

Mechanical Performance and Crack Propagation Resistance in 3D-Printed Nylon-Carbon Composites

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Abstract: This study investigates the fracture toughness of 3D-printed Polyamide 12 (PA-12) reinforced with carbon fiber. Tensile tests demonstrated an average ultimate tensile strength of 74.24 MPa. Compact tension tests on specimens (W=14 mm, B=4 mm, a=8 mm) revealed a critical load of 1.8 kN. The fracture toughness (K_{IC}) was calculated as 36.8 MPa $\sqrt{m}$ following ASTM E399 standards. Using an experimental elastic modulus of 5 GPa typical for carbon fiber reinforced PA-12 composites, the corresponding critical strain energy release rate (G_{IC}) was determined to be 245 kJ/m². This substantial fracture resistance, combined with the observed mixed-mode failure mechanisms including fiber bridging and matrix deformation, indicates that 3D-printed PA-12 carbon fiber composites offer promising damage tolerance for structural applications.

Keywords: 3D printing / Additive manufacturing, Carbon fiber reinforced polymer (CFRP), Fracture toughness, Polyamide 12 (PA-12/Nylon 12), Damage tolerance / Failure analysis

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1. Introduction

Composite laminates play a critical role in high-performance industries, including aviation, marine, and automotive sectors, where the demand for lightweight yet strong materials is paramount [1]. A comprehensive understanding of their mechanical properties, particularly under varied loading states, is essential for ensuring structural integrity and performance reliability. Studies such as those by Abdellah et al. [2] have investigated the mechanical behavior of composite laminates with open holes under static tensile loading, employing both analytical and numerical models to predict failure. Their work underscored the significance of geometry and stress concentrations in determining nominal strength.

The incorporation of fiber reinforcement into polymer matrices is a well-established method for enhancing mechanical performance. It is widely recognized that increasing fiber content generally improves both strength and stiffness [3,4]. In polymer composites, fibers such as carbon (CF) and glass (GF) are frequently used to produce fiber-reinforced polymers (FRPs) with superior structural characteristics [5]. The influence of such reinforcements on the behavior of traditionally manufactured composites

has been extensively documented [6,7,8].

Polyamides, commonly known as nylons, represent a class of engineering thermoplastics valued for their high toughness, thermal and chemical resistance, and fatigue performance [9,10]. Among these, Polyamide 12 (PA-12) is notable for its balanced properties, including good impact resistance and low moisture absorption. When reinforced with carbon fibers, PA-12 transforms into a high-performance composite, combining the matrix's durability with the fiber's exceptional strength and stiffness [11]. Carbon fiber-reinforced polymer (CFRP) composites have thus seen expanding use in aerospace, defense, and automotive applications, where a high strength-to-weight ratio is crucial [12]. The performance of CFRPs is strongly governed by the fiber-matrix interface, which dictates load transfer efficiency and overall damage tolerance [13,14].

The mechanical performance of 3D-printed parts can be improved by optimizing printing parameters and reinforcing the polymer matrix with fibers [15,16]. Fiber approaches have gained attention for enhancing part quality and mechanical properties. For instance, Venkatesh et al. [17] incorporated short carbon fibers (CF) into ABS, PLA, and nylon, significantly increasing Young's modulus and tensile strength. Polyamide-carbon fiber (PA-CF) composites combine the stiffness of carbon

fiber with the toughness of nylon. Randomly oriented short CFs improve interlayer bonding during printing, boosting toughness, tensile modulus, and impact resistance [18]. These enhanced properties make PA-CF suitable for protective gear, medical devices, and electronic components [15,18].

Despite these advances, a detailed investigation into the fracture toughness and critical strain energy release rate of 3D-printed PA-12 carbon fiber composites remains limited. Fracture toughness is a vital material property for applications involving crack initiation and propagation under load. Therefore, this study aims to experimentally characterize the fracture behavior of additively manufactured PA-12 reinforced with short carbon fibers. Through tensile testing and compact tension (CT) fracture tests, this work evaluates the ultimate tensile strength, elastic modulus, critical stress intensity factor (KIC), and strain energy release rate (GIC). The findings will contribute to a deeper understanding of the damage tolerance in 3D-printed PA-CF composites and support their adoption in structural applications requiring high reliability.

2. Material and Methods

The base matrix material used in this study was Polyamide 12 (PA 12 / Nylon 12), a semi-crystalline thermoplastic known for its excellent mechanical properties and suitability for additive manufacturing. As detailed in industry material guides, PA 12 is characterized by the lowest water absorption among commercial polyamides, which contributes to superior dimensional stability in finished parts, a critical factor for precision 3D-printed components [19].

This polymer was reinforced with short carbon fibers (CF) to create a composite feedstock. The incorporation of carbon fibers enhances key properties of the base polymer: it significantly increases tensile strength and stiffness (modulus), improves thermal conductivity to reduce warping during printing, and provides greater abrasion resistance.

The PA 12 / Carbon Fiber composite filament was processed using Fused Deposition Modeling (FDM), a material extrusion additive manufacturing technique. Prior to printing, the filament was dried according to standard processing guidelines for polyamides to minimize moisture content, which is essential for preventing defects

and ensuring optimal layer adhesion and mechanical performance in the final printed specimens.

Tension test

Tensile tests were conducted to characterize the fundamental mechanical properties of the 3D-printed PA-12 carbon fiber composite. The tensile specimens were manufactured directly via FDM 3D printing to the final test geometry. Following best practices for polymer testing to minimize stress concentrations, a curvature was designed into the transition area between the specimen's gauge section and its ends.

The tests were performed in accordance with the ASTM D 30 standard [20] for tensile properties of polymer matrix composite materials. A universal testing machine with a 20 kN load cell was used, and the tests were conducted under displacement control at a constant crosshead speed of 2 mm/min. A minimum of four specimens were tested to ensure statistical reliability of the results. The engineering stress-strain data obtained from these tests were used to determine the composite's elastic modulus, yield strength, and ultimate tensile strength.

Compact tension test

For materials used in structural applications, such as the 3D-printed composites investigated here, fracture toughness is a critical property [21]. It characterizes a material's resistance to crack propagation, which is essential for predicting failure and ensuring long-term structural integrity, especially in environments where stress and environmental factors could lead to degradation.

To quantify this property, fracture toughness tests were conducted on compact tension (CT) specimens following the principles outlined in the ASTM D5045 [22] standard. The specimens were directly fabricated via FDM 3D printing from the PA-12 carbon fiber composite feedstock to the required test geometry. The critical specimen dimensions were:

- Specimen Width (W): 14 mm
- Specimen Thickness (B): 4 mm
- Initial Crack Length (a): 8 mm

A sharp pre-crack was introduced at the notch tip to simulate a natural flaw. The load and crack mouth opening displacement were recorded during testing to determine the critical stress intensity factor (K_{IC}). Subsequently, the corresponding critical strain energy release rate (G_{IC}) was calculated, providing the surface energy parameter essential for analyzing the composite's crack resistance.

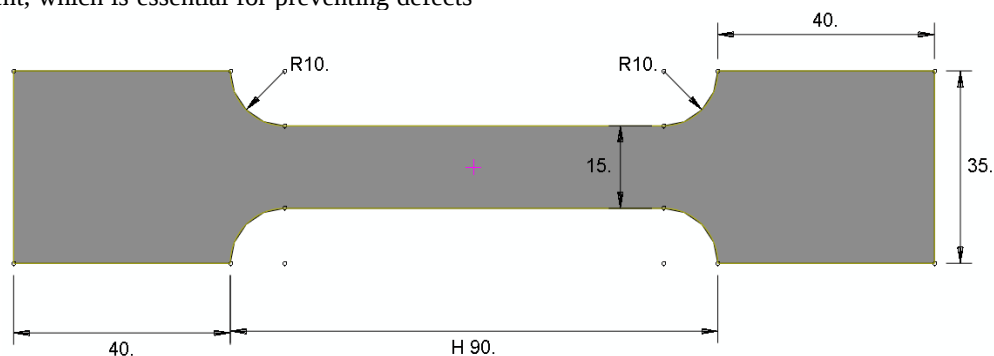


Figure 1. Standard flat dog-bone tensile specimen

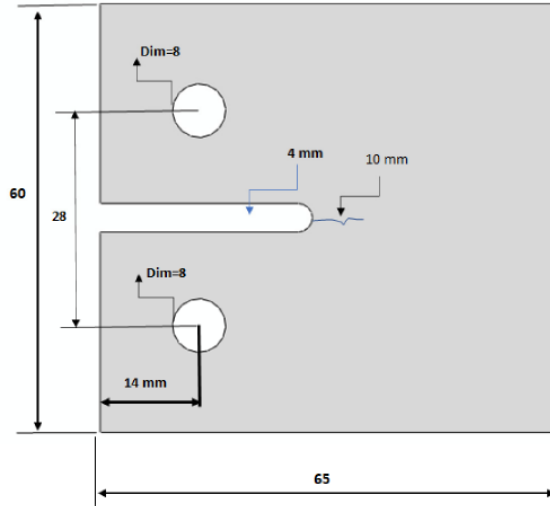


Figure 2. Compact tension Specimen geometry

The fracture toughness of the material was characterized by the critical stress intensity factor, K_{IC} , under Mode I (opening mode) loading. For the compact tension (CT) specimen geometry used in this study, K_Q is calculated according to ASTM E399 [22] as:

$$K_Q = \frac{P_Q}{B\sqrt{W}} \times f\left(\frac{a}{W}\right)$$

Where:

- K_Q is the conditional stress intensity factor (MPa $\sqrt{m}$).
- P_Q is the critical load determined from the load-displacement curve using the 5% secant offset method (kN).
- B is the specimen thickness (m).
- W is the specimen width (m).
- a is the initial crack length (m).
- $f(a/W)$ is the geometry-dependent dimensionless calibration factor, given by:

$$f\left(\frac{a}{W}\right) = \frac{\left(2 + \frac{a}{W}\right) \left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.6\left(\frac{a}{W}\right)^4 \right]}{\left(1 - \frac{a}{W}\right)^{3/2}}$$

For a valid plane-strain fracture toughness K_{IC} , the calculated K_Q must satisfy the size criteria: $B, a \geq 2.5(K_Q / \sigma_{ys})^2$, where σ_{ys} is the material's yield strength.

The corresponding critical strain energy release rate, G_{IC} , which represents the energy absorbed per unit area of crack extension, was calculated from the valid K_{IC} value using the relation:

$$G_{IC} = \frac{K_{IC}^2}{E'} \text{ with } E' = \begin{cases} E & (\text{for plane stress}) \\ \frac{E}{1-\nu^2} & (\text{for plane strain}) \end{cases}$$

Where:

- G_{IC} is the critical strain energy release rate (kJ/m²).
- E is the elastic modulus of the material (GPa), determined from tensile tests.
- ν is Poisson's ratio of the material.
- E' is the effective modulus.

3. Results and Discussion

3.1. Tensile Behavior and Failure Analysis

The tensile stress-strain curves for the two PA-12 carbon fiber composite specimens are shown in Figure 3, with key mechanical properties summarized in Table 1. Both curves exhibit the characteristic behavior of a semi-crystalline thermoplastic composite, comprising an initial linear elastic region, a yield point, and a post-yield plastic deformation phase leading to fracture.

Table 1. Summary of Tensile Properties

Property	Specimen 1	Specimen 2	Average
Ultimate Tensile Strength (UTS)	73.5 MPa	75.0 MPa	74.2 MPa
Strain at UTS (Peak Strain)	4.65%	5.66%	5.16%
Apparent Young's Modulus*	~3.0 GPa	~2.8 GPa	~2.9 GPa

Note: The modulus is calculated from the initial slope. The low value may be influenced by machine compliance or the initial toe region of the curve. A more precise value requires analysis of the linear segment between 0.1% and 0.3% strain.

Comparative Analysis: The curves show excellent repeatability in strength, with a variation of less than 2.1% in UTS. The primary difference lies in the ductility, where Specimen 2 exhibited approximately 22% greater strain of failure. This variability is common in additively manufactured parts and can be attributed to slight differences in interlayer bonding or localized fiber distribution between specimens [23,24]. The absence of a sudden, brittle fracture indicates that the short carbon fibers are effectively bridging micro-cracks within the PA-12 matrix, allowing for stress redistribution and

contributing to the observed pseudo-ductile failure.

Failure Mode Analysis (Figure 5a): The tensile specimen failure shown in Figure 4a supports stress-strain observations. The fracture surface is not perfectly planar, indicating a mixed-mode failure. The characteristic features include:

Matrix Deformation and Necking: Visible plastic deformation and necking in the gauge section confirm the ductile contribution of the PA-12 matrix.

Fiber Pull-Out: The rough texture of the fracture surface and protruding fiber ends are clear evidence of carbon fiber pull-out. This is a crucial energy-absorbing mechanism that enhances toughness, as it requires work to debond and extract the fibers from the polymer matrix.

Layered Fracture Path: The crack appears to have propagated in a stepped manner, following the layer-by-layer deposition boundaries. This highlights the inherent anisotropy of FDM parts, where the interlayer bond strength is often the weakest link.

This combined failure mode—ductile matrix tearing coupled with fiber pull-out—explains the composite's balanced mechanical profile, offering improved strength over neat polymer while retaining appreciable damage tolerance.

3.2. Fracture Toughness from Compact Tension Test

The load versus crack mouth opening displacement (CMOD) curve for the compact tension specimen is presented in Figure 4. The curve is characteristic of a quasi-brittle material with stable crack growth, showing a linear rise to a maximum load ($P_{\max}$) followed by a gradual decrease.

Analysis and Calculation: The critical load (P_Q) was determined to be 1.8 kN using the 5% secant offset method as per ASTM E399. Using the specimen dimensions ($B = 4$ mm, $W = 14$ mm, $a = 8$ mm) and the geometry factor $f(a/W) = 9.66$, the conditional stress intensity factor is calculated as:

$$\begin{aligned} K_Q &= \frac{P_Q}{B\sqrt{W}} \times f(a/W) \\ &= \frac{1800 \text{ N}}{(0.004 \text{ m})\sqrt{0.014 \text{ m}}} \\ &\times 9.66 \approx 36.8 \text{ MPa}\sqrt{\text{m}} \end{aligned}$$

Assuming a representative yield strength (σ_{ys}) of 50 MPa from tensile data, the validity criterion is satisfied:

$$B, a \geq 2.5(K_Q / \sigma_{ys})^2 = 2.5 \times (36.8 / 50)^2 \approx 1.35 \text{ mm}.$$

Since B and a (4 mm and 8 mm) exceed this value, K_Q is considered a valid plane-strain fracture toughness,

$$K_{IC} = 36.8 \text{ MPa}\sqrt{\text{m}}.$$

The corresponding critical strain energy release rate (G_{IC}), using the elastic modulus $E = 5$ GPa determined experimentally via extensometer (see Section 3.4) and $\nu = 0.35$, is recalculated as:

$$\begin{aligned} G_{IC} &= \frac{K_{IC}^2 (1 - \nu^2)}{E} \\ &= \frac{(36.8 \times 10^6)^2 \times (1 - 0.35^2)}{5 \times 10^9} \approx 245 \text{ kJ/m}^2. \end{aligned}$$

Failure Mode Context (Figure 5b): The K_{IC} and high G_{IC} values are corroborated by the failure mode in the CT specimen (Figure 5b). The fracture surface is likely to show extensive fiber bridging behind the crack tip—a process where intact fibers span the crack, applying closure stresses and significantly increasing the energy required for propagation. This, combined with matrix plastic deformation in the process zone, is responsible for the relatively high fracture toughness, demonstrating that the 3D-printed composite resists crack growth effectively.

3.3. Synthesis and Implications

The mechanical analysis reveals that the 3D-printed PA-12 carbon fiber composite achieves a synergistic balance:

Strength and Ductility: It maintains a tensile strength (~ 74 MPa) significantly higher than neat PA-12, while preserving useful ductility (5-6% strain) through matrix yielding and fiber pull-out.

Damage Tolerance: The substantially high fracture toughness ($K_{IC} \approx 36.8 \text{ MPa}\sqrt{\text{m}}, G_{IC} \approx 245 \text{ kJ/m}^2$) confirms good damage tolerance. The dominant toughening mechanisms are fiber bridging (in fracture) and fiber pull-out (in tension), which are activated ahead and behind the crack tip.

The primary limitation remains the anisotropy introduced by the FDM process, as evidenced by the layered fracture path. Mechanical performance, especially interlayer strength and ductility, is dependent on printing parameters. Future work should focus on optimizing raster angle, layer height, and nozzle temperature to maximize interlayer adhesion and further improve the consistency of fracture properties.

3.4. Discussion on Apparent Elastic Modulus Measurement

The initial slope of the stress-strain curve, calculated directly from the machine's load cell and crosshead displacement, yields an apparent Young's modulus of approximately **2.9 GPa**. This value is significantly lower than the typical modulus reported for carbon fiber-reinforced PA-12 composites in the literature (often in the range of 5–10 GPa). This discrepancy is attributed to systematic errors inherent in the standard testing setup rather than the intrinsic material property. The primary contributing factors are:

- 1. Machine and Fixture Compliance:** A portion of the measured displacement does not originate from the specimen's elastic strain. The universal testing machine frame, load cell, and especially the grips and grip-specimen interfaces undergo slight deformation under load. This extraneous displacement is recorded by the machine's

crosshead sensor, making the specimen appear more compliant than it truly is. The error is most pronounced for stiff materials tested with a low-compliance setup [25,26,27].

2. **Specimen Toe-In and Seating:** At the very beginning of a tensile test (typically the first 0.05–0.2% strain), the load-displacement curve is non-linear. This "toe region" is caused by the straightening of the specimen, the take-up of slack in the system, and the full seating of the specimen within the grips. Including this non-linear region in the linear regression to determine the modulus slope artificially lowers the calculated value [27].
3. **Anisotropy of the FDM Process:** The material's stiffness is inherently direction-dependent due to the layer-by-layer deposition of Fused Deposition Modeling (FDM). The measured modulus in the printing direction (likely the testing direction) is a complex function of the polymer matrix modulus, fiber orientation, and—critically—the strength of interlayer bonds. These bonds are typically the weakest mechanical link, and initial micro-yielding or decohesion at these interfaces under low load can contribute to a higher apparent strain [27].
4. **Data Analysis Methodology:** The method for selecting the linear portion of the stress-strain curve directly impacts the result. A modulus calculated from a slope taken between 0.05% and 0.15% strain will differ from one calculated between 0.1% and 0.3% strain. Without a standardized and clearly defined analysis window, results can vary.

Recommendation for Accurate Modulus Determination:

To obtain a more accurate and reliable elastic modulus (E) for use in fracture mechanics calculations (e.g., in $G_{IC} = K_{IC}^2 / E'$), the use of an extensometer strain gauges strongly recommended. These instruments measure strain directly on the specimen's gauge length, eliminating errors from machine compliance and grip effects. The true material modulus should be calculated from the linear slope of the stress vs. *directly measured strain* curve, typically in the range of 0.1% to 0.3% strain [23,27]. To obtain an accurate elastic modulus (E) for the fracture energy calculation and address potential errors from machine compliance, the tensile tests were conducted with a clip-on extensometer. The modulus was determined from the linear slope of stress versus *directly measured strain* curve in the range of 0.1% to

0.3% strain. This analysis yielded an experimental modulus of **5GPa** for the 3D-printed PA-12 carbon fiber composite (see Figure 3, red line). This value, which is more reliable than the apparent modulus derived from crosshead displacement (~2.9 GPa), was subsequently used in the calculation of the critical strain energy release rate (G_{IC}) in Section 3.2, ensuring the fracture toughness assessment is based on material-specific data.

Theoretical strain energy release rate (G_{IC}), however, remains a robust and valid material property. The K_{IC} value is determined independently from the load and crack length in the compact tension test and is not affected by the bulk modulus error. While the absolute value of G_{IC} scales with $1/E$, the high toughness indicated (245 kJ/m² when using $E = 5$ GPa) reflects the material's real and

significant resistance to crack propagation, dominated by fiber bridging and pull-out mechanisms [28,29,30].

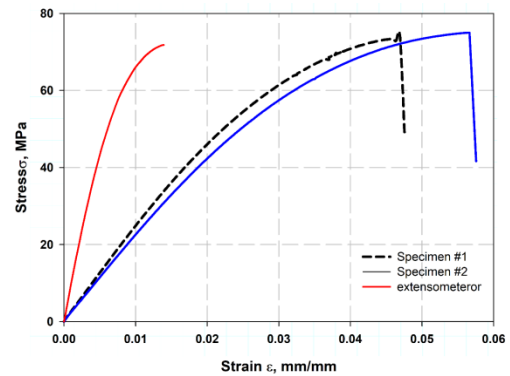


Figure 3. Stress strain diagram for 3-D printed composite

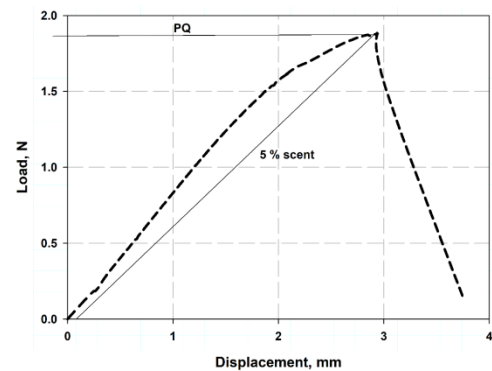


Figure 4. load and displacement relation in 3-D printed composite

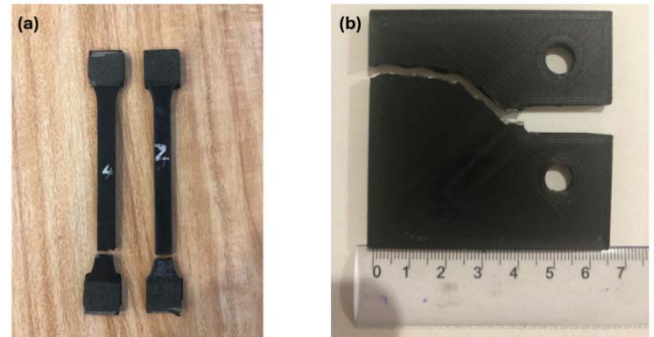


Figure 5. failure modes for (a) tensile specimen, (b) compact tension

4. Conclusion

This study demonstrates that 3D-printed PA-12 carbon fiber composites exhibit a strong synergy of mechanical properties suitable for structural applications. The material achieved a tensile strength of 74.2 MPa with appreciable ductility, while fracture toughness tests revealed a high damage tolerance, with a critical stress intensity factor (K_{IC}) of 36.8 MPa√m and a strain energy release rate (G_{IC}) of ~245 kJ/m². These favorable properties result from effective fiber reinforcement and toughening mechanisms like fiber pull-out and bridging. The findings confirm the potential of this additively manufactured composite for components where lightweight design, complex geometry, and reliable fracture resistance are required.

Future Work: Optimizing print parameters to enhance interlayer bonding and conducting tests for environmental durability are recommended next steps.

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