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Evaluation of Tensile Properties and Damage of Continuous Fibre Reinforced 3D-printed Parts

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Abstract. Three-dimensional (3D) printing technology has been traditionally used for the production of prototypes. Recently, developments in 3D printing using Fused Deposition Modelling (FDM) and reinforcement with continuous fibres (fiberglass and carbon fibre), have allowed the manufacture of functional prototypes, considerably improving the mechanical performance of the composite parts. In this work, we characterise the elastic tensile properties of fibre reinforced specimens, considering the variation of several parameters available during the printing process: fibre orientation, volume fraction, fill pattern, reinforcement distribution. Tensile tests were performed according to ASTM D638 to obtain Young's modulus and ultimate strength for different material configurations available during the printing process. We also perform a fractographic analysis using Scanning Electron Microscopy (SEM) to give an insight of the failure mechanisms present in the specimens.

Introduction

Three-dimensional (3D) printing technologies have emerged as a new paradigm for machine design. Functional parts produced by additive manufacturing (AM) are changing the way practitioners tackle design bounds, with models highly optimised using more advanced CAD/CAE tools. Nowadays, the 3D printing industry is growing fast, and moving from the segment of rapid prototyping (RP) and marketing to include fully functional machine parts, leading to a new industrial revolution [1], [2]. Most popular 3D printing technologies include: fused deposition modelling (FDM), selective laser melting (SLM), stereolithography (STL), laminated object manufacturing (LOM) [3], and are available for printing polymers [4], [5] and metals [6], [7].

Several authors have worked on the evaluation of the dimensional accuracy and the mechanical properties of parts manufactured by FDM, both in industrial and desktop printers [4], [8]–[11], desktop printers usually using ABS, polycarbonate (PC) or polylactic acid (PLA) as thermoplastic raw materials [12]. Research on new thermoplastic materials has been done, including thermoplastics with embedded metallic particles [13], reinforced with short carbon fibres [14] or natural fibres [15]–[17].

In 2014, a new FDM technology using continuous filament fabrication (CFF™) was presented [18]. The printer allows printing functional parts of composite nylon reinforced with continuous fibreglass, carbon fibre, etc. The addition of carbon fibres considerably increases the stiffness and strength of the pieces, compared to those made in ABS. However, to be able to use these functional parts, and

introduce this technology in the design process, it is necessary to investigate the mechanical response of the composite printed parts and the effect of the different printing parameters.

The use of carbon fibre reinforcement was studied by Mori et al. [19] using a RepRap, replicating rapid prototype. However, the fibres were manually set during the printing process with a fixed orientation and distribution, and not enough thermal bonding to improve the adherence in the fibre-matrix interface. Melenka et al. [20] studied the effect of the addition of concentric rings of continuous fibres on a nylon matrix. It was verified that the modulus of elasticity and ultimate tensile strength increase with the volume fraction. Additionally, a prediction model of the elastic constants was developed using the average stiffness method.

For industrial applications, to ensure that fibre-reinforced 3D-printed components meet the required design specifications, it is necessary to understand their tensile mechanical properties. In this work, the behaviour under tensile stress tests of 3D-printed specimens manufactured in nylon matrix and reinforced with continuous fibres of glass or carbon is characterized. For this study, the 3D printer Mark Two from Markforged [21] was used. In the next section, we present the parameters of the tensile test according to ASTM D638 [22] and the parameter configurations chosen to manufacture the test specimens. Then, we present the results, including an analysis of the dimensional accuracy of the printer, the results obtained from the tensile tests for the modulus of elasticity, ultimate strength and Poisson's coefficient, for each material configuration. We perform a comparison between different fill patterns, fibre orientation and fibre material. Finally, conclusions are presented.

Materials and methods

Mechanical tests. The 3D-printed specimens were evaluated by performing tensile tests using an MTS Bionix 370.02, with a load cell of 25 KN. Longitudinal deformation and contraction of the cross-section of the test specimens were measured using the LVDT of the machine and an LX500 laser extensometer, with a test speed of 5 mm/min. The tensile test specimens were produced using the printer Mark Two from Markforged, following ASTM D638, geometry type IV [22], as shown in Figure 1. STL files were produced in a CAD software and exported to the software Eiger for preparation.

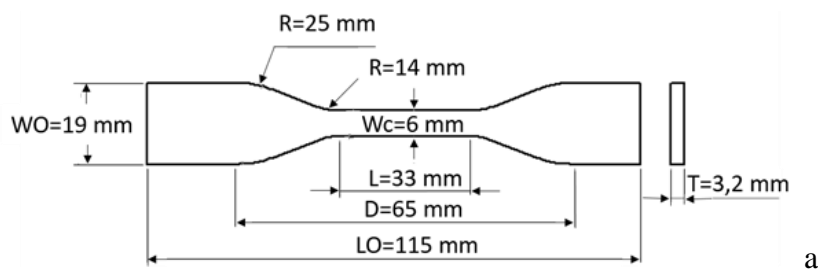


Figure 1. Geometry of the specimen for tensile test of 3D-printed parts according to ASTM D638 type IV.

Printing parameters and internal structure. The 3D printer Mark Two allows the variation of several printing parameters which could potentially modify the mechanical response of the final produced part. In **Error! Reference source not found.** we show the chosen values for different printing configurations. In the experimental tests, we studied the influence of the density, fill pattern, fibre material, and fibre orientation on the mechanical response.

Results

Dimensional accuracy. The measurement of the geometry of the specimens was carried out to evaluate the dimensional accuracy of the Mark Two 3D printer, and to verify the cross-sectional area

of the specimens. The measurements were compared with the nominal dimensions according to the ASTM D638 TYPE IV standard. A t-Student test with a p-value significance test of <0.05 was applied to statistically determine the difference between the nominal value and the measured values for the section widths W_c , W_O and the thickness t , with the highest percentage difference for the thickness, Table 2. The results are consistent with other studies evaluating the dimensional accuracy of 3D-printed parts [23].

Table 1. Printer parameters for nylon and continuous filament fabrication (CFF).

	Nylon	CFF
Layer height (mm)	0.1	0.1
Fill density (%)	20, 50	20
Fill pattern	Triangular, Rectangular, Hexagonal	Triangular
Infill layers	24	18
Wall layers	2	2
Roof and floor layers	4	4
Fibre material		Fibreglass, Carbon
Fibre orientation		0° , 45° , 90°
Fibre fill type		Isotropic
Total fibre layers		6
Total layers	32	32

Table 2. Measurements of the thickness (t) for reinforced specimens.

	Length [mm]	(%)	p-value
Nominal dimension	3.2		
Specimen with fibres at 0° (STDV)	3.30 (0.03)	3.15	<0.001
Specimen with fibres at 45° (STDV)	3.28 (0.03)	2.76	<0.001
Specimen with fibres at 90° (STDV)	3.32 (0.07)	3.81	<0.001

Tensile tests results. The effect on the mechanical properties of the variation of material parameters defined during the printing process is investigated. The modulus of elasticity, the ultimate tensile strength and Poisson's ratio of different configurations were determined from the experimental results. In Table 3 we show the results for two fill densities for the nylon matrix: 20% and 50%, using three different fill patterns: triangular, rectangular, and hexagonal. As expected, the triangular pattern yields higher values for the stiffness and ultimate strength. Increasing the fill density to 50% only increases the elastic modulus by 3.3%, and the strength by 5.5%.

Table 3. Experimental mechanical properties at 20% and 50% density for different filling patterns.

	20%			50%		
	Triangular	Rectangular	Hexagonal	Triangular	Rectangular	Hexagonal
Elastic modulus [MPa]	244	156	178	252	165	200
Ultimate tensile strength [MPa]	18	13	15	19	16	17
Poisson's ratio	0.57	0.18	0.46	0.39	0.31	0.12

In Table 4 we show the results for specimens printed with continuous filament fabrication, using fibreglass at different orientations: 0° , 45° and 90° with respect to the axial direction of the load. We observe the effect of the reinforcement with fibreglass at 0° , which yields the highest elastic modulus (1610 MPa) and ultimate strength (83 MPa). With fibres aligned with the transverse direction, the strength and stiffness are characterized by the nylon matrix.

Table 4. Experimental mechanical properties of CFF reinforced with fibreglass.

	0°	45°	90°
Elastic modulus [MPa]	1610	558	391
Ultimate tensile strength [MPa]	83	37	22
Poisson's ratio	0.27	0.25	0.24

We produced specimens with different types of fibres: fibreglass and carbon fibre, using the parameters in Table 1, see Figure 2. We observe that with carbon fibre reinforcement we reach stiffness values of 4.4 GPa and ultimate strength of 104 MPa, Table 5, for the chosen printing configuration.

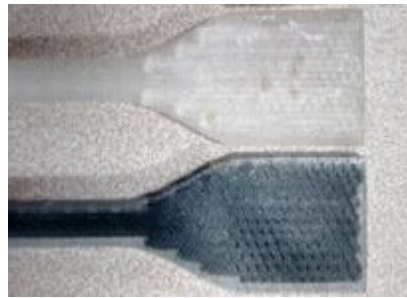


Figure 2. ASTM D638 type IV specimens for tensile tests printed with: fibreglass (top) and carbon fibre (bottom) reinforcement.

Table 5. Experimental mechanical properties of CFF fibreglass and carbon fibre.

	Fibreglass	Carbon
Elastic modulus [MPa]	1610	4431
Ultimate tensile strength [MPa]	83	104

Microscopy. Three specimens of 3D-printed parts reinforced with fibreglass were prepared for fractographic analysis using scanning electron microscopy (SEM). We show in Figure 3 the images for fibres oriented at (a) 0° and (b) 45°, corresponding to the cross-section in the fracture area and a close-up view of the reinforced areas. The reinforced roof and floor layers, and the infill layer can be clearly identified. Composite models assume perfect bonding between the fibres and the matrix. Note that for the 0° orientation we can see fibre pull-out, which indicates imperfect fibre-matrix bonding.

Summary

Three-dimensional printing using FDM with continuous filament fabrication (CFF) has potential to produce functional parts with high strength and stiffness. To be able to use this technology for industrial applications it is necessary further investigation on the mechanical response of the printed parts. We performed ASTM tensile tests to evaluate the elastic modulus and ultimate strength of FDM-printed parts, modifying printing parameters to obtain different composite material features. Moreover, we obtained SEM images of the fractured cross section to observe the damage mechanisms of the fibre, matrix and interface. Different fibre patterns prove useful to improve mechanical properties of the composite 3D-printed parts.

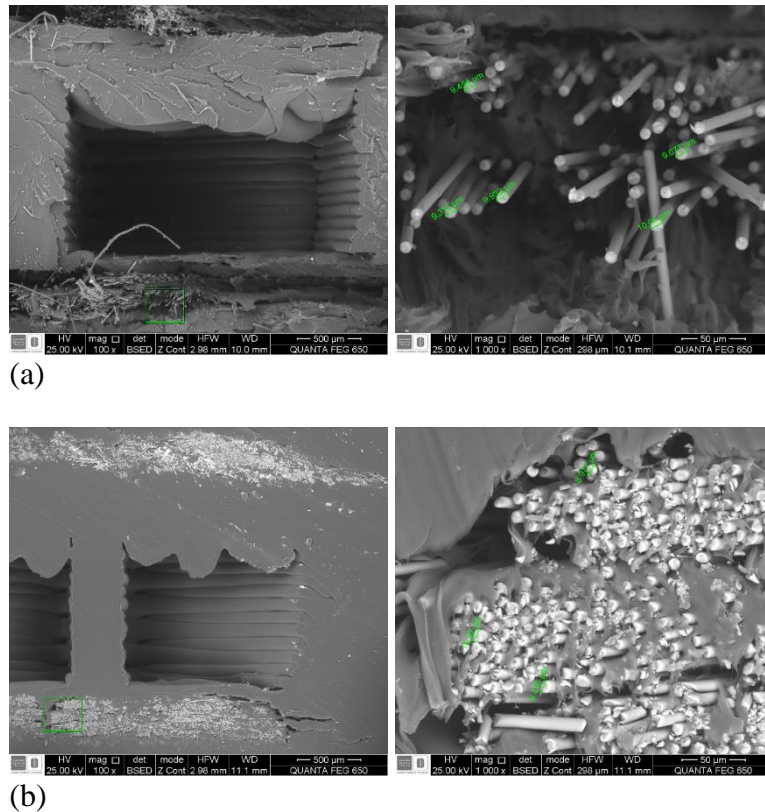


Figure 3. Scanning electron microscopy (SEM) fractography of 3D-printed parts reinforced with fibreglass, cross section and close-up: (a) fibres oriented at 0° , (b) fibres at 45° .

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