Study of mechanical properties under compression failure in reinforced composite materials produced by additive manufacturing

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Abstract. In this work, we study the mechanical properties under compression of composite materials with reinforced-rigid-matrix produced by additive manufacturing. The study considers different fiber orientations and number of reinforcement layers of the specimens. The experimental investigation was carried out for parts produced with a nylon matrix and fiberglass reinforcement. The composite material was manufactured through fused deposition modeling (FDM) in a Markforged Mark Two 3D printer, which allows the production of specimens satisfying the ASTM D3410 standards. Different filling patterns were analyzed (triangular, hexagonal and rectangular), as well as, the reinforcing fiber angles (0°, ±30°, and ±45°), and the number of reinforcement layers (6, 12 and 18). The different configurations are analyzed in order to establish their performance under compression. Results indicate that to obtain a highly resistant material, more layers should be added and the fibers oriented parallel to the load axis.

1. Introduction

Composite materials reinforced by fibers have applications in many fields thanks to their high force-weight, rigidity-weight ratios [1-3], and offer a much greater resistance to weight than monolithic structural materials. Thus, many industries have decided to use these materials, e.g., aerospace, automotive, oil & gas, etc. [3], for engineering applications, and research on new material models has grown [4]. During the last years, significant research has been performed for the tensile strength, fatigue resistance, and the hardness in composites, but the compressive stress in these materials has shown little improvement [5].

Regarding compression loading conditions, results by different authors highlight various types of failure modes, where the predominant ones are failure by shear, micro-buckling, crushing and delamination [5-7]. For rigid resins, given their high elastic modulus, it was found that the dominant failure mode was by shear in the fibers on a macroscopic scale [8]. In Ref. [5] the authors performed electronic fractography and noticed different types of fractures in the specimens due to failure by shear.
and also micro-buckling in fibers. In general, micro-buckling is a typical phenomenon of composite materials when subjected to longitudinal compression stress [9].

Traditionally, fused deposition modeling (FDM) has been used to print only prototypes as the mechanical properties of the parts are not high enough for engineering applications. In the last years, a printing technology that enables the production of reinforced composites using continuous filament fabrication (CFF) yields the possibility to produce functional parts using additive manufacturing [10-12]. However, to be able to design mechanical components using this technology it is necessary to first understand the mechanical response and micromechanics of the new material model. Research on tensile and flexural loading conditions are available in the literature [11,13,14], however, more research is needed to fully understand the capabilities of this new manufacture technology for design purposes, especially if we consider the large number of possible material models obtained by changing printing parameters.

In this work, we investigate the mechanical properties for compression loading conditions of reinforced composite materials produced by additive manufacturing. We consider the variation of different printing parameters such as the orientation of the reinforcing fiber, filling pattern, and number of layers. In the next section, we present the methodology, describing the experimental setup. Then, we show the results obtained for the compression tests following ASTM D3410 [15] standard and the fractographic analysis. Finally, the conclusions are presented in the final section.

2. Methods and materials

The test specimens were manufactured using a nylon matrix and fiberglass reinforcement, printed with a Markforged Mark Two 3D printer. The design of the tests was carried out as specified in section 8.2 of the ASTM D3410 standard [15]. Five (5) test pieces for each test were printed, with a width in the gage section of 10mm for 0° fiber orientation, and 25mm for the rest. The thickness of 3mm was chosen considering the compression stress and the expected longitudinal modulus. In addition, the printer allows changing different parameters to modify the material distribution, which are shown in the next sections.

The compression tests for the composite laminated materials need some special fixtures for the acquisition of data. For the experiments, we used the fixture proposed in [16], which is part of the ASTM D3410 standard [15]. The ASTM standard proposes the use of wedges that are attached to the specimens, which are optional, and were not used in the tests [15]. The MTS Bionix universal testing machine was used, which was set at an advance speed of 1.5 mm/min. The tests were carried out at room temperature, and the specimens were stored with silica to avoid that the humidity could affect the properties of the material. The verticality of the specimen is checked with a laser sensor.

2.1. Filling pattern

The first test was performed by varying the different filling patterns of the matrix as shown in Figure 1. The printing parameters of the test are presented in Table 1. Moreover, a preliminary test was made to analyze the influence of the length of the specimen in the range allowed by the standard between 10mm and 25mm.

![Figure 1](image-url)  
**Figure 1.** (a) Hexagonal pattern, (b) triangular pattern, (c) rectangular pattern.
Table 1. Printing parameters used for the tests.

| Filling Pattern | Triangular, hexagonal, rectangular |
|-----------------|----------------------------------|
| Reinforcement   | fiberglass                       |
| Orientation     | $90^\circ$                       |
| Reinforcement layers | 12                             |

2.2. Orientation of the reinforcement

We fixed the filling pattern to triangular and analyze in detail the orientation of the reinforcement material. The first parameter that was modified for this reinforcement was the orientation angle of the fiber, the values of the angle are shown in Table 2.

Table 2. Parameters for reinforcement angles.

| Filling pattern | Triangular |
|-----------------|------------|
| Reinforcement material | fiberglass |
| Orientation     | $0^\circ$, $\pm 30^\circ$, $\pm 45^\circ$ and $90^\circ$ |
| Reinforcement layers | 12 |

2.3. Number of reinforcement layers

We analyzed the influence of the number of layers with fiber, which increases the volume fraction of the reinforcement and, consequently, the strength and rigidity of the composite. Notice that the maximum volume fraction for the fiber is approximately 80%. More than that, the matrix does not offer proper support, obtaining a material less resistant. The specimens have a total of the 30 printed layers, there is a range available between 2 and 22 reinforced layers. With this information, the experiment was designed as shown in Table 3.

Table 3. Parameters for the number of reinforcement layers.

| Filling pattern | Triangular |
|-----------------|------------|
| Reinforcement   | fiberglass |
| Orientation     | $\pm 30^\circ$ |
| Fiber layers    | 6 (20%), 12 (40%) and 18 (60%) |

In order to determine the mode of failure, which can occur for different reasons that cannot be identified at first sight, the ASTM D3410 standard has a classification system in section 11.10 [15]. After the specimen fails, force continues to be applied until the fracture propagates, making it easier to identify the different failure modes. At the end of the test, we proceeded to identify the failure using the standard identification codes. The type of failure of the specimen is determined by its external visual aspect, to evaluate its acceptability. Then, we calculated the mechanical properties of the composites, and the average values were obtained for the fractured specimens. Finally, an internal analysis of the microstructure was done by fractography to evaluate the response of the structure to the mechanical loads. An SEM Quanta 650 FEG scanning electron microscope was used. The samples were placed on metal stubs with carbon adhesive tape, and they were coated with gold in a Quorum 150ES coating equipment.

3. Results and discussion

First, we test the length of the gage section. For longer gage sections, the possibility that buckling failure will be generated increases, reducing the load carrying capacity. For this reason, the minimum allowed length was fixed for the rest of the samples. The average results for different lengths analyzed are presented in Table 4.

In Table 5, we show the results of the tests for different filling patterns with a gage section of 10mm. Note that, as expected, the triangular pattern is the most resistant due to its geometric configuration [14]. We choose the triangular filling pattern for subsequent tests.
Table 4. Values of the maximum stress for different lengths of the gage section of the specimen. Triangular filling pattern

| Test section (mm) | Maximum stress (MPa) |
|-------------------|----------------------|
| 25                | 29.39                |
| 12                | 37.55                |
| 10                | 42.64                |

Table 5. Maximum stress at different filling patterns.

| Filling pattern | Maximum stress (MPa) |
|-----------------|----------------------|
| Triangular      | 42.64                |
| Rectangular     | 37.88                |
| Hexagonal       | 33.76                |

Failure modes have a classification according to section 11.10 of the ASTM D3410 standard [15]. Test specimens with different types of failures were visually analyzed, considering acceptable the fractures in the gage section, with the code TGM (Transverse Shear, Gage, Middle), indicating a shear failure in the middle zone of the gage section. Not acceptable tests were assigned the code TIT (Transverse Shear, Inside Grip/Tab, Top), indicating that the failure was in the area of the clamps.

In Figure 2, we show the results for the reinforced composite with different orientation of the fiber. Notice that the specimens with fibers that tend to be parallel to the load have a greater elastic modulus but show lower values of the ultimate stress. The maximum strength was obtained for the specimens printed at 30 degrees (56.2 MPa). Fiberglass oriented at 90° was not considered because the fibers are perpendicular to the load, resulting in a buckling failure of the matrix, which is not an acceptable mode in the standard.

![Figure 2. σ vs. ε for the different angles analyzed with 12 reinforcement layers.](image1)

![Figure 3. σ vs. ε for fiberglass at 30 degrees varying the number of reinforcement layers.](image2)

In Figure 3, we fixed the angle to 30 degrees and study, the influence of the number of reinforcement layers. The ultimate strength increases with the number of reinforced layers, as expected. For 18 layers we obtained the maximum value of 80 MPa. On the other hand, with the material reinforced with 6
layers, the lowest compressive stress was obtained, due to the small number of fibers that support the load, producing an early break.

Figure 4 shows the top view of a fiberglass test tube oriented at 30 degrees. The effects of compression can be seen in the sample, presenting multiple failure modes in the fracture zone. The main and most visible failure is the one given by shear (in-plane shear), which indicates a total fracture of the fibers, which agrees with the tendency of shear of ±45 degrees with respect to the direction of the mechanical load (y-axis), see Figure 4(a). According to Odom and Adams [7], this type of failure occurs due to the absence of adequate lateral stability, which could also generate micro-buckling, a failure that can be also appreciated. Delamination buckling is also shown in Figure 4 (a), which is an interlaminar failure mode presented as a micro-buckling that generates delamination along certain fibers.

![Image](image1.png)

**Figure 4.** (a) Top view of the fiber failure oriented at 30°, (b) brooming failure mode, (c) kink-band fracture.

In Figure 4(b), we can observe a detail of brooming in the failure zone, a surface mode that is distinguished because the fibers that fracture overlap each other. The next failure mode that can be seen in Figure 4(c) is a shearing rupture kink-band failure, which is identified by microfractures in the fibers, because they begin to present local micro-buckling due to compression, which finally leads to
fragmentation, generating a smooth change in the orientation of the same, relating in this way the shearing effect.

Figure 5 shows another failure mode where the characteristics of the fragmentation of the fibers are indicated. In this case, fiber crushing is represented by multiple ruptures as stellate fibers along the filaments in the gage area. This characteristic is typical of compression in the interlaminar mode, given the collision of the fibers when the load continues to be applied.

![Figure 5. Multiple fractures in the fiberglass, dislocated in different directions.](image)

4. Conclusions
The number and orientation of fibers of the reinforcing material have a strong effect on the maximum compression stress and the elastic modulus. Values for the mechanical properties are obtained for several material configurations, considering the angle of the fibers, number of reinforced layers, and filling patterns. From the results obtained, it is concluded that, to find the most resilient material configuration, under the proposed parameters of printing, it is necessary to prioritize the orientation of the fibers of the reinforcement material and the layers that are to be added, since the more fibers the material and more parallel to the axis of load loading, you will get a fragile and highly resistant material.

In the SEM microscopy analysis, it was possible to identify the different failure modes presented by the specimens, such as micro-buckling, a failure mode commonly found under compression. The fracture propagated mainly by shear.

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