Compression tests performed in reinforced rigid matrix composite varying the reinforcement material

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Abstract. In this work, we investigate the behavior under compression for a nylon-matrix composite, reinforced with Kevlar, fiberglass, and carbon fiber. The composite is produced by additive manufacturing (AM) using fused deposition modeling (FDM). The specimens are printed with the Markforged Mark Two 3D printer, following the ASTM D3410 standard. The tests are performed by changing the reinforcement material, the filling pattern is fixed to a triangular shape, the angle at 0° and we use 12 layers for all the specimens. Kevlar reinforcement shows a non-linear elastic response for the stress-strain curve, whilst carbon fiber and fiberglass reinforcements show linear elastic behavior. Results indicate that the incidence of a particular failure mode is highly dependent on the type of material used in the reinforcement.

1. Introduction
The composite materials reinforced with fibers have applications in different fields, due to their high force-weight, and stiffness-weight ratios, creating strong and very light materials [1,2]. Among the most important industries that have decided to use these materials are: aerospace, automotive, sports, among others [3,4]. Composites have had great acceptance since its introduction in the sixties, but due to the different fiber-matrix combinations, there is no complete information on the mechanical properties of these compounds [5].

During the last years, significant improvements have been achieved in tensile strength, fatigue resistance and hardness in reinforced composites, but unfortunately, the compression strength in these materials has shown little improvement [6]. The effect of the mechanical properties of composite materials, specifically their response to compression forces, has been first investigated using different polymer matrix compounds [7]. Odom and Adams [8] used unidirectional carbon-epoxy compounds to analyze the different failure modes presented under compression tests, while Chaudhuri and Garala [9] focused on improving the compressive strength of carbon fiber reinforced composites using a carbon-glass composite. With the development of ultra-high modulus carbon fibers, CFRP have been widely used, especially in the aerospace sector [10]. However, their behavior under compression stress is approximately 60-70% of the tensile strength and has been considered a limiting factor by the designers. Authors highlight different failure modes, where the predominant ones are shear failure, micro-buckling,
crushing, and delamination. [6,8,11]. In general, micro-buckling is considered a typical phenomenon of composite materials when subjected to longitudinal compression loads [10], as shown by electron microscopy studies [6]. The incomplete fusion between the matrix and the fiber is produced during the curing process, these imperfections modify the function of the matrix, which helps to support the compression load applied to the material [12]. When the load applied to the composite is analyzed in these micro sections with imperfections, a shear stress is generated in the matrix [13], and can also lead to bends with different orientations and widths [14].

Recently, composite materials can be manufactured by additive manufacturing (AM) [15] using fused deposition modeling (FDM), a technique commonly known as 3D printing, which is a method where a plastic filament is deposited in layers to produce a three-dimensional object or part. This procedure has been used mainly in engineering for producing prototypes. Using continuous filament fabrication (CFF) it is possible to use reinforced materials to produce functional parts [16-18]. In order to use this new technology to produce functional parts, it is necessary to understand the mechanical response under different loading conditions and the micromechanics of the new material model.

In this work, we study the compression strength and Young’s modulus in composite materials according to section 12, from ASTM D3410 standard. For materials where a non-linear behavior in the stress-strain curves is evident, as the deformation increases, the stiffness of the compound is reduced [13]. The maximum strength under compression loads does not necessarily correspond to the start of yielding in the matrix, but is dictated by the interaction between the non-linearity of the matrix and the initial misalignment of the fibers [19]. For this reason, we make an approximation using Hollomon’s empirical equations [20], since they provide better agreement with the experimental results, in order to obtain Young’s modulus. In the next section, we present the methodology of the study, followed by the results of the experimental tests. Finally, we present the conclusions.

2. Materials and methods

The compression tests were performed according to ASTM D3410. Compression tests on fiber-reinforced composites require a specific fixture to perform a correct data collection. For this project, we used the fixture developed by the Institute of Technology and Research of Illinois (IITRI), which helps to avoid buckling and is also part of the ASTM D3410.

The Markforged Mark Two 3D Printer was used to produce the test specimens, which allows manufacturing reinforced composites with a nylon matrix and three different types of reinforcement: fiberglass, carbon, and Kevlar fibers. ASTM D3410 specifies the dimensions for the specimen of 140mm (L) x 10mm (H) x 3mm (W), and the minimum amount of 5 specimens per test performed. The thickness of 3mm was chosen to take into account the compression stress and longitudinal modulus expected. In addition, the 3D printer uses the software Eiger, which allows modifying different parameters to obtain different configurations for the produced parts. The tests were performed with a layer height of 0.1mm, a triangular filling pattern with a density of 50%, 4 roof and floor layers, and 2 wall layers, parameters which remain constant. The analysis was performed for the available materials to identify their mechanical response, see Table 1.

| Table 1. Settings to identify the characteristics of the reinforcement. |
|--------------------------|-------------------------|
| Filling pattern          | Triangular              |
| Reinforcement            | Fiberglass, Kevlar, Carbon fiber |
| Fiber angle              | 0°                      |
| Number of layers         | 12                      |

A universal MTS Bionix testing machine was used, which was set up at a standard crosshead displacement of 1.5mm/min. The tests were done at room temperature and the specimens were stored with silica to avoid the humidity. ASTM D3410 suggests the use of tabs made from different materials and glued to the specimens, characteristic that is optional and was not used in this study.
By performing these tests, different failure modes can occur for many separate reasons that cannot be seen at a glance. To determine these failure modes, the ASTM D3410 has a section that allows classifying its acceptability. After the failure of the specimen, the load continued to be applied, such that the fracture can propagate, making it easier to identify the different modes [6]. At the end of the test, the first analysis was to detail the type of fracture (external) to determine its acceptability, following the Failure Identification Codes, proposed by the standard. The calculation of the mechanical properties of these composites is described in section 12 of ASTM D3410. Calculations and the average values were estimated for 5 accepted broken specimens.

Finally, the internal analysis of the microstructure was carried out, the samples were placed on metal stubs with carbon adhesive tape, and they were coated with gold in a Quorum 150ES coating equipment. In order to establish the structure-mechanical behavior relationship, Quanta 650 FEG environmental scanning electron microscope was used, where images were taken in high vacuum with an acceleration voltage of 25kV, through a detector for secondary electron images (SE) (Everhart Thornley detector ETD) and likewise for backscattered electron detector (BSED) type SSD.

3. Results and discussion
Failure modes have a classification according to ASTM D3410. In Figure 1, test specimens with different fractures are presented, showing the section where fiber rupture was recorded. These were analyzed in an external visual way. The acceptable failure occurred in the gage section of the specimen, identifying them with the three-part-identification TGM, “Transverse Shear, Gage, Middle”, while the one that presented fiber breakage in the top and bottom sections of the specimen, was identified as TIT, “Transverse Shear, Inside Grip/Tab, Top”, defined as non-acceptable.

The study focused on analyzing the difference between the materials available on the printer, considering the angle with the highest Young’s modulus (0°). As known from the literature, the most resistant material is the carbon fiber followed by fiberglass and, finally, Kevlar. Both, carbon fiber and fiberglass presented fracture or cracking in some fibers in the extreme part of the test specimens, Figure 2(a), before reaching the ultimate strength, when the test specimen fails in the acceptance testing section, Figure 2(b).

Moreover, in Figure 3, when a change in the gradient of the curve happens, the rupture or cracking of fibers occurs, but the test continues until the load-bearing capacity is lost, as shown in the graph. The
curves continue increasing until the specimen fails in the gage section. For this reason, Young’s modulus calculated for these materials was considered an apparent modulus. Figure 4 and Table 2 include the response for Kevlar fibers, which exhibits lower values of the mechanical properties and a non-linear behavior.

Figure 3. Stress-strain of carbon fiber and fiberglass until the failure.

Figure 4. Stress-strain of specimens from all materials for 12 layers and 0°.

Table 2. Experimental mechanical properties.

| Reinforcement material | Compressive strength (MPa) | Young’s Modulus (MPa) |
|------------------------|---------------------------|-----------------------|
| Carbon fiber           | 108.1                     | 463.6                 |
| Fiberglass             | 43.9                      | 243.8                 |
| Kevlar fiber           | 31.1                      | 233.5                 |

In order to find Young’s modulus for the Kevlar composite, a model that adjusted the curve of the graph to an approximate real value was used [20]. From the stress-strain curves for the materials studied, it is shown that carbon fiber has the highest compression strength and displays the maximum apparent Young’s modulus, with a significant difference w.r.t. fiberglass and Kevlar.

The microscopy analysis shows many details that are useful to complement the results obtained experimentally in the compression test. Figure 5 shows the cross section of a test specimen of carbon fiber in its gage section. For this analysis, we consider two printings of 6 reinforced layers of carbon fiber. The nylon layers melt completely, and this indicates a good cohesion between the matrix and the fiber. Also, empty spaces in nylon are observed, where the printing could be improved, but these are not significant in comparison with the number of fibers adhered to the matrix.

Figure 6 shows the same carbon fiber specimen which is printed at 0° w.r.t. the direction of the load. Notice the rupture of these filaments in different places, where the predominant failure mode is given by shear through the thickness of the specimen, leaving fractured fibers and disoriented filaments. This is the presumed feature that yields high values in the mechanical properties. In addition, the nylon melts surrounding the filaments providing support and increasing their resistance.

It is possible to identify small fragments of carbon fiber in Figure 7. This characteristic is specific to shear failures, which gives support to the hypothesis of irregular propagation of the fracture and also
multiple failure modes occurring due to the layers of fibers that crash during the test [6]. The fragments are disoriented along the failure section, preventing an easy identification of the failure direction. In Figure 8, the support provided by the matrix is clearly presented, which stays attached to the fibers to improve their mechanical properties. In this case, a fractured filament is suspended and held by the nylon.

4. Conclusions
The results indicate that the failure mode evidenced by each specimen tested is mainly related to the reinforcement material. The specimens were printed with an orientation of 0°, this shows good results for Young’s modulus, although the maximum compressive stress was reduced by the fracture of fibers outside the gage section, which weakened it. Therefore, the way in which the material is deposited by the printer is the cause of this failure. Finally, through SEM microscopy analysis, it was possible to identify the different failure modes during compression loads, where micro-buckling was found as a common failure detected under compression. The fracture is propagated mainly by shear, confirming the high strength of carbon fiber.

After analyzing the results of the properties, a cost-benefit relation can be established to prioritize the characteristics when manufacturing a composite. Carbon fiber is the most expensive material, with a value that doubles the others, establishing a relationship that indicates better properties at a higher price and defining the reinforcement material as the most important criterion when designing the pieces.

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