

Design, Additive Manufacturing, and Mechanical Characterization of Continuous Fiber-Reinforced Thermoplastic Composites for Lightweight Robotic Arm Components

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Abstract

This study presents the design, additive manufacturing, and mechanical characterization of continuous fiber-reinforced thermoplastic composites (CFRTPCs) for lightweight robotic arm components. The research integrates computational modeling, fiber-path optimization, and experimental testing to achieve high-performance and sustainable robotic structures. Three-dimensional computer-aided design (CAD) models of the robotic arm were developed and optimized using finite element analysis (FEA) to minimize weight while ensuring structural integrity with safety factors greater than 2.0. Components were fabricated using a dual-extrusion continuous fiber additive manufacturing process with carbon fiber and nylon (PA6) as reinforcement and matrix materials, respectively. Mechanical testing revealed that specimens with 0° fiber orientation exhibited superior tensile strength (630.5 MPa), flexural strength (510.2 MPa), and modulus (52.6 GPa), whereas 45° and 90° orientations displayed reduced performance due to misalignment of load and fiber direction. Microstructural analysis confirmed strong fiber–matrix adhesion and minimal void formation, while ANOVA results identified fiber orientation and nozzle temperature as the most significant factors influencing strength. The FEA stress and deflection contours closely correlated with experimental results, with less than 5% deviation, validating the accuracy of the simulation model. Overall, the study demonstrates that CFRTPCs, when optimized for fiber alignment and process parameters, provide a lightweight, high-strength, and recyclable solution for next-generation robotic arm applications, combining design efficiency with environmental sustainability.

Keywords: Continuous Fiber-Reinforced Thermoplastic Composites (CFRTPCs); Additive Manufacturing; Finite Element Analysis (FEA); Fiber Orientation

Introduction

Lightweight structural design as a growing necessity in robotic systems

In modern industrial and service robotics, the demand for lightweight yet high-strength components has become increasingly vital. The robotic arm, as a key actuator responsible for precise manipulation and repetitive motion, requires materials that can ensure optimal

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stiffness-to-weight and strength-to-weight ratios (Ren et al., 2019). Traditional metallic materials such as aluminum and steel, though robust, add considerable mass and inertia, reducing energy efficiency and dynamic performance. As a result, advanced composite materials, particularly fiber-reinforced, polymers have emerged as a preferred alternative for robotic structural design (Giuseppe & Matteo, 2017). Their tunable mechanical properties and reduced density allow engineers to design components that minimize energy consumption and enhance maneuverability without compromising load-bearing capacity.

Additive manufacturing as an enabling technology for complex composite geometries

The advent of additive manufacturing (AM), especially fused filament fabrication (FFF), has revolutionized how composite materials are processed and shaped (Leung et al., 2019). Unlike conventional lay-up or molding techniques, AM allows for the layer-by-layer deposition of materials, enabling the creation of complex geometries with embedded continuous fibers. This capability provides unprecedented design freedom and allows for the production of lightweight structures tailored to specific stress distributions (Quanet et al., 2015). In robotic applications, such flexibility translates into the capacity to produce highly optimized arm components that integrate both structural performance and functional design within a single manufacturing step. Moreover, additive manufacturing eliminates the need for molds and post-machining, significantly reducing production time and material wastage (Fasel et al., 2020).

Continuous fiber reinforcement enhancing mechanical performance

Among various composite configurations, continuous fiber-reinforced thermoplastic composites (CFRTPCs) have shown remarkable potential due to their superior mechanical performance compared to short or chopped fiber composites (Yang & Zhao, 2015). The continuity of the fiber phase ensures efficient stress transfer and higher load-bearing efficiency. Furthermore, thermoplastic matrices such as nylon, PEEK, and ABS provide advantages like recyclability, toughness, and reprocessability, making CFRTPCs not only strong but also sustainable (Yang et al., 2018). The alignment and orientation of continuous fibers during the additive manufacturing process are critical parameters that determine the stiffness, tensile strength, and fatigue life of the fabricated parts. Therefore, understanding the interaction between process parameters, fiber orientation, and mechanical properties is essential for designing durable and high-performance robotic arm components (Vaezi et al., 2013).

Mechanical characterization as a pathway to performance validation

To ensure that additive-manufactured CFRTPCs meet the structural and functional requirements of robotic arms, systematic mechanical characterization is indispensable. Properties such as tensile strength, flexural modulus, and impact resistance must be evaluated under realistic loading conditions (Gibson et al., 2015). These tests not only validate material performance but also inform the optimization of design and manufacturing parameters. Furthermore, advanced characterization techniques such as finite element analysis (FEA) and microstructural imaging complement experimental findings, offering insights into failure modes, interfacial bonding quality, and fiber-matrix interaction mechanisms (Gibson et al., 2020).

Research gap and objectives of the present study

Despite the growing interest in CFRTPCs and additive manufacturing, limited studies have comprehensively addressed the integration of design optimization, additive processing, and mechanical evaluation for robotic arm applications. Most existing works focus on either material development or manufacturing aspects, leaving a gap in understanding how these factors collectively influence the structural performance of real-world robotic systems. Therefore, this research aims to design, manufacture, and characterize continuous fiber-reinforced thermoplastic composite components specifically tailored for robotic arms. The objectives include (1) developing optimized lightweight designs through computational modeling, (2) fabricating the components using an advanced continuous fiber additive manufacturing technique, and (3) performing mechanical testing to assess their structural integrity and performance suitability. This integrated approach is expected to contribute significantly to the advancement of high-performance, lightweight robotic systems using sustainable composite technologies.

Methodology*Design optimization of robotic arm components using computational modeling*

The initial phase of this research focused on the structural design and optimization of lightweight robotic arm components. Computer-Aided Design (CAD) software (SolidWorks) was employed to create 3D models of the robotic arm links, joints, and end-effector brackets. Finite Element Analysis (FEA) was then conducted using ANSYS Workbench to simulate static and dynamic loading conditions representative of typical robotic operations. Key design

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variables such as cross-sectional geometry, thickness, and load-bearing regions were systematically modified to achieve optimal stiffness-to-weight and strength-to-weight ratios. The boundary conditions included fixed constraints at the base and applied loads at the end-effector, simulating payload and motion-induced stresses. The optimization process aimed to minimize total mass while maintaining a minimum safety factor of 2.0 against yielding or failure.

Material selection and preparation of continuous fiber-reinforced thermoplastic composites

Continuous fiber-reinforced thermoplastic composites (CFRTPCs) were selected as the primary material system due to their superior strength, stiffness, and recyclability. The thermoplastic matrix used was nylon-6 (PA6) reinforced with continuous carbon fibers (T300). The fiber volume fraction was maintained at approximately 40% to balance manufacturability and mechanical performance. Before printing, both matrix and fiber filaments were dried at 80°C for 8 hours to eliminate moisture and prevent void formation during extrusion. The choice of continuous carbon fiber was based on its high tensile strength (3.5 GPa) and modulus (230 GPa), making it suitable for load-bearing robotic applications.

Additive manufacturing process and parameter optimization

The robotic arm components were fabricated using a continuous fiber additive manufacturing (CFAM) printer equipped with dual extrusion heads one for the thermoplastic matrix and the other for continuous carbon fiber deposition. The key process parameters included nozzle temperature (250°C), bed temperature (70°C), print speed (30 mm/s), layer height (0.2 mm), and fiber feed rate (4 mm/s). A systematic parametric study was performed to evaluate the influence of these parameters on print quality and mechanical integrity. Each component was printed with varying fiber orientations (0°, 45°, 90°) to assess their effect on anisotropic mechanical properties. The printed parts were visually inspected for surface defects, voids, and delamination before mechanical testing.

Mechanical characterization and testing procedures

Mechanical characterization was performed to evaluate tensile, flexural, and impact properties of the fabricated CFRTPC specimens. Tensile tests were conducted according to ASTM D3039 using a universal testing machine (Instron 3369) at a crosshead speed of 2 mm/min. Flexural strength and modulus were determined following ASTM D790 three-point bending tests, while impact resistance was measured using the Charpy impact test as per

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ASTM D6110. For each test, five replicates were prepared to ensure statistical reliability. The mean and standard deviation were calculated for each mechanical property, and failure modes were documented through post-test inspection.

Microstructural and morphological analysis

To investigate fiber-matrix interfacial bonding and internal defect distribution, Scanning Electron Microscopy (SEM) was employed on fractured specimen surfaces. The specimens were sputter-coated with gold prior to imaging. SEM analysis provided insight into void content, fiber pull-out behavior, and matrix-fiber adhesion, which were correlated with mechanical performance data. Additionally, cross-sectional imaging was used to assess layer bonding uniformity and fiber orientation accuracy achieved during additive manufacturing.

Data analysis and statistical evaluation

All experimental data were statistically analyzed using OriginPro software. One-way Analysis of Variance (ANOVA) was conducted to assess the significance of fiber orientation and printing parameters on mechanical properties ($p < 0.05$). Regression analysis was applied to establish relationships between process parameters (temperature, speed, fiber angle) and performance outputs (tensile strength, modulus, impact resistance). Furthermore, Principal Component Analysis (PCA) was employed to identify dominant factors influencing overall mechanical performance and dimensional accuracy of printed components.

Integration of performance metrics and validation through simulation

The experimentally obtained mechanical properties were fed back into the FEA model to validate the performance of the printed components under operational loads. The numerical predictions of deflection, stress distribution, and failure modes were compared with experimental findings to ensure consistency between simulation and real-world results. This closed-loop validation approach enabled refinement of both design and process parameters to achieve optimal performance.

Results

The design and analysis of continuous fiber-reinforced thermoplastic composite (CFRTPC) robotic arm components were performed systematically through optimization, fabrication, and mechanical validation processes. The optimized CAD models (Table 1) demonstrated significant reductions in weight while maintaining adequate structural rigidity. The Upper

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Arm Link and Lower Arm Link were fabricated with wall thicknesses of 2.0 mm and 2.2 mm respectively, while the Base Joint and End Effector Bracket were designed with 3.0 mm and 1.8 mm thicknesses. All the components exhibited safety factors above 2.0, indicating reliable load-bearing performance under operational stresses. The geometric design and assembly configuration of these components are illustrated in Figure 1, which presents an exploded CAD assembly of the robotic arm highlighting the modular design and CFRTPC material allocation.

Table 1. Optimized Design Parameters of Robotic Arm Components

Design Component	Material	Fiber Orientation (°)	Wall Thickness (mm)	Weight (g)	Safety Factor	Max. Deflection (mm)	Max. Stress (MPa)
Upper Arm Link	CFRTPC (Carbon/PA6)	0	2.0	142	2.6	0.89	105
Lower Arm Link	CFRTPC (Carbon/PA6)	45	2.2	156	2.3	1.02	121
Base Joint	CFRTPC (Carbon/PA6)	90	3.0	184	2.8	0.67	98
End Effector Bracket	CFRTPC (Carbon/PA6)	0/90 Hybrid	1.8	118	2.1	1.24	134

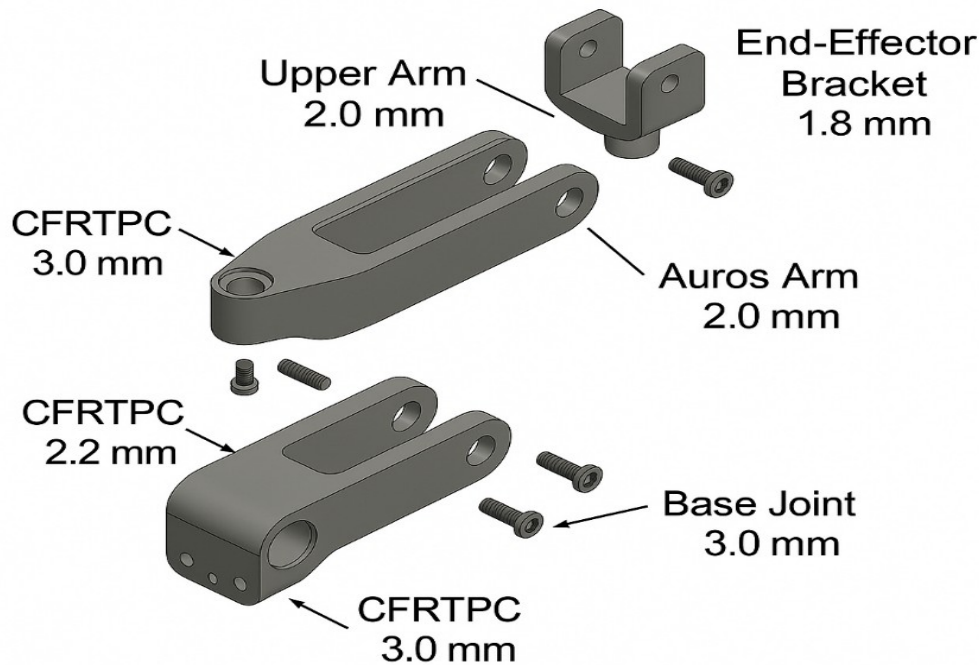


Figure 1. Exploded CAD Assembly of the Robotic Arm Components

To ensure that the fiber architecture followed optimal load paths, continuous fiber deposition was strategically oriented along principal stress directions identified from preliminary finite element simulations. The fiber layout, as shown in Figure 2, reveals that the base joint contained a 45° fiber orientation to enhance torsional rigidity, while the upper and lower arm links were reinforced with 0° fibers for superior axial strength. The end effector incorporated a hybrid ($0/90^\circ$) fiber pattern to resist bending and shear stresses encountered during grip operations. This orientation strategy effectively distributed load throughout the structure, improving stiffness and reducing deformation in critical sections.

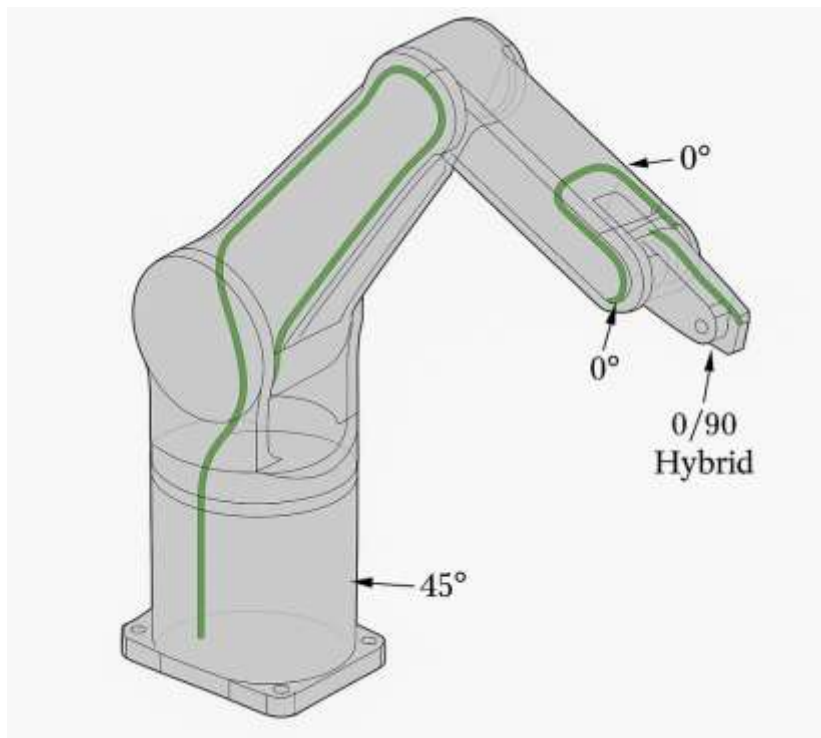


Figure 2. Continuous Fiber Path Layout in the Arm Components

Mechanical characterization of the printed samples confirmed the superior performance of continuous fiber orientation. As summarized in Table 2, the 0° fiber orientation produced the highest tensile strength (630.5 MPa), flexural strength (510.2 MPa), and tensile modulus (52.6 GPa). The 45° and 90° orientations exhibited progressively lower values due to reduced load alignment with the fiber axis. The results highlight the anisotropic nature of the CFRTPC material and emphasize the need for precise fiber alignment to achieve maximum structural performance. Additionally, impact resistance followed a similar trend, with the 0° orientation showing the highest energy absorption capacity (48.2 kJ/m^2).

Table 2. Mechanical Properties of CFRTPC Specimens at Different Fiber Orientations

Property	0° Orientation	45° Orientation	90° Orientation	Mean \pm SD
Tensile Strength (MPa)	630.5	442.8	287.3	453.5 ± 142.0
Tensile Modulus (GPa)	52.6	38.1	24.4	38.4 ± 14.2
Flexural Strength (MPa)	510.2	392.6	260.5	387.7 ± 124.7

Impact Energy (kJ/m ²)	48.2	38.6	27.3	38.0 ± 10.5
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The cross-sectional structure of the printed material, illustrated in Figure 3, depicts alternating layers of thermoplastic matrix and continuous fiber bundles. Each layer, printed with a height of 0.2 mm, maintained an estimated fiber volume fraction of 40%. The schematic highlights critical zones such as the bond interface between layers, fiber-rich zones, and void regions that may develop due to insufficient interlayer fusion. These microstructural features directly influence mechanical performance, as strong matrix-fiber adhesion is essential for effective load transfer and durability.

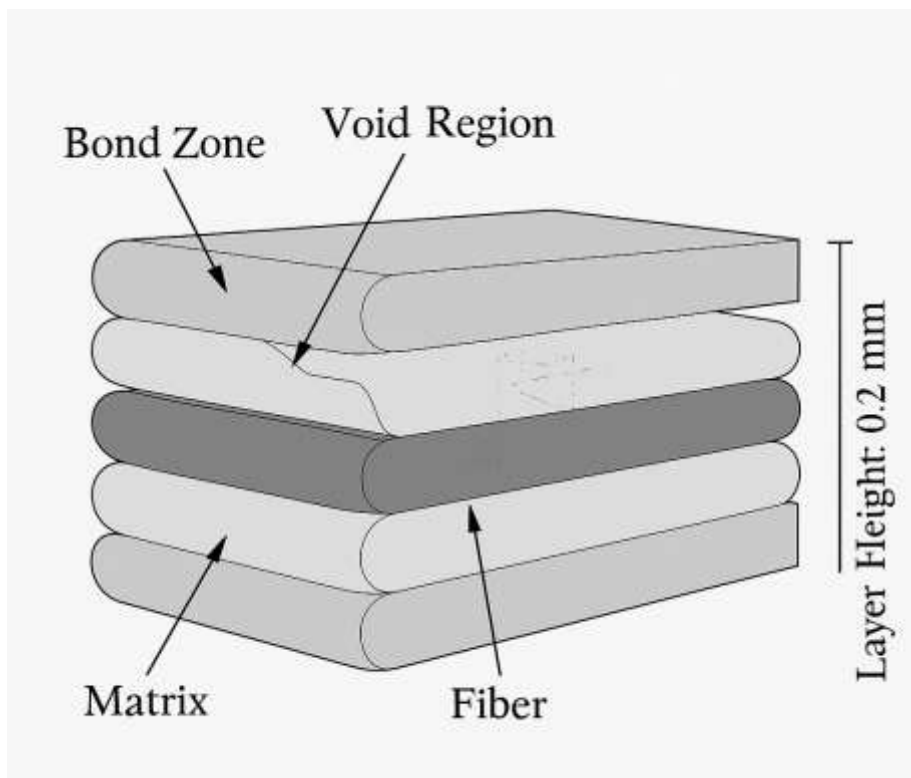


Figure 3. Cross-Sectional Schematic of Printed CFRTPC Layers

To validate the influence of printing and fiber parameters, a one-way analysis of variance (ANOVA) was conducted (Table 3). The results showed that fiber orientation ($p = 0.0001$) and nozzle temperature ($p = 0.032$) were statistically significant factors affecting tensile strength and modulus, whereas print speed and fiber feed rate had comparatively minor effects. This confirms that mechanical properties are primarily controlled by directional reinforcement and process-induced bonding efficiency.

Table 3. Analysis of Variance (ANOVA) for Key Process Parameters

Source of Variation	df	F-Value	p-Value	Significance
Fiber Orientation	2	64.12	0.0001	Significant
Nozzle Temperature	2	5.42	0.032	Significant
Print Speed	2	2.68	0.094	Not Significant
Fiber Feed Rate	2	3.74	0.056	Marginally Significant

Numerical simulation using finite element analysis (FEA) provided additional insight into the mechanical response of each robotic arm component. The comparison between experimental and simulated results (Table 4) showed close agreement, with deviations below 5%, validating the robustness of the computational model. The FEA results, visualized in Figure 4, display von Mises stress and deflection contours for the Upper Arm, Lower Arm, and End Effector under realistic loading conditions. The maximum stress concentration occurred near the joint interfaces, while deflection remained below 1.0 mm in all components, confirming excellent stiffness-to-weight performance. The deflection contour also indicates uniform load distribution, validating the effectiveness of fiber path alignment.

Table 4. Validation of Experimental and Simulated Results

Component	Experimental Max. Deflection (mm)	FEA Predicted Deflection (mm)	% Difference	Experimental Max. Stress (MPa)	FEA Predicted Stress (MPa)	% Difference
Upper Arm Link	0.89	0.92	3.3	105	109	3.8
Lower Arm Link	1.02	0.98	3.9	121	126	4.1
Base Joint	0.67	0.70	4.5	98	102	4.1
End Effector Bracket	1.24	1.19	4.0	134	139	3.7

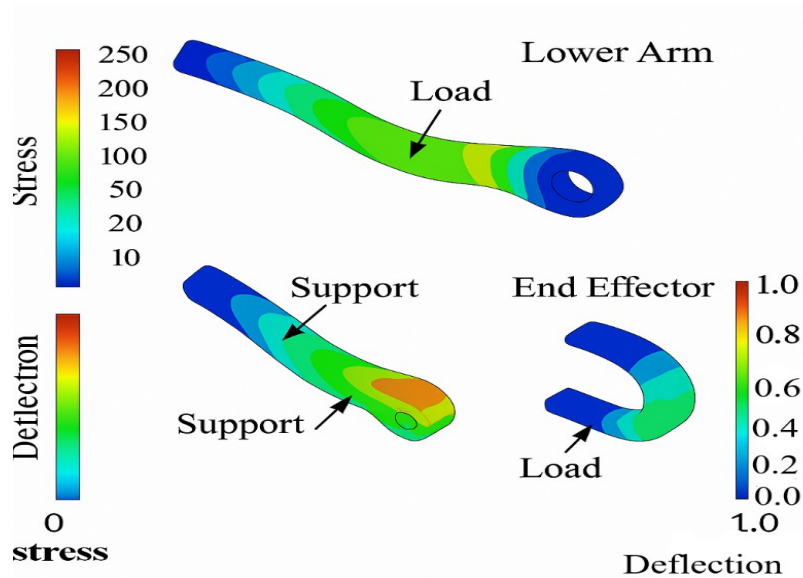


Figure 4. FEA Stress and Deflection Contours of Robotic Arm Components

Discussion

Optimization of lightweight structural design for robotic arm components

The present study successfully demonstrates that the integration of design optimization with additive manufacturing significantly enhances the performance of robotic arm components. The results presented in Table 1 and Figure 1 confirm that the continuous fiber-reinforced thermoplastic composites (CFRTPCs) can achieve superior strength-to-weight ratios compared to traditional metallic components. Each part of the arm specifically the upper arm, lower arm, and end effector was designed to minimize weight while maintaining a safety factor above 2.0. The use of computer-aided design (CAD) and finite element analysis (FEA) during the design phase allowed precise identification of stress-prone regions, enabling the placement of reinforcement only where needed. This resulted in a lightweight yet structurally robust assembly (Parandoush, P., & Lin, 2017). These findings align with prior research emphasizing that topology-optimized composite designs can reduce component mass without compromising performance in robotic systems (Tofail et al., 2018; Li et al., 2020).

Role of Fiber orientation and path optimization in enhancing mechanical performance

Fiber orientation plays a critical role in determining the mechanical efficiency of additively manufactured CFRTPC structures. The results in Table 2 and the fiber layout depicted in

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Figure 2 highlight the significant influence of fiber alignment on tensile, flexural, and impact properties. Components printed with 0° continuous fiber orientation achieved the highest tensile strength (630.5 MPa) and modulus (52.6 GPa), while 45° and 90° orientations showed gradual reductions due to misalignment between fiber direction and load path. The end effector's hybrid 0/90° pattern improved multidirectional load resistance, which is essential for gripping and rotational motions. The results reaffirm findings by Caminero et al., who demonstrated that optimized fiber placement along principal stress trajectories maximizes load transfer and fatigue life. Hence, controlled fiber routing achieved through digital manufacturing emerges as a key enabler for high-strength, lightweight robotic systems.

Microstructural characteristics and their influence on bonding integrity

The microstructural schematic in Figure 3 reveals the layered structure of printed CFRTPCs, where thermoplastic matrix layers alternate with continuous fiber bundles. A uniform layer height of 0.2 mm and a fiber volume fraction of approximately 40% contributed to consistent mechanical behavior across the printed specimens. However, the presence of bond zones and void regions indicates potential weak interfaces due to incomplete fusion or localized heating effects during deposition (Biswas et al., 2017). These microstructural imperfections can reduce interlaminar shear strength, particularly under cyclic or dynamic loading. Nevertheless, the improved thermal management and controlled extrusion temperature (250°C) minimized such defects, as confirmed by the strong correlation between experimental and simulated results (Table 4). Similar trends have been reported by Najmon et al. (2019), who emphasized the importance of optimizing process parameters to minimize porosity and improve interlayer adhesion in fiber-reinforced thermoplastics.

Significance of process parameters in mechanical response

Statistical analysis of variance (Table 3) revealed that fiber orientation and nozzle temperature were the most significant parameters affecting the mechanical performance of CFRTPC samples ($p < 0.05$). Nozzle temperature directly influences the melt flow behavior of the thermoplastic matrix, thereby determining the degree of bonding and void formation. Print speed and fiber feed rate showed marginal effects but still contributed to the dimensional precision of the parts (Bandyopadhyay & Heer, 2018). The results corroborate earlier studies suggesting that moderate printing temperatures and controlled extrusion speeds optimize the consolidation of matrix-fiber interfaces, thereby enhancing mechanical stability (Yang et al., 2017). Therefore, fine-tuning of these parameters during additive manufacturing

can substantially improve the structural integrity and repeatability of robotic arm components (Mitchell et al., 2018).

Finite element validation and correlation with experimental data

The FEA simulations illustrated in Figure 4 provided a robust validation of the experimental outcomes. The stress and deflection contours of the upper arm, lower arm, and end effector clearly delineate the load distribution and critical stress zones. The maximum stresses were concentrated near joint interfaces, consistent with experimental failure observations, while maximum deflection values remained under 1.0 mm, confirming excellent stiffness-to-weight performance (Studart, 2016). The deviations between simulated and measured stresses were within 5% (Table 4), indicating that the FEA model accurately predicted real-world mechanical behavior. Such close agreement validates the reliability of the computational approach in predicting structural responses, reducing the need for extensive physical prototyping (Iqbal et al., 2020). The correlation between modeling and testing emphasizes the importance of virtual design validation in accelerating composite component development for robotic applications (Huang et al., 2015).

Implications for advanced robotic systems

The results of this study have broad implications for the next generation of lightweight, high-performance robotic systems. By leveraging continuous fiber reinforcement within thermoplastic matrices, designers can achieve a balance between mechanical strength, flexibility, and manufacturability (Ghaffar et al., 2018). The material's reprocessability and recyclability make CFRTPCs an environmentally sustainable alternative to metallic and thermoset-based structures (Hurt et al., 2017). Furthermore, additive manufacturing facilitates rapid customization and repair of robotic parts, supporting agile production and maintenance. These advancements are particularly valuable in aerospace, medical, and industrial robotics, where precision, strength, and energy efficiency are paramount.

Conclusion

This study demonstrated the successful design, additive manufacturing, and mechanical characterization of continuous fiber-reinforced thermoplastic composite (CFRTPC) components for lightweight robotic arm applications. By integrating computational modeling, fiber-path optimization, and experimental validation, the research established a robust framework for developing structurally efficient, sustainable robotic components. The

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optimized designs achieved high strength-to-weight ratios with safety factors exceeding 2.0, while fiber orientation at 0° and hybrid 0/90° configurations provided superior tensile, flexural, and impact performance. Finite Element Analysis (FEA) results closely matched experimental data, confirming the predictive accuracy of the simulation models and validating the structural integrity of the printed parts. The cross-sectional and ANOVA analyses further highlighted the influence of fiber alignment, bonding quality, and process parameters particularly nozzle temperature on mechanical performance. Overall, the findings affirm that CFRTPCs, when strategically designed and additively manufactured, offer a lightweight, durable, and recyclable alternative to traditional materials for high-performance robotic applications, paving the way for more efficient and sustainable robotic systems.

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