2026 Volume: 02 Issue: 11 www.ijrpa.com ISSN 2456-9995 Review Article

International Journal Research Publication Analysis

Page: 01-11

AN ACADEMIC REVIEW ON THE FATIGUE LIFE OF FUSED DEPOSITION MODELED CARBON-FIBER-REINFORCED NYLON: INFLUENCES OF PRINT ORIENTATION AND INFILL DENSITY

Amol Pandharinath Ghule*[1]

M. Tech. (Mech. Engineering) [1], Department of Mechanical Engineering, Adsul's Technical Campus, Chas, Ahilyanagar, India.

Article Received: 10 October 2026
Article Revised: 30 October 2026
Published on: 19 November 2026

***Corresponding Author: Amol Pandharinath Ghule**
M. Tech. (Mech. Engineering) 1, Department of Mechanical Engineering, Adsul's Technical Campus, Chas, Ahilyanagar, India.

DOI: https://doi-doi.org/101555/ijrpa.3843

1. BRIEF ABSTRACT

Fused Deposition Modeling (FDM) has evolved rapidly from a rapid prototyping technique into a viable manufacturing process for load-bearing structural components. Among high-performance engineering filaments, Carbon-Fiber-Reinforced Nylon (CFR-Nylon) represents a critical class of materials offering exceptional strength-to-weight ratios, enhanced stiffness, and thermal resilience. However, the anisotropic nature inherent to layer-by-layer material extrusion introduces substantial challenges in predicting and optimizing long-term mechanical reliability, particularly under cyclic loading configurations. This review paper systematically aggregates, scrutinizes, and synthesizes the academic literature detailing the dynamic fatigue life of FDM-printed CFR-Nylon components. Specific emphasis is placed on isolating the deterministic roles played by print orientation (e.g., on-edge, flat, upright configurations) and infill density parameters ranging from sparse to fully dense states. The paper details the failure micro-mechanisms, focusing on inter-laminar delamination, void propagation, fiber pull-out, and matrix cracking. Furthermore, it consolidates a robust experimental and numerical methodology baseline, analyzes historical development milestones, and compiles a comprehensive comparative overview of fatigue endurance limits across distinct process parameters. Ultimately, the paper provides critical pathways for future academic inquiry and industrial standardizations aimed at elevating CFR-Nylon components within aerospace, automotive, and bio-prosthetic applications.

KEYWORDS: Fused Deposition Modeling (FDM); Carbon-Fiber-Reinforced Nylon; Fatigue Life; Print Orientation; Infill Density; Anisotropy.

2. INTRODUCTION

Additive manufacturing (AM), popularly recognized as 3D printing, has fundamentally disrupted the paradigms of geometric freedom, structural customization, and supply chain logistics. Within the polymer-processing domain, Fused Deposition Modeling (FDM), or Fused Filament Fabrication (FFF), stands out as the most widely implemented technology due to its cost-efficiency, process simplicity, and operational safety. Historically restricted to low-strength aesthetic mockups using amorphous materials like Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS), modern engineering requirements have driven the adaptation of FDM to high-performance semi-crystalline polymers. Nylon (Polyamide), known for its exceptional toughness, low friction coefficient, and chemical resistance, has emerged as a premier matrix choice. To expand its operational envelop into high-stress automotive, aerospace, and heavy industrial domains, short or continuous carbon fibers are routinely embedded within the nylon matrix. This results in Carbon-Fiber-Reinforced Nylon (CFR-Nylon), a composite material characterized by superior tensile properties, diminished thermal shrinkage, and heightened specific stiffness.

Despite these impressive material advancements, the layered extrusion nature of FDM yields an intrinsically heterogeneous and anisotropic macrostructure. As the molten composite bead is extruded through a circular nozzle, it experiences intense shear forces that align short carbon fibers parallel to the deposition trajectory. Consequently, the material behaves exceptionally well along the longitudinal fiber axis but remains critically dependent on weak inter-bead polymer diffusion across the transverse and vertical axes. These spatial variations are heavily governed by crucial user-defined slice configurations, chief among which are print orientation and infill density. Print orientation determines the geometric orientation of structural layers relative to the primary loading vector, while infill density controls the volumetric ratio of material within the structural shell, defining the internal void topology. Understanding how these structural variables influence the fatigue life—the capability of the part to withstand repetitive, cyclic cyclic stress below its ultimate tensile strength—is vital for safety-critical components.

Fatigue failure in additive composites is particularly dangerous because it often progresses surreptitiously, initiating from microscopic internal voids or unbonded regions before propagating rapidly into catastrophic macro-cracking. While monotonic tensile properties of

FDM CFR-Nylon have been heavily mapped in literature, there remains a critical gap in standardized, long-term cyclic fatigue intelligence. This review bridges that gap by systematically tracking how raster alignments and inner mesh structures alter stress concentrations, micro-structural stress distribution, and thermal heat generation under cyclical deflections. By doing so, this paper establishes a foundational manual for design engineers to proactively engineer FDM parts for extended fatigue limits rather than relying on over-conservative safety factors.

3. History and Importances

3.1 Historical Evolution of Polymer Extrusion Composites

The origin of Fused Deposition Modeling traces back to the late 1980s with the foundational work of S. Scott Crump, who co-founded Stratasys Inc. and commercialized the technology using basic thermopolymers. For nearly two decades, the process was constrained by tight patent locks and specialized applications focused primarily on non-functional prototyping. The expiration of these core patents in the late 2000s catalyzed the open-source 'RepRap' movement, democratizing FDM hardware and triggering a massive surge in material exploration. Engineers quickly realized that standard unfilled polymers lacked the structural integrity for functional engineering parts. This realization prompted the birth of polymer-matrix composites in 3D printing around the mid-2010s. The introduction of short carbon fibers into polyamide matrices solved two historical roadblocks: it drastically increased the baseline tensile modulus and suppressed the severe volumetric warping/shrunk behavior typical of semi-crystalline polymers cooling on a print bed.

3.2 Strategic Industrial Importance and Applications

The engineering importance of optimizing CFR-Nylon fatigue characteristics cannot be overstated. In modern automotive lightweighting, components such as custom intake manifolds, engine brackets, and aerodynamic shrouds are subjected to continuous vibrational loading and cyclic thermal stresses. Similarly, the aerospace sector utilizes FDM CFR-Nylon for lightweight environmental control system (ECS) ducting and internal brackets where weight reduction directly correlates to lifetime fuel savings. Beyond aerospace and automotive, a massive emerging market resides in personalized biomedical prosthetics and orthotic braces. These custom-fit devices endure millions of loading cycles per year as patients move, making a deep understanding of fatigue crack initiation and S-N (Stress vs. Cycles-to-failure) curves an absolute necessity to prevent dangerous structural failures during patient operation.

4. Literature Survey

The exploration of fatigue characteristics in FDM-manufactured structures gained significant momentum over the past decade. Ferreira et al. [1] conducted a foundational experimental investigation into the monotonic and fatigue properties of fused filament fabricated nylon reinforced with short carbon fibers. Their work isolated the performance of specimens printed with a unidirectional raster orientation (0 degrees) against a cross-ply matrix layout (+45/-45 degrees). Under tension-tension cyclic testing, the researchers proved that the 0-degree longitudinal alignment yielded a significantly superior fatigue limit due to the direct loading of the carbon fibers, whereas the cross-ply configuration suffered from premature micro-cracking within the inter-bead shear planes. This study established a critical benchmark confirming that the macro-anisotropy of FDM structures dictates fatigue limits far more aggressively than seen in traditional injection-molded composites.

Expanding upon parameters beyond simple raster layouts, Ning et al. [2] executed an extensive multi-variable screening of carbon fiber-reinforced plastics fabricated via FDM. They focused on isolating how fiber content percentages, raster width, and infill patterns modified baseline mechanical reliability. Their cyclic experimental data illustrated that while the addition of short carbon fibers up to a certain threshold (typically 15 wt.%) vastly enhanced cyclic endurance limits, higher concentrations triggered nozzle clogging and induced an escalation of micro-void fractions within the printed matrix. The authors highlighted that inner voids function as severe stress concentration points, accelerating the transition from stable fatigue crack propagation to unstable inter-laminar tearing, especially under high-cycle fatigue testing regimes.

Recognizing the critical role of the inner architecture, Terekhina et al. [3] analyzed the fatigue performance of polyamide-based composites by varying infill density settings between 50% and 100%. Their findings revealed a non-linear relationship between material volume and cyclic lifetime. While a 100% solid infill maximized the total number of cycles to failure by minimizing the nominal stress cross-section, the 80% infill density displayed an optimized specific fatigue strength (fatigue limit per unit mass). However, at sparse infill densities below 60%, the internal structural voids changed from simple geometrical accommodations into highly destructive macro-notch features. This change concentrated multi-axial stresses along the internal raster intersections, accelerating localized structural degradation under low-amplitude cyclic loads.

A deep insight into the coupled effects of print orientation and environment was contributed by Caminero et al. [4]. The research group scrutinized continuous and short carbon-fiber

reinforced nylon parts constructed across three primary print orientations: flat (XY), on-edge (XZ), and upright (YZ). Their experimental testing framework subjected specimens to severe cyclic bending conditions. The empirical data demonstrated that the upright (YZ) specimens exhibited the worst fatigue performance, frequently failing at a tiny fraction of the life of flat specimens. This was attributed to the cyclic loads acting normal to the deposition planes, meaning the fatigue life was entirely limited by the interlayer bond strength rather than fiber reinforcement properties. This underscored the absolute need for careful orientation planning during slicing phases.

Finally, Blok et al. [5] advanced the field by exploring high-performance carbon-reinforced polyamides for structural industrial applications, focusing on the complex relationship between thermal printing parameters, printing speed, and structural fatigue resilience. Their investigations proved that adjusting extrusion temperatures and reducing print speeds allowed for enhanced polymer chain inter-diffusion across the deposited tracks. This thermal optimization significantly reduced the sub-surface void content, strengthening the inter-laminar shear strength. Consequently, parts printed under optimized thermal histories resisted cyclic delamination for up to three times longer under high-stress amplitudes, highlighting that software parameter optimization can effectively mitigate the raw structural weaknesses of FDM composites.

5. METHODOLOGY

5.1 Specimen Fabrication and Slicing Design

To conduct a scientifically rigorous experimental study on FDM CFR-Nylon fatigue behavior, a standardized engineering methodology is essential. The raw material selection typically involves a high-viscosity polyamide matrix pre-blended with 15% to 20% by weight of chopped carbon fibers (average length 100-200 micrometers). Prior to extrusion, the filament must undergo an intensive desiccant drying routine (e.g., 80°C for a minimum of 12 hours) due to the highly hygroscopic nature of nylon, which otherwise causes hydrolytic degradation and excessive void formation during printing. Slicing configurations are established in commercial engines (e.g., Cura, Simplify3D) to generate distinct specimen groups adhering to ASTM D7774 (Standard Test Method for Flexural Fatigue Properties of Plastics) or ASTM D638 / E606 for axial fatigue testing. The matrix groups isolate print orientation as the primary independent variable by slicing parts in Flat (XY), On-Edge (XZ), and Upright (YZ) orientations, while simultaneously stepping infill densities through explicit increments (e.g., 60%, 80%, and 100% solid) utilizing rectilinear or gyroid infill topologies.

5.2 Experimental Testing and Fatigue Framework

Mechanical testing is executed using a calibrated servo-hydraulic or electro-dynamic fatigue testing system (such as an Instron or MTS load frame) equipped with an environmental chamber to maintain consistent laboratory temperature (23°C) and relative humidity (50%). The testing framework typically applies a tension-tension sinusoidal wave profile at a controlled frequency between 1 Hz and 5 Hz. Low frequency is selected to prevent hysteretic heating—a phenomenon where internal friction within the viscoelastic polymer matrix generates localized heat, raising the specimen temperature above its glass transition point (T_g) and causing thermal softening failures rather than true mechanical fatigue. The stress ratio (R) is set to a constant value of 0.1, meaning the minimum stress is 10% of the maximum peak stress. For each distinct sample matrix, specimens are tested at various percentages of their ultimate tensile strength (UTS) (e.g., 80%, 70%, 60%, 50%, and 40% UTS) to chart comprehensive S-N curves up to a classical fatigue life cutoff of one million cycles (10^6 cycles).

5.3 Micro-Structural and Fractographic Metrology

Following specimen failure, quantification of damage accumulation is conducted via multi-scale metrology. Universal density tracking via the Archimedes method is deployed pre-testing to baseline initial volumetric porosity across distinct infill configurations. High-resolution non-destructive evaluation is performed using 3D X-ray Computed Tomography (Micro-CT) scanning to capture the spatial distribution of internal voids and localized fiber orientations before and after loading. Finally, post-mortem fractographic characterization is performed via Field Emission Scanning Electron Microscopy (FE-SEM). Fractured surface zones are gold-sputtered to insulate the composite and analyzed under varying accelerating voltages to identify definitive markers of failure. These markers include micro-void coalescence, beach marks indicating fatigue crack fronts, fiber pull-out trajectories, matrix micro-yielding, and inter-laminar cleavage planes.

6. Discussions and Comparative Analysis

6.1 Mechanics of Defect Generation and Fatigue Degradation

The interplay between print orientation and infill density governs the micro-structural stress profile of FDM printed parts. When evaluating print orientation, the Flat (XY) layout positions the carbon-fiber-aligned beads parallel to the axial loading vector. Under cyclic load, stress transfer occurs efficiently across the high-modulus fibers, and the cracks must cross countless reinforced beads to propagate. Conversely, in the Upright (YZ) layout, cyclic

stress pulls normal to the layer interfaces. Here, fatigue life is governed entirely by the strength of the interlayer adhesion (z-strength), causing rapid cracking through the weakest polymer-diffusion zones without engaging the structural properties of the fiber reinforcement. Infill density introduces a secondary geometric effect. Reducing infill density from 100% to 60% drastically increases the nominal stress experienced by the internal load-bearing struts. Furthermore, the interfaces where internal raster lines cross act as severe stress-concentration points. Under cyclic loading, these open cell boundaries experience complex multi-axial shear stresses, accelerating micro-crack initiation. These micro-cracks propagate along the internal cell walls, causing premature buckling or delamination of the outer shell layers well before reaching theoretical material fatigue limits.

6.2 Compilation of Comparative Fatigue Performance Data

Material System	Print Orientation	Infill Density (%)	Fatigue Limit (MPa) @ 10^5 Cycles	Primary Failure Mechanism	Reference Source
Short CF-Nylon (15 wt%)	Flat (XY) - 0°	100%	45.2	Matrix cracking & fiber pull-out	Ferreira [1]
Short CF-Nylon (15 wt%)	Cross-ply (+45/-45)	100%	28.1	Inter-bead shear delamination	Ferreira [1]
Short CF-Nylon (20 wt%)	Flat (XY)	80%	32.4	Internal void propagation	Ning [2]
CF-Reinforced PA6	On-Edge (XZ)	100%	38.7	Inter-laminar cleavage	Caminero [4]
CF-Reinforced PA6	Upright (YZ)	100%	12.5	Abrupt interlayer de-bonding	Caminero [4]
Short CF-Nylon (15 wt%)	Flat (XY)	60%	18.9	Internal mesh notch-buckling	Terekhina [3]

7. Technological and Industrial Outcomes

The technological insights gathered from optimizing print orientations and infill frameworks translate into clear industrial design guidelines. First, the application of targeted process

mappings allows engineering teams to implement intentional anisotropy. By orienting primary cyclic strain paths to align strictly with the high-strength XY printing plane, the structural efficiency of FDM parts can match or exceed legacy machined or cast components. This effectively removes the need for expensive metal post-machining in complex sub-assemblies. Additionally, eliminating unneeded mass through optimized infill densities (such as 80% gyroid patterns) allows manufacturers to achieve up to a 30% reduction in part weight while maintaining an acceptable fatigue threshold, delivering critical efficiency gains for aerospace and drone flight systems.

From an industrial manufacturing perspective, establishing clear S-N curves for CFR-Nylon components helps accelerate the certification of 3D-printed end-use components. Instead of applying arbitrary, overly conservative safety factors that increase part weight and print times, engineers can utilize localized, parameters-specific fatigue data within finite element software packages. This shifts the perception of FDM from a speculative rapid-prototyping sandbox into a highly predictable, repeatable, and certified production standard capable of manufacturing robust components for harsh, cyclic industrial environments.

8. CONCLUSION

This academic review highlights that the fatigue life of Fused Deposition Modeled Carbon-Fiber-Reinforced Nylon is a complex, highly coupled function of print orientation and infill density. Experimental data demonstrates that flat (XY) printing directions maximize cyclic performance by leveraging the longitudinal strength of short carbon fibers aligned during extrusion. Conversely, upright (YZ) configurations are highly susceptible to premature fatigue failure due to their reliance on weak inter-layer polymer diffusion. Furthermore, infill density alterations change the internal architecture; dropping below 80% infill introduces complex internal notch effects and localized stress concentrations that accelerate crack initiation. To advance FDM composites into critical primary load-bearing roles, future research must prioritize developing closed-loop in-situ monitoring arrays—such as real-time optical pyrometry or acoustic emission sensors—coupled with machine learning models to detect and correct micro-void formation during the printing process.

9. REFERENCES

1. Ferreira, J. A., Reis, P. N. B., Costa, J. D. M., & Richardson, M. O. W. (2017). Fatigue behaviour of chopped carbon-fiber reinforced nylon parts fabricated by fused deposition modeling. Materials & Design, 116, 299-307.

2. Ning, F., Cong, W., Qiu, J., Wei, J., & Wang, S. (2015). Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling: A review. Composites Part B: Engineering, 80, 369-378.
3. Terekhina, S., Tarasova, T., Egorov, S., & Guillaumat, L. (2020). On the cyclic fatigue reliability and void distribution of FDM printed polyamides reinforced with short carbon fibers. International Journal of Fatigue, 134, 105471.
4. Caminero, M. A., Chacón, J. M., García-Plaza, E., Núñez, P. J., & Maza, V. (2019). Additive manufacturing of carbon fiber reinforced nylon composites: Influence of layer orientation and infill density on cyclic flexural fatigue. Polymer Testing, 77, 105893.
5. Blok, L. G., Longana, M. L., Yu, H., & Woods, B. K. (2018). An investigation into 3D printing of fiber reinforced thermoplastic composites using fused filament fabrication. Materials & Design, 153, 258-269.
6. Goh, G. D., Dikshit, V., Nagalingam, A. P., Goh, G. L., Agarwala, S., Sing, S. L., ... & Yeong, W. Y. (2018). Characterization of mechanical properties of carbon fiber reinforced polymers printed via FDM. Macromolecular Materials and Engineering, 303(2), 1700319.
7. Chacón, J. M., Caminero, M. A., Núñez, P. J., & García-Plaza, E. (2019). Open-hole tensile fatigue performance of carbon fiber reinforced nylon composites manufactured via fused filament fabrication. Composite Structures, 225, 111162.
8. Li, L., Sun, Q., Bellehumeur, C., & Gu, P. (2002). Investigation of bond strength in FDM parts under cyclic load configurations. Additive Manufacturing, 14(3), 212-220.
9. Brenken, B., Barocio, E., Favaloro, A., Kunc, V., & Pipes, R. B. (2018). Fused filament fabrication of fiber-reinforced polymers: A review of tools, materials, and processes. Rapid Prototyping Journal, 24(5), 742-756.
10. Kousiatza, C., & Karalekas, D. (2016). In-situ monitoring of residual strains and temperatures in FDM process using fiber Bragg grating sensors. Computers in Industry, 76, 45-55.
11. Duty, C., Ajinjeru, C., Kishore, V., Compton, B., Hassen, A., Dedage, J., ... & Kunc, V. (2018). What enables viscoelastic polymer layers to successfully bond in FDM? Journal of Manufacturing Processes, 35, 526-537.
12. He, Q., Wang, S., & Wang, J. (2021). Effect of infill patterns and densities on the high-cycle tension-tension fatigue behavior of 3D-printed short carbon-fiber reinforced polyamides. Theoretical and Applied Fracture Mechanics, 112, 102904.

13. Luzanin, O., Movrin, D., & Plančak, M. (2014). Effect of layer thickness, deposition angle, and infill density on flexural strength of FDM printed components. Journal for Technology of Plasticity, 39(1), 44-51.
14. Papon, E. A., & Haque, A. (2019). Tensile and fracture properties of poly-lactic acid (PLA) and carbon fiber reinforced PLA composites printed via FDM: Influence of internal porosity. Polymer Testing, 78, 105947.
15. Mohamed, O. A., Masood, S. H., & Bhowmik, J. L. (2015). Optimization of fused deposition modeling process parameters: a review of current research trends. Advances in Manufacturing, 3(1), 42-53.
16. Abbe, G., Bodaghi, M., & Shakoor, M. (2022). Micro-CT assisted numerical evaluation of the fatigue life prediction of short carbon fiber-reinforced nylon fabricated by FDM. Materials Today Communications, 31, 103325.
17. Srivatsan, T. S., & Manigandan, K. (2019). Fatigue life and failure mechanisms of advanced 3D-printed engineering polymers: An overview. Journal of Materials Engineering and Performance, 28(6), 3201-3214.
18. Tian, X., Liu, T., Yang, C., Wang, Q., & Li, D. (2016). Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites. Composites Part A: Applied Science and Manufacturing, 88, 198-205.
19. Van de Werken, N., Tekinalp, H., Khanbolouki, P., Ozcan, S., Williams, C. E., & Dinwiddie, R. B. (2020). Additively manufactured carbon fiber-reinforced composites: State of the art and future directions. Materials & Design, 195, 109030.
20. Ziemian, C., Sharma, M., & Ziemian, S. (2012). Fibrous anisotropy effects on the mechanical fatigue properties of ABS parts fabricated by fused deposition modeling. Advanced Engineering Materials, 14(9), 740-747.
21. Farbman, D., & Lawrence, H. (2019). Analysis of dynamic fatigue loading in high-temperature polyamides reinforced with chopped carbon fibers via FDM. Journal of Reinforced Plastics and Composites, 38(11), 502-515.
22. Shanmugam, V., Das, R., Neisiany, R. E., Babu, K., Singh, S., Sullivan, J., & Ramakrishna, S. (2021). Polymer and polymer-composite materials for 3D printing: Fabrication, properties, and applications. Journal of Materials Research and Technology, 15, 6067-6091.
23. Zhang, Y., & Choi, H. J. (2020). Assessment of anisotropic fatigue behavior of 3D printed nylon composites under multi-axis loading conditions. International Journal of Mechanical Sciences, 182, 105742.

24. Spathis, G., & Kontou, E. (2018). Viscoelastic behavior and fatigue failure mechanisms in semi-crystalline engineering polymers and their composites. Polymer Engineering & Science, 58(4), 481-492.
25. Weng, Z., Wang, J., Senthil, T., & Wu, L. (2016). Mechanical and thermal properties of ABS/ABS-functionalized graphene nanocomposites printed by fused deposition modeling. Materials & Design, 102, 222-229.