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Fused Filament Fabrication over fabrics – experiments and applications

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Abstract: The focus of this paper is to explore the use of Fused Filament Fabrication technology, a material extrusion additive manufacturing technology, by depositing melted Polilactic Acid (PLA) over a substrate – fabric - instead of on an empty building tray. The textile's composition, nozzle and building plate temperature, printed PLA thickness and printed geometry have been considered as variables that could influence the structural and adhesion properties on this study so, therefor, were took into consideration and tested throughout the printing process through specimens printed with different combined parameters. The aim of this exploration process was developing an experimental procedure to study the limitations and capabilities of this printing technology over textiles, and which different variables' combination would contribute to a better overall result in the development of a self-supporting textile based structural model, that could be apply in different contexts without the need of any extra external support. Results showed that PLA adherence to the fabric is correlated with nozzle/building plate temperature and printing thickness: higher temperature and thickness provide higher adherence. The weave of the textile didn´t reflect on better results but the polyester felt fabric exhibit maximum adherence with printed PLA in all sets of temperatures. In addition, geometries with reinforcement lines along the fabric stress direction provided better structural results. These results enable new application possibilities for the FFF technology combined in fabrics such as in interior, fashion and shoe ware design.

Keywords: 3D printing, Textile fabrics, Layer thickness, Structural structure, Adhesion.

1. Introduction

Fused Filament Fabrication (FFF) also known under the Stratasys Inc trademark Fused Deposition Modelling (FDM) is a material extrusion additive manufacturing (AM) technology used to easily print three-dimensional models by depositing melted non-toxic thermoplastic material, layer by layer, through a stablished path created directly from a mathematically sliced digital Computer-Aided Design (CAD) file [1]. This AM technology can accurately manufacture items on a single step, without the need to use any additional moulds or tools and reducing the waste of unnecessary materials. Speed is also an important benefit of this printing process, models are rapidly produce using all extension of the building plate to efficiently prototype them [2]. FFF technology is adaptable to a variety of applications. While the typical FFF process builds a part button-up on an empty building tray, the material deposition over a substrate, as demonstrated with this study, is possible as well [3].

Nowadays there are several technologies available, which can be used to apply some sort of functionalization to textiles [4]. However, 3D printing offers integrated manufacturing opportunities to directly deposit supporting elements onto them at a cost-effective way, adding value as an add-on technology used to blend small reinforcing 3D printed elements with traditionally produced textile fabrics eliminating, this way, the need to preform additional joining processes like sewing or gluing [4-7]. The use of this technology also minimizes the textile waste and the energy, water and chemical consumption, contributing to the improvement of the ecological footprint of this method [4]. In this regard, the exploration of FFF technology over fabrics and the mechanical properties of the resulting PLA + fabric specimens are relevant properties to study in order to achieve an optimization of all the different parameters that influence the development of a textile structural model. It has been proof that the PLA deposition creates a stiffer and more stable fabric [8], being the focus of this case study the development of a flexible structural model that could be applied in different contexts, without the need of any additional components. These self-supporting fabrics can be used in a wide variety of application such as ultra-lightweight furniture and lighting applications in interior design; structural parts in fashion and shoe ware; as well as a new tool for exploration in the makers community.

The remaining paper is divided into 3 sections where the used methodology, achieved results and drawn conclusions are explained.

2. Methodology and experimental procedure

This experimental study was developed using an Ultimaker 3 3D printer with a 230 mm by 250 mm rectangular building plate, using a 2,85 mm diameter rigid PLA filament over four white types of fabric: 100% cotton, 100% polyester, 100% polyester felt and 65% polyester plus 35% cotton. Other parameters used were: nozzle and building plate temperature combinations of 200 ºC/60 ºC, 220 ºC/70 ºC and 240 ºC/80 ºC and printing thickness of 0,25 mm, 0,50 mm and 0,75 mm. The slicing program used was Ultimaker Cura 4.7. The developed experimental procedure is presented thereafter in three steps.

2.1. First step

The initial step consisted on designing 12 rectangular geometry with 150 mm length by different widths and thickness, where different variables could be tested at the same time (figure 1(a)). The first 9 rectangles had 0,25 mm thickness and increased width 0,25 mm to the next, starting with 1 mm. The remaining three rectangles were 150 mm by 25 mm with 0,25 mm, 0,50 mm, 0,75 mm thickness respectively.

(a) (b)

Figure 1. (a) CAD of the designed geometry. **(b)** Designed geometry being printed on the cotton fabric.

The selected fabrics were fixed, alternately, on the building plate glass and printed with different parameters each time (figure 1(b)). These prints will be used to determine the adherence performance between the printed PLA and the fabric regarding the formed combinations of thickness, width, nozzle/building plate temperature and type of fabric variables and, further on, as samples of the structural performance of the different variables' combinations. On this step the temperatures used to print the geometry on each set of four fabrics were 200 ºC/60 ºC, 22 ºC/70 ºC and 240 ºC/80 ºC nozzle and building plate temperatures respectively. The only element differing from test to test inside the same set was the type of fabric used. With all the printing tests completed, the adherence property was visually tested in all the specimens. A summary of those results is presented further on this document.

2.2. Second step
On the second step, 25 mm by 50 mm specimens were created by cutting the three 150 mm by 25 mm (figure 2(a)) rectangles from the previous step's prints. These smaller rectangles were the specimens used on a three-point bending test, with 30 mm distant supports (figure 2(b)), to evaluate which combination of variables tested before provided the highest flexural strength. Detailed results are presented further on this document.

(a) (b)

Figure 2. (a) 150 mm by 25 mm specimens. **(b)** Three-point Bending test.

2.3. Third step
The results gathered on the three-point bending test and along the rest of this case study were the starting point for the development of the last step. Based on those results, new hexagonal geometries were designed and printed onto the fabrics, which demonstrate a better performance – polyester felt, and 65% polyester plus 35% cotton. Beside these two types of fabric, the nozzle and building plate temperature and printing thickness were other redefined parameters to proceed with the study. Regarding temperatures, the set performing the maximum flexion force of 220 ºC nozzle and 70 ºC building plate temperature was selected. Regarding printing thicknesses 0,25 mm showed no satisfactory results and was dismiss. A linear 1 mm diamond shape with a size of 50 mm by 175 mm characterized all designed geometries (figure 3). The resulted specimens were the base to determine which fabric and geometry combination would provide the best structural result.

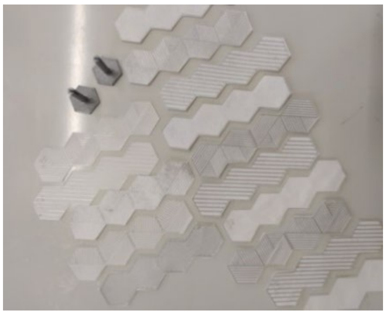


Figure 3. Printed geometries.

All the specimens were printed applying the same parameters besides the used fabric and printing thickness. Each geometry could be printed four times combining the 0,50 mm and 0,75 mm thickness with the selected fabrics however, for a improved efficiency, a numerical analysis using SolidWorks static simulation was performed. Additional results are presented further on this paper.

3. Results and Discussion

On this section the conclusive results achieved during the experimental process are presented into three main subcategories.

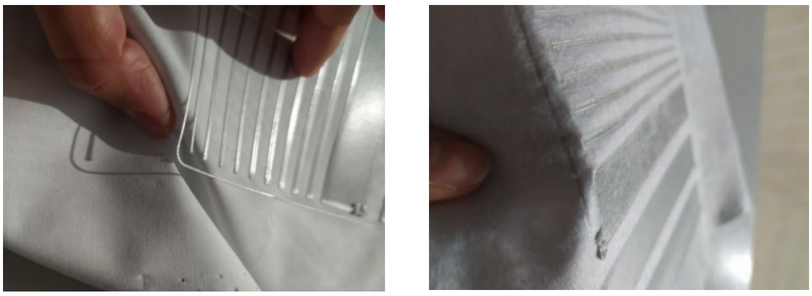
3.1. Material adhesion and minimum width

The 12 prints resulted from the first experiments were tested to establish which combination would provide better adherence and structural results. This was a visual and manual test consisting in cause the peel of PLA by hand. It was possible to observe that PLA adherence to the fabric is correlated with the nozzle/building plate temperature and printing thickness. Higher temperatures provide higher adherence (table 1).

Table 1. Summary adherence results.

Fabric	Nozzle / building plate temperature		
	200 ºC/ 60 ºC	220 ºC/ 70 ºC	240 ºC /80 ºC
100% Cotton	Bad	Average	Good
100% Polyester	Bad	Average	Good
100% Polyester Felt	Great	Great	Great
65% Polyester + 35% Cotton	Bad	Average	Good

The same occurs with printing thickness. Higher thickness provide higher adherence. In another hand, the textile's wave, predictively achieving higher impregnation of PLA on a more open weft, was not reflective of better results, once three of the four selected textiles (figure 4(a)) performed similar results. Nevertheless, the polyester felt fabric (figure 4(b)) exhibit maximum adherence with printed PLA in all sets of temperatures.



(a) (b)

Figure 4. (a) Lack of adherence on the 65% polyester plus 35% cotton fabric. **(b)** Adherence showed on polyester felt fabric.

The lower temperature tests performed on the polyester fabric and on the cotton fabric resulted on some PLA detachment due to the use of the lowest nozzle/building plate temperature. The lower temperature test with 65% polyester plus 35% cotton fabric achieved more satisfactory results with an improvement of PLA and fabric adherence despite still remaining possible to unstick thinner parts of the material. The same temperature on the polyester felt fabric lead to an impossible peeling the material off.

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On the mid-range temperature tests using the polyester, the cotton and the 65% polyester plus 35% cotton fabrics it was possible to observe an increase of the, in spite of still being possible to unstick some material. As observed previously the test performed on the polyester felt fabric achieved maximum adherence results and these nozzle/building plate temperatures led to an improved contour.

The test with the same polyester felt fabric with the highest nozzle/building plate temperature provided equal maximum adherence with printed PLA. The remaining three high temperature tests performed on the 65% polyester plus 35% cotton, polyester and cotton fabrics showed an increase of the adherence, requiring more than a simple handling to peel off the printed PLA.

3.2. *Three-point Bending Test*

This test made it possible to conclude the maximum flexion force of each specimen. With that information, it would be possible to select the temperatures/fabric/thickness combination with better performance to develop further on this case study. The visualization of this test results in a graphic with 36 lines representing each 25 mm by 50 mm specimen tested. The main graphic was divided into three corresponding to the specimens with 0,25 mm (figure 5(c)), 0,50 mm (figure 5(b)), 0,75 mm (figure 5(a)) thickness.

(a)
(b)
(c)

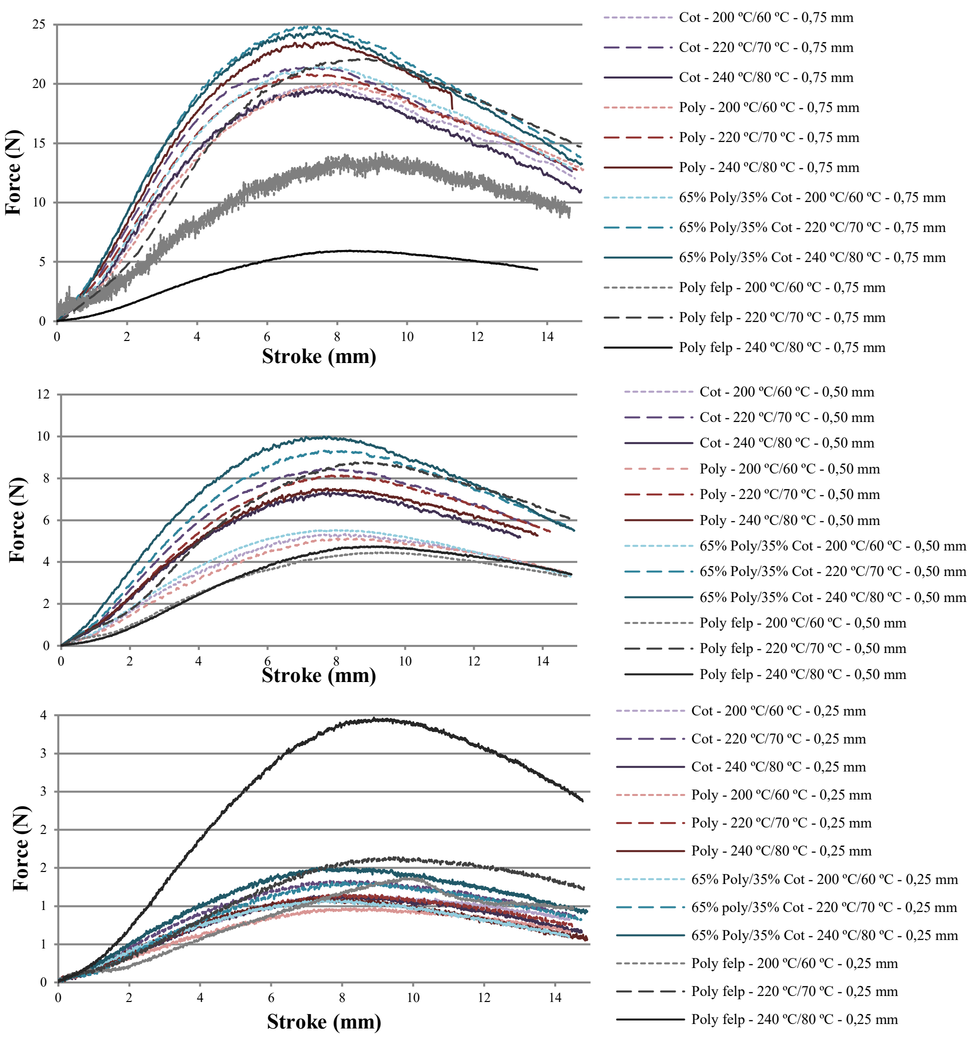


Figure 5. Three-point bending test graphic for **(a)** 0,75 mm thickness specimens **(b)** 0,50 mm thickness specimens **(c)** 0,25 mm thickness specimens.

With this visual representation is possible to observe that:

- The 65% polyester plus 35% cotton fabric printed with 220 ºC nozzle and 70 ºC building plate temperature represents the specimen with the highest applied force of 24,96 N.
- The polyester felt fabric printed with 240 ºC nozzle and 80 ºC building plate temperature represents the specimen with 0,75 mm thickness with the lowest flexural strength.
- The polyester felt fabric printed with 200 ºC nozzle and 60 ºC building plate temperature represents the specimen with 0,50 mm thickness with the lowest flexural strength.
- The 65% polyester plus 35% cotton fabric printed with 240 ºC nozzle and 80 ºC building plate temperature represents the specimen with 0,50 mm thickness with the higher flexural strength.
- The polyester felt fabric printed with 240 ºC nozzle and 80 ºC building plate temperature represents the specimen with 0,25 mm with the higher flexural strength.
- The polyester fabric printed with of 200 ºC nozzle and 60 ºC building plate temperature represents the specimen with 0,25 mm with the lowest flexural strength.

By grouping all the results of the maximum applied forces on a table (table 2) it was possible to observe that, overall, that force increases from the temperature set of 200 ºC/60 ºC to the 220 ºC/70 ºC although it decreases to the 240 ºC/80 ºC and that the printing thickness of 0,25 mm does not provide to the fabric the structural support needed.

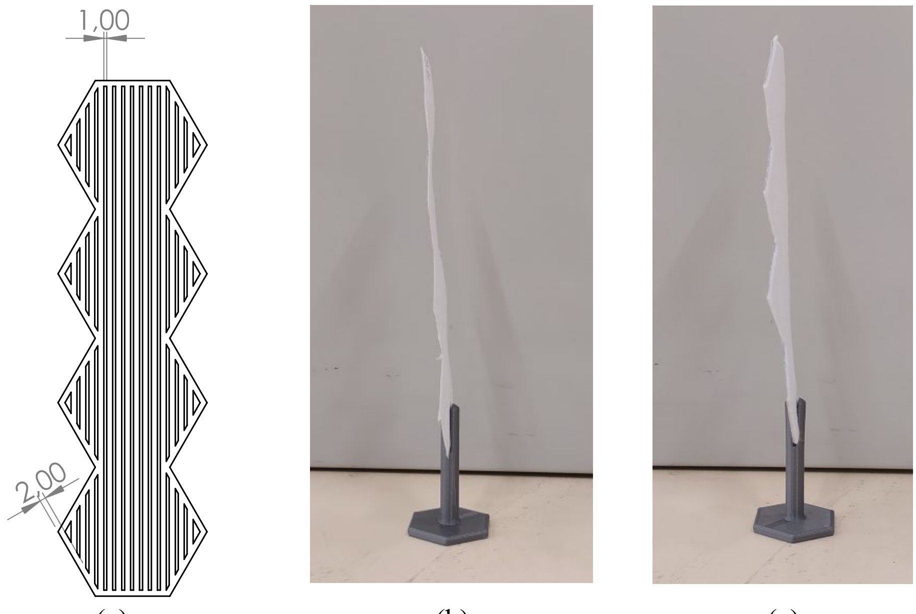
Table 2. Maximum forces applied to each combination on the Three Point Bending Test.

Fabric	Thickness	Nozzle / bed temperature		
		200 ºC/ 60 ºC	220 ºC/ 70 ºC	240 ºC /80 ºC
100% Cotton	0,25 mm	1,18 N	1,36 N	1,16 N
	0,50 mm	5,38 N	8,53 N	7,36 N
	0,75 mm	19,93 N	21,49 N	19,53 N
100% Polyester	0,25 mm	1,00 N	1,19 N	1,13 N
	0,50 mm	5,19 N	8,16 N	7,55 N
	0,75 mm	20,22 N	20,88 N	23,60 N
100% Polyester Felt	0,25 mm	1,41 N	1,66 N	3,50 N
	0,50 mm	4,49 N	8,83 N	4,78 N
	0,75 mm	15,10 N	22,25 N	6,00 N
65% Polyester + 35% Cotton	0,25 mm	1,11 N	1,34 N	1,53 N
	0,50 mm	5,55 N	9,37 N	10,07 N
	0,75 mm	21,47 N	24,96 N	24,44 N

3.3. Self standing structure proof-of-concept
To create a self-standing structure that could respond as a proof of concept for the liability of the structural model, several prints were made with the designed geometries, and placed on a standing pedestal. The first tests consisted of printing the lowest density pattern geometry on the polyester felt fabric, with a printing thickness of 0,50 mm and 0,75 mm respectively. The 0,50 mm reinforced structure was weak and unstable, bending considerably when positioned vertically. The 0,75 mm reinforcement structure was more stable representing that the thickness increase led to a lower bending curve. The following tests consisted of printing the highest density pattern geometry on the same fabric, with a printing thickness of 0,50 mm and 0,75 mm. On these tests, increasing the printing thickness did not represent an enhancement on the structural effect but this material density provides higher structural support when compared with other geometries. Nevertheless, the existence of some horizontal lines confers some weak points to the piece. The next tests consisted of printing the middle-density pattern geometry on the same polyester felt fabric, with a printing thickness of 0,5 mm and 0,75 mm. The

diagonal lines that composed this geometry contribute to a minor rotation of the structure when positioned vertically. As observed previously increasing the printing thickness led to no significant change. The following tests consisted of printing the lowest material density geometry onto the 65% polyester plus 35% cotton fabric, with a printing thickness of 0,75 mm and 0,50 mm. This textile, as proved earlier, showed lower adherence to the PLA but when placed vertically, probably due to the fact that the PLA reinforcement was placed more superficially resulting in a higher thickness PLA + fabric sandwich, it demonstrates higher structural support when comparing to the same print onto the polyester felt. On the other hand, decreasing the geometry thickness led to the decrease of the structural effect. The consecutive tests printed the highest material density pattern on the same previous fabric, with a printing thickness of 0,75 mm and 0,50 mm. The results were similar to the previous ones despite the higher material density although decreasing the printing thickness did not affect the overall structural effect on this specimen. The final tests addressed a middle material density pattern on the same polyester plus cotton fabric, with a printing thickness of 0,75 mm and 0,50 mm. The results are correlated with the ones observed on the seventh and eighth tests.

To test the real viability of each geometry its CAD was subject to a SolidWorks bending simulation. The first test was performed on a totally infield geometry to predict the lowest flexion curve possible to achieve, resulting to be 10,50 mm. Follow steps consisted of designing and testing new geometries until achieving a similar result. With the previous experience, horizontal shapes were avoided and the design along the stress direction prioritized. The designed geometry (figure 6(a)) that achieve the most approximated bending result – 16,28 mm - was formed by vertical linear shapes with 1 mm width. It was then printed onto both polyester felt fabric and 65% polyester plus 35% cotton fabric (figure 6(b)) with 0,75 mm thickness. Polyester felt fabric (figure 6(c)) showed a slightly worst result because it conferred a slight wave to the final shape.



(a) (b) (c)

Figure 6. (a) Better results geometry. **(b)** Better results geometry printed into the 65% plus 35% fabric. **(c)** Better results geometry printed into the polyester felt fabric.

4. Conclusion

Through the different experiences in this experimental study, it was possible to conclude that if the right geometry is developed it is possible to provide structural support to printed fabric. The main observation to have in account is to design the reinforcement geometry lines along with the part main influence on the reinforcement adhesion and reinforced part strength. There are some additional characteristics that can lead to the increase of this support, not yet physically tested on the study, such as a fabric printed on both sides with the same geometry and the appliance of some curvature to the printed piece. Future work will further investigate these possibilities and explore applicability case studies.

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