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OPTIMIZATION OF DESIGN AND FDM PROCESS PARAMETERS FOR ENHANCED MECHANICAL PERFORMANCE OF 3D PRINTED WOVEN FABRIC STRUCTURES

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ABSTRACT

Fused Deposition Modeling (FDM) is a widely used additive manufacturing technique capable of producing textile-like structures using thermoplastic polymers. This study focuses on optimizing 3D printed woven fabrics using PLA filament. Mechanical characterization through tensile and flexural testing was conducted in both warp and weft directions. A Taguchi L9 orthogonal array was employed for efficient experimental design. The results were analyzed using response table and main effect plots, and the mechanical properties were optimized using regression modeling in MINITAB. Findings reveal that different properties are governed by different parameters. Layer height significantly influenced strength while design played a key role in modulus. Directional anisotropy was observed with notable differences in mechanical behavior between warp and weft orientations. Optimal parameter combinations were identified for individual properties. Twill design with higher layer height and temperature showed enhanced flexibility, while basket weaves with moderate settings favored strength. The study provides valuable insights for tailoring FDM-printed textile structures, paving the way for high-performance, customizable, and scalable fabric applications.

KEYWORDS: fiber, yarn, fabric formation, manufacture, processing, weaving, 3-D printing.

INTRODUCTION

Additive manufacturing (AM), or 3D printing, is a technology where a digitally designed object is physically built by the addition of material in layers one by one [1]. This technology has revolutionized the modern manufacturing [2,3]. This is possible due to its potential to enhance rapid prototyping, improve design processes, check industrial pollution by waste reduction, increase sustainability, and lower costs which are the major advantages of AM as compared to conventional subtractive manufacturing methods [4]. Manufacturing by material extrusion, among the seven groups categorized by ASTM [5], is one of the most popular AM methods [3,6]. Fused Deposition Modeling (FDM), or Fused Filament Fabrication (FFF), is a type of material extrusion AM method where a polymer-based monofilament is introduced to the 3D printer machine, heated and extruded through the nozzle in the molten form and deposited on the printer bed layer by layer to form the desired product [7]. There are several materials that can be used in FDM process out of which polylactic acid (PLA), polyamide/nylon (PA), acrylonitrile butadiene styrene (ABS), polyvinyl alcohol (PVA), thermoplastic elastomer (TPE), polycarbonate (PC), polyethylene terephthalate glycol (PETG), polypropylene (PP) etc., are some of the majorly used ones [2,7]. Due to its capability to accommodate a wide range of materials, cost and eco-friendly manufacturing, and speed prototyping as well as manufacturing, it is well accepted by the researchers, innovators and manufacturers in a wide range of applications not limited to aerospace, medicine, automobiles, textiles, etc. [3,7].

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Additive manufacturing researches associated with textiles can be tracked back as early as early 2010s for printing on textiles [8,9] as well as printing of textiles [10]. Several researchers has printed and studied woven and knitted textile-like structures [11,12] over the course of time. Forman et. al [13] introduced thin, flexible, breathable quasi-woven fabric using FDM by using complex geometries with periodic layer gaps. Takahasi and Kim [14] controlled filament movement to interlace PLA into warp/weft directions to develop 3D printed woven flexible fabric structures. Melnikova et. al. [10] used FDM and selective laser sintering (SLS) to combine traditional textile structures with 3D printing. Dutch designer Iris van Herpen designed and printed a custom gown for a wedding to mark as a world's first 3D printed wedding dress that took 600 hours to complete including 41 printing hours [15]. Literature also shows that several efforts has been made to print chainmail structures that mimics flexible textile structures [16]. Despite all these efforts and achievements made, additive manufacturing of textiles is still in a nascent state and needs more research. Most of the researchers have concluded that the mechanical properties are compromised for these FDM 3D printed textile-like structures and have repeatedly shown a trade-off between the strength and flexibility [10,17] which is not the case for traditional fabrics.

The mechanical properties of 3D printed parts depend on geometry of the printed part, as well as several other printing parameters such as extrusion temperature, layer height, infill pattern, infill density, print speed, build orientation, raster angle, nozzle diameter, etc.[1,2,7,9]. Alafaghani et. al. [18] reported that extrusion temperature and layer thickness were significant for tensile properties (Young's modulus, tensile strength, yield strength). Increasing the extrusion temperature from 170°C to 185°C led to significant improvements in tensile strength (from ~29 MPa to ~45 MPa), yield strength (from ~26 MPa to ~39 MPa), and Young's modulus. Similarly, increasing the layer height from 0.1 mm to 0.3 mm showed an improved mechanical performance. Abouelmajd et.al. [19] found that 190°C was the optimized extrusion temperature among three extrusion temperatures among 190°C, 200°C and 210°C for maximizing flexural strength and flexural modulus of FDM printed PLA samples. This shows that optimizing printing parameters and designs is essential to achieving the desired degree of mechanical performance in 3D printed fabric structures. Hence, this research aims to optimize the strength and flexibility of such fabrics by tuning design, layer height, and extrusion temperature using Taguchi Method.

Taguchi method is a statistical method that uses a set of orthogonal arrays with the least possible experiments to examine multiple variables. The optimum result is predicted based on signal-to-noise (S/N) ratio which is why it is a robust and reliable method [20]. This is the reason behind its popularity among researchers for optimization of process parameters in FDM processes [21].

MATERIALS AND METHODS

DESIGN OF WOVEN FABRICS

Three types of woven fabric designs, 2/1 twill, 2/2 basket and 2/2 warp rib were designed in CAD software SolidWorks® as shown in Fig. 1 to feed them into the FDM machine for 3D printing. The repeating unit (unit cell) of the designed fabrics are shown in Fig. 2. The diameter of each yarn in all three fabric designs is 1 mm. Each yarn is placed 3 mm apart (measured center to center) from the adjacent yarn in warp and weft directions as shown in Fig. 3. Thickness of all the fabrics is 3 mm. 2/1 twill woven fabric has 3 yarns in each direction within a unit cell. Hence, a fabric with 31 yarns in both warp and weft directions is generated which contains 10-unit cells in each direction in a square layout measuring 90 mm × 90 mm. The 31st extra yarn in both directions is removed after printing. Similarly, 2/2 basket weave design and 2/2 warp rib design contain 4 yarns in a single unit cell. Hence fabrics of 33 yarns containing 8-unit cells in each direction are made in a 96 mm square layout. The 31st, 32nd and 33rd yarns (3 extra yarns) in both directions are removed after printing. This ensured that all the 3 designs had the same number of yarns (30) and fabric area.

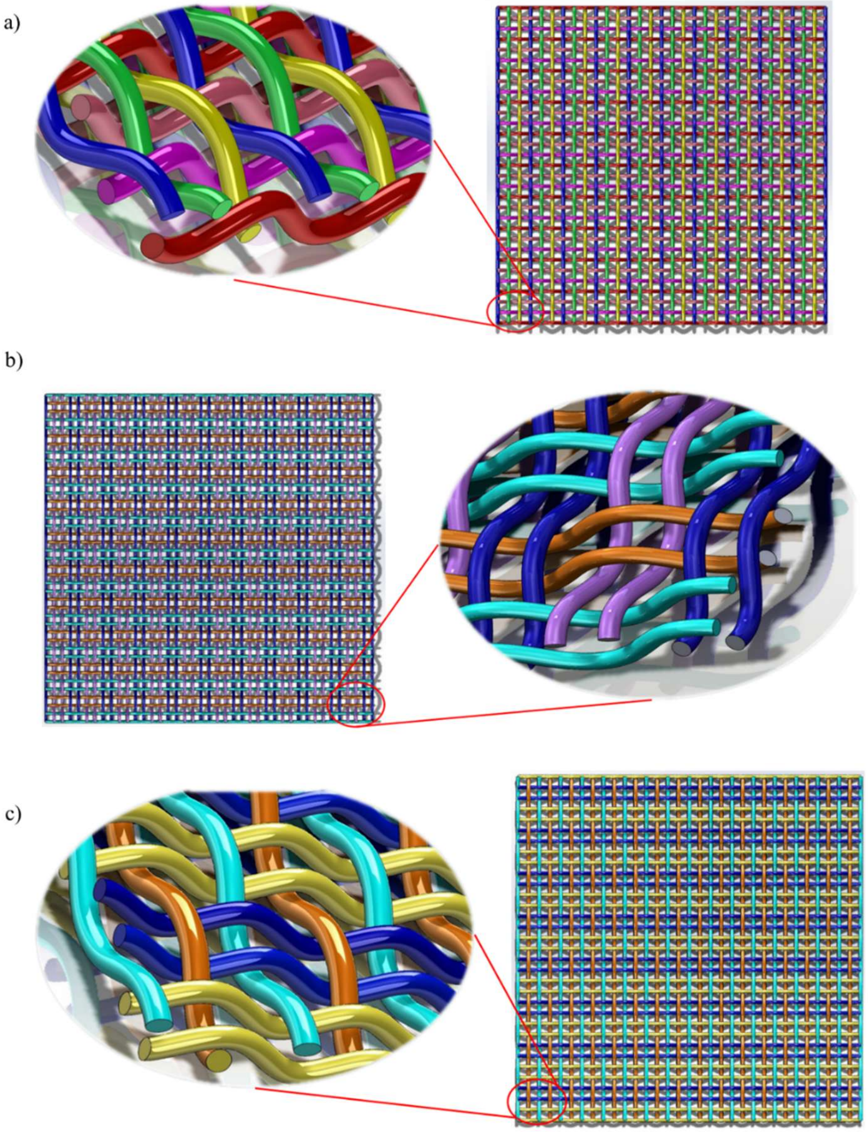

Fig. 1: Top view of **a)** 2/1 twill, **b)** 2/2 basket and **c)** 2/2 warp rib woven fabrics designed in SolidWorks® along with zoomed sections to show the arrangement of yarns in each fabric

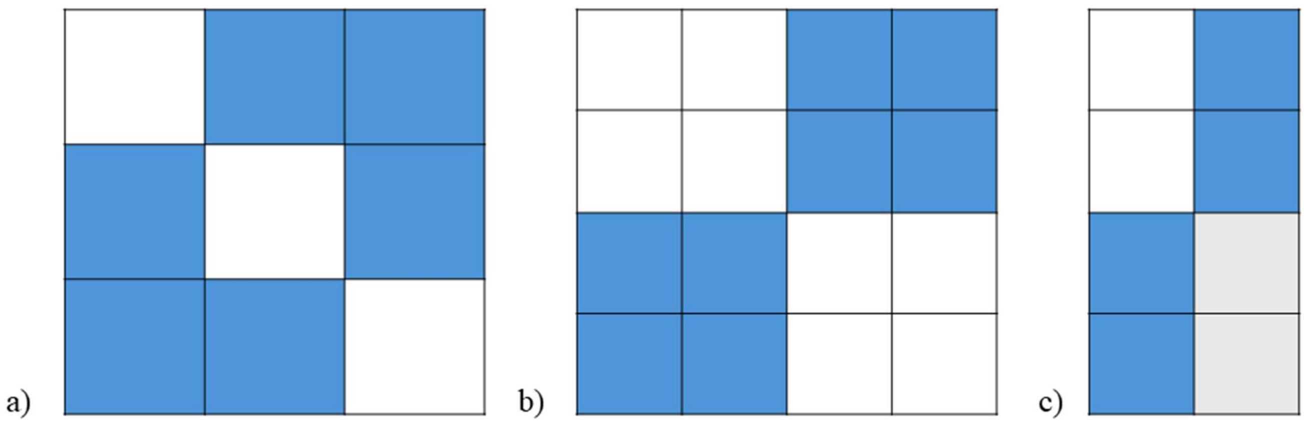

Fig. 2: Unit cell (repeat unit) of **a)** 2/1 twill **b)** 2/2 basket and **c)** 2/2 warp rib woven fabrics

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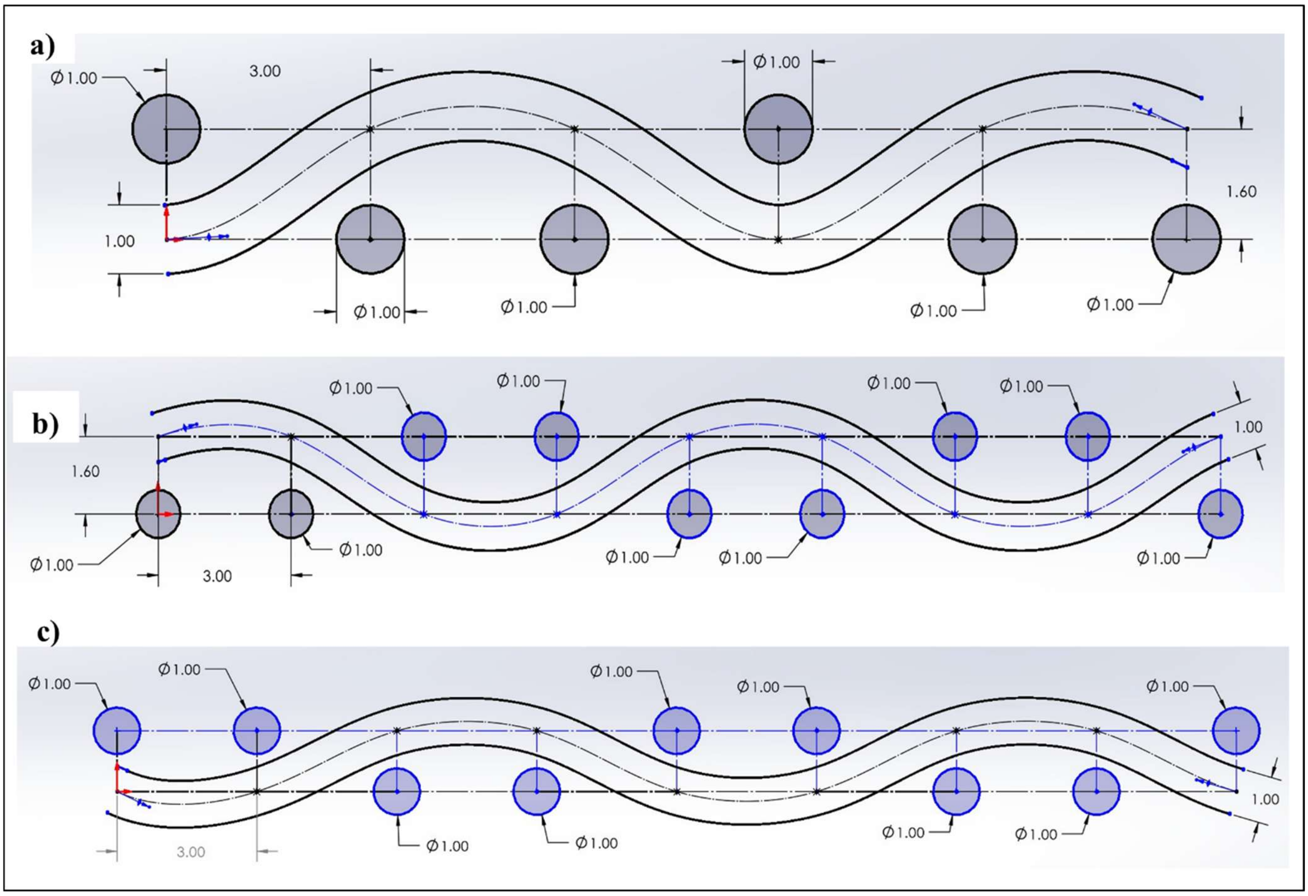

Fig. 3: Warp profiles of **a)** 2/1 twill, **b)** 2/2 basket and **c)** 2/2 warp rib woven fabrics along with the dimensions (mm)

DESIGN OF EXPERIMENTS (DOE)

In order to optimize the mechanical properties of 3D printed fabrics, fabric design and two process parameters, namely layer height and extrusion temperature, are taken into consideration with 3 levels each. Taguchi robust design of experiments is adopted to form L9 orthogonal design table as shown in Table 1 for carrying out the experiments in this research. 2/1 twill, 2/2 basket weave and 2/2 warp rib are the three different levels of the designs and 0.2 mm, 0.3 mm, 0.4 mm and 205 °C, 220 °C, 235 °C are the three different levels of layer height and extrusion temperature, respectively.

Table 1: Taguchi L9 orthogonal design of experiment

Sample Number	Design	Layer Height (mm)	Extrusion Temperature (°C)
1	Twill	0.2	205
2	Twill	0.3	220
3	Twill	0.4	235
4	Basket	0.2	220
5	Basket	0.3	235
6	Basket	0.4	205
7	Warp Rib	0.2	235
8	Warp Rib	0.3	205
9	Warp Rib	0.4	220

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MATERIALS AND MANUFACTURING

Polylactic acid (PLA) is used in this research for the manufacturing of fabrics. PLA is one of the widely used materials in FDM process as it is a biodegradable thermoplastic material. PLA is also known for its excellent processibility as it requires less energy and temperature to process the FDM parts [21]. Table 2 summarizes the properties of PLA [7].

Table 2: Properties of polylactic acid (PLA)

Property	Value
Melting temperature-T_m (°C)	146.4–180
Glass transition temperature-T_g (°C)	45–63.4
Stress (MPa)	21–60
Strain (%)	2–9.3
Elastic Modulus (GPa)	3.4–7.0

A LulzBot Taz Pro (Fargo additive manufacturing equipment) 3D printer is used to process 2.85 mm diameter PLA monofilament and print the designed fabrics. Firstly, the designed fabrics are saved in the (stereolithography) .STL file format and converted into machine-readable G-Code using the slicing software Cura LulzBot Edition 3.6.40. They are then fed into the machine set up for printing. Default standard printing profile with 100% infill density is adopted for this research which has a print speed of 45 mm/s, infill speed of 45m/s, wall speed of 35 mm/s and travel speed of 140 mm/s. Because of complex and tiny intricate geometries (yarn diameter as low as 1 mm and empty spaces between the yarns) associated with the fabrics, it is necessary to customize the printer settings too, for smooth functioning and control of the machine nozzle. The customized settings are shown in Table 3. The definition to all these terminologies associated with the printer can be found in the LulzBot Taz Pro user manual [22]. The fabrics are printed in upright fashion as they do not require any kind of support for printing, which significantly reduces the material required and the printing time. It also facilitates that the yarns are not fused to each other and can be easily separated for the testing of the yarns. The sets of yarns printed along the horizontal axis are referred to as warp yarns and those printed along the vertical axis are referred to as weft yarns in this research.

Table 3: Customized printer settings

Printer Settings	Default Value	Customized Value
Retraction distance	1 mm	3 mm
Maximum retraction count	99	999
Retraction minimum travel	1 mm	0.5 mm
Minimum extrusion distance window	2	1

CHARACTERIZATION

Instron 5900 universal testing machine with 25 mm gauge length is used for testing the samples in this research and ASTM D3822 standard test method is used for tensile tests and ASTM D 790-17 standard test method is adopted for 3-point bending test [23,24].

Once the printing of the fabrics is completed, individual yarns are separated to test for mechanical properties of the yarns. The yarns in weft direction are not possible to separate as they are very fragile and get damaged while trying to manually separate them. Hence, individual yarns in warp direction only are subjected to tensile tests. The average result of 10 yarns for each sample is evaluated. Furthermore, fabrics are cut into two equal halves so that they have 15 yarns each in warp direction. Similar samples are made such that the fabric has 15 yarns each in the weft direction as well. These cut-out fabrics are also subjected to tensile tests. Apart from tensile

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tests, three-point bending test is performed to evaluate the flexural properties of the printed fabrics in both warp and weft directions.

Tensile strength, tensile modulus, flexural strength and flexural modulus were measured as the mechanical properties and Taguchi analysis of the obtained results were carried out using statistical software MINITAB. The impact of the designs and process parameters on the aforementioned mechanical properties were studied. S/N ratios were used to identify the optimum level for the design and process parameters. The "larger-is-better" criterion was applied for strength related properties. A "smaller-is-better" approach was preferred for modulus (which indicates rigidity) because low rigidity is desirable in flexible fabric structures. The same method was applied to both tensile and flexural behaviors. Furthermore, the printing time for each sample was also recorded in hours. Relation of printing time to design and process parameters was also analyzed using the "smaller-is-better" criterion, aiming for shorter production times.

RESULTS AND DISCUSSION

FABRIC YARN'S (WARP) TENSILE PROPERTIES

The analysis of the results show that the design and printing process parameters influence the tensile properties of warp yarns of a fabric. As seen in the response table for means of tensile strength in Table 4, tensile strength varies with different levels of the given parameters. Layer height has the highest value for delta and ranked 1 indicating its highest influence on the tensile strength of the yarn, followed by temperature and design. The main effect plots of the tensile strength of the fabric's warp yarns is shown in Fig. 4.The range (difference between the highest mean value and lowest mean value) of mean of means and mean of S/N ratios is maximum for Layer height followed by temperature and is least for design showing same order of influence of given parameters in the tensile strength of the warp yarns as before. Furthermore, these figures of the means and signal to noise (S/N) ratios show the effects of different levels of given parameters on tensile strength of yarns of the fabric as well. The 2^{nd} level of layer height, i.e., 0.3 mm, provides the optimum average tensile strength of the yarn among three levels of layer height. The tensile strength is generally seen to be decreasing with increasing layer height in 3D printed structures [25]. But in context of complex and tiny geometries such as fabric yarns, very small layer heights introduce weaker interlayer bonding regions due to the presence of many layers, reducing the strength of the fabric yarns in smaller layer heights [17]. As a result, better strength is obtained at some intermediate layer heights as shown by the results for the fabric yarns. The order of tensile strength of yarns with respect to design is basket weave followed by warp rib and twill weave. The tensile strength of the yarns decreases with increasing temperature and reaches an optimum at 205 °C. This result of better tensile strength at lower temperatures might be because the strength of the polymers may degrade as the processing temperature is increased.

Table 4: Response table for means of tensile strength of warp yarn of fabrics

Level	Design	Layer Height	Temperature
1	36.80	36.03	42.64
2	42.23	44.62	39.18
3	39.25	37.63	36.46
Delta	5.43	8.59	6.18
Rank	3	1	2

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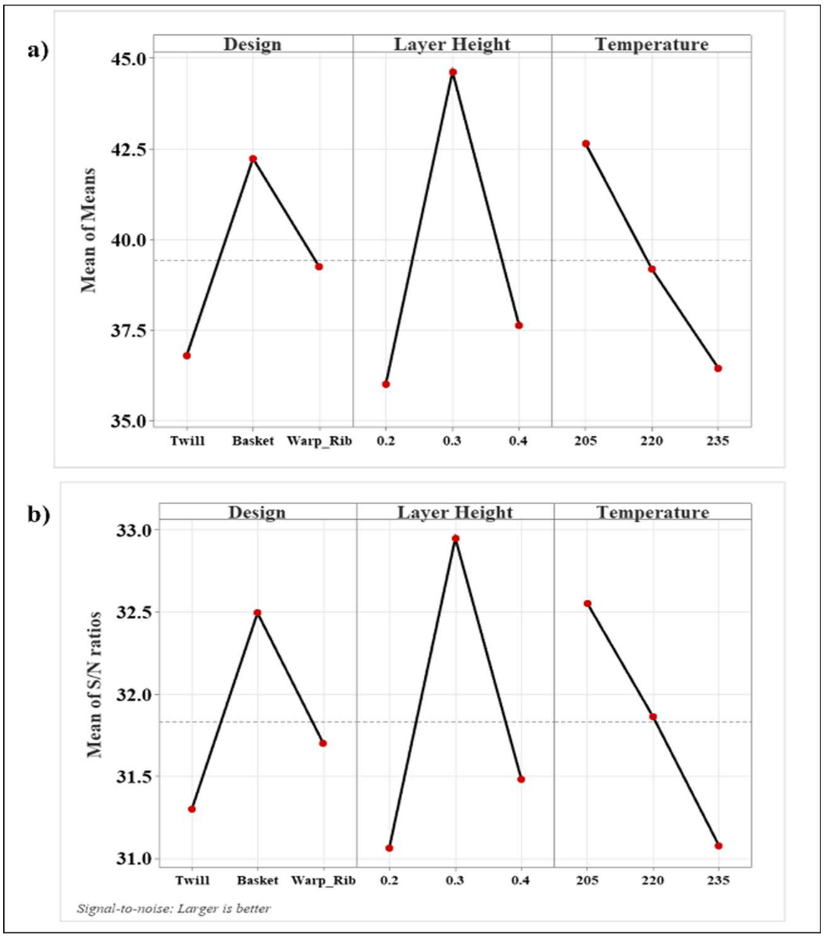

Fig. 4: Main effect plots for tensile strength (MPa) of warp yarn of fabrics: **a)** Mean of means **b)** Mean of S/N ratios

It is observed that the design and printing parameters also influence the tensile modulus of the yarn of a fabric. The order of influence of given parameters on tensile modulus is observed to be different than that of the tensile strength of the yarns. The response table for means of tensile modulus in

Table **5** shows that design has the highest effect on the tensile modulus of the fabric yarns, with highest delta value, followed by temperature and layer height. Furthermore, the main effect plots for means of tensile modulus in Fig. 5(a) show the effects in each parameter level. As seen before for tensile strength, the tensile modulus of yarns is also found to be maximum for basket weave design. The tensile modulus decreases with increasing temperature and similar effect is seen for layer height as well. Main effect plot for S/N ratios in Fig. 5(b) suggests that the optimum tensile modulus of yarns is for twill weave with 0.4 mm layer height printed at 235°C extrusion temperature.

Table 5: Response table for means of tensile modulus of warp yarn of fabrics

Level	Design	Layer Height	Temperature
1	805.1	873.7	966.7
2	982.3	901.3	820.0
3	822.0	834.5	822.8
Delta	177.2	66.9	146.7
Rank	1	3	2

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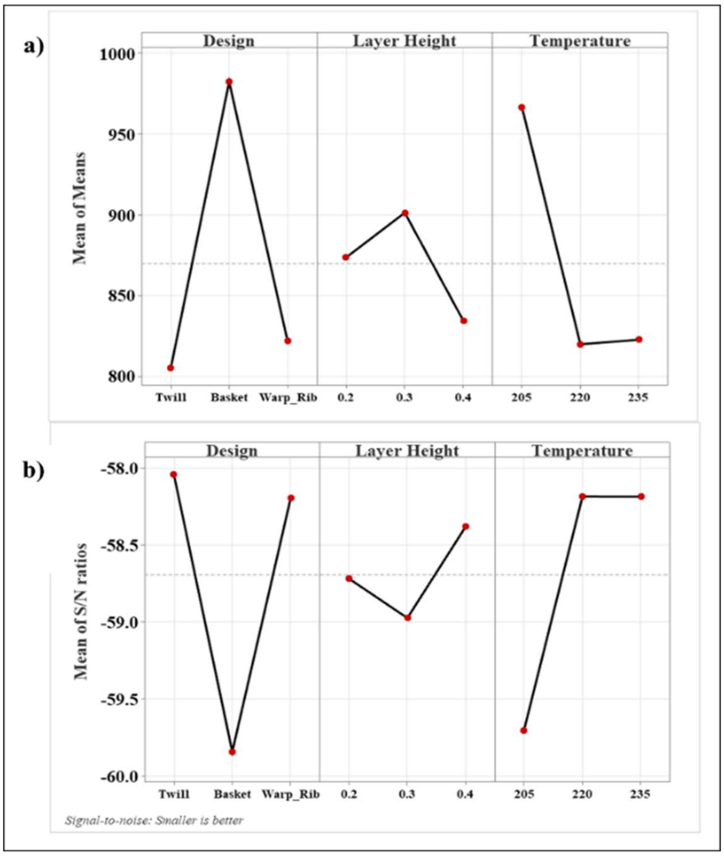

Fig. 5: Main effect plots for tensile modulus (MPa) of warp yarn of fabrics: **a)** Mean of means **b)** Mean of S/N ratios

FABRIC'S TENSILE PROPERTIES (WARP DIRECTION)

The results demonstrate a different order of influence in tensile strength of a fabric in warp direction than that of the individual yarns. As shown in the response table for means of tensile strength of fabric in warp direction in Table 6, the value of delta is maximum for design which indicates that the design has the maximum effect in the tensile strength of 3D printed fabrics in warp direction. The order of influence is design followed by layer height and temperature which is confirmed by main effect plots for means and S/N ratios as shown in Fig. 6. The main effect plots further present the variation of tensile strength with respect to each level of design and printing parameters and their order. Main effect plots for means in Fig. 6(a) show that the tensile strength for fabric in warp direction is maximum for basket weave and decreases with increasing extrusion temperature. Furthermore, the optimum design and process parameters for fabric's tensile strength in warp direction are basket weave with 0.3 mm layer height and 205 °C printing temperature as shown in Fig. 6(b).

Table 6: Response table for means of tensile strength of fabrics in warp direction

Level	Design	Layer Height	Temperature
1	23.82	29.43	29.72
2	31.39	31.00	28.39
3	28.87	23.66	25.98
Delta	7.57	7.34	3.74
Rank	1	2	3

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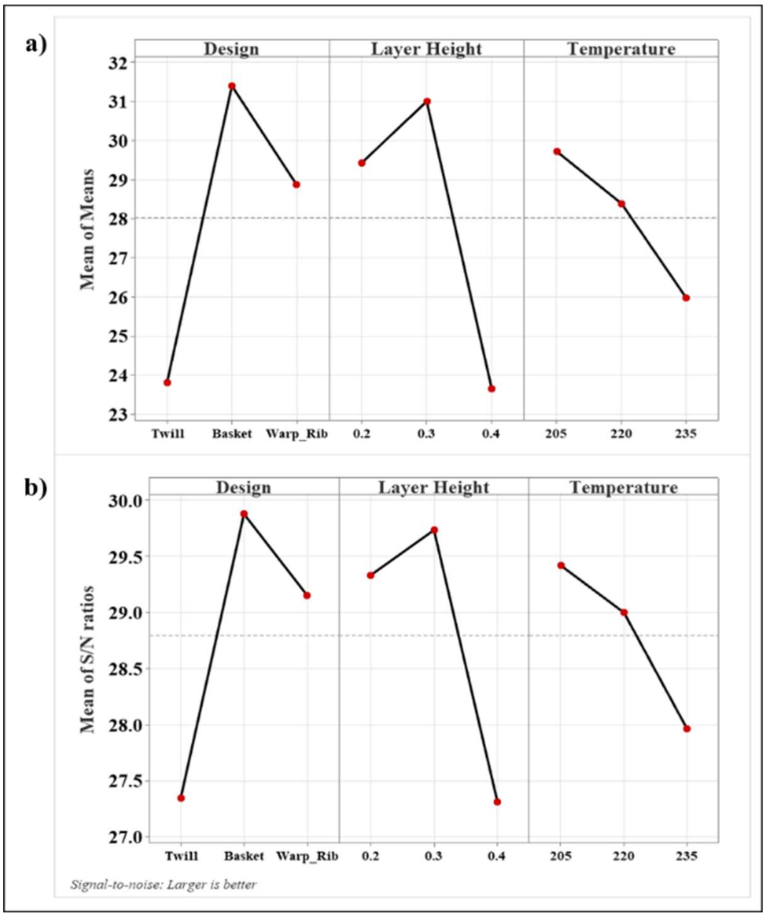

Fig. 6: Main effect plots for tensile strength (MPa) of fabrics in warp direction: **a)** Mean of means **b)** Mean of S/N ratios

The order of influence of tensile modulus is not identical to the tensile strength of fabric in warp direction. The response table for means of tensile modulus of fabric in warp direction is shown in

Table 7 which indicates that the layer height has the maximum influence. The layer height is ranked as 1st, followed by design ranked as 2nd and temperature as 3rd. The nature of order of influence of various levels of design and printing parameters on tensile modulus for the fabric is found to be slightly different from that of the individual warp yarns although the optimum levels are the same. The tensile modulus for fabrics in warp direction is found to decrease with the increasing layer height and increasing extrusion temperature as shown by the main effect plots for means in Fig. 7(a). Twill design is observed to have the optimum average tensile modulus. The S/N analysis for tensile modulus of the fabric in warp direction in Fig. 7(b) shows that the optimized design and parameters are twill design, 0.4 mm layer height and 235°C extrusion temperature.

Table 7: Response table for means of tensile modulus of fabrics in warp direction

Level	Design	Layer Height	Temperature
1	497.2	584.1	580.0
2	525.2	546.9	523.2
3	587.3	478.8	506.6
Delta	90.1	105.4	73.4
Rank	2	1	3

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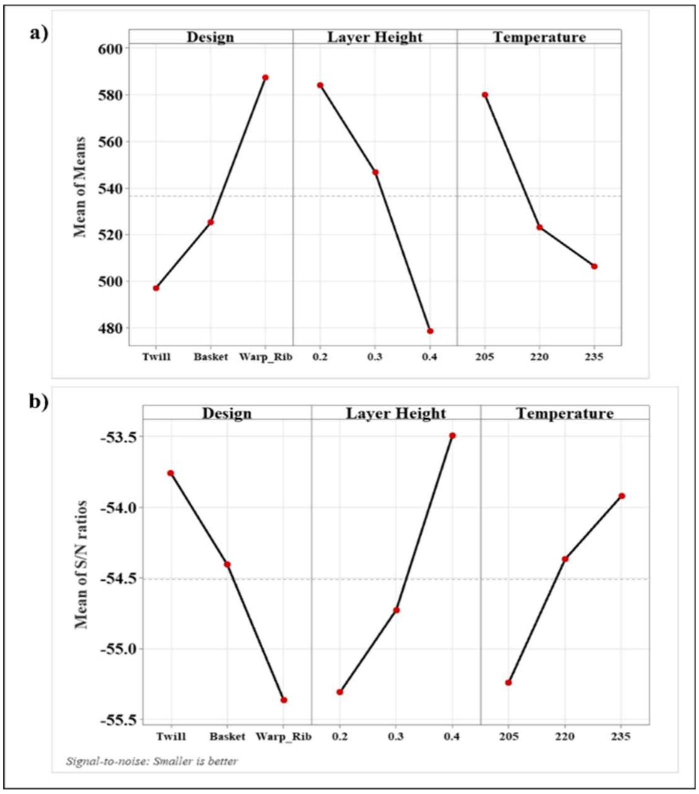

Fig. 7: Main effect plots for tensile modulus (MPa) of fabrics in warp direction: **a)** Mean of means **b)** Mean of S/N ratios

FABRIC'S TENSILE PROPERTIES (WEFT DIRECTION)

The nature of deposition of material is different in the weft direction and warp direction of a fabric. Since the fabric is printed in upright position layer by layer, warp yarns are a continuous deposition of the material to form a string of yarn along the fabric length whereas the weft yarns are result of gradual deposition of the material layer by layer on the cross-section of the weft yarn. On the 3D printer, warp yarns are horizontal and weft yarns are vertical. This results in dissimilar mechanical properties in warp and weft directions. Hence, the tensile strength of the fabric is significantly lower in the weft direction. The influence of the given parameters is also different in the weft direction of the fabric than in the warp direction. The response table for means of tensile strength in weft direction of the fabric is shown in Table 8 which ranks layer height as 1st, temperature as 2nd and design as 3rd; however, the delta value for temperature and design are comparable and lower as compared to that of layer height. This indicates that the layer height has the maximum effect on the tensile strength of the fabric in weft direction and the rest of the printing parameters have low impact. This is because of the low layer height/yarn length ratio requiring numerous thin weft yarn layers in the cross direction to form the weft yarn. The main effect plots in Fig. 8 demonstrate the influence of each level of design and printing parameters on tensile strength of fabric in the weft direction. The tensile strength of the fabric in the weft direction decreases with increasing layer height due to dissimilar material deposition in weft yarns. Each deposited segment represents only a small portion of the weft yarn. When the layer height is increased, it reduces the accuracy of material deposition on top of the previous layer due to the wavy geometry of the yarns, which causes dimensional inaccuracy and leads to larger gaps, unsupported areas and voids between layers. This weakens the bonding between adjacent layers, thereby lowering the tensile strength of the fabric in the weft direction. Therefore, using a smaller layer thickness is more favorable for achieving maximum tensile strength in the weft direction. Other optimized parameters for design

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and temperature are basket weave and 220°C respectively for maximum tensile strength of the fabric in weft direction.

Table 8: Response table for means of tensile strength of fabrics in weft direction

Level	Design	Layer Height	Temperature
1	5.480	8.598	5.253
2	6.212	4.478	6.618
3	5.717	4.332	5.537
Delta	0.732	4.267	1.365
Rank	3	1	2

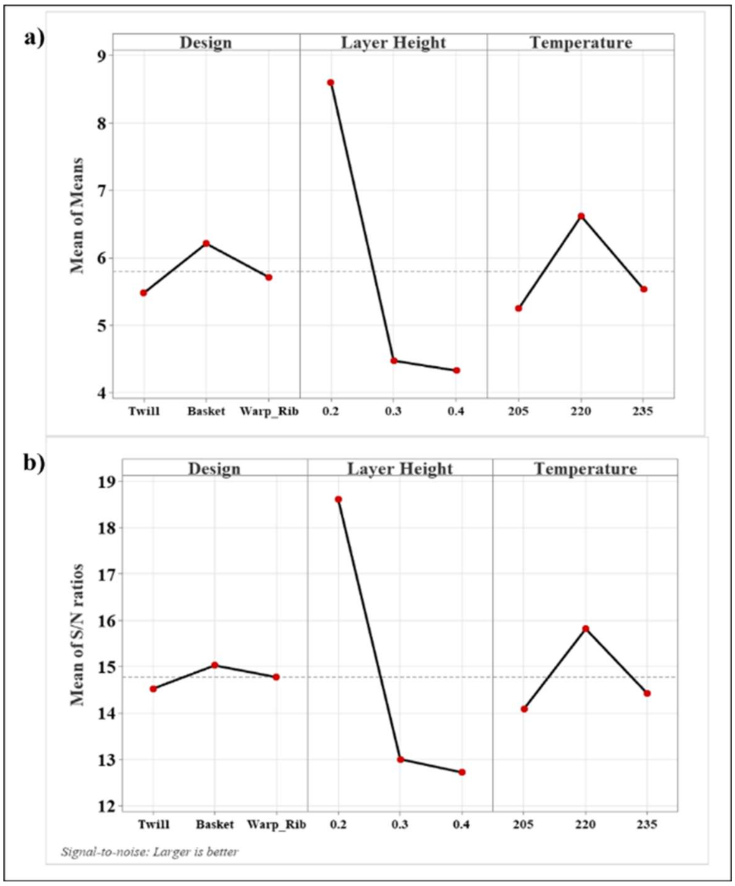

Fig. 8: Main effect plots for tensile strength (MPa) of fabrics in weft direction: **a)** Mean of means **b)** Mean of S/N ratios

The response table for means of tensile modulus of fabric in weft direction (Table 9) shows that the values of delta for layer height and design are comparable and ranked 1st and 2nd respectively and they are significantly higher than the remaining parameter, temperature, which is ranked as 3rd. It implies that layer height has a major effect on the tensile modulus of fabric in the weft direction followed by the design. The main effect plots in Fig. 9 show the variation of tensile modulus for each level of different parameters. Fig. 9(a) demonstrates that the tensile modulus of fabric in weft direction decreases with increasing layer height, the reason being similar as discussed earlier for tensile strength of fabric in weft direction. The S/N analysis in Fig. 9(b) shows that the optimized parameters for the required tensile modulus are twill design, 0.4 mm layer height and 220 °C extrusion temperature.

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Table 9: Response table for means of tensile modulus of fabrics in weft direction

Level	Design	Layer Height	Temperature
1	347.6	470.4	382.8
2	486.5	409.2	384.6
3	363.9	318.4	430.6
Delta	139.0	152.0	47.9
Rank	2	1	3

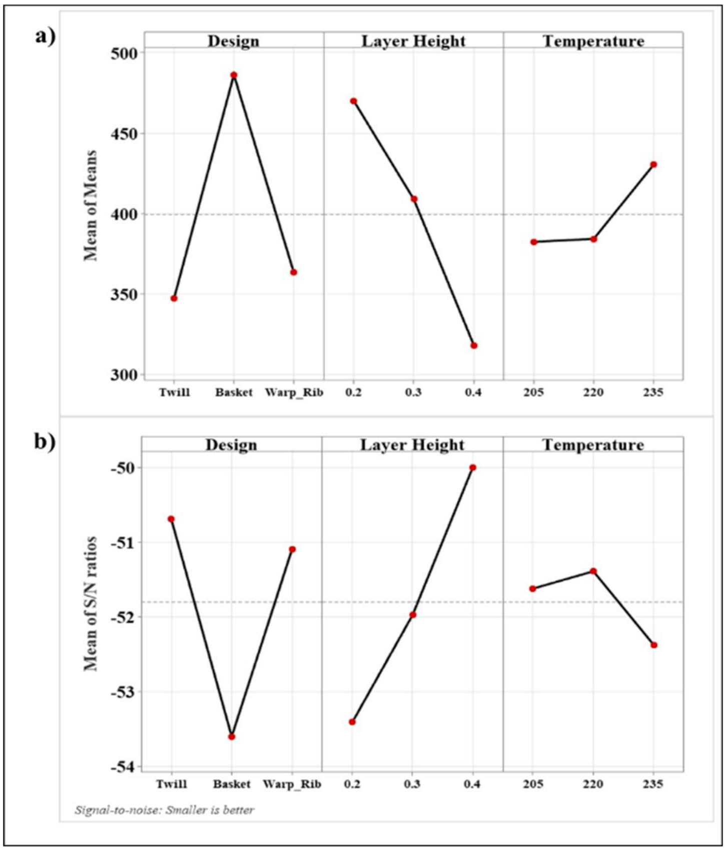

Fig. 9: Main effect plots for tensile modulus (MPa) of fabrics in weft direction: **a)** Mean of means **b)** Mean of S/N ratios

FABRIC'S FLEXURAL PROPERTIES (WARP DIRECTION)

The response table for means of flexural strength in Table 10 shows that the influence of design on flexural strength of fabric in warp direction is minimal. The delta value for the design is significantly lower than those of layer height and temperature. The temperature has the major influence on the fabric's warp directional flexural strength as it is ranked 1st with the highest delta value followed by the layer height which is ranked as 2nd. The results are supported by the main effect plots for means in Fig. 10(a). The difference between the highest and lowest mean values of flexural strength is maximum for temperature followed by layer height and is minimal for design, which is almost a straight line, indicating extremely low effect. The S/N analysis in Fig. 10(b) shows the influence of each parameter level on the flexural strength in warp direction of the fabric. The flexural strength of the fabric in warp direction decreases with increasing extrusion temperature and vice versa. The basket design is the optimal design, 0.3 mm is the optimal layer height and 205°C is the optimal extrusion temperature to obtain the maximum flexural strength in warp direction of the fabric as presented by the main effect plots for S/N ratio.

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Table 10: Response table for means of flexural strength of fabrics in warp direction

Level	Design	Layer Height	Temperature
1	1949	2083	2638
2	1979	2175	1652
3	1958	1628	1596
Delta	29	547	1043
Rank	3	2	1

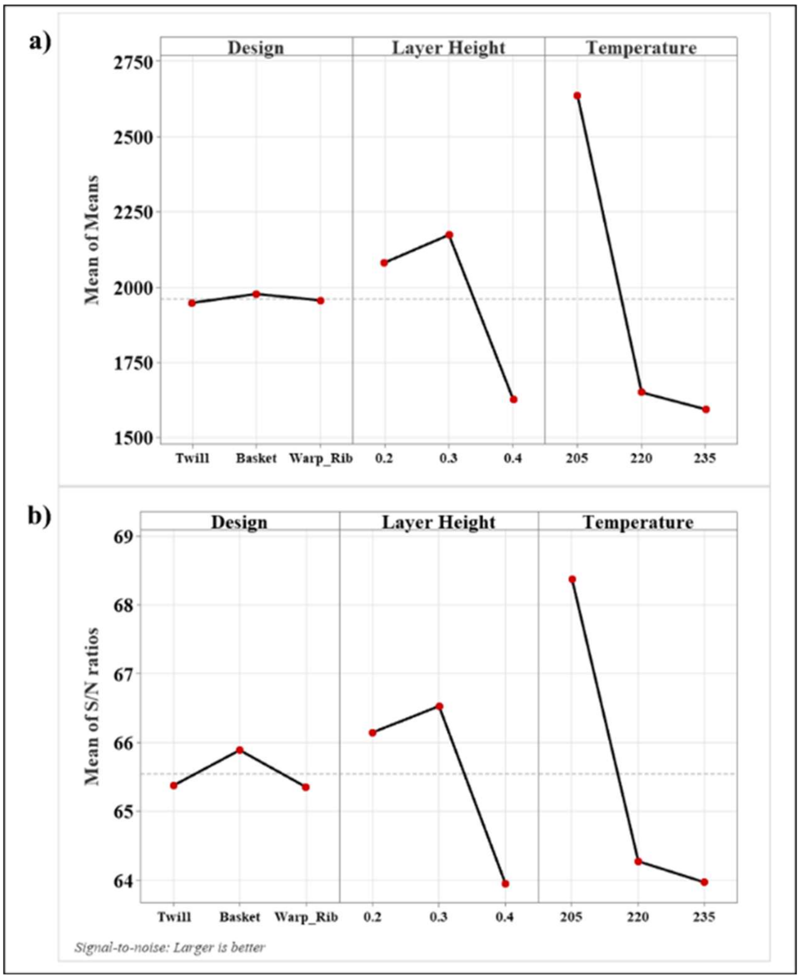

Fig. 10: Main effect plots for flexural strength (KPa) of fabrics in warp direction: **a)** Mean of means **b)** Mean of S/N ratios

Similar results of the influence of design and process parameters can be seen for the flexural modulus of the fabric in warp direction. As presented in the response table in Table 11, the temperature is ranked 1st with maximum delta value followed by layer height. The results show that design has minimal effect on the flexural modulus as compared to the layer height and temperature. Findings are supported by the main effect plots. The main effect plots for means in Fig. 11(a) show that the flexural modulus of the fabric in warp direction is reduced with increasing extrusion temperature as seen earlier for the flexural strength of the fabric in warp direction. Optimized design and parameters for flexural modulus of the fabric in warp direction are twill design, 0.4 mm layer height and 235°C extrusion temperature as shown by the S/N analysis in Fig. 11(b).

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Table 11: Response table for means of flexural modulus of fabrics in warp direction

Level	Design	Layer Height	Temperature
1	42.75	46.56	57.70
2	43.93	48.27	37.41
3	44.39	36.24	35.96
Delta	1.64	12.04	21.74
Rank	3	2	1

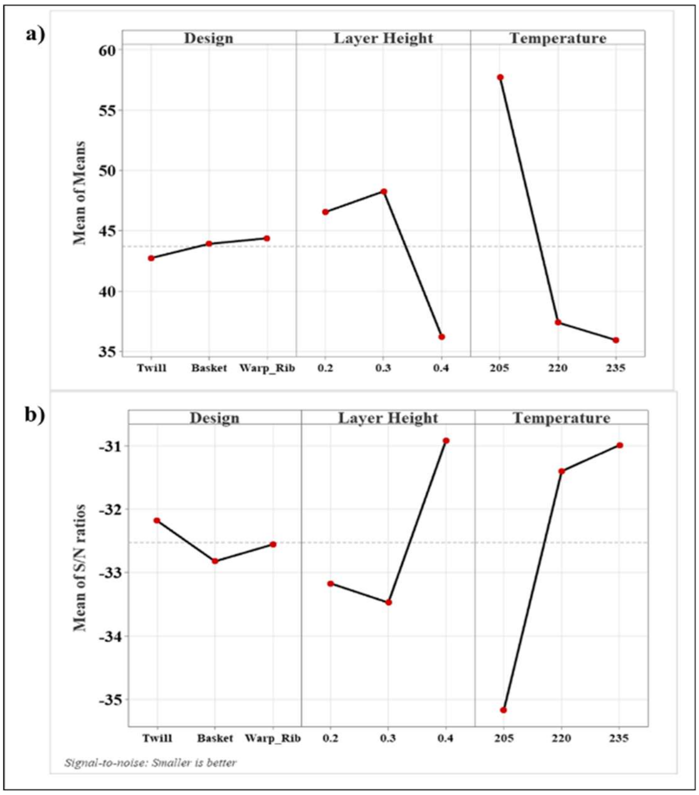

Fig. 11: Main effect plots for flexural modulus (MPa) of fabrics in warp direction: **a)** Mean of means **b)** Mean of S/N ratios

FABRIC'S FLEXURAL PROPERTIES (WEFT DIRECTION)

The influence of design and printing parameters on the flexural strength of the fabric in weft direction is completely different from the ones in warp direction. This is due to the way the material has been deposited while printing the fabric in two orthogonal directions which made the fabric anisotropic. The response table for means in Table 12 shows that the layer height has the most influence on the flexural strength due to its highest delta value. It is followed by the design which had the least influence in the warp direction for the flexural strength. Temperature has the least influence, which was previously ranked 1st in the warp direction. Since the material is deposited as short segments of layers in the weft direction, these segments act as the major regions where the failure can occur. Flexural strength decreases with increasing layer height because it causes less overlapped material deposition due to the wavy geometry of the yarns. This forms larger gaps between bonding layers that lead to weaker regions, similar to the effects as previously observed for tensile strength in the fabric's weft direction. The main effect plots in Fig. 12(a) show the effect of different levels of parameters on the flexural strength of fabric in weft direction. The flexural strength is seen to increase with increasing extrusion temperature which does not have a significant effect since its delta value compared to layer height and design is significantly

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low indicating minimal significance. The bonding between the adjacent layers is efficient if PLA is extruded at elevated temperature but the material might also degrade at higher temperatures resulting in lower flexural strength. But since the weft yarns are made of tiny segments deposited in layers, the effect of material degradation due to deposition at higher temperature does not dominate over the effect of efficient bonding at higher temperatures resulting in better flexural strength at higher extrusion temperature. The best parameters for obtaining maximum flexural strength of a fabric in weft direction are obtained using the S/N analysis in Fig. 12(b) and found to be basket design, 0.2 mm layer height and 235 °C extrusion temperature.

Table 12: Response table for means of flexural strength of fabrics in weft direction

Level	Design	Layer Height	Temperature
1	536.3	851.7	592.3
2	733.0	621.0	655.0
3	656.3	453.0	678.3
Delta	196.7	398.7	86.0
Rank	2	1	3

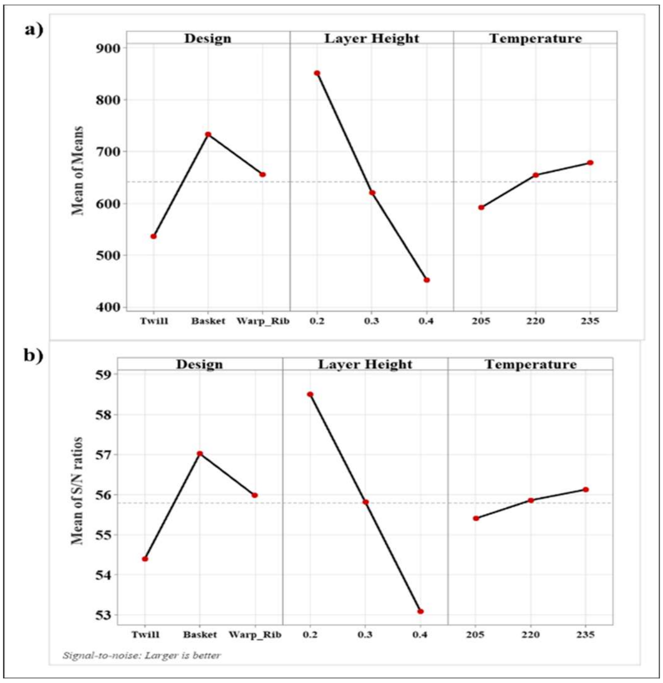

Fig. 12: Main effect plots for flexural strength (KPa) of fabrics in weft direction: **a)** Mean of means **b)** Mean of S/N ratios

Similar nature of results for flexural modulus, as seen for flexural strength, are obtained for fabrics in weft direction. The layer height has shown the maximum influence on the flexural modulus with the highest delta value as demonstrated by the response table for means in Table 13. Design follows layer height while temperature has the least influence on the flexural modulus of fabric in weft direction. The main effect plot for means in Fig. 13(a) shows a sharp decrease of flexural modulus with increasing layer height and a gradual increase in flexural modulus with increasing extrusion temperature because of the same reasons as discussed earlier for the flexural strength of fabric in weft direction. The main effect plot for S/N ratio in Fig. 13(b) gives the optimized parameters for the desired flexural modulus of fabric in weft direction which are twill design, 0.4 mm layer height extruded at 205 °C temperature.

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Table 13: Response table for means of flexural modulus of fabrics in weft direction

Level	Design	Layer Height	Temperature
1	9.683	16.320	11.163
2	14.037	12.183	12.637
3	13.087	8.303	13.007
Delta	4.353	8.017	1.843
Rank	2	1	3

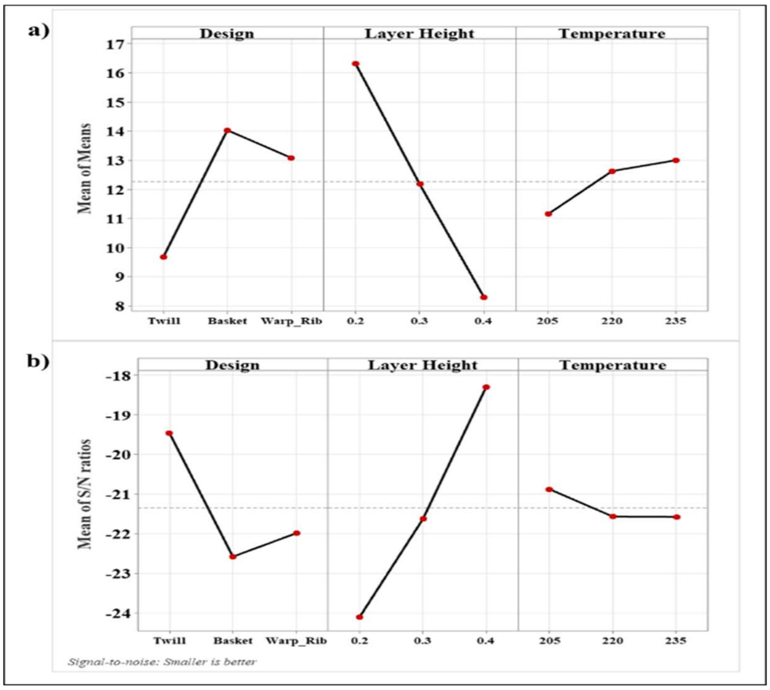

Fig. 13: Main effect plots for flexural modulus (MPa) of fabrics in weft direction: **a)** Mean of means **b)** Mean of S/N ratios

PRINTING TIME OF FABRICS

The response table for means of printing time in Table 14 shows that the design has a slight influence on the printing time and ranked as 2nd. The printing time is minimum for twill design and more and similar for basket and warp rib weave designs. It is because the twill design has 31 yarns in each direction whereas basket and warp rib has 33 in each direction. The layer height has significant effect on the printing time and ranked 1st as it decides on how much material to extrude at a given time in each layer. The delta value is significantly lower for extrusion temperature indicating its minimal effect on printing time and ranked as 3rd. The results are supported by the main effect plots for means in Fig. 14(a) as well, as the range of the maximum and minimum mean values of printing time is maximum for layer height followed by design and minimal for temperature, almost a straight line, indicating extremely low effect. Furthermore, the S/N analysis shows the influence of each parameter level on the printing time of a fabric. The printing time decreases with increasing layer height and vice versa. Since “smaller is better” approach is adopted for printing time, the twill design is the optimal design, 0.4 mm is the optimal layer height and 235°C is the optimal extrusion temperature to obtain the minimum printing time of a fabric as presented by the main effect plots for S/N ratio in Fig. 14(b).

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Table 14: Response table for means of printing time (hours) of fabrics

Level	Design	Layer Height	Temperature
1	3.150	4.553	3.330
2	3.403	3.087	3.357
3	3.467	2.380	3.333
Delta	0.317	2.173	0.027
Rank	2	1	3

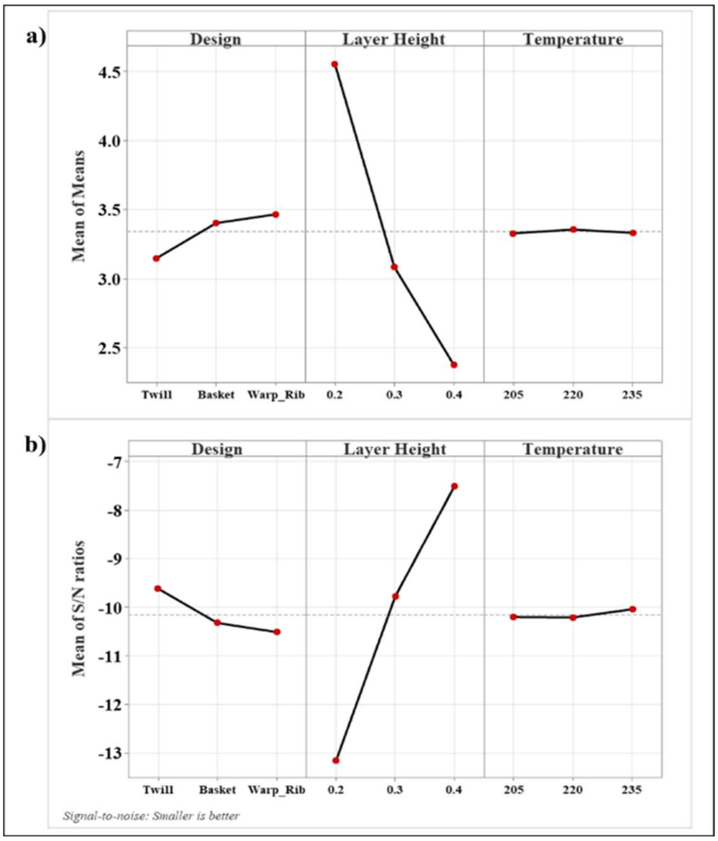

Fig. 14: Main effect plots for printing time of fabrics in hours: **a)** Mean of means **b)** Mean of S/N ratios

OPTIMIZED PARAMETERS

Table 15 presents the optimized mechanical properties of woven fabrics produced using fused deposition modeling (FDM). Optimized results of the mechanical properties presented are obtained using the regression analysis using the optimized design and process parameters as inputs in MINITAB. These optimized design and process parameters for each mechanical property were obtained using the S/N ratio analysis. “Larger is better” and “Smaller is better” schemes were adopted for strength and modulus, respectively. Each mechanical property, including tensile strength, tensile modulus, flexural strength, and flexural modulus, is evaluated for both yarns and fabrics along the warp and weft directions. The table ranks the influence of three parameters for each property and identifies which had the greatest impact on performance. For instance, layer height emerged as the most influential factor for yarn tensile strength, while design had the greatest effect on yarn tensile modulus and warp tensile strength of the fabric. The results show that either design, layer height or temperature can have major

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influence on the mechanical properties of 3D printed woven fabrics. Hence, it is necessary to control either of these parameters depending on the mechanical property of interest of the fabrics.

The table also reveals a clear disparity between the warp and weft directions for similar mechanical properties. For instance, the fabric's tensile strength in the warp direction reaches an optimized value of 33.27 MPa under a basket design with 0.3 mm layer height and 205 °C extrusion temperature. However, in the weft direction, even under optimized conditions (basket design, 0.2 mm layer height, 220 °C), the tensile strength is only 8.35 MPa, which is nearly four times lower. These variations are mainly due to the difference in nature of deposition of materials in the two given orthogonal directions as discussed in the previous section. Furthermore, significant variation in the tensile modulus of individual yarns and fabrics in warp direction is noticed. The results in this study show that the tensile modulus of yarns is higher than that of the fabric, which is dissimilar to the results found in the previous research [17]. It should be noted that both scenarios are possible and depend mainly on the difference in load distribution in the yarns and fabrics. The tensile modulus of yarn being higher than the modulus of fabric is attributed to the fact that the crimp is lower in the isolated yarn as it loses waviness to some extent when it is removed from the fabric. It does not interact with the perpendicular yarns when isolated and can align more freely under load. In contrast, the warp yarns within the fabric experience higher crimp due to interlacing with weft yarns. Under tensile loading, the initial phase of deformation in the fabric is primarily used to straighten this crimp, rather than stretching the yarns. This reduces the initial slope of the stress-strain curve and results in lower tensile modulus compared to the single yarns.

The optimized results show that the twill design with a higher layer height of 0.4 mm and elevated temperatures (up to 235 °C) produced superior modulus values, such as 785.52 MPa for yarn tensile modulus and 407.83 MPa for fabric tensile modulus in the warp direction. In contrast, the basket design with lower layer heights (0.2–0.3 mm) and moderate extrusion temperatures was more favorable for some other strength-related properties, such as tensile strength of 45.30 MPa, weft flexural strength of 975.33 KPa, etc. Furthermore, some flexural properties were found to be highly influenced by temperature which emphasizes the importance of thermal control in FDM process. The table underscores that while all three parameters affect mechanical performance, layer height consistently plays a dominant role across multiple properties, making it a critical variable in the optimization of 3D printed fabric structures

Table 15: Optimized mechanical properties of yarns and woven fabrics with corresponding optimized design and process parameters

Mechanical Properties	Rank of influence	Optimized design and process parameters			Optimized value for corresponding mechanical properties
		Design	Layer Height (mm)	Extrusion Temperature (°C)	
Yarn's Tensile Strength (Warp)	1) Layer Height 2) Temperature 3) Design	Basket	0.3	205	45.30 MPa
Yarn's Tensile Modulus (Warp)	1) Design 2) Temperature 3) Layer Height	Twill	0.4	220	785.52 MPa
Fabric's Tensile Strength (Warp)	1) Design 2) Layer Height 3) Temperature	Basket	0.3	205	33.27 MPa
Fabric's Tensile Modulus (Warp)	1) Layer Height 2) Design	Twill	0.4	235	407.83 MPa

	3) Temperature				
Fabric's Tensile Strength (Weft)	1)Layer Height 2)Temperature 3)Design	Basket	0.2	220	8.35 MPa
Fabric's Tensile Modulus (Weft)	1)Layer Height 2)Design 3)Temperature	Twill	0.4	220	271.56 MPa
Fabric's Flexural Strength (Warp)	1)Temperature 2)Layer Height 3)Design	Basket	0.3	205	2.50 MPa
Fabric's Flexural Modulus (Warp)	1)Temperature 2)Layer Height 3)Design	Twill	0.4	235	26.72 MPa
Fabric's Flexural Strength (Weft)	1)Layer Height 2)Design 3)Temperature	Basket	0.2	235	975.33 KPa
Fabric's Flexural Modulus (Weft)	1)Layer Height 2)Design 3)Temperature	Twill	0.4	205	4.75 MPa

CONCLUSIONS

This research explored the influence of design and FDM process parameters, namely layer height and extrusion temperature on the mechanical properties of 3D printed woven fabric structures using PLA. Using Taguchi L9 experimental design and subsequent statistical analysis in MINITAB, it was found that the significance of each parameter varied across different mechanical properties and directional orientations. Layer height consistently played a dominant role in determining strength and modulus. Design also significantly affected modulus-related properties. Temperature showed a critical influence on the flexural behavior of the 3D printed woven fabrics. It is observed to be most influencing parameter for some properties in warp direction while layer height dominates the same properties in weft direction. Notably, the level of parameter influence differed across properties and directions, emphasizing the anisotropic nature of FDM-printed woven structures.

Optimized parameter combinations were identified for each mechanical property, offering insights into the trade-offs between printing efficiency, structural performance, and mechanical behavior. However, the current Taguchi L9 design does not account for parameter interactions, which are likely to further influence outcomes. Future research should incorporate full factorial or response surface methodologies to explore these interactions more thoroughly. Overall, the findings provide a solid foundation for improving the performance and additive manufacturability of 3D printed textile structures, with promising implications for both academic research and industrial-scale applications.

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