Interlaminar tensile strength for composite materials made by additive manufacturing

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Abstract. The low interlaminar tensile strength of fiber reinforced composite materials presents serious challenges in the design of structures with a considerable radius of curvature, which is commonly found in a wide range of fields such as aeronautics, civil engineering, maritime industry, energy industry, among others. The objective of the present research was to analyze the interlaminar tensile strength, in the interlaminar layer of a material composed of fiberglass as reinforcement in nylon matrix, using a curved beam elaborated by additive manufacturing. To achieve this, tests were carried out according to ASTM Standard, and to determine which parameters significantly influence the failure of the composite material, variations were made in the thickness of the test specimens, which were manufactured following the criteria of the standard. The results obtained allow the assessment of interlaminar tensile strength and specimen behavior after failure.

1. Introduction

Composite materials provide improved mechanical properties and new challenges in the design process [1–4]. The use of composite materials in structural applications whose geometry includes important radii of curvature requires studying new forms of failure and fracture, which do not occur in traditional materials [5,6]. Among the mechanical properties to be studied in additive manufacturing materials is the interlaminar tensile strength (ILTS), which consists of the fracture of the laminate along the plane that separates the different layers of the composite material, causing a decrease in the stiffness and strength of the material, which finally leads to the failure.

Delamination in composite materials can result from the following factors: load misaligning which induces off-plane loads; discontinuities in the structure creating local out of plane loads; low-speed impacts; cyclic loading; incomplete curing; and the introduction of foreign particles [7]. The primary fiber transports the load to regions of partial curvature, but sudden changes of this or undulations present in the layers can generate radial stresses. This stress works as delamination stress in open mode causing the delamination to begin and grow under the service load [7–9].

Currently there are several methods to determine the ILTS. Some procedures that involve loads applied directly to the specimen can be found in the standards ASTM C297 [10] and ASTM D7291 [11], while indirect methods are described in [7,12–14]. Specific analyzes about the benefits and consequences of the aforementioned methods were carried out in [15,16]. Also, numerical methods to predict ILTS are proposed in various studies such as those made in [13,17,18].

In this work, indirect load methodology and four points bending test (FPBT) following ASTM D6415 [19] were used. In this test, there is a pair of loads on each of the arms of the specimen, generating only
bending stress in the analyzed section. This methodology has some advantages over other indirect methods, such as simplified analysis in the ILTS evaluation, stress independence from the angle position, constant moment on the testing section and the auto-alignment of the test specimen [20]. Also, it is a more realistic approach to determine the strength to interlaminar traction for various applications with geometric curve. Cui [21] and Jackson [20] validated the use of bent beams as test specimens for the four points bending test to obtain resistance to interlaminar traction values.

The purpose of this study is to analyze the variation of the ILTS of a composite material produced by additive manufacturing, constituted of a nylon matrix and reinforced with fiberglass, making variations in the thickness of the test specimens. Additive manufacturing emerges as an important technological innovation that yields a radical shift in machine design paradigm. To make the most of this new technology in our manufacturing industries, it is necessary to fully understand material behavior.

2. Materials and methods
The methodology employed for the tests followed the ASTM D6415 standard [19], which determines the resistance to interlaminar traction of a bent (curve) test specimen made of a composite polymer-matrix material reinforced with fiber. In the standard, the parameter curved beam strength (CBS) is defined as the bending moment per width unit applied on the specimen that produces a sudden decrease of the load. For the experiment, a sampling of 3 groups of 6 test specimens each of different thickness, see Table 1 and Figure 2, was performed. The specimens were made with the Markforged 3D printer Mark Two, that allows adding fiberglass reinforcements in the printing process [22,23], see Figure 1. In addition, the printing produces a core with a honeycomb structure. The specimens were initially modeled with the use of the software SolidWorks 2018 and, afterward, processed with Eiger software to configure the printing parameters.

![Figure 1. Printing process of test specimens.](image1)

![Figure 2. Test specimens with different thickness.](image2)

| Thickness t (mm) | Number of specimens | Volume (cm³) | Volume of nylon (cm³) | Volume of fiberglass (cm³) |
|------------------|---------------------|--------------|-----------------------|---------------------------|
| 2                | 6                   | 6.390        | 6.390                 | 0.00                      |
| 4                | 6                   | 11.41        | 11.25                 | 0.16                      |
| 8                | 6                   | 19.92        | 19.72                 | 0.20                      |

A universal testing machine, Bionix workbench with an MTS 515 hydraulic unit, with a four-point bending fixture, was used to perform the test, see Figure 3. The cylindrical loading bars of the bending fixture have a diameter of 10 mm (0.39 in) and are fixed over adjustable holders. The length of the lower section beams is 100 mm (3.94 in) and the length of the upper section beams is 75 mm (3 in).

The test was made by applying a variable load at a constant speed of 0.5 cm/s with the objective to produce a constant bending moment throughout the testing section. The data was registered with the MTS Test Suite Multipurpose Elite Software. A distance of 75 mm (l₀) between the lower cylinders and 48 mm (l₁) between the upper cylinders was measured in the assembly, see Figure 4.
Figure 3. Different positions for test specimens: (a) mounting, (b) test start, (c) failure.

Figure 4. Test specimen diagram.

To determine CBS on the first decrease of the load, indicating the initial delamination, we need to know the actuating moment, as the FPBT subjects the specimen to a pure bending moment in the curved section. The applied moment is the product of the force of one of the cylindrical bars, $P_b$, and the distance between two bars along one leg. The strength is calculated considering the total force in the first decrease, and the distance is determined using the geometry of the specimen. Thus, CBS expression reads [24] in Equation (1):

$$CBS = \left(\frac{P}{2w\cos(\theta)}\right) \left(\frac{dx}{\cos(\theta)} + (D + t)\tan(\theta)\right)$$  \hspace{1cm} (1)
where $\theta$ is the angle of the loading arm, $d_x$ is for the horizontal distance between the centers of the adjacent upper and lower rollers ($h - l_t$)/2, $D$ denotes the diameter of the loading rollers, $w$ is the width, and $t$ is the thickness.

To evaluate $\theta$, we need to calculate the vertical distance between the rollers, $d_y$, considering the vertical displacement, subjected by the fixture, from the initial value of $d_y$, see Equation (2):

$$d_y = d_x \tan(\theta_i) + \frac{D + t}{\cos(\theta_i)} - \Delta$$

The initial value of $d_y$ is evaluated using the initial angle, $\theta_i$, and the geometry. The initial angle $\theta_i$ is half the global angle between the arms of the specimen before the test.

To determine the tensile modulus in Equation (6), we use the rule of mixtures [25] in Equation (9):

$$E_\theta = V_{\text{fiber}} + V_{\text{matrix}} E_m, \quad E_r = E_f \left[ \frac{E_m}{V_f E_m + V_m E_f} \right]$$

The materials used in the preparation of the specimens have the characteristics shown in Table 2 [26].

| Plastic Matrix | Nylon | Fiber Reinforcement | Fiberglass |
|----------------|-------|---------------------|------------|
| Tensile Modulus (GPa) | 0.94 | Tensile Reinforcement (MPa) | 590 |
| Tensile Stress at Yield (MPa) | 31 | Tensile Modulus (GPa) | 21 |
| Tensile Strain at Yield (%) | 27 | Tensile Strain at Break (%) | 3.80 |
3. Results
Figure 5 to Figure 7 show the relationship between the applied force and the elastic deformation presented for the six specimens with unidirectional fiberglass layers, and with thicknesses of 2 mm, 4 mm and 8 mm, respectively. Notice that the specimens deform elastically until they reach a maximum load depending on the test samples thickness and its composition.

![Figure 5](image1.png)  
**Figure 5.** Load-displacement for 2 mm thickness sample.

![Figure 6](image2.png)  
**Figure 6.** Load-displacement for 4 mm thickness sample.

![Figure 7](image3.png)  
**Figure 7.** Load-displacement for 8 mm thickness sample.

The specimens do not fail due to delamination because of their high content of elastic material as matrix. In addition, it can be associated with the honeycomb pattern of the printing, since the model presents a high energy absorption factor. The curved beam and interlaminar strengths measured using this test method are extremely sensitive to fiber volume and void content. According to the numerical results obtained, an apparent final stress value was obtained which can be associated with the delamination model, however, the fracture model does not allow to validate this condition.

4. Conclusions
Three main conclusions have been obtained from this study which confirms the ASTM D6415 standard [19]. The volume of reinforcement material used in the manufacturing of the specimens is fundamental to determine the interlaminar tensile strength. The additive manufacturing process is carried out by filament deposition in layers, however, the distribution of the material in the specimen does not exhibit failure due to delamination. The process of printing by additive manufacturing for the manufacture of samples did not allow to visualize failure by delamination in this model due to the configuration of honeycomb which presents a high energy absorption factor and void content. Further studies with higher volume fractions to evaluate inter and intralaminar stresses are required.
Acknowledgments
The authors acknowledge the support from the project FM-2018-1, Convocatoria VIE, Universidad Industrial de Santander.

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