Impact of support structure on surface roughness and mechanical properties of PLA 3D printed parts by FDM

Impact de structure de support sur la rugosité de surface et les propriétés mécaniques des pièces en PLA imprimées en 3D par FDM

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ABSTRACT. This study investigates the effect of support infill angle and its density, transverse at 90°, inclined at 45°, axial direction at 0° and crossed filament by (0°/90°), (45°/-45°) and (0°/45°) on surface quality and mechanical properties using three different strategies. The surface roughness and flexural properties of the specimens are analysed and compared as well as the material waste and printing time. According to results of this study, the variations in the support infill angle resulted in diverse flexural strength and surface quality.

RÉSUMÉ. Cette étude examine l'effet de l'angle de remplissage du support, transversal à 90°, incliné à 45°, direction axiale à 0° et filament croisé par (0°/90°), (45°/-45°) et (0°/45°) sur la qualité de la surface et les propriétés mécaniques en utilisant trois stratégies différentes. La rugosité de la surface et les propriétés de flexion des éprouvettes sont analysées et comparées, ainsi que la perte de matériau et le temps d'impression. Selon les résultats de cette étude, les variations de l'angle de remplissage du support ont donné lieu à une résistance à la flexion et à une qualité de surface différentes.

KEYWORDS. Additive manufacturing, FDM, Support structures, Support infill angle, Mechanical properties and surface quality.

MOTS-CLÉS. Fabrication additive, FDM, Structure de support, Angle de remplissage du support, Propriétés mécaniques et qualité de surface.

1. Introduction

Fused deposition modeling (FDM) is one of the seven categories of additive manufacturing [NAH 23] and is the most and the extensively employed additive manufacturing technology to produce the intricate geometries used in in a wide range of engineering applications. This process is widespread used because of its ability to build the complex parts in reasonable time and cost. However, one of the major challenges associated with FDM is the need for support structures during the printing process especially optimized parts. Support structures are necessary to provide a stable base for overhanging features (hole,overhang angle,length and bridges) and prevent distortion or collapse of the 3D printed part. However, the addition of support structures can increase production time, material usage, and post-processing efforts, leading to higher costs and longer lead times. Furthermore, removing the support structures can be a challenging and time-consuming process, potentially leading to damage or deformation of the printed part.

Several research studies have been conducted on minimizing support usage or developing new support approaches by integrating topology optimization parameters such as Liu et al [LIU 17] that integrated the self-support manufacturability constraint in additive manufacturing process, Ouchaoui et al [OUC 23] examined the impact of topology optimization parameters on topology quality, strength and computational costs. Antar et al [ANT 22] [ANT 23] possibility to topologically optimize a mesostructured part printed take into account the manufacturong parameters through a numerical approach.

Soluble materials have also been used by several researchers as ANTAR et al [ANT 23] explored the structural performance of the optimized design in a three-point bending test using polyvinyl alcohol

(PVA) as the soluble support structure . Although soluble materials offer numerous advantages in the 3D printing field, they may not be suitable for intricate components. In certain circumstances, alternative non-soluble materials are indispensable.

Therefore, understanding the impact of support structures on FDM production is crucial for optimizing the process and achieving high-quality, cost-effective, and efficient manufacturing. Numerous studies have suggested different designs for support structures, with the goal of optimizing their impact on printed qualities. Started by Jiang et al [JIA 18] conducted a comprehensive review of fifty-seven scholarly articles focusing on optimization of support structures. These papers were categorized into six distinct groups in order to lay the groundwork for a standardized framework that can guide future research Ameen et al [AME 19] studied the impact of various model interior fill and support structures on building time, material utilization, and overhang surface deformation in Fused Deposition Modeling (FDM) 3D printing. The study aimed to identify the most efficient and cost-effective settings for constructing overhang surfaces in FDM processes. Their findings highlighted that sparse low material fill for model material fill and smart support structures were the optimal choices for minimizing building time, material consumption, and support removal time. Additionally, their study suggested that surround and sparse support structures were more effective in reducing deformation in overhang surfaces. Jiang et al [JIA 19]. examined the effects of three support strategies on printed qualities, including surface roughness and flexural properties. Their results showed that parts 3D printed using the zigzag support method exhibited the highest flexural modulus, while lined support consumed the least support material and printing time. Line and concentric support methods have been investigated by Stringer et al [STR 18]. Their results showed that the printed qualities of concentric support method (surface roughness, deformation, roundness and angle accuracy) are all better than those of line support but it requires more print time and support material consumption than line support method. Patil et al [PAT] studied aimed to improve efficiency in 3D printing processes by studying existing support structures like linear, cross, triangular, concentric, and zig-zag, and generating hybrid structures based on the results. The hybrid structure "Zigzag L1" was identified as showing the best performance in terms of strength, time, and material usage.

In cases where support structures are unavoidabl, there remains a research gap in the identification of the suitable support approach tailored to specific printer settings, aiming to achieve maximum strength and enhanced print precision in Fused Deposition Modeling (FDM).

In this study, the effect of support infill angle and strategy on part properties (surface roughness and flexural properties) 3D printed by FDM process is investigated, considering support waste and printing time to select the appropriate setting for enhancing the printed parts. The angle and type of support structure will directly affect the supported geometry’s performance and volume of support structure, and therefore the final printing surface quality.

2. Material and method

To investigate the impact of support structure on printed qualities, we used a density of 30% for each of the three different infill angles. Three different support structure strategies : line, rectilinear, and grid as provided by Idea Maker 4.3.2 have been used in this study. Figure 1 illustrates the specimens with their support, different support infill angles, and their dimensions. The white regions presented the part and red regions presented the support. All of specimens were additively manufactured under the same condition and each combination has been printed three times. Total of the specimens tested is 18 samples. RAISE 3D E2™ 3D printer double extruder has been used, the nozzle has a diameter of 0.4 mm and uses a 1.75 mm diameter polylactic acid (PLA) filament. The parameters used for printing the specimens are depicted in table.1.

Parameter	Value	
	Part	Support structure
Layer thickness	0.2 mm	-
Printing speed	60 mm/s	45 mm/s
Infill percentage	30%	30%
Number of perimeters	2	-
Temperature	225°C	220°C
Build orientation	XYZ	
Bed temperature	60°C	

Table 1. *Printing parameters of the specimens with different support strategies.*

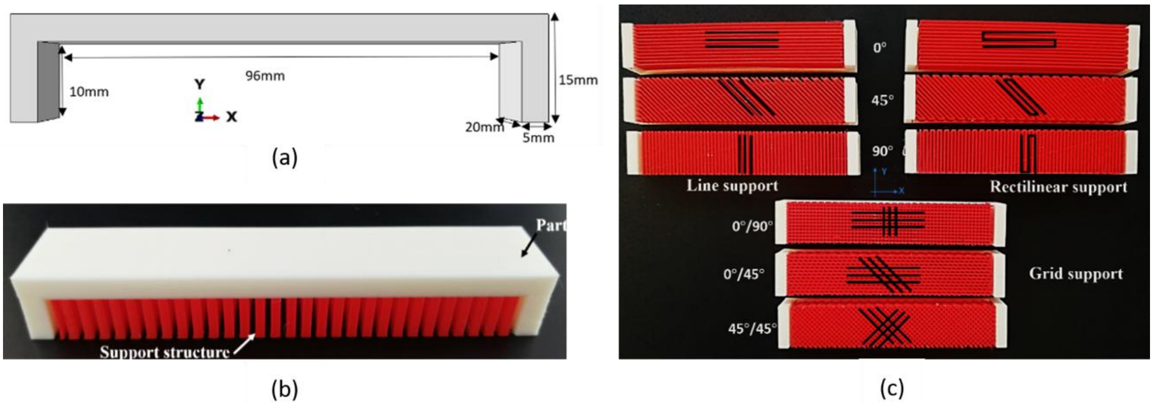


Figure 1. *(a) Dimension of the specimen (b) part with its support. (c) parts with different support strategies*

The specimens are three-point bending tested according to ASTM D790 standard using MTS 810 machine with maximum load of 100 KN as it shown in Figure 2. The distance between the spans is 82.3mm. The bending test is performed using a vertical displacement of 2.2 mm/min, the load-displacement curves have been recorded.

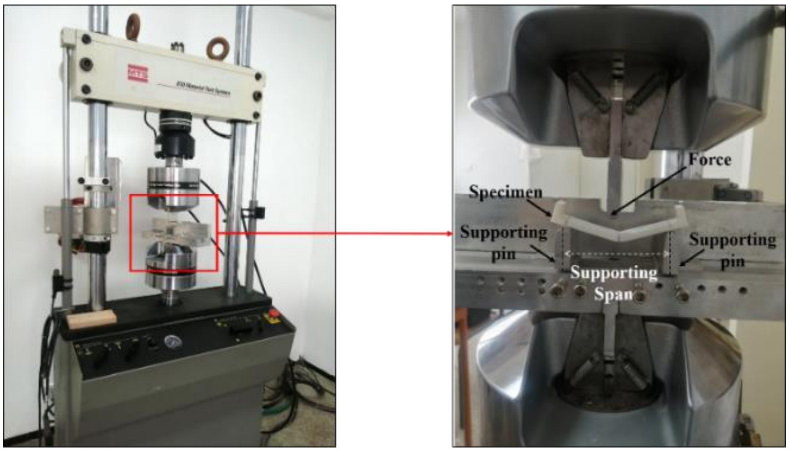


Figure 2. *Three-point bending test set up of the specimen using MTS-810 machine.*

3. Experimental results and discussion

The impact of various support infill angles was evaluated through the examination of support material quantity, printing, surface roughness and flexural properties

3.1. *Support usage and printing time*

Mass of the part with and without support in different support strategies are listed in Table 2. The parts were weighted with an analytical balance PRACTUM 124-1S Germany. According to Table 2, the 0° line for two density cases was the lightest, followed by the zigzag and the grid. Line support strategy of 0° is the best choice from the perspective of mass of part or material consumption.

Support strategy	Support infill angle	Mass with support (g) ±0.0001	Mass of final part (g)	Time (s)
Line	0°	15.4956	8.8219	4800
	45°	15.8527	8.845	5520
	90°	15.803	8.895	5700
Rectilinear	0°	15.9441	8.8927	4920
	45°	16.6742	8.8965	5280
	90°	16.612	8.8649	5340
Grid	0°/ 90°	16.3381	9.1958	5460
	45°/−45°	16.2815	9.002	5700
	0°/ 45°	16.2887	8.9185	5400

Table 2. *Average mass in different support strategies.*

The required time to additively manufacture a part and its support is also presented in Table 2. Clearly, the line support strategy consumes the least time to complete the printing of all the part. The printing time increases as the angle of support infill angle increases. This is because greater angles generally require many supports to maintain the overhanging segments of the printed object. This is principally explained by the fact that line support method is the least consuming in terms of support materials. Furthermore, this is also due to the print path of nozzle, because the rectilinear support strategy method required less time than grid method but consumes more material than grid, which corresponds to the nozzle path of Grid that is longer than rectilinear to fill the layer. It was also observed that the removal of line support structures was easier to remove as compared to the rectilinear and grid support structures.

3.2. *Surface roughness measurements*

Surface roughness, as a non-directional series of parameters is calculated as follows:

$$R_a = \frac{|y_1|+|y_2|+|y_3|+\cdots+|y_n|}{n} \quad [1]$$

Where Ra measures within a certain sampling length the arithmetic average of the peaks and valleys of the plastic surface.

Surface quality of the supported area determining by the surface roughness Ra is calculated after the removal support structures in different support infill angles. In the absence of a suitable measuring instrument designed for this particular surface type, our study has led us to explore alternative approaches for the analytical evaluation of surface roughness. Subsequently, we decided to utilize the arithmetic average deviation. This process involved identifying ten equally spaced points on the sample, distributed symmetrically on both sides, and then measuring the deviations between these points and a baseline. Despite recognizing the challenges presented by the rough texture of the elements, this technique enabled us to gather relevant data.

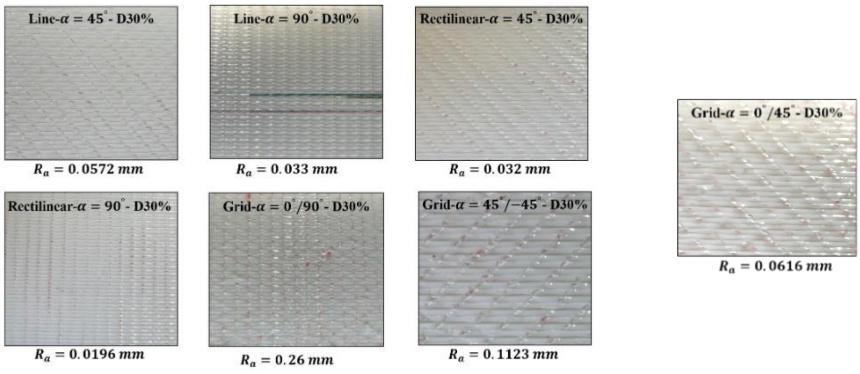


Figure 3. *Surface roughness value of the specimens after removing supports of different support infill angles.*

Figure 3 illustrates the Ra values of the tested specimens. The exclusion of 0° case for the line and the rectilinear support strategy is attributed to the extremely unsatisfactory surface finish (very poor surface finish). The best surface roughness was obtained in printed part of rectilinear support strategy, Ra = 0.0196 mm with a 90° infill angle. On the other hand, the worst surface roughness was obtained in printed part of grid support strategy Ra = 0.26 mm with a 0°/90° infill , the surface roughness decreased significantly with the inclination of the support infill angle for the identical support strategy, and the rectilinear support strategy of 90° is the best surfac e roughness behavior in all FDM 3D printed parts analyzed.

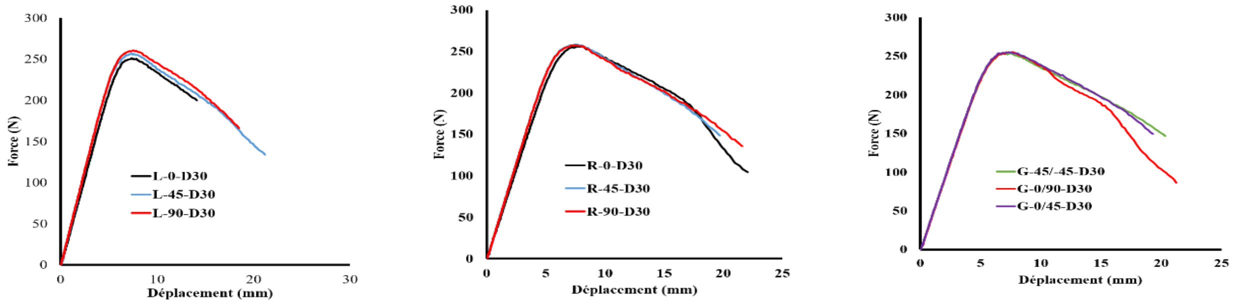
3.4. *Flexural properties*

The selection of the bending test was made in order to explore the mechanical characteristics of the structures via the assessment of the bending stress and strain, which were computed in accordance with the standard norm ISO D790-(2019) [STA 19].

$$\sigma_f = \frac{3FL}{2bd^2} \qquad [2]$$

$$\varepsilon_f = \frac{6Dd}{L^2} \qquad [3]$$

Where, F is the maximum load (N), L length of support span (mm), b and d are the width and depth of the sample (mm). D is the maximum deflection of the center of sample (mm). The force-displacement curves acquired from bending experiments on parts production with varying support infill angles are depicted in Figure 4. The line support strategy with an inclination of 90° exhibits the highest maximum force value among the various combinations, with the zigzag and grid support strategies following suit.



(a) (b) (c)

Figure 4. *Force-displacement curves of parts printed in different support infill angle: (a) Line (b) Rectilinear and (c) Grid.*

Table 3 provides a summary of the data collected regarding the flexural characteristics. It is observed that, the line positioned at 0° exhibits the greatest bending stress, followed by the zigzag and the grid. The purpose of this study is to identify an appropriate configuration that minimizes printing time while maximizing flexural properties and achieving optimal surface quality, which is not currently the situation.

Each support strategy has its own advantages and disadvantages, as indicated by the support infill angle associated with each type. Based on our results, the 0°-line support strategy consumes the least material and printing time due to the short nozzle path. However, the quality of the finished surface is very poor.

Support strategy	Support infill angle	Max Load (N)	Max Displacement (mm)	Flexural stress (MPa)	Flexural strain (%)
Line	0°	278.23	7.749	68.7200277	3.4320321
	45°	283.3	6.905	69.972267	3.0582245
	90°	289.65	7.391	71.5406535	3.2734739
Rectilinear	0°	213.14	6.06	52.6434486	2.683974
	45°	237.19	6.415	58.5835581	2.8412035
	90°	277.79	7.73	68.6113521	3.423617
Grid	0°/ 90°	264.79	7.242	64.1334234	3.2074818
	45°/−45°	154.1	6.141	38.061159	2.7198489
	0°/ 45°	211.33	6.297	52.1963967	2.7889413

Table 3. *Flexural characteristics of the parts tested.*

Therefore, to achieve the maximum load that the structure can support, the 90°-line support strategy is better than the zigzag and grid for density of 30% .

4. Conclusion

In this study, the impact of support infill angle and infill pattern of support structures on printed behaviours (surface roughness, printing time, flexural properties) was investigated. Three support infill angles in three support strategies (Line, Rectilinear and Grid) from IdeaMaker 4.3.2 were tested with PLA filament. We conclude as follows:

- The different filling angles of the support material can have a significant impact on the mechanical characteristics of the final FDM printed parts. This is mainly due to differences in support design and surface roughness resulting from different support strategies.
- From the results, part manufactured in line support method with 90° support infill angle has the largest flexural stress followed by rectilinear and Grid.
- 0° in line support strategy consumes the least support material and time, however it had bad finished surface quality.
- For infill angle of 90 degrees of rectilinear support strategy, we achieved a better surface finish.
- According to the rectilinear support infill angle, the support infill angle should be selected in the opposite direction to that of the part infill angle. Furthermore, aligning the direction of support filaments in contrast to that of the part improves both stiffness and facilitates the removal of support. This methodology enhances the structural integrity and optimizes the subsequent procedures, thereby enhancing the overall efficiency of the manufacturing process.

- Printing time increases with increasing filling support angle.

There is no definitive rule for selecting the optimum infill angle, because the choice depends on the specific requirements of the final structural in each case.

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