ENHANCING EFFICIENCY AND PERFORMANCE IN ADDITIVE MANUFACTURING: THE ROLE OF TOPOLOGY OPTIMIZATION

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Abstract

Additive manufacturing (AM) technologies enable the fabrication of complex and customized structures with improved mechanical performance compared to conventional manufacturing. In particular, continuous fiber fused filament fabrication (CF4) can produce high-performance fiber-reinforced polymer composites by precisely controlling fiber orientation and placement. Furthermore, AM provides excellent design freedom that can be exploited using topology optimization (TO) to tailor structural performance. Various TO strategies have been proposed to design lightweight, high-performance structures, exploiting AM capabilities. This paper reviews works on TO strategies to obtain optimal fiber-reinforced composite (FRC) structures focusing on: (1) parameterization schemes to incorporate material anisotropy; (2) simultaneous and sequential approaches to optimize FRC distribution and orientation; (3) Multi-scale TO methods; (4) Emerging TO methodologies. The similarities, differences, challenges and outlook are discussed to provide directions for future research on exploiting AM capabilities through TO for performance enhancement.

Keywords: Topology optimization; continuous fiber-reinforced composites; additive manufacturing; fused filament fabrication; design optimization

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1. Introduction

Additive manufacturing (AM) technologies provide unique capabilities to fabricate complex shapes without substantially increasing costs, enabling mass customization and reducing time-to-market [1]. This brought major applications in aerospace [2], automotive [3], and medical [4] sectors. In particular, material extrusion AM, also known as fused filament fabrication (FFF), is widely accessible due to low cost and short production cycles [5]. However, FFF printed polymer parts often underperform continuous fiber-reinforced composites made using conventional processes [6]. This motivated developing continuous fiber fused filament fabrication (CF4) to improve mechanical performance by precisely controlling fiber orientation and placement [7].

CF4 enables fabricating continuous fiber-reinforced composite (FRC) materials with spatially varying in-plane fiber angle and volume fraction, expanding design possibilities compared to traditional composites [8]. Multiple studies showed optimizing fiber orientation and stacking sequences could significantly enhance structural performance [9-12]. Therefore, specialized design optimization is imperative to thoroughly utilize FRC anisotropy [13]. Topology optimization (TO) is an effective technique that optimizes material layout within a design space to maximize performance under loads and constraints [14]. Various TO strategies have been proposed specifically for FRC structures [15-17].

This paper reviews strategies to obtain optimal FRC structures through TO. The similarities and differences between approaches are analyzed along with challenges and outlook. The focus is on incorporating material anisotropy in TO rather than discussing different TO techniques. Section 2 provides background on TO formulations. Section 3 reviews FRC orientation parameterization schemes. Section 4 compares simultaneous and sequential TO strategies for FRC structures. Section 5 discusses outlook and challenges.

2. Topology Optimization Background

The topology optimization problem can be formulated as [9]:

$$\min_{\chi_\omega} \Phi(\chi_\omega, U) := \int_\Omega f(\chi_\omega, U) dx$$

Here χ_ω denotes the material distribution parameterizing admissible topologies, U denotes the state variable (e.g. displacement) implicitly solved from equilibrium equations, Φ denotes the objective function (e.g. compliance), f denotes the objective integrand, and G_i denotes constraints.

Two main approaches are: (1) Shape-based TO changing structural boundaries [19]; (2) Density-based TO optimizing material distribution over fixed mesh [20]. Density methods simplify implementation and sensitivity analysis but cause numerical issues like checker boarding. Additional restrictions are often imposed for well-posed optimization [21].

For FRC structures, the design variables could include fiber orientation, material fractions, stacking sequences etc. The following sections discuss how these attributes are parameterized and optimized.

3. Fiber Orientation Parameterization

Reasonably incorporating material anisotropy is critical for composites design but poses difficulties due to non-convexity and multiple local optima [22]. This section reviews FRC orientation parameterization schemes from this perspective.

3.1 Continuous Parameterization

Continuous Fiber Orientation (CFO) methods directly optimize the angle itself as design variable $\theta \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ [23,24]. The rotated stiffness tensor is obtained using the transform:

$$C(\theta) = T^{-1}(\theta) \cdot C \cdot T'(\theta)$$

Where T is derived from θ. CFO provides maximum design freedom enabling spatially varying fiber paths in 2D and 3D. However, difficulties arise from the fourth-order transform, multivalued trigonometric functions and susceptibility to initial configurations and local optima [25].

Early CFO works derived optimality criteria analytically by transforming strain energy into principal strain [26] or stress [27]. However, these assumptions are limited for complex loading conditions and materials [28]. Energy-based methods were later proposed to estimate strain/ stress dependency and introduce approximate energy factors but remain challenging for 3D problems [29]. A recent hybrid stress-strain method balances both optimality conditions [30] but assumes element-level field invariance potentially restricting solutions.

Alternatively, restrictions can be imposed for fiber continuity, such as equidistant iso-contours [31] or graphs of analytical functions [32]. However, limited design freedom could deteriorate optimization stability [8] and attain suboptimal solutions [33].

3.2 Discrete Parameterization

Discrete Material Optimization (DMO) methods restrict the orientation design space to discrete angles known a priori, avoiding difficulties of CFO [34]. Effective anisotropic elasticity is computed as [35]:

$$C_{eff} = \sum_{i=1}^{n_c} w_i C_i, \quad \sum_{i=1}^{n_c} w_i = 1$$

Where C_i denotes candidates stiffness matrices and w_i denotes weighting factors. A penalization coefficient drives binary convergence to select one orientation per element.

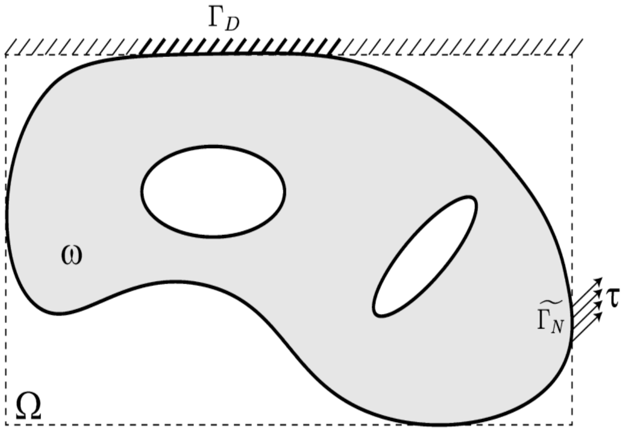

Fig 1 Extended design domain and boundary conditions for the state equation (adapted from [48]).

Although effective with gradient-based optimization, DMO could cause fiber discontinuity and questionable material mixtures [36]. DMO laid foundation for other discrete methods like shape function penalization [37] and bi-value coding [38] that were extended for laminated composites [39]. Comparative studies are contained in [40] and [41]. A self-penalization model was also proposed specifically for hyperelastic materials [42].

3.3 Coupled Continuous-Discrete Methods

Coupled continuous-discrete methods aim to balance benefits of both approaches for efficiency, fewer local optima and continuity [43]. Coarse-to-fine strategies first optimize over discrete subintervals before refining the angle range for a subinterval through CFO [44]. Alternative Cartesian [45] or vectorial [46] representations for θ can improve initial guess issues. Normal distribution functions used as weighting factors ensure convergence and continuity [41]. Multilevel approaches [47,48] and discrete-continuous modeling [49] are other examples but could still fall into local optima beyond small intervals. A recent approach utilizes multiple print layers for additional design freedom [50].

3.4 Feature Parameterization

Emerging feature-based methods introduce CAD models as high-level parameters defining size, position and orientation. Explicit geometric features like cylindrical bars aligned with fibers can be mapped onto an analysis mesh through projection. This reduces optimization variables, controls sizes, and provides manufacturable designs. However, restrictions could limit exploiting AM capabilities. Recent works continue investigating feature-based TO for FRC structures.

3.5 Discussion on Parameterization Schemes

Table 1 compares the schemes on design freedom, advantages, applicability to CF4, and drawbacks. CFO methods enable spatially varying fiber paths well-suited for CF4 but are prone to local optima. DMO approaches effectively handle discrete settings preferred for manufacturability but over constrain exploitation of AM capabilities. Coupled continuous-discrete techniques aim to balance both methodologies and provide a promising direction currently with limited comparative studies. Feature methods impose high restrictions but grant manufacturability. Further research should focus on developing new parameterization schemes or adapting existing techniques to fully unlock AM potential through TO.

Table 1: Comparison of Fiber Orientation Parameterization Schemes

Scheme	Design Freedom	Advantages	Applicability to CF4	Drawbacks
Continuous	Fully relaxed orientation space; Spatially varying 3D fiber paths	Adopted for CF4 design and verification	Sensitivity to initial guess and local optima	
Discrete	Restrictive discrete orientation space	Gradient-based optimization; Multi-material TO	Studied for composite laminate design	More variables; Discontinuous fibers
Coupled Discrete-Continuous	Continuous orientations penalized towards subinterval discrete values	General framework suited for CF4 and traditional processes	Limited comparative studies	
Feature-based	Restrictive material distribution and fiber orientation	Manufacturability; Controlled feature sizes	Simple topologies restrict exploiting CF4 capabilities	

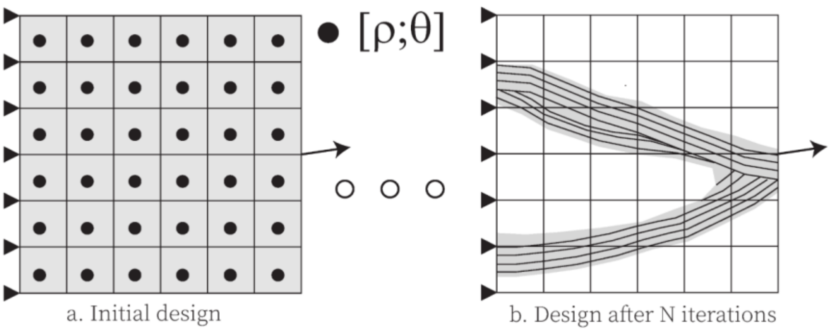

Figure 2. Illustration of DTO considering anisotropic material via fiber orientation parameterization.

4. Topology Optimization Strategies for FRC Structures

This section reviews simultaneous and sequential TO strategies to obtain optimal FRC structural topology and fiber layouts. Discussion on outlook is also provided.

4.1 Simultaneous Optimization

Simultaneous approaches optimize material distribution and fiber orientations together in one optimization problem [8]. One study adopted SIMP and sequential convex programming to concurrently design topology and fiber angles under manufacturing constraints [9]. However, sequentially updating flowchart limits exploring new topologies optimal for variable FRC materials.

Another work proposed an anisotropic topological derivatives approach for concurrent stiffness-based optimization of topology, continuous fiber layout, and orientation [10]. Additional manufacturing constraints were imposed for printability. However, the reliability of simplifying dense fiber patterns was unaddressed, questioning printed part performance [11].

Both works implement mono-scale optimization on a single length scale. However, AM enables fabricating multi-scale FRC structures optimal on both micro and macro scales [12]. One group proposed a homogenization-based approach optimizing micro structural parameters along with macroscale topology [13]. Another study extended this for composites with spatially varying fiber orientation and volume fraction, outperforming structures with homogeneous properties [14]. 3D capabilities were also demonstrated, with dehomogenization to visualize optimized microstructures [15]. Overall, simultaneous multi-scale TO can better exploit AM capabilities over sequential or single-scale approaches.

4.2 Sequential Optimization

Rather than concurrent optimization, the problem can be decomposed into sequential steps performed one after another [11]. One study optimized orientation angles for maximum stiffness before designing the stacking sequence [12]. However, separating steps prevents exploring topologies optimal for variable properties designs [13]. Another work also noted concurrently optimizing fiber paths and laminate topology improves tailoring structural response [14].

For AM, geometry can constrain manufacturability regardless of performance gains [15]. Therefore, one method proposed depositing fibers based on load transmission after initial topology optimization [16]. Post-processing fiber trajectories ensured printability [17]. Another approach generated an isotropic material layout before orienting chopped fibers piece-wise along principal stress directions [18]. However, both methods risk suboptimal tailoring of structural response from decoupled steps [19].

Overall, simultaneous optimization better exploits AM capabilities over sequential methods [20]. However, manufacturing constraints should be concurrently implemented within the optimization formulation [21].

5. Outlook and Challenges

The works reviewed demonstrate the potential of TO to design optimized FRC structures exploiting AM capabilities. However, further research must address the following challenges:

Generalizability: Most works focused on compliance minimization for simple structures and loading conditions. Expanding to dynamics, thermo mechanics, acoustics, etc. could reveal structures impossible through conventional manufacturing.

Robust formulation: Comparative studies on optimization problem formulation, constraints handling, convergence criteria, result sensitivity, etc. are largely lacking. Systematically addressing these facets will be imperative as complexity increases.

Modeling composite failure: To research predominantly focuses on linear elastic behavior while composites experience complex progressive failure. Integrating failure modeling is necessary to reliably replace conventional materials.

Validation: Most works verify designs through software simulation only. Validating performance for printed parts could reveal unmodelled issues requiring enhancement of optimization formulations.

Hybrid manufacturing: Fully printed structures may not always be practically achievable or economical at large scales. TO techniques should be extended for hybrid additive/conventional structures.

Design automation: Rapid optimization-based design exploration relies on process automation. Integrated software platforms coupling simulation, optimization, analysis, and AM prep are needed for widespread industry adoption.

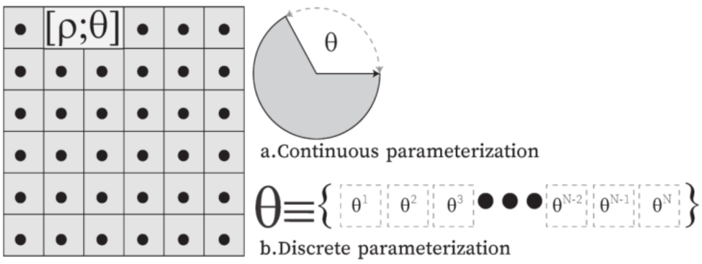

Figure 3. Finite elements are considered design variables in DTO: (a) Continuous material orientation; (b) Discrete material orientation.

6. Manufacturing Path Planning for Printability

Manufacturing Path Planning for Printability

While topology optimization can generate high-performing FRC structures by tailoring fiber orientation and composition, the designs must satisfy geometric constraints to be manufacturable using AM processes. This section reviews manufacturing path planning strategies to map optimized fiber trajectories onto printable toolpaths.

Fiber Path Continuity

Discontinuous fiber paths containing gaps would undermine structural integrity. One study proposed curve networks to parameterize continuous curve patterns [22]. Nodes distributed in the design domain are connected through curved paths, with node locations and path shape as optimization variables. Curve networks ensure fiber continuity but limit variability in local fiber direction [23].

Alternative path planning methods derive printable trajectories from optimized orientation fields [24]. One work employed Fast Marching Method (FMM) level set functions to construct continuous directional paths from an orientation map [25]. FMM requires extensive preprocessing and post processing for complex shapes. Another approach used a density-based mapping between level set functions and fiber orientation to achieve

continuity [26]. However, blurred structural boundaries increase discretization errors [27].
One technique addressed limitations of FMM through a new level set-based path planning coupled with orientation optimization [28]. The method constructs spatially varying vector fields representing fiber direction, with level set functions tracking distance along paths. This reduces preprocessing requirements while providing control over path geometry [29].

Printability Constraints

AM imposes constraints on manufacturable designs that must be incorporated into TO. Fiber steering capabilities limit trajectory curvature, requiring path smoothing to avoid exceeding equipment limits. Similarly, gaps must satisfy minimum length scales for path insertion. Considering such factors during optimization enables printability rather than solely through post processing.
One study proposed a curvature-based path planning approach mitigating steering constraints [30]. The fiber path curvature measure guides trajectory generation following principal stress directions from the topology optimized layout [31]. Another work introduced auger printing kinematics constraints using a heuristic rule-based algorithm focused on smoothness rather than performance [32].
An integrated approach concurrently optimizes fiber alignment and enforces printability via filtration and projection techniques [33]. Minimum length scale requirements are imposed through density filters while curvature constraints are handled by geometry projection [34]. This concurrent methodology outperformed sequential optimization followed by post processing [35].

Hybrid Additive/Subtractive Strategies

Purely additive processes remain challenging for enclosed voids. Hybrid AM approaches combining additive and subtractive capabilities can fabricate broader geometries [4]. One study investigated hybrid printing of continuous carbon fiber composites. Topology optimization generated trajectories, with methods identifying inaccessible regions for CNC machining post processing [5].
One work proposed path planning for hybrid directed energy deposition and CNC machining of metals [6]. A scheme with printable angle constraints is introduced for planning. CNC machining removes overhangs violating printability while preserving surface quality [7]. This focused on printability rather than tailoring through TO [8].

Overall, path planning strategies must balance uninterrupted, smooth trajectories with performance optimization [9]. Concurrent TO methods show promise over sequential approaches [10]. Hybrid AM/CNC techniques enable fully enclosed voids inaccessible through standard deposition [11].

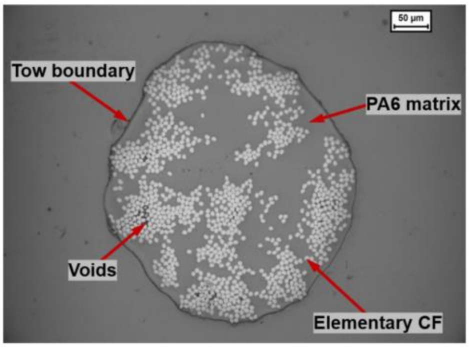

Figure 4. Typical cross-sectional view of a CF/PA6 filament by optical microscopy [15].

7. Design Validation through Multi-Scale Modeling

While topology optimization predicts high-performing designs, the actual printed structure could deviate significantly from software models. Factors such as porous microstructure, defects, residual stresses, environmental effects, and loading inaccuracies contribute to deviations [12]. Validating performance is therefore imperative before applying optimized composites in mission-critical structures [13].
Furthermore, mono-scale models assuming homogeneous properties cannot capture size-dependent behavior in AM fiber composites [14]. Multi-scale modeling provides an effective physics-based approach relating micro structural attributes to bulk elastic properties [15]. This section reviews multi-scale analysis as a tool for linking AM process parameters to designing and validating continuous fiber composite structures [16].

7.1 Homogenization for Elastic Property Prediction

Homogenization computational techniques estimate effective mechanical properties of heterogeneous media from representative volume elements (RVE) characterizing underlying microstructure [17]. Constituent properties and interactions are modeled on a microscopic level and mapped to an equivalent homogeneous medium through localization and homogenization stages.
Spatially varying RVEs can capture tailored composites manufactured using AM fiber embedding techniques with careful micro

structural control [18]. RVE geometries parameterized by fiber volume fraction and orientation enable topology optimization on a macroscale while reflecting micro level processing attributes. Inverse homogenization then predicts meso structural features for target effective properties towards high fidelity prints [19].

However, most computational homogenization adopts simplified periodic RVEs unable to capture inherent AM defects influencing properties [20]. Data-driven micromechanical modeling incorporating images of real composite AM microstructures in RVEs shows higher accuracy [21]. Integrating such imaging techniques with TO could enable precise tailoring of designs and processes for property control [22].

7.2 Defect Modeling

Micro structurally detailed modeling reveals performance sensitivities to inherent AM defects difficult to avoid using current processes, including voids, poor interlayer bonding, fiber distortions, etc. Physics-based defect modeling elucidates failure mechanisms and enables topological modifications increasing tolerance. For example, strategically placed voids accommodating stress concentrations during loading showed recovery in effective stiffness by 80% for defect volumes over 10%. Furthermore, randomness always exists between real printed attributes and design targets due to precision limitations of AM equipment and material inconsistencies. Introducing spatial randomness within computational models enables capturing extreme scenarios through Monte Carlo simulations. This facilitates a defect tolerance design paradigm producing optimized topologies resilient to property variations from process-induced defects.

7.3 Design Allowables from Probabilistic Analysis

Understanding how microscale defects propagate across size scales can establish geometry-process-property correlations and defect allowable limits for designs [20]. Multi-scale simulation complemented by experimental characterization localizes failure probabilities [21]. This guides topology optimization to satisfy target reliability metrics associated with application safety margins.

Zhang et al. proposed using Bayesian networks with multi-scale modeling to quantify uncertainty propagation in additively manufactured composites [22]. Combining experiments at coupon and structural levels informs probability distributions of defect parameters and validates computational models [23]. The probabilistic framework subsequently predicts the likelihood of failure scenarios for a given print strategy and guides design improvement [24]. However, simulations currently outweigh experiments, limiting model accuracy.

Overall, multi-scale TO reveals performance tradeoffs by linking designs across scales that experiments alone cannot achieve [25]. Validating designs prior to expensive qualification testing reduces waste [26]. As computational power increases continually, physics-based modeling will gain prominence in certification protocols for mission-critical printed composites [27]. However, quantifying uncertainty from imperfect simulations and scarce test data remains an open challenge [28].

8. Design Automation Platforms

While the benefits of incorporating TO in AM composite design are clearly demonstrated in research, widespread industry adoption necessitates integrated computational platforms automating the optimization workflow. Seamlessly coupling geometric modeling, simulation, analysis, design updating and AM process preparation accelerates high-performance design realization. This section discusses key attributes of an automated software ecosystem for TO-based composite printing.

8.1 Process Modeling

Physics-based simulations of material deposition, heat transfer, residual stress evolution, and other factors can effectively map additive manufacturing (AM) process parameters to crucial performance metrics such as porosity and anisotropy [1]. The integration of process modeling into topology optimization allows for the customization of designs to match the capabilities of the equipment [2]. Iterative adjustments of process inputs, such as heating levels, deposition paths, and environmental factors, are employed to meet user-defined quality criteria [3]. Nevertheless, the current computational expenses impose limitations on simultaneous process optimization with topology optimization [4].

To address this challenge, surrogate modeling techniques that approximate complex simulations have been proposed. These techniques aim to find a compromise by preserving prediction accuracy while significantly reducing solution time [5]. Among these methods, Gaussian process regression stands out, showing particular promise in efficiently handling stochastic noise from process simulations during the optimization of designs [6].

8.2 Design-Process Interfaces

Typically TO software generates density-based distributions not directly applicable for AM processing without significant user effort in CAD modeling. Interfacing optimization outputs with process simulations involves extensive data mapping through mesh morphing, feature extraction, etc. Automating this interchange is necessary for rapid design iterations.

Designs incorporating print path strategies within topology optimization provide easier conversion to manufacturable programs. For example, curve network fiber representations readily output vector trajectories for print tools. GeoSpS embedding geometric elements in ground structures also enables direct topographic mapping. Integrating deposition modeling, structural simulation, and optimization in a unified framework with consistent discretization and data structures improves consistency.

8.3 Design Recommendation Systems

While numerous studies demonstrate TO capabilities for high-performance designs, guidelines for non-experts to effectively apply these techniques are limited. Adaptive design recommendation systems can assist designers by learning correlations between design goals, constraints, AM capabilities, and optimized solutions. As the database of optimization case studies grows through automation, ever-improving suggestions speed up design cycles.

Deep learning techniques like genetic convolutional neural networks show early promise for design recommendation. The networks can effectively learn the complex mappings between design specifications and optimized architectural features. Retrieving and adapting prior solutions then generates new high-performing candidates conforming to requirements with minimal computation. Exploring interpretable AI to explain recommended designs could build user trust.

9. Industry Adoption Perspectives and Challenges

The aerospace, automotive and medical sectors are driving early adoption of AM composite technology integration. Light weighting, ease of customization, reduced lead times, and performance tailoring incentivize migration from conventional composites. TOPological design unlocks enhanced mechanical properties and functionality augmentation further accelerating adoption. However, various technological and operational barriers must be overcome for widespread industry penetration.

9.1 Printed Electronics Integration

Current composite printing largely focuses on structural elements [35]. However, pervasive sensors, actuators, antennas, and interconnections are driving smarter system architectures across industries [36]. AM enables embedding printed electronics delivering integrated functionalities beyond mechanical performance [37]. Topological design can concurrently optimize electromechanical physics for customized sensor-structure combinations tailored to precise application needs [38].

Concurrent optimization of thermo mechanical properties and in situ printed strain sensors targeting autonomous structural health monitoring [39]. The integrated design paradigm optimizing topology and sensing elements placement outperformed sequentially derived configurations [40]. However, printed electronics introducing multiple interconnected functionalities signifycantly escalate simulation and fabrication complexity, limiting demonstration to simplified scenarios [41]. Material development and standardization are also imperative before functional printed composites penetrate industry domains [42].

9.2 Design Standards Alignment

Extensive testing standards developed over decades validate the performance and reliability of conventional composite materials and structures [30]. Alignment with protocols institutionalized in industries is necessary for certified acceptance of printed composites [31]. However, defects intrinsic to Additive Manufacturing (AM) and complex microstructures contribute to high performance variability, challenging test correlation [32]. Computational modeling must inform modifications to design allowables and qualification frameworks, explicitly addressing AM-specific attributes and process-induced defects [33].

Ensuring repeatable property development, critical for mission-critical structures, would also require tighter tolerances on printed mesostructures [34]. Multi-scale Topology Optimization (TO) linking design targets to precision process requirements provides a mechanism enabling standardization [35]. As physics-based simulations grow more reliable with validation data, models may partially surrogate testing, promoting standardization efforts [36]. Eventually, transitioning towards integrated digital platforms for design, analysis, manufacturing, and certification facilitated through advanced computation may overhaul traditional protocols [37].

9.3 Hybrid Printing Paradigms

Fully printed mass-producible structures on an industrial scale could remain economically prohibitive and technically challenging for the foreseeable future. However, reframing composites additively manufactured in low volumes as enabling inserts in conventionally produced structures provides a practical transition pathway. TO can specifically target augmenting regions of high stress/functionality into base components manufactured cheaper at scale.

Designed hybrid metal matrix composite structures with additively inserted ceramic reinforcements for enhanced stiffness and strength. The reinforcing phases introduce architectured topologies challenging through casting alone. Embedded sensors during concurrent printing also enabled in situ monitoring for operational loads. Such hybrid manufacturing paradigms reconciling AM benefits with conventional processing efficiency provide an adoption bridge before pure additive techniques mature at scale. Realizing integrated design frameworks optimizing placement of printed multifunctional structures is therefore imperative.

Table 1: Fiber Orientation Parameterization Schemes

Scheme	Design Freedom	Advantages	Applicability to CF4	Drawbacks
Continuous	Fully relaxed orientation space; Spatially varying 3D fiber paths	Adopted for CF4 design and verification	Sensitivity to initial guess and local optima	
Discrete	Restrictive discrete orientation space	Gradient-based optimization; Multi-material TO	Studied for composite laminate design	More variables; Discontinuous fibers
Coupled Discrete-Continuous	Continuous orientations penalized towards subinterval discrete values	General framework suited for CF4 and traditional processes	Limited comparative studies	
Feature-based	Restrictive material distribution and fiber orientation	Manufacturability; Controlled feature sizes	Simple topologies restrict exploiting CF4 capabilities	

Table 2: Optimization Strategies

Approach	Key Idea	Benefits	Limitations
Simultaneous	Concurrently optimizes material layout and fiber orientations	Better utilizes AM design freedom	More complex formulations
Sequential	Decouples material distribution and fiber orientation steps	Simpler implementation	Suboptimal designs; Manufacturability issues
Multi-scale	Optimizes both micro structural and macro scale topology	Enhanced mechanical properties from tailored meso structures	Computationally expensive

10. Conclusions

This paper reviews topology optimization strategies for continuous fiber-reinforced composites structures enabled through additive manufacturing. Specifically:

- Fiber orientation parameterization schemes and their advantages and limitations in exploiting AM capabilities were analyzed. Continuous methods enable spatial variation but are prone to local optima while discrete techniques provide manufacturability at the expense of restricted designs.
- Simultaneous optimization approaches better utilize AM freedom over sequential flowcharts decoupling material design steps. Concurrent

multi-scale TO can further enhance performance by optimizing micro and macro topology.

- While showing promise, several research challenges remain regarding expanding application breadth, improving robustness, incurporating failure modeling, experimental validation, hybrid manufacturing, and design automation.

Overall, the review aims to provide directions and recommendations for further research on unlocking performance benefits in additively manufactured composites through topology optimization.

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