The studies have to be conducted to minimize the support waste by devising the appropriate support strategies. Therefore, in this paper, the effect of support strategy on printed qualities is researched in FDM processes. The FDM is considered in this work because, it is the most common and widely used AM technology, due to its simplicity and low cost. Moreover, it needs support structures for assisting overhang, hole or edge features, resulting in wasted material and printing time [4, 16, 17, 18]. In this work, theoretical analysis and experimental study are performed to analyze the effect of the different support structures (or the infill) on the quality of the FDM produced parts. The aim of this work is the evaluation of the effect of model interior fill and support structures on the building time, model material and support structures material and overhang structure deformation and thereupon selecting the appropriate setting.

2 Fused Deposition Modeling

FDM process can be defined as a material extrusion AM process, which begins by feeding the thermoplastic material from a spool of thin plastic filament as shown in Figure 1. This thermoplastic is melted in a liquefier head by a resistance heater. Afterwards, the molten thermoplastic is extruded to form a thin layer which is solidified to form one layer of the part, starts from the lower level of the shape, layers are deposited on previous layers, laminating and fusing together in a layer by layer fashion [19, 20, 21, 22]. The FDM process is based on the extrusion of heated feedstock plastic filaments through a nozzle tip to deposit layers onto a platform to build parts layer by layer directly from a digital model of the part. The simplicity, reliability, and affordability of the FDM process have made this 3D printing manufacturing technology widely recognized and adopted by industry, academia, and consumers. The FDM process has also been widely used by research and development sectors to improve the process, develop new materials, and apply the FDM systems in a wide range of engineering applications. The following sections describe the FDM parameters considered in this study.

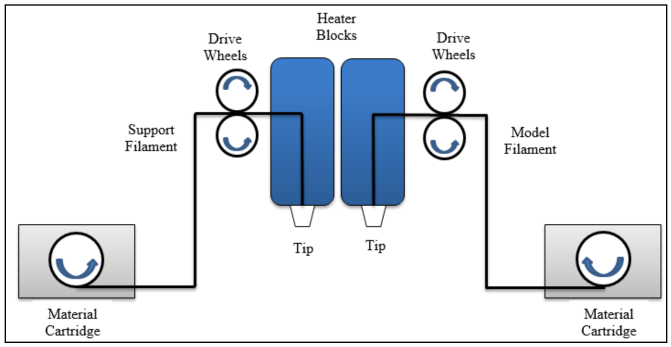

Figure 1: Schematic of FDM process

FDM process consists of several parameters, however in the current study model interior and support structures fills are considered. The model interior fill establishes the type of fill used in interior areas of the fabricated part. The solid, sparse high density, and sparse low density were the model interior fill types as shown in Figure 2 (a). The solid style is needed when a stronger, more durable part is desirable. The sparse high density is the default model interior style and it is highly recommended. Similarly, the sparse low density interior can be identified as a "honeycombed/hatched style.

Support structure is essential in building the overhang structures in order to prevent the overhang deformations. It is used to brace the model material during the build process and it's removed when the part is completed. Figure 2 (b) shows different types of support structures fills, such as surround, basic, sparse and smart for FDM overhang parts. The surround denotes that the supporting structure covers the building piece and a tighter interior arrangement is adopted, while basic denotes that the supporting structure is generated in a suspended midair building process and a tighter interior arrangement is also adopted. The sparse represents that the supporting structure is generated in a suspended midair building process but a looser interior arrangement is adopted instead.

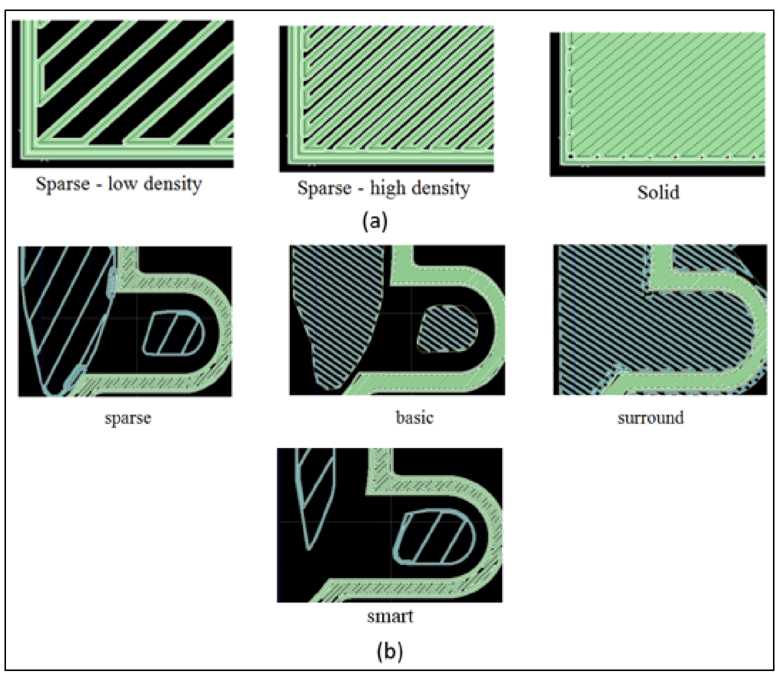

Figure 2: FDM Build setting (a) Model interior fill; (b) Support interior fill

In the current study one factor at a time DOE approach was employed to evaluate the effect of the model interior fill (Solid model, Sparse high density and Sparse low density) and support structures (Surround, Smart, Basic, Sparse) on the building time, model as well as support materials consumed and overhang structure deformation. The effect of layer thickness was assumed negligible owing to the prismatic nature (no curvatures) of overhang surfaces considered in this study. As a consequence, the layer thickness was fixed at 0.254 mm.

3 Material and Approach

The ledge overhang structure having dimensions of 5 mm solid long, 20 mm wide and 30 mm height with 30 mm overhang long and 5 mm overhang portion thickness was designed as shown in Figure 3. It was chosen because the region which forms the overhang portion parallel with the build plate represents its critical geometry and self-supporting layers are not possible in this area.

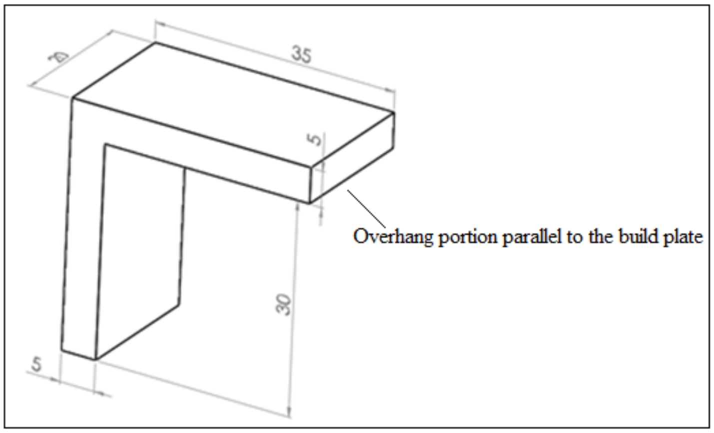

Figure 3: Ledge overhang structures dimensions

The CAD models of specimens were saved in Standard Tessellation Language (STL) file and imported into Materialize Magic software for error fixing. The most common STL errors such as gaps, bad contours, noise shells, overlapping and intersecting triangles etc., were removed before generating support structures. The STL file then imported into Catalyst software to adjust the building parameters and generate the support structure as shown in Figure 4.

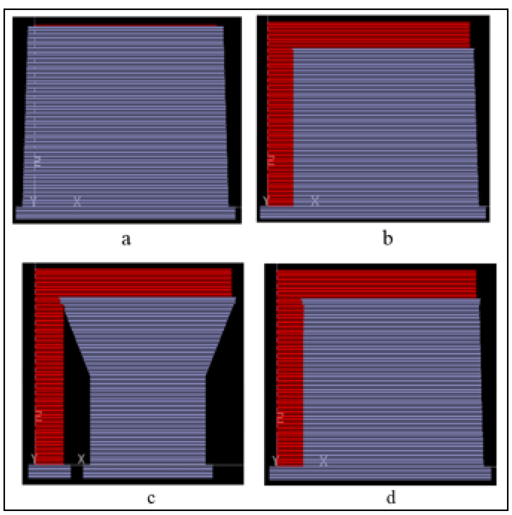

Figure 4: Overhang structure with a) Surround support b) Basic support c) Smart support d) Spares support

The Acrylonitrile butadiene styrene (ABS) thermoplastic in filament form, was melted using a specially designed nozzle head and extruded to build the physical model. Figure 5 shows the chemical composition of ABS materials and the Figure 6 shows the microstructure of ABS filament.

Element	Weight%	Atomic%
C K	93.23	95.74
O K	4.23	3.26
Al K	0.79	0.36
Si K	0.35	0.15
Cl K	1.40	0.49
Totals	100.00	

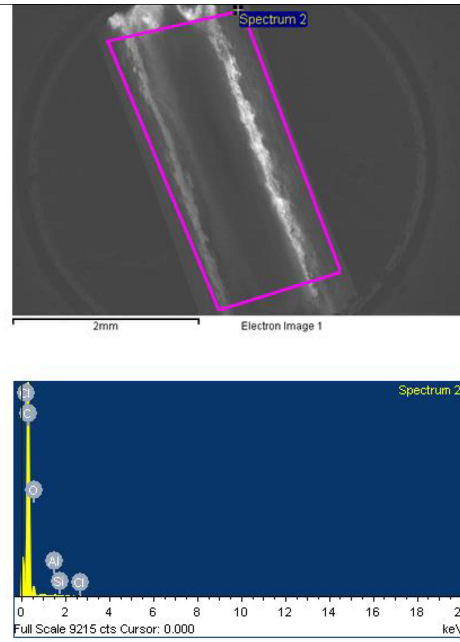

Figure 5: Chemical composition of ABS

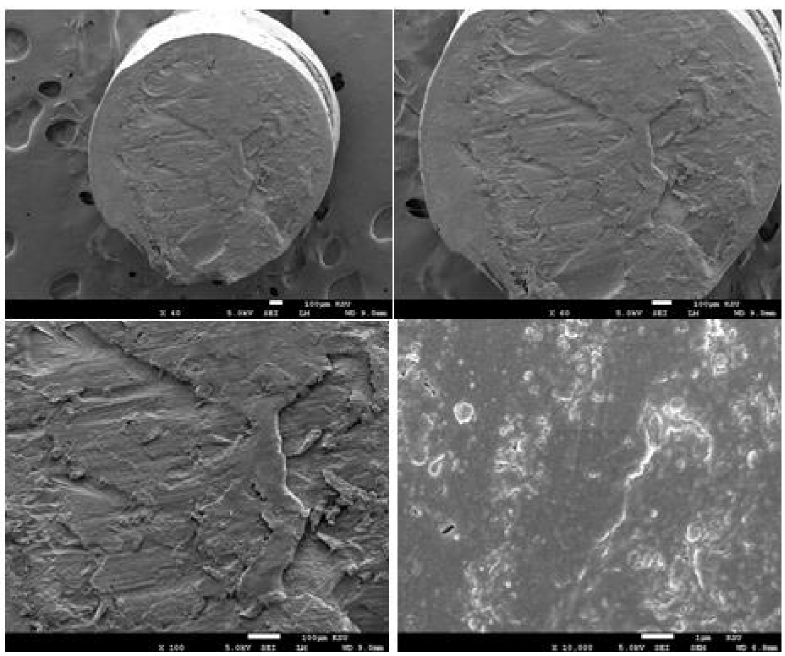

Figure 6: Scanning Electron Microscopy (SEM) image of ABS filament

The Dimension Elite machine from Stratasys ® Company as shown in Figure 7 working on FDM technology was used to fabricate the overhang specimens. The generated slices were constructed in the machine by building one layer at a time upon others using ABS thermoplastic material.

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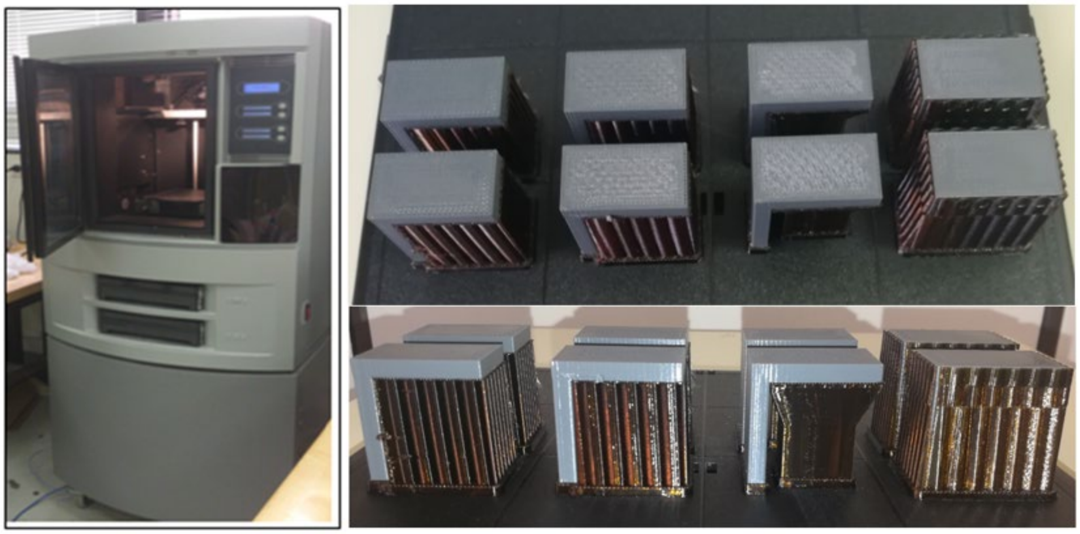

Figure 7: Dimension Elite FDM Machine and some fabricated specimens

Figure 8 (a) and (b) shows the top and side views of specimens with different model interior fill and support structures fill during the building process.

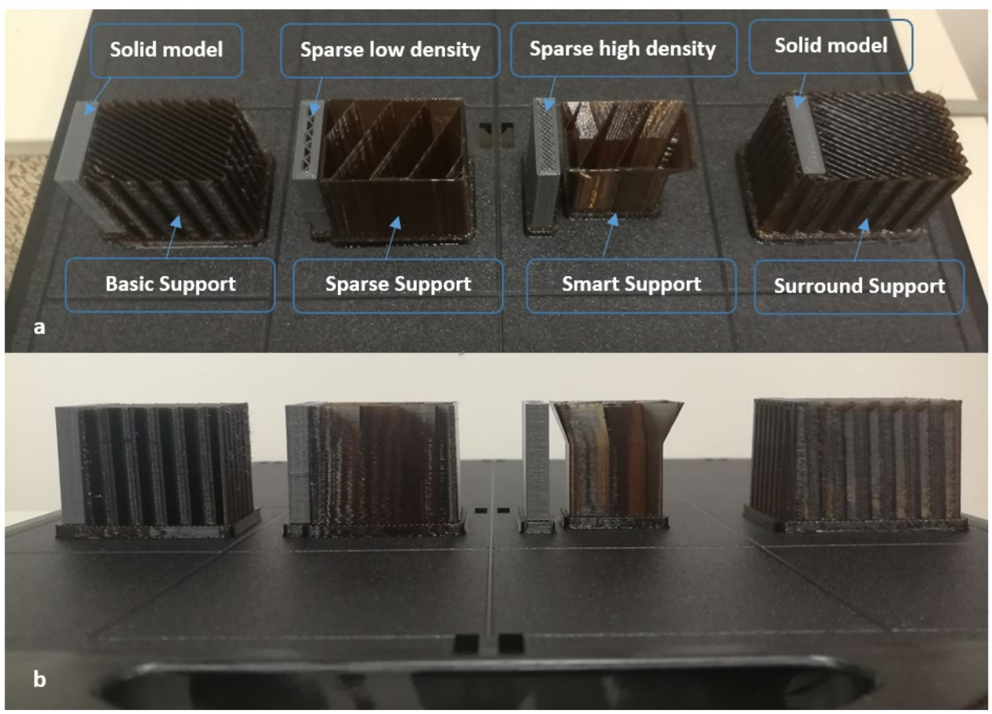

Figure 8: Specimens during building a) top view b) side view

The fabricated specimens were subjected to ultrasonic machine with chemical solvent dissolution (post processing) to remove the support structures.

In order to evaluate the overhang deformation, the 3D comparison analysis in Geomagics Control was utilized [23]. The 3D comparison analysis has been identified as one of the robust and comprehensive techniques, to distinctly represent the surface deviations between the test geometry and the reference CAD model [24, 25]. Before performing deformation analysis, three regions (Root, Center and Cusp) were defined on the overhang surface as shown in Figure 9. The “Root” region represented the region closer to the fixed end of the overhang surface, while the region “Cusp” represented the free end of the overhang surface.

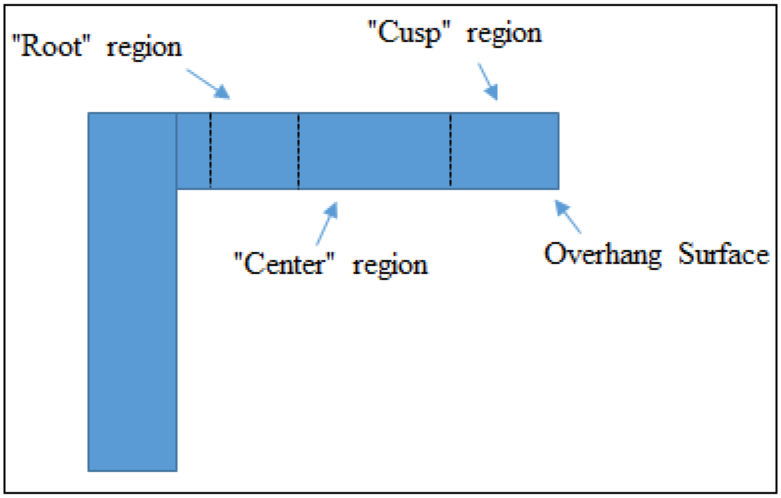

Figure 9: Representation of three regions (locations) on the test specimen

The average surface deviation each at three mentioned regions was computed in order to quantify the overhang deformation. The deformation analysis process commenced with the acquisition of point cloud data of the overhang surfaces using the laser scanner mounted on the Faro Platinum arm as shown in Figure 10.

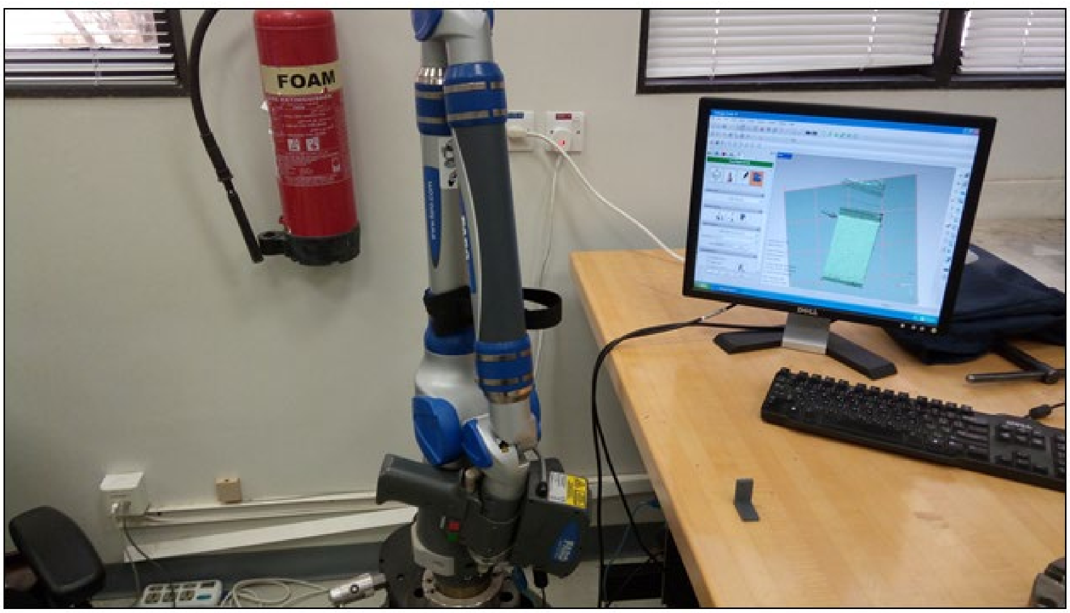

Figure 10: Acquisition of point cloud data for test specimens using Faro Platinum arm

After the digitization of test specimens, the best fit alignment procedure was implemented to accurately superimpose the test part on the reference CAD model. The best fit alignment had to be carried out to ensure that both the test and the reference surfaces were positioned in the same coordinate system. Once the two surfaces (test and reference) were aligned, twenty five points each on three regions were determined and the average deviations were estimated in each region. Several iterations were performed to finally reach the average deviations in the three regions. The average deviation statistic was used because it helped in determining the deformation profile along the overhang surface.

4 Results and Discussions

The building time, model material and support structures materials were acquired directly from the analysis software which gave exact values. To evaluate the effect of support structure fill on the removability of the support structures the time for removing the support structure was used as a measure. The model was monitored throughout the duration

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of post processing in order to record the time for removing the support structure. Figure 11 shows the models with support structures after four hours.

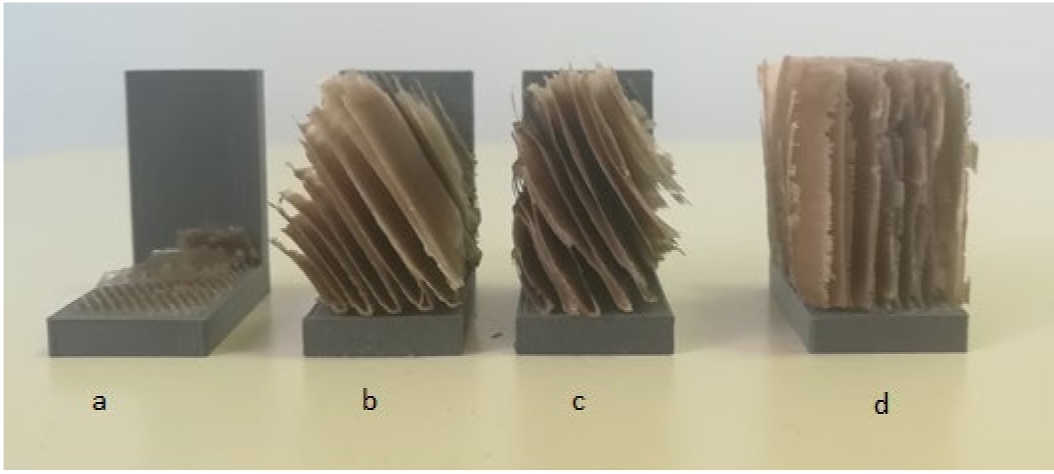

Figure 11: Specimens during support removal a) Smart b) Sparse c) Basic d) Surround

After fabrication, all the specimens were visually inspected at first place in order to validate if they were from any defect. To begin with, the building time was analyzed by varying the model and support material fills. The building time comprised of model and support materials extrusion and base plate descent after each layer. As shown in Figure 12, it was analyzed that the support structure fill had a tremendous effect on the build time as compared to the model interior fill. There was a significant difference in build time when the geometry and the density of the support structure fills were changed. The graphical analysis also confirm that the smart support structure fill exhibited the minimum building time as compared to spares, basic and surround support. However, in case of the model interior fills the building time was almost similar in each case. In fact, the sparse high density fill resulted in the minimum build time and the solid model fills had the highest build time for all support structures. It is also worth noting that there was not much difference in the building times of the sparse low and sparse high material fills.

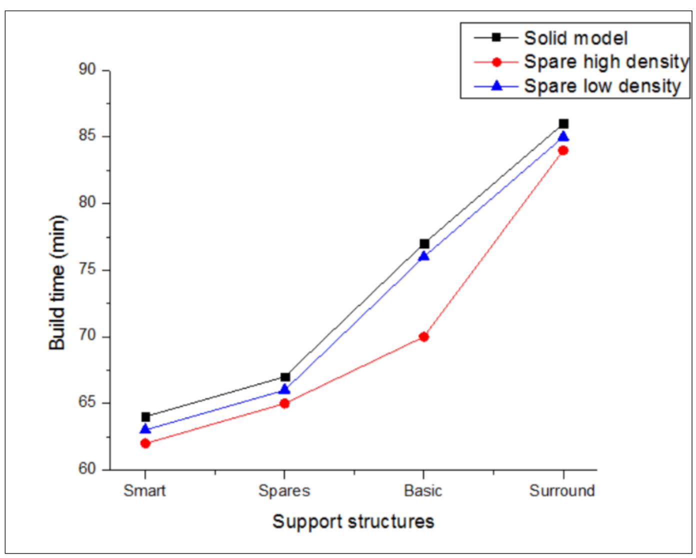

Figure 12: Effect the model interior fill and support fill on the building time

The investigation of different model interior and support structure fills on model material consumption resulted in the plot as shown in Figure 13. It was revealed from this plot that model interior fills possessed a significant effect on model material consumption. As the density of model material fills increased, the material consumption also increased. The solid model fills resulted in the highest model material consumption while the sparse low density fills resulted in the lowest model material consumption.

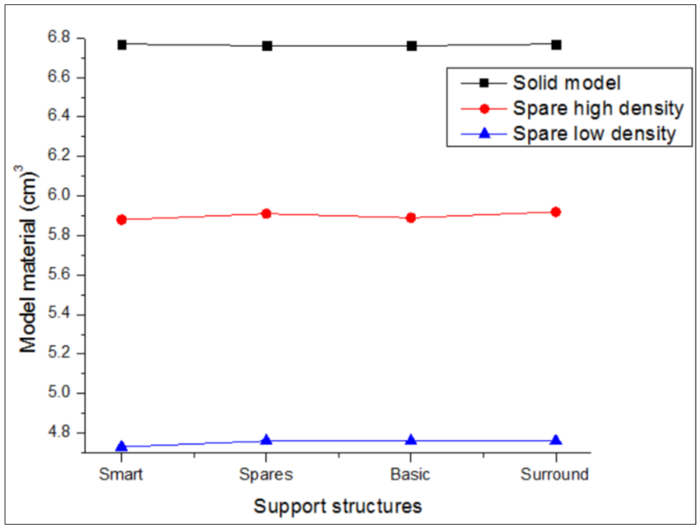

Figure 13: Effect the model interior fill and support fill on model material consumption

Similarly, the results in Figure 14 showed that the support structure fill had an appreciable effect on the support structure material consumption. Moreover, the support material consumption increased with increase in the volume and density of the support structure fills. The smart support structure fill resulted in minimum support material consumption and the surround fill consumed maximum volume of the support material.

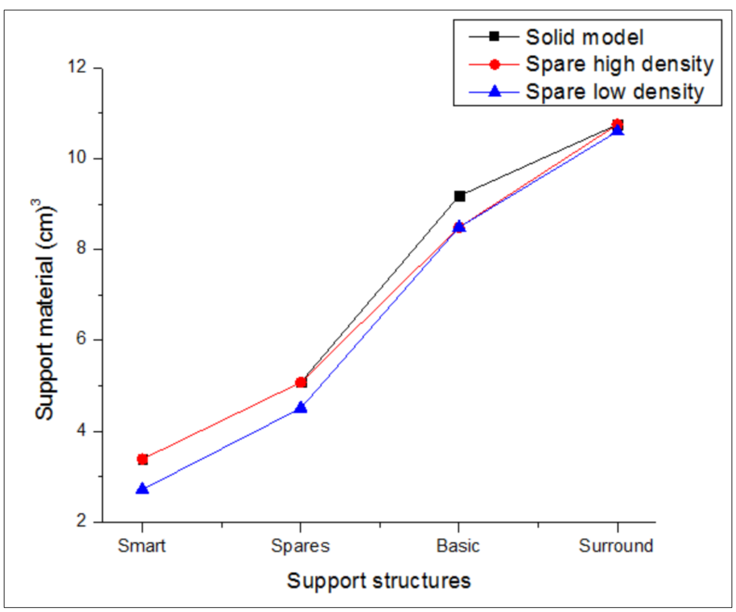

Figure 14: Effect the model interior fill and support fill on support material consumption

The results as shown in shown in Figure 15 depicts that the smart support structures required the lowest time of about 4.5 hours for their removal. However, the surround support fill required the highest time of more than 11 hours. It was also observed that the removal of sparse support structures were easier to remove as compared to the basic support structures.

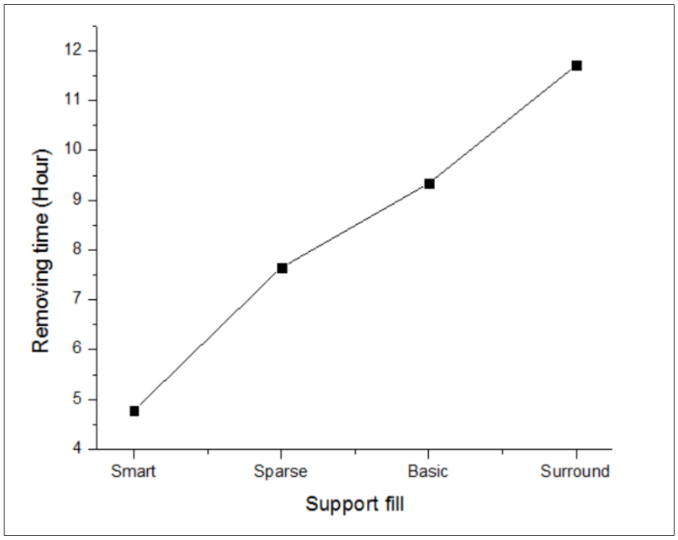

Figure 15: Effect the support fill on the support removal

The results of the 3D comparison from the analysis software has been represented graphically in Figure 16. From the analysis, it can be realized that warping or shrinking effect occurred in all the overhang surfaces irrespective of the model material fill or type of support structure. Indeed, the uneven distribution of heat resulted in the origination of internal stresses and lead to the bending of the part in a downward direction as can be seen through deformation profile in Figure 16. As a consequence of the thermoplastic polymer becoming cold after warming up to the glass transition temperature, it has the tendency to shrink. Although, the presence of support structure subside the influence of warping effect, but it cannot be completely excised out owing to many other factors, such as temperature gradient, type of support structure, geometry type, etc.

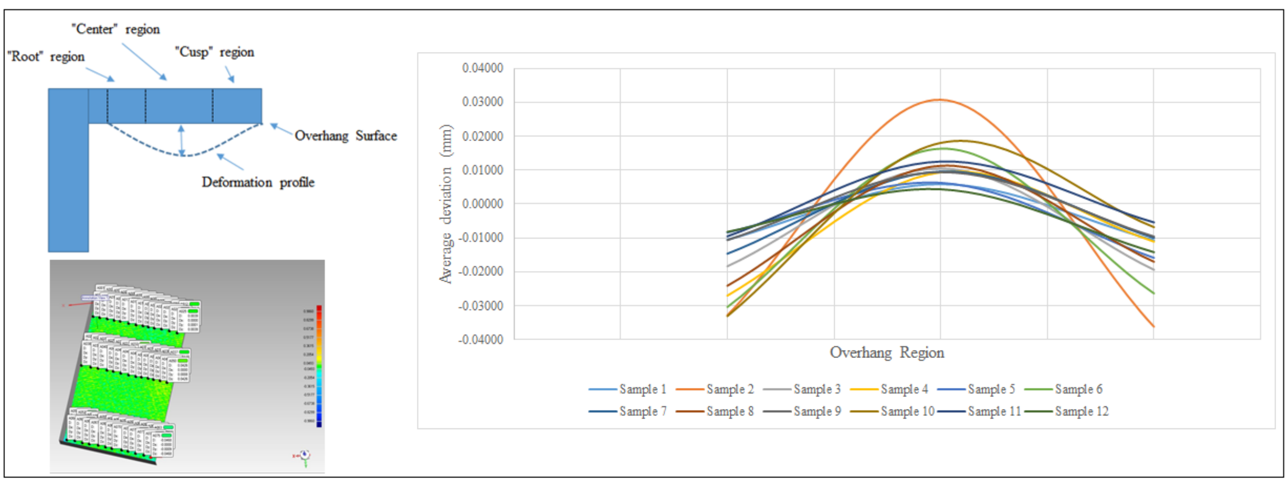

Figure 16: Outcome obtained from 3D Comparison analysis

When the combination of various material fills and support structures were investigated, it was revealed that the surround as well as sparse support structures and sparse low material fill resulted in least deformation. After analyzing the various performance indicators, it can be inferred that sparse low material fill should be preferred option while fabricating parts using FDM. The reason can be attributed to its relatively low building time, lowest material consumption as well as minimum deformation in the overhang structures. Similarly, when the support structures were analyzed, the smart support structure provided lowest building time, minimum support material consumption as well as lowest support removal time. However, while analyzing the deformation of overhang structures, smart support structures did not provide satisfactory results. The surround as well as sparse type of support structures produced minimal deformation in the overhang surfaces.

5 Conclusion

The influence of different model material fills and type of support structures on building time, material consumption, support removal time as well as overhang deformation has been investigated in this work. The outcomes from various analysis corroborates that kind of material fill and the type support structure inevitably effect the performance the FDM process in terms of both process time as well as the quality of fabricated parts. Therefore, it is imperative, especially in case of overhang surfaces to employ an appropriate combination of model material fills and support structures for acquiring adequate results. The deformation analysis using 3D comparison conformed that the overhang surface bent in the upward direction, quite similar to the profile of downward bell shaped curve. Although, support structures are crucial to minimize the warping effect, but they cannot entirely eliminate surface deformation due to the presence of many other factors, such as part orientation factor, temperature variation, layering effect, geometry complexity, etc. Moreover, the heedful investigation suggested sparse low material fill as the best choice for model material fill in FDM production. Similarly, this study identified smart type as the best option for support structure if the objective is to minimize building time, support material consumption as well as support removal time. However, the surround as well as sparse type of support structures represented a better alternative if minimal deformation is the preferred objective in the overhang surfaces. The future work aims towards a comprehensive investigation with other complex overhang geometries, a large number of sample specimens, deformation analysis using a touch trigger probe of the fixed coordinate measuring machine in addition to 3D comparison analysis.

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