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ENHANCING THE STRUCTURAL PERFORMANCE OF 3D PRINTED OBJECTS THROUGH G CODE OPTIMIZATION VIA FEA IN THE FDM PROCESS

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ABSTRACT

Additive manufacturing, an innovative process that assembles materials layer by layer from 3D model data, is recognized as a transformative technology across diverse industries. Researchers have extensively investigated the impact of various printing parameters of 3D printing machines, such as printing speed, nozzle temperature, and infill, on the mechanical properties of printed objects. Specifically, this study focuses on applying Finite Element Analysis (FEA) in G code modification in Fused Deposition Modeling (FDM) 3D Printing. FDM involves extruding a thermoplastic filament in layers over a build plate to create a three-dimensional object. In the realm of load-bearing structures, the Finite Element Analysis (FEA) process is initiated on the target object, employing the primary load to identify areas with high-stress concentrations. Subsequently, optimization techniques are used to strategically assign printing parameter combinations to improve mechanical properties in potentially vulnerable regions. The ultimate objective is to tailor the G code, a set of instructions for the printer, to strengthen particular areas and improve the printed object's overall structural integrity. To evaluate the suggested methodology's efficacy, the study conducts a comprehensive analysis of printed objects, both with and without the optimized G code. Simultaneously, mechanical testing, such as tensile testing, demonstrates quantitative data on structural performance. This comprehensive analysis aims to identify the impact of G code alteration on the finished product. Preliminary experimental results using simple tensile specimens indicate notable improvements in structural performance. Importantly, these improvements are achieved without any discernible mass increase, optimizing material usage and reducing the cost of additive manufacturing. The modified G code targets to strengthen critical areas using updated printing parameters without a net increase in the overall material consumption of the object. This finding holds significant implications for industries reliant on additive manufacturing for load-bearing components, offering a promising avenue for improved efficiency and durability. Integrating advanced techniques, such as G code modification and finite element analysis (FEA), as the additive manufacturing landscape evolves presents a pathway toward optimizing mechanical properties. By contributing valuable insights and laying the groundwork for further exploration and refinement of these methodologies, this study paves the way for enhanced structural performance in various additive manufacturing applications. Ultimately, it encourages innovation and progress in the field, propelling the industry toward new heights of efficiency and reliability.

Keywords: Finite Element Analysis, G-Code Optimization, 3D Printing, Additive Manufacturing

1. INTRODUCTION

Additive manufacturing is a groundbreaking technology used across many industries. It has been widely used in manufacturing industries, biomedical applications, aerospace, and buildings nowadays [1][2]. Because of the wide possibility of applications, researchers have examined how different printing factors, like temperature and speed, affect the strength of printed items for better product quality. For instance, researchers have [3] investigated the influence of temperature and material variation on the mechanical properties of parts fabricated with FDM additive manufacturing, revealing temperature as a significant factor affecting tensile strength and process optimization. Additionally, Tessa Jane Gordelier et al. [4] review strategies for optimizing FDM additive manufacturing for maximum tensile strength, identifying key factors influencing mechanical properties. Moreover, the thermal behavior of 3D printers has been investigated, which provided insights into optimizing FDM processes for improved printing quality and efficiency. Adjustments to FDM technique process parameters have drawn significant attention from researchers. For example, Murugan et al. [5] investigated how different parameters influence 3D printed structures. Their findings highlighted the notable impact of layer height on ultimate tensile strength and printing duration, while extrusion temperature significantly affects the elastic modulus. Notably, nozzle temperature is crucial in determining the mechanical properties and overall quality of FDM printed parts, especially with PLA as the printing material. Many researchers have observed that increasing nozzle temperatures enhances the mechanical properties of PLA printed materials [6]. This finding was verified by Alsoufi et al. [7], who found the highest tensile strength when the nozzle temperature was raised from 180°C to 220°C for parts with 100% infill. Moreover, print speed along the platform significantly influences the quality of 3D-printed parts. Traditionally, the operating speeds of FDM 3D printers used for PLA printing are low, usually less than 100 mm/s [8]. Researchers, such as Napolitano et al. [9], have even analyzed PLA's mechanical properties at 110mm/s, revealing that higher printing speeds lead to the highest tensile strength for PLA materials. Therefore, exploring higher speeds is crucial for understanding how PLA materials perform under conditions of increased velocity, potentially resulting in enhanced material properties, reduced printing times, and broader applications for PLA materials in 3D printing. Also, the nozzle temperature has an impact on mechanical characteristics. Elevating the nozzle temperature to 230°C maximized the tensile properties of PLA parts showed maximized tensile property at 230°C. Additionally, research by Yang et al. [10] and Heidari-Rarani et al. [11] emphasized the importance of optimizing printing speed for FDM 3D printing to improve the mechanical characteristics of PLA samples. They concluded that optimizing printing speed is essential for achieving better mechanical properties in FDM-printed PLA parts. However, conflicting findings exist, as noted in some works [12] [13], where it has been suggested that the mechanical properties [18] of PLA materials decrease with increased printing speed. An experimental work by Rezaeian and colleagues [14] examined printing speeds at various rates and the mechanical and fracture performance of FDM-ABS parts. Their optimal results were obtained when printing at 70 mm/s, exhibiting the highest elongation and fracture resistance compared to specimens at different nozzle speeds. Summarizing these works proves that increasing the temperature and decreasing printing speed can be important in increasing product strength in 3D printing. Still, the unwanted fact is that increasing the temperature results in higher power consumption. If we decrease the speed of printing for large-scale operations, it will increase the cycle time of production, which is also not acceptable for large-scale applications. In solution to this issue, this work describes some experiments to determine if it is possible to increase the temperature to the specific regions where the product faces maximum stress while bearing load and if it is possible to decrease the speed in that region so that the power consumption of the 3D printing machines can be controlled. Also, the production time is not hampered. Here, for identifying the high-stress regions, finite element analysis has been performed to guide and optimize the G-Codes for those high-stress layers that print in high temperatures in high-stress regions and keep the printing process slower. The effect of increasing the nozzle temperature and decreasing the printing speed has been verified by tensile testing using the MTS Tensile testing machine, and the peak load, peak stress, and modulus have been compared with the specimen from the constant temperature and speed settings to prove if it can be a solution to the existing issue.

2. MATERIALS AND METHODS

For this experimental investigation, a rectangular specimen of 100 mm in height, 40 mm in width, and 3 mm in width with a strategically positioned 10 mm radius aperture was chosen to primarily evaluate the effects of changing the temperature and speed of 3D Printing.

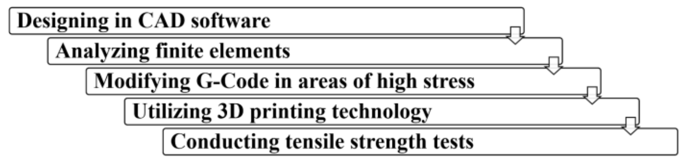


FIGURE 1: PROPOSED FEA-GUIDED G-CODE ADJUSTMENT PROCESS

Finite element analysis (FEA) was executed to identify regions susceptible to high stress. At first, the design was divided into more minor, manageable elements through meshing. Cubic elements of 2 mm have been used to discretize the geometry for this analysis. PLA material has been selected to understand how the material behaves under various load conditions, while one side of the rectangular is kept fixed, and a force of 2000 N has been applied to the other side of the shape as a boundary condition. Once the mesh is generated, boundary conditions and the material properties are assigned, FEA solves the system of equations derived from the equilibrium of forces and compatibility of displacements. After the solution is obtained, von Mises stress is calculated for each element in the mesh.

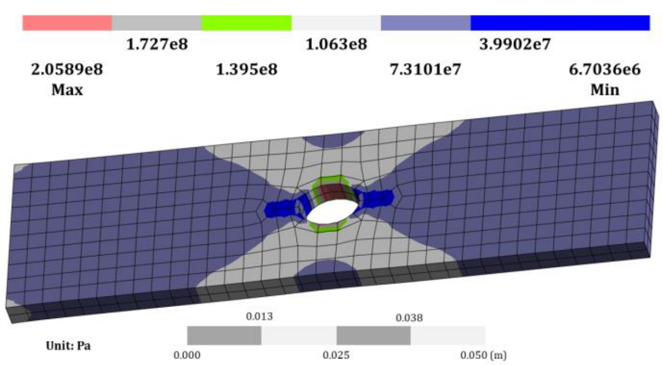
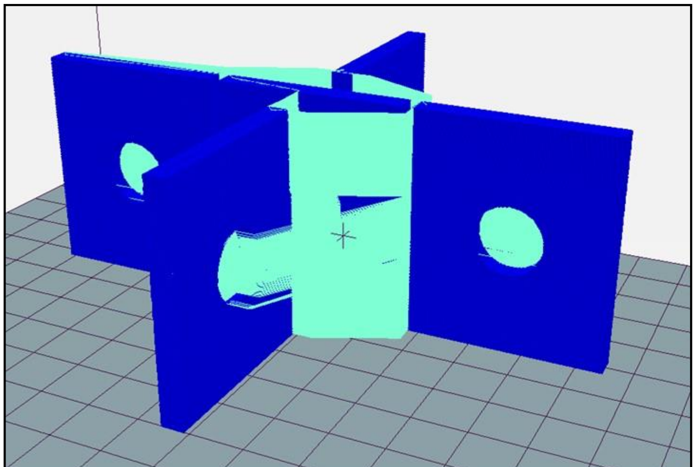


FIGURE 2: STRESS CALCULATION VIA FINITE ELEMENT ANALYSIS ON THE SPECIMEN

Ordinarily, the slicer defaults on the printing temperature for Ultimaker S3 machines to 200 degrees Celsius. While printing the geometry in a 3D printer, the resolution was kept to the Fine

(0.1 mm) setting, and line infill and shell thickness of 4 mm by 200 mm were used. The specimens were printed with the default temperature setting and then tested with the MTS tensile testing machine. After that, for the modified samples, temperature modification in the high-stress region areas changed the G-code so that the printer stopped and increased the temperature by 10 degrees as the previous research states increase of printing temperature improves the product strength [7] [10]. Then, the layers were printed with the modified settings. The rest of the parameters were kept the same to analyze the effect of temperature increases.



Speed Modification		
Slicer Command	**G Code**	**Remarks**
30884	;LAYER:200	
	M220 S80	Decreased Speed by 20%
30885	;TYPE:WALL-OUTER	
30886	;MESH:High Width.stl(2)	
30887	G1 F2700 E172.4176	
30888	G1 F1200 X116.543 Y111.803 E172.60345	
30889	G1 X113.456 Y111.803 E172.6228	
30890	G1 X113.456 Y141.443 E172.80865	
30891	G1 X116.543 Y141.443 E172.82801	
30892	G0 F9000 X116.543 Y141.243	
30893	G0 X116.143 Y141.043	
30894	;TYPE:WALL-INNER	
	M220 S100	Print in Regular Speed

Temperature Modification		
Slicer Command	**G Code**	**Remarks**
30884	;LAYER:200	
	M104 S210	Pause Print & Set Nozzle Temperature to 210
30885	;TYPE:WALL-OUTER	
30886	;MESH:High Width.stl(2)	
30887	G1 F2700 E172.4176	
30888	G1 F1200 X116.543 Y111.803 E172.60345	
30889	G1 X113.456 Y111.803 E172.6228	
30890	G1 X113.456 Y141.443 E172.80865	
30891	G1 X116.543 Y141.443 E172.82801	
30892	G0 F9000 X116.543 Y141.243	
30893	G0 X116.143 Y141.043	
30894	;TYPE:WALL-INNER	
	M104 S210	Pause Print & Set Nozzle Temperature to 200

FIGURE 3: MODIFIACATION OF G-CODE FOR HIGH-STRESS REGION LAYERS

A A similar procedure was employed for printing on the Flashforge Adventure 4 Lite printer to modify the G-Code specifically for layers experiencing higher stress levels. In line with this approach, the printing speed was reduced within the high-stress regions. Subsequently, specimens printed at default speed settings were compared with those printed using modified speed settings in a tensile testing scenario to discern any discrepancies. This approach draws upon previous research findings [12] [13], which have consistently highlighted the efficacy of temperature increases and speed decreases in enhancing the strength of 3D printed specimens. Leveraging insights gleaned from prior analyses conducted by researchers, the G-Code was adjusted accordingly to align with established optimization strategies.

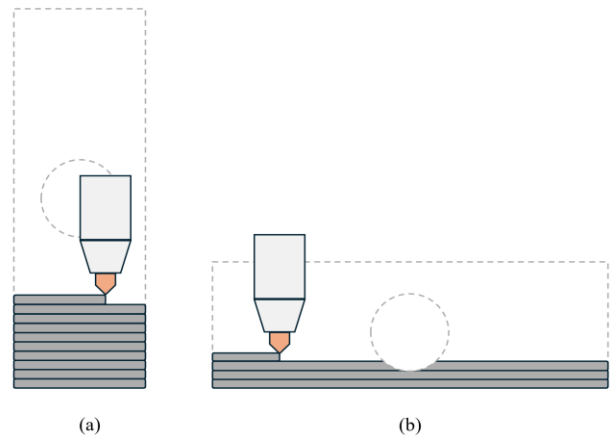


FIGURE 4: (a) PRINTING IN VERTICAL DIRECTION (b) PRINTING IN HORIZONTAL DIRECTION

For both cases, the specimens were printed with vertical and horizontal directions [16] with the machine default settings of 20% infills with a line infill pattern. As we wanted not to affect the printing quality by the infills, we printed the specimen with 100% infill [15].

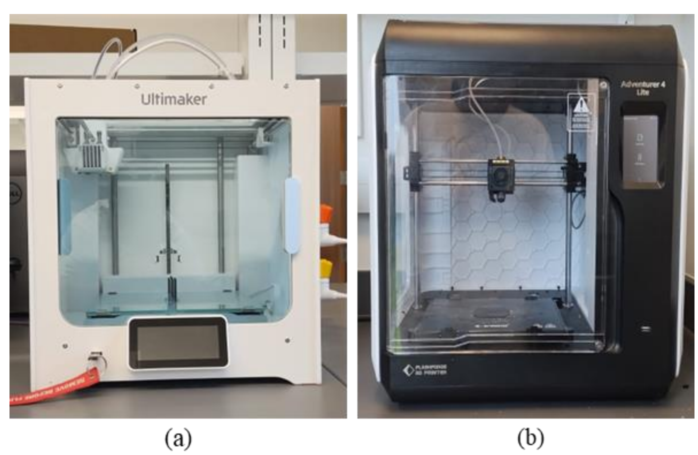


FIGURE 5: (a) ULTIMAKER S3 (b) FLASHFORGE ADVENTURE 4 LITE

Ultimaker S3 and Flashforge Adventure 4 lite were used for this experiment to determine if the two different 3D printers show consistency.

Printer Settings	Infill	SL. No.	Peak Load (N)	Peak Stress (N/mm²)	Modulus (N/mm²)	Strain at Break (mm/mm)	Used Printer
Temperature Modification	20%	1	2144.6	57.2	933.95	0.065	Ultimaker
	20%	2	2046.03	54.6	854.75	0.069	Ultimaker
	20%	3	2141.93	57.1	988.299	0.062	Ultimaker
	20%	4	2108.6	56.2	949.725	0.062	Ultimaker
	20%	5	2114.09	56.4	871.473	0.067	Ultimaker
Default Settings	20%	6	2337.07	62.3	789.035	0.083	Ultimaker
	20%	7	2208.65	58.9	1151.46	0.059	Ultimaker
	20%	8	2036.28	54.3	995.702	0.059	Ultimaker
	20%	9	2075.06	55.3	1003.87	0.057	Ultimaker
	20%	10	2206.16	58.8	892.95	0.068	Ultimaker
Speed Modification	20%	11	2049.69	54.7	1024.97	0.057	Ultimaker
	20%	12	2131.2	56.8	891.704	0.068	Ultimaker
	20%	13	2095.31	55.9	989.391	0.057	Ultimaker
	20%	14	1965.09	52.4	931.048	0.069	Ultimaker
	20%	15	2148.18	57.3	920.048	0.07	Ultimaker
Temperature Modification	100%	16	2578.45	68.8	1298.07	0.056	Ultimaker
	100%	17	2854.04	76.1	1237.51	0.064	Ultimaker
	100%	18	2959.74	78.9	1281.62	0.066	Ultimaker
	100%	19	3222.49	85.9	1284.32	0.07	Ultimaker
	100%	20	3118.12	83.1	1232.97	0.07	Ultimaker
Default Settings	100%	21	2818.21	75.2	1242.42	0.064	Ultimaker
	100%	22	2866.93	76.5	1347.9	0.06	Ultimaker
	100%	23	2828.93	75.4	1245.69	0.062	Ultimaker
	100%	24	2945.17	78.5	1359.33	0.062	Ultimaker
	100%	25	2816.18	75.1	1289.61	0.063	Ultimaker
Speed Modification	100%	26	2726.47	72.7	1166.58	0.064	Ultimaker
	100%	27	2844.28	75.8	1287.83	0.061	Ultimaker
	100%	28	3000.67	80	1209.9	0.068	Ultimaker
	100%	29	2888.93	77	1387.53	0.059	Ultimaker
	100%	30	2872.89	76.6	1239.09	0.065	Ultimaker
Temperature Modification	100%	31	1872.93	49.9	1048.64	0.048	Ultimaker
	100%	32	1908.58	50.9	1226.69	0.044	Ultimaker
	100%	33	1681.06	44.8	1177.17	0.039	Ultimaker
	100%	34	1860.93	49.6	1194.37	0.042	Ultimaker
	100%	35	1779.23	47.4	1113.53	0.043	Ultimaker
Default Settings	100%	36	1637.37	43.7	1096.83	0.04	Ultimaker
	100%	37	1644.34	43.8	1119.66	0.039	Ultimaker
	100%	38	1710.15	45.6	1114.48	0.041	Ultimaker
	100%	39	1708.59	45.6	1196.61	0.039	Ultimaker
	100%	40	1651.92	44.1	1061.91	0.041	Ultimaker
Default Modification	100%	41	198.593	5.3	145.755	0.04	Flashforge
	100%	42	222.406	5.9	188.23	0.033	Flashforge
	100%	43	243.4	6.5	220.211	0.032	Flashforge
	100%	44	200.201	5.3	147.127	0.036	Flashforge
	100%	45	239.656	6.4	197.92	0.035	Flashforge
Speed Mofification	100%	46	269.37	7.2	199.051	0.036	Flashforge
	100%	47	230.92	6.2	296.649	0.023	Flashforge
	100%	48	317.572	8.5	267.844	0.032	Flashforge
	100%	49	255.832	6.8	208.41	0.033	Flashforge
	100%	50	265.555	7.1	225.569	0.033	Flashforge

FIGURE 4: DATA OBTAINED FROM THE TENSILE TESTING MACHINE

For each sample, a comprehensive evaluation of mechanical properties was conducted through meticulous tensile testing utilizing an MTS tensile tester, a well-established and standardized procedure recognized for its reliability in assessing material behavior under tension [17]. The testing procedure was performed with the careful mounting of the specimens onto grips capable of accommodating a width of 3mm. Subsequently, a precisely controlled tensile load is applied to the specimen with strain rate of 1mm/min until fracture occurs, allowing for the systematic observation and recording of critical data points throughout the test duration. This includes the meticulous documentation of load-displacement and stress-strain curves, facilitating a detailed analysis of the material's response to varying stress levels. From this extensive dataset, mechanical properties are extracted and recorded for each specimen, encompassing key parameters such as peak load, peak stress, Young's modulus, and strain at the break point. These recorded properties serve as invaluable indicators of the material's inherent strength and stiffness characteristics, offering profound insights into the efficacy of temperature and speed optimization strategies employed in high-stress regions of specimens derived from 3D printers. Through this rigorous testing regimen, the experiment aims to validate and quantify the tangible improvements realized through meticulous adjustments in printing parameters, thereby enhancing the overall mechanical integrity and performance of the printed specimens.

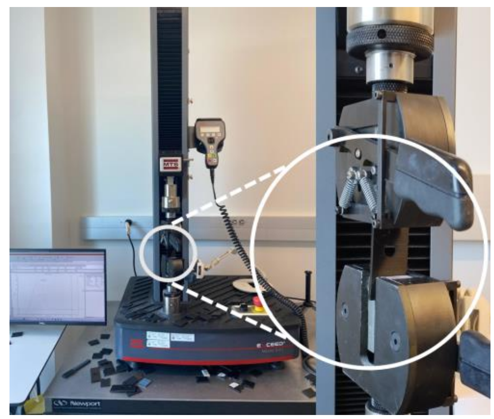


FIGURE 6: TENSILE TESTING UTILIZING THE MTS TENSILE TESTING MACHINE

3. RESULTS AND DISCUSSION

3.1 Effect of Increasing Temperature

The experimental findings indicate a significant enhancement in the mechanical properties of printed specimens when the printing temperature is increased in high-stress regions [19]. For example, when the temperature was increased with 100% infill in the high-stress region, several vital parameters exhibited notable improvements. The average peak load experienced an enhancement of 8.98%, demonstrating increased load-bearing capacity under these conditions [19]. Similarly, peak stress significantly increased by 8.89%, indicating better resistance to deformation and failure. The modulus, a measure of material stiffness, experienced a notable rise of 3.06%, suggesting improved structural integrity and rigidity [19]. Additionally, the strain at the break increased by 8%, indicating enhanced ductility and deformation capacity before failure [19]. These improvements were particularly pronounced when printing in the vertical direction. These findings align closely with previous research [7] [10], reinforcing the validity and significance of the observed enhancements resulting from temperature adjustments in high-stress regions.

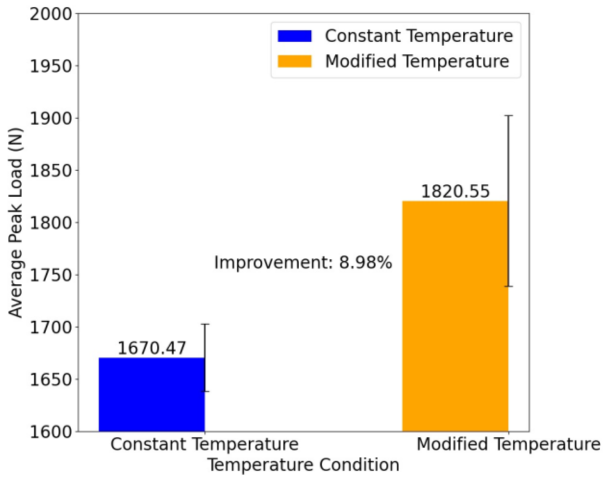


FIGURE 7: PEAK LOAD COMPARISON: DEFAULT VS. MODIFIED TEMP (ULTIMAKER S3)

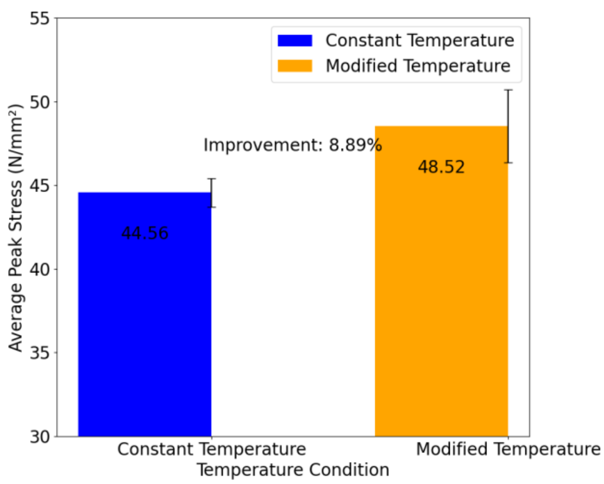


FIGURE 8: PEAK STRESS COMPARISON: DEFAULT VS. MODIFIED TEMP (ULTIMAKER S3)

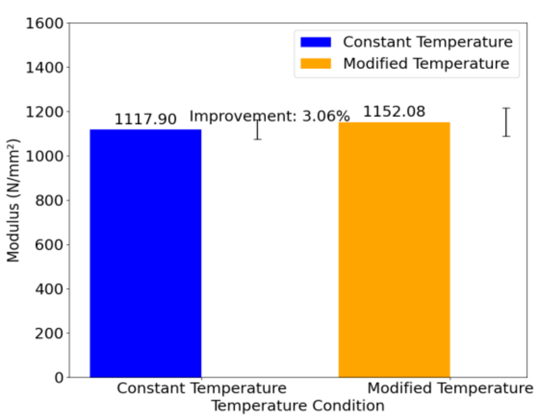


FIGURE 9: MODULUS COMPARISON: DEFAULT VS. MODIFIED TEMP (ULTIMAKER S3

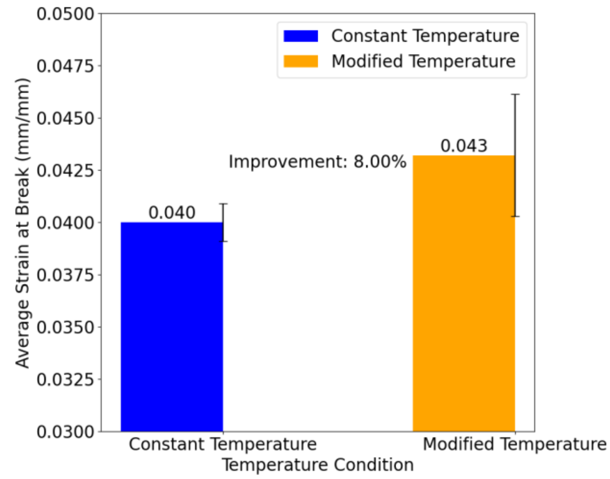


FIGURE 10: AVERAGE MODULUS COMPARISON: DEFAULT VS. MODIFIED TEMP (ULTIMAKER S3)

However, for the 20% infill, the mechanical properties of the printed specimen from the 3D printers degraded the mechanical properties, which is visualized in Figure 9, and the outcome matches the findings from previous research [16] [19] [20].

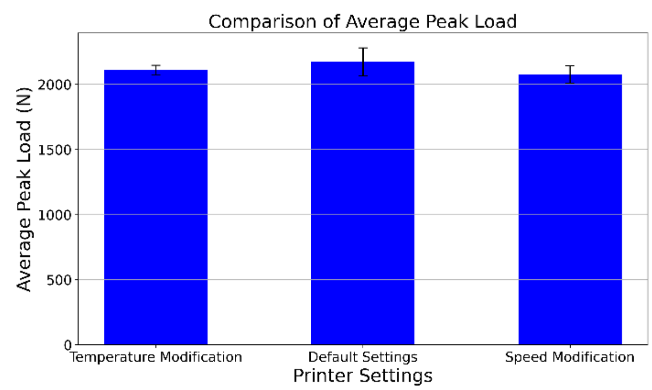


FIGURE 9: PEAK LOAD COMPARISON WITH 20% INFILL (ULTIMAKER S3)

3.1 Effect of Decreasing Speed

Decreasing the printing speed with 100% infill in the high-stress region resulted in noticeable improvement across various mechanical parameters. The average peak load, peak stress, modulus, and strain at the break experienced significant enhancements, showing increases of 21.28%, 33.17%, and 21.77%, respectively. These findings corroborate earlier research studies [12] [13] [14], further validating the efficacy of this approach in enhancing 3D printing mechanical performance. However, it's worth noting that the experiment revealed a degradation in the average strain at break, indicating the need for further investigation and analysis in future studies. Additionally, when applying a 20% infill, the reduction in printing speed led to a degradation of mechanical properties similar to the effects observed with increased temperature.

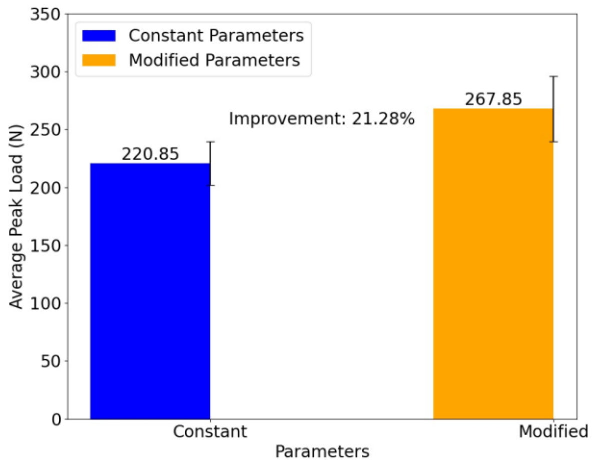


FIGURE 11: PEAK STRESS COMPARISON: DEFAULT VS. MODIFIED SPEED (ADVENTURE 4 LITE)

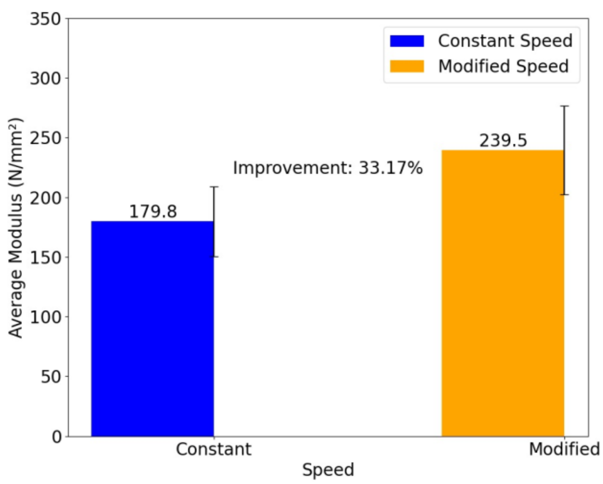


FIGURE 12: COMPARING AVERAGE PEAK STRESS: DEFAULT VS. MODIFIED PRINT SPEED (ADVENTURE 4 LITE)

Interestingly, even though both our selected geometry and specimens from the Ultimaker S3 were produced using the same Fused Deposition Modeling (FDM) technology and adhered to identical printing settings, a visible discrepancy in mechanical properties was observed. The observed discrepancy in mechanical properties between our selected geometry and Ultimaker S3 specimens, despite sharing the same Fused Deposition Modeling (FDM) technology and printing settings, underscores the complexity inherent in additive manufacturing processes. This observation prompts a comprehensive investigation into the underlying factors contributing to these variations, beyond mere G-code alterations. It suggests the presence of nuanced variables, such as material composition, printer calibration, and environmental conditions, which may exert significant influence on the final product's mechanical performance [21] [22]. This necessitates further research and comparative analysis to unravel the intricate interplay of these multifaceted factors. By gaining deeper insights into these underlying mechanisms, we can refine optimization strategies aimed at enhancing the consistency and reliability of additive manufacturing processes. Such findings hold significant implications for advancing the understanding and practice of additive manufacturing in various industries.

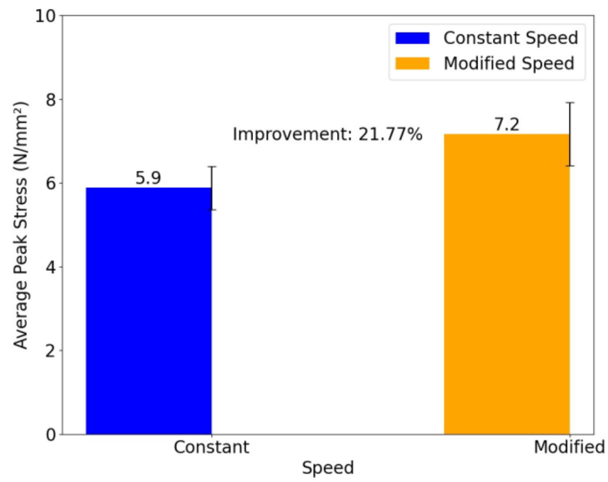


FIGURE 13: PEAK STRESS COMPARISON: DEFAULT VS. MODIFIED PRINT SPEED (ADVENTURE 4 LITE)

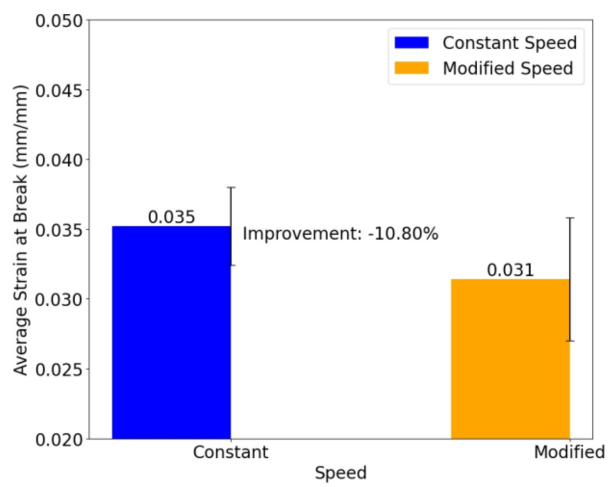


FIGURE 14: COMPARING AVERAGE PEAK STRESS: DEFAULT VS. MODIFIED PRINT SPEED (ADVENTURE 4 LITE)

4. CONCLUSION

In conclusion, our preliminary study underscores the profound impact of optimizing 3D printing parameters based on geometrical finite elements of PLA materials. We observed significant improvements in mechanical properties, which have been tested using MTS Tensile testing, validating the positive effect of the alteration of the G-code. Moreover, keeping the printing temperature lower helps reduce power consumption, and also the decreased printing speed for only specific stress-sensitive regions improves production cycle time. The idea generated from this experimental study can be used for more complex structures to prove its practicality for more efficient energy usage and optimized printing experience.

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