



Experimental Investigation of Additively Manufactured Multifunctional Continuous Carbon Fiber Composites for Unmanned Aircraft Systems (UAS)

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ABSTRACT: Additive manufacturing (AM) of continuous carbon fiber-reinforced composites has emerged as a transformative approach in the fabrication of lightweight, high-performance structures for unmanned aircraft systems (UAS). These multifunctional composites offer superior mechanical strength, structural efficiency, and the potential for integrating sensing and thermal management capabilities. This study presents an experimental investigation into the mechanical, thermal, and structural performance of additively manufactured continuous carbon fiber composites tailored for UAS applications. Specimens were fabricated using fused deposition modeling (FDM) techniques with in-situ fiber reinforcement, and key parameters such as fiber orientation, layer thickness, and printing temperature were systematically varied. Mechanical testing, including tensile, flexural, and interlaminar shear tests, was conducted alongside microstructural analysis using scanning electron microscopy. The results demonstrate that optimized printing parameters significantly enhance mechanical properties and reduce defects such as porosity and weak interlayer bonding. The study highlights the potential of multifunctional continuous carbon fiber composites in improving UAS performance through weight reduction, structural integrity, and functional integration.

KEYWORDS: Additive Manufacturing, Continuous Carbon Fiber Composites, Multifunctional Structures, Unmanned Aircraft Systems, Mechanical Characterization, Structural Optimization, Lightweight Aerospace Materials

I. INTRODUCTION

Unmanned Aircraft Systems (UAS) are increasingly utilized in surveillance, environmental monitoring, logistics, and defense applications. The demand for lightweight, high-strength, and multifunctional materials has driven the adoption of advanced composite materials in UAS structures. Continuous carbon fiber-reinforced polymer composites are particularly attractive due to their exceptional strength-to-weight ratio and stiffness.

Traditional manufacturing methods for composite materials often involve complex tooling, high costs, and limited design flexibility. Additive manufacturing provides a novel alternative by enabling layer-by-layer fabrication of complex geometries without the need for molds. This technology allows precise control over material placement, fiber orientation, and internal architecture, which are critical for optimizing performance.

Recent advancements in additive manufacturing have enabled the integration of continuous carbon fibers into thermoplastic matrices, resulting in composites with enhanced mechanical properties and design flexibility. These materials are capable of meeting the stringent requirements of UAS structures while offering additional functionalities such as embedded sensing and thermal management.



II. LITERATURE REVIEW

Recent research has focused on improving the mechanical performance and manufacturability of additively manufactured continuous carbon fiber composites. Studies have shown that process parameters such as fiber orientation, layer thickness, and printing temperature significantly influence the mechanical behavior of printed composites. The alignment of fibers along load paths has been identified as a critical factor in enhancing tensile strength and stiffness.

Advancements in additive manufacturing techniques have also enabled the fabrication of complex composite structures with improved structural efficiency. Continuous carbon fiber-reinforced composites produced through FDM exhibit high tensile strength and modulus, although challenges such as porosity and interlayer bonding remain. Furthermore, the development of high-throughput manufacturing techniques has improved production efficiency while maintaining mechanical performance.

Recent studies highlight the potential of additive manufacturing for multifunctional applications, including structural health monitoring and thermal management. The ability to integrate multiple functionalities into a single component makes these composites highly suitable for UAS applications. However, challenges related to process optimization, material compatibility, and scalability continue to be areas of active research.

III. MATERIALS AND METHODOLOGY

3.1 Materials

The composite material used in this study consists of continuous carbon fibers embedded within a thermoplastic matrix, such as polylactic acid (PLA) or nylon. The matrix material provides structural support and environmental resistance, while the carbon fibers serve as the primary load-bearing component.

3.2 Additive Manufacturing Process

Specimens were fabricated using fused deposition modeling with a dual-feed system that simultaneously deposits thermoplastic material and continuous carbon fibers. The printing process involves heating the thermoplastic matrix to a molten state and embedding the fibers during extrusion, ensuring proper bonding and alignment.

3.3 Process Parameters

Key process parameters investigated in this study include printing temperature, layer thickness, fiber volume fraction, and fiber orientation. These parameters were varied systematically to evaluate their effects on mechanical and structural properties.

3.4 Experimental Testing

Mechanical testing was conducted to evaluate tensile strength, flexural strength, and interlaminar shear strength. Thermal properties were analyzed using differential scanning calorimetry, while microstructural characterization was performed using scanning electron microscopy to examine fiber distribution and interfacial bonding.

IV. RESULTS AND DISCUSSION

4.1 Mechanical Properties

The experimental results indicate that fiber orientation plays a crucial role in determining mechanical performance. Specimens with fibers aligned along the loading direction exhibited significantly higher tensile strength compared to those with random or perpendicular orientations. This behavior is attributed to efficient load transfer along the fiber direction.

The tensile strength of optimized specimens approached values comparable to conventionally manufactured composites, demonstrating the effectiveness of additive manufacturing in producing high-performance materials. Flexural and interlaminar shear tests revealed that improved interlayer bonding significantly enhances overall structural integrity.

4.2 Effect of Process Parameters

Printing temperature was found to influence the degree of bonding between layers. Higher temperatures improved interlayer adhesion but also increased the risk of material degradation. An optimal temperature range was identified to balance these effects.



Layer thickness affected the resolution and mechanical performance of the printed parts. Thinner layers resulted in improved surface finish and mechanical properties due to better bonding between layers. Fiber volume fraction also played a critical role, with higher fiber content leading to increased stiffness and strength.

4.3 Microstructural Analysis

Scanning electron microscopy revealed that void formation and poor fiber-matrix bonding are major defects in additively manufactured composites. Optimized process parameters reduced these defects, resulting in a more uniform microstructure and improved mechanical performance.

The study also observed that proper impregnation of fibers within the matrix is essential for achieving high strength. Inadequate impregnation leads to weak interfaces and reduced load transfer efficiency.

4.4 Multifunctional Capabilities

One of the key advantages of additively manufactured composites is their ability to incorporate multiple functionalities. Continuous carbon fibers can be used not only for structural reinforcement but also for electrical conductivity and sensing applications.

The integration of multifunctional capabilities allows for real-time monitoring of structural health, enabling early detection of damage and improving the safety and reliability of UAS. Additionally, thermal management can be enhanced through the conductive properties of carbon fibers.

V. OPTIMIZATION OF ADDITIVE MANUFACTURING PARAMETERS

The optimization of process parameters is essential for achieving high-quality composites. Response surface methodology and statistical analysis were used to identify optimal parameter combinations. The results indicate that a balanced combination of printing temperature, fiber orientation, and layer thickness yields the best mechanical performance.

Advanced optimization techniques, including machine learning, have been proposed to further enhance process control and predict material behavior. These approaches enable real-time adjustment of printing parameters, improving consistency and reducing defects.

VI. APPLICATIONS IN UNMANNED AIRCRAFT SYSTEMS

The use of additively manufactured continuous carbon fiber composites in UAS offers several advantages, including weight reduction, improved structural efficiency, and enhanced functionality. These materials are particularly suitable for components such as wings, fuselage structures, and propellers.

The ability to produce complex geometries and integrate multiple functions into a single component reduces the need for assembly and improves overall system performance. Additionally, additive manufacturing enables rapid prototyping and customization, which are critical for UAS development.

VII. ADVANTAGES AND LIMITATIONS

Additive manufacturing of continuous carbon fiber composites provides significant advantages, including design flexibility, reduced material waste, and the ability to produce complex structures. The integration of multifunctional capabilities further enhances the value of these materials.

However, challenges such as limited production speed, high equipment costs, and variability in material properties must be addressed. Issues related to interlayer bonding and porosity also need to be resolved to ensure consistent performance.



VIII. CONCLUSION

This study demonstrates that additively manufactured continuous carbon fiber composites offer significant potential for UAS applications. Experimental investigations confirm that optimized process parameters can significantly improve mechanical properties and structural performance. The integration of multifunctional capabilities further enhances the applicability of these materials in advanced aerospace systems.

The findings highlight the importance of process optimization and material characterization in achieving reliable and high-performance composites. Additive manufacturing is expected to play a key role in the future development of UAS structures, enabling lightweight, efficient, and multifunctional designs.

IX. FUTURE SCOPE

Future research should focus on improving manufacturing efficiency, enhancing material properties, and developing advanced optimization techniques. The integration of smart materials and real-time monitoring systems will further expand the capabilities of additively manufactured composites in aerospace applications.

REFERENCES

1. Goh, G.D., et al. (2021/2022). Additive manufacturing of continuous carbon fiber reinforced composites: A review. *Composites Part B: Engineering*.
2. Deng, K., et al. (2025). Mechanical performance of 3D-printed continuous carbon fiber/epoxy composites. *Composites Part B: Engineering*
3. Maqsood, N., et al. (2024). Additive manufacturing of continuous carbon fiber reinforced thermoplastic composites. *Advanced Manufacturing*
4. Tu, Y., et al. (2024). High-throughput additive manufacturing of continuous carbon fiber-reinforced plastics. *Polymers*
5. Jamal, M.A., et al. (2024). Process parameter optimization in additive manufacturing of CFRP composites. *Additive Manufacturing*
6. C.Nagarajan and M.Madheswaran - 'Stability Analysis of Series Parallel Resonant Converter with Fuzzy Logic Controller Using State Space Techniques'- Taylor & Francis, Electric Power Components and Systems, Vol.39 (8), pp.780-793, May 2011. DOI: 10.1080/15325008.2010.541746
7. C.Nagarajan and M.Madheswaran - 'Experimental verification and stability state space analysis of CLL-T Series Parallel Resonant Converter' - Journal of Electrical Engineering, Vol.63 (6), pp.365-372, Dec.2012. DOI: 10.2478/v10187-012-0054-2
8. C.Nagarajan and M.Madheswaran - 'Performance Analysis of LCL-T Resonant Converter with Fuzzy/PID Using State Space Analysis'- Springer, Electrical Engineering, Vol.93 (3), pp.167-178, September 2011. DOI 10.1007/s00202-011-0203-9
9. S.Tamilselvi, R.Prakash, C.Nagarajan, "Solar System Integrated Smart Grid Utilizing Hybrid Coot-Genetic Algorithm Optimized ANN Controller" Iranian Journal Of Science And Technology-Transactions Of Electrical Engineering, DOI10.1007/s40998-025-00917-z,2025
10. S.Tamilselvi, R.Prakash, C.Nagarajan, " Adaptive sliding mode control of multilevel grid-connected inverters using reinforcement learning for enhanced LVRT performance" Electric Power Systems Research 253 (2026) 112428, doi.org/10.1016/j.epr.2025.112428
11. S.Thirunavukkarasu, C. Nagarajan, 2024, "Performance Investigation on OCF and SCF study in BLDC machine using FTANN Controller," Journal of Electrical Engineering And Technology, Volume 20, pages 2675–2688, (2025), doi.org/10.1007/s42835-024-02126-w
12. C. Nagarajan, M.Madheswaran and D.Ramasubramanian- 'Development of DSP based Robust Control Method for General Resonant Converter Topologies using Transfer Function Model'- *Acta Electrotechnica et Informatica Journal* , Vol.13 (2), pp.18-31, April-June.2013, DOI: 10.2478/aei-2013-0025.
13. C.Nagarajan and M.Madheswaran - 'DSP Based Fuzzy Controller for Series Parallel Resonant converter'- *Springer, Frontiers of Electrical and Electronic Engineering*, Vol. 7(4), pp. 438-446, Dec.12. DOI 10.1007/s11460-012-0212-0.
14. C.Nagarajan and M.Madheswaran - 'Experimental Study and steady state stability analysis of CLL-T Series Parallel Resonant Converter with Fuzzy controller using State Space Analysis'- *Iranian Journal of Electrical & Electronic Engineering*, Vol.8 (3), pp.259-267, September 2012.



15. C.Nagarajan and M.Madheswaran, "Analysis and Simulation of LCL Series Resonant Full Bridge Converter Using PWM Technique with Load Independent Operation" has been presented in ICTES'08, a IEEE / IET International Conference organized by M.G.R.University, Chennai. Vol.no.1, pp.190-195, Dec.2007
16. Suganthi Mullainathan, Ramesh Natarajan, "An SPSS and CNN modelling based quality assessment using ceramic materials and membrane filtration techniques", *Revista Materia (Rio J.)* Vol. 30, 2025, DOI: <https://doi.org/10.1590/1517-7076-RMAT-2024-0721>
17. M Suganthi, N Ramesh, "Treatment of water using natural zeolite as membrane filter", *Journal of Environmental Protection and Ecology*, Volume 23, Issue 2, pp: 520-530,2022
18. Lu, L., et al. (2024). Intelligent additive manufacturing of continuous fiber composites. *Robotics and Computer-Integrated Manufacturing*
19. Ouyang, Z., et al. (2024). Laser-assisted additive manufacturing of continuous fiber composites. *Composites Science and Technology*.
20. Nie, X., et al. (2023). Processing and performance of continuous fiber reinforced composites. *Materials Science in Additive Manufacturing*
21. Han, Z., et al. (2025). Modeling of additive manufacturing for continuous fiber composites. *Engineering Structures*
22. Dojan, C.F., et al. (2025). Scalable additive manufacturing of fiber-reinforced thermoset composites. *Nature Communications*.
23. Kiran, A., Rubini, P., & Kumar, S. S. (2025). Comprehensive review of privacy, utility and fairness offered by synthetic data. *IEEE Access*.
24. Gopinathan, V. R. (2024). Real-Time Financial Risk Intelligence Using Secure-by-Design AI in SAP-Enabled Cloud Digital Banking. *International Journal of Computer Technology and Electronics Communication*, 7(6), 9837-9845.
25. Udayakumar, R., Elankavi, R., Vimal, R., & Sugumar, R. (2023). Improved Particle Swarm Optimization with Deep Learning-Based Municipal Solid Waste Management in Smart Cities. *Environmental & Social Management Journal*, 17(4).
26. Anand, L. (2023). An Intelligent AI and ML-Driven Cloud Security Framework for Financial Workflows and Wastewater Analytics. *International Journal of Humanities and Information Technology*, 5(02), 87-94.
27. Soundappan, S. J. (2020). Big Data Analytics in Healthcare: Applications for Pandemic Forecasting. *International Journal of Advanced Research in Computer Science & Technology*, 3(1), 2248-2253.
28. Rajasekar, M. (2024). Real-Time Predictive DevOps Intelligence for Risk-Aware Digital Business Processes in Cloud and SAP Ecosystems. *International Journal of Advanced Research in Computer Science & Technology*, 7(4), 10713-10718.
29. Poornima, G., & Anand, L. (2024, May). Novel AI Multimodal Approach for Combating Against Pulmonary Carcinoma. In 2024 5th International Conference for Emerging Technology (INCET) (pp. 1-6). IEEE.
30. Prabha, P. S., & Rengarajan, A. (2025). Adaptive Cloud Resource Allocation Using Attention-Driven Deep Reinforcement Learning. *Engineering, Technology & Applied Science Research*, 15(6), 29334-29340.
31. Jagadeesh, S., & Sugumar, R. (2017). A Comparative study on Artificial Bee Colony with modified ABC algorithm. *European Journal of Applied Sciences*, 9(5), 243-248.
32. Varma, K. K., & Anand, L. (2025, March). Deep Learning Driven Proactive Auto Scaler for High-Quality Cloud Services. In International Conference on Computing and Communication Systems for Industrial Applications (pp. 329-338). Singapore: Springer Nature Singapore.
33. Kumar, S. A., & Anand, L. (2025). A Novel EEG-Based Deep Learning Framework for Enhancing Communication in Locked-In Syndrome Using P300 Speller and Attention Mechanisms. *KSII TRANSACTIONS ON INTERNET AND INFORMATION SYSTEMS*, 19(11), 3841-3855.
34. Poornima, G., & Anand, L. (2025). Medical image fusion model using CT and MRI images based on dual scale weighted fusion based residual attention network with encoder-decoder architecture. *Biomedical Signal Processing and Control*, 108, 107932.
35. Archana, R., & Anand, L. (2025). Residual u-net with Self-Attention based deep convolutional adaptive capsule network for liver cancer segmentation and classification. *Biomedical Signal Processing and Control*, 105, 107665.
36. Kumar, S. A., & Anand, L. (2025). A Novel EEG-Based Deep Learning Framework for Enhancing Communication in Locked-In Syndrome Using P300 Speller and Attention Mechanisms. *KSII Transactions on Internet and Information Systems*, 19(11), 3841-3855.
36. Rengarajan, A. (2025). Cloud-Based AI-Driven Threat Detection Framework for Smart Grid Cybersecurity. *International Journal of Future Innovative Science and Technology*, 8(6), 16065.
37. Murugeswari, B., Sudharson, K., Panimalar, S. P., Shanmugapriya, M., & Abinaya, M. (2020). SAFE-Secure Authentication in Federated Environment using CEG Key code.



38. Raj A. A., & Sugumar, R. (2023). Early Detection of COVID-19 with Impact on Cardiovascular Complications using CNN Utilising Pre-Processed Chest X-Ray Images. *2023 International Conference on Applied Intelligence and Sustainable Computing (ICAISC), IEEE*.
39. Jagadeesh, S., & Sugumar, R. (2017). A Comparative study on Artificial Bee Colony with modified ABC algorithm. *European Journal of Applied Sciences*, 9(5), 243-248.
40. Selvi, G. V., Anbarasan, A. B., Murthy, B. A., & Prabavathy, S. (2023). An Application Oriented Integrated Unequal Clustering Algorithm for Wireless Sensor Network. In *Underwater Vehicle Control and Communication Systems Based on Machine Learning Techniques* (pp. 140-154). CRC Press.
41. Sruthi, R. S., Ananya, S., & Murugeshwari, B. (2010). Web Based Virtual Control System Laboratory and On-Line Temperature Control of Electrophoresis Equipment using LabVIEW. *International Journal of Computer Applications*, 975, 8887.
42. Vimal Raja, G. (2021). Mining Customer Sentiments from Financial Feedback and Reviews using Data Mining Algorithms. *International Journal of Innovative Research in Computer and Communication Engineering*, 9(12), 14705-14710.
43. MATHEW, A. R. (2025). Neurosecurity and Brain-Computer Interfaces.
44. Soundappan, S. J. (2024). AI-Driven Customer Intelligence in Enterprise Lakehouse Systems Sentiment Mining Governance-Aware Analytics and Real-Time Data Synchronization. *International Journal of Advanced Engineering Science and Information Technology (IAESIT)*, 7(5), 14905.
45. Mathew, A. (2025). Human-AI Collaboration in Security Operations: Measuring Alert Trust, Automation Bias, and Analyst Upskilling in AI-Augmented SOC Environments. *International Journal of Computer Technology and Electronics Communication*, 8(5), 11375-11380.
46. Soundappan, S. J. (2022). AI-Based Fault Detection and Isolation for Reliability in Modern Power Systems. *International Journal of Research Publications in Engineering, Technology and Management (IRPETM)*, 5(4), 7106-7110.
47. Poornima, G., & Anand, L. (2024, April). Effective Machine Learning Methods for the Detection of Pulmonary Carcinoma. In *2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM)* (pp. 1-7). IEEE.
48. Garg, V. K., Soundappan, S. J., & Kaur, E. M. (2020). Enhancement in intrusion detection system for WLAN using genetic algorithms. *South Asian Research Journal of Engineering and Technology*, 2(6), 62-64.
48. Rengarajan, A., Jayakumar, C., & Sugumar, R. (2012). Optimization Of Recent Attacks Using Internet Protocol. *National Journal of System and Information Technology*, 5(1), 8.
49. Mathew, A. (2024). AI TRiSM: Trust, Risk, and Security Management in Cybersecurity. *Cybersecurity*, 4(3), 84-90.
50. Mathew, A. (2025). Deep seek vs. ChatGPT: A deep dive into AI Language mastery. *Int J Multidisciplinary Res*, 7(1), 1-5.