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Additive Manufacturing of Continuous Fibre Reinforced Composites: Process, Characterisation, Modelling, and Sustainability

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ABSTRACT

Continuous fibre reinforced polymer (CFRP) composites are significantly important materials with efficient structural performance because of their ability to combine high stiffness and high strength with lightweight properties. This makes them a critical material choice for applications in aerospace, automotive, and transport sectors where reducing the mass without compromising mechanical integrity is essential. Recently, additive manufacturing has been adopted as an advanced manufacturing technique to precisely place continuous fibre reinforcements within polymeric matrices. These additive manufacturing techniques increased freedom in the design and fabrication of polymeric composites by allowing control of fibre density and orientation and as a result tailoring material behaviour at the local material points. This capability also allows engineers to design and manufacture complex geometries with CFRP composites that were not achievable through traditional composite fabrication methods. This review first highlights the state-of-the-art in additive manufacturing of continuous fibre-reinforced polymer composites and then focusses on different aspects of the domain, including discussions on conventional and novel additive manufacturing techniques, mechanical characterisation and testing methods, numerical and computational modelling approaches, various functional applications, and sustainability of additive manufacturing polymeric composites. This review also aims to provide insight into the current body of work, existing limitations, and emerging research frontiers related to the advantages of reinforcing composites with fibres through the additive manufacturing process. Despite the persisting challenges, the reviewed studies demonstrate that this methodology shows great promise within the manufacturing spectrum.

1 | Introduction

The manufacturing industry has undergone major transformations in recent decades. From early practices of shaping natural materials to achieve desired geometries, the field has progressed toward automated manufacturing, advanced material synthesis, and additive manufacturing (AM), demonstrating remarkable advances in capability and precision. This recent progress in manufacturing technologies enables the fabrication of advanced materials with highly sophisticated geometries such as metamaterials and lattice-structured materials [1, 2], smart functional materials [3–5], and even structures with graded properties [6]. These progresses then facilitated structural optimisation, light-weighting [7], repair, re-manufacturing [8], and recycling that caused a reduction in material waste and improved sustainability [9], which were unachievable for a long time through traditional manufacturing processes.

These innovations in manufacturing not only revolutionised the fabrication of single material components such as metals and polymers but also opened new opportunities in the manufacturing of multi-material components such as composite materials. A composite material is a composition of two or more materials that are identified with different physical and chemical properties and are combined and distributed in a certain ratio and pattern. For the category of reinforced composites, these constituent materials are generally identified in two classes: matrix material and reinforcements. As the name suggests, the matrix forms the continuous phase that shapes the component, binds and protects the reinforcement, and transfers loads between reinforcement elements. The reinforcement is the main load-bearing element and can be incorporated as particles, short fibres, continuous or long fibres, and laminate or sandwich layers. It significantly influences the stiffness and strength of the material and can also produce anisotropic behaviour, improved thermal or electrical conductivity, and improved dimensional stability, depending on its type, architecture, and volume fraction [10, 11].

The fibre-reinforced polymeric (FRP) composite is one of the significant categories of composite materials for industrial applications. They can be distinguished on the basis of several factors aligned directly with their constituent properties. Such distinctions can be identified in terms of material selection, functionality, production feasibility, and mechanical characteristics [12]. For example, the matrix material binds the fibres together, protects them from environmental damage, and contributes significantly to the thermal or chemical properties of FRP composites. The most commonly used matrix materials for FRP composites are epoxy resins, unsaturated polyesters (UP), vinyl ester resins, and phenolic resins as thermosetting materials and polypropylene (PP), polyamide (nylon; e.g., PA6, PA66), polycarbonate (PC), polyether-ether-ketone (PEEK), polylactic acid (PLA), and polyethylene terephthalate glycol-modified (PETG) as thermoplastics. Furthermore, fibres in an FRP composite have the primary role of a load-bearing element within the material domain and contribute significantly to the stiffness and strength of the polymeric composite. Some of the commonly used reinforcement fibre materials are carbon fibres (short or continuous); glass fibres (E-glass, or S-glass); basalt fibres; aramid fibres such as kelvar and Twaron; and natural fibres such as jute, flax, hemp, sisal, and even bamboo [13–17].

When it comes to the functionality of the composite, some of the features facilitated by reinforcement fibres are high strength, thermal conductivity, electrical conductivity, and directional property enhancements. Recent attempts to combine these features with the distinct properties of matrix materials result in the creation of various novel types of advanced composites, each exhibiting a range of functionalities that do not exist in traditional materials. For example, by accommodating the usage of shape memory polymers (SMP) as matrix materials, novel structural 4D-printed composites are manufactured [18–21]. Furthermore, from a manufacturing point of view, the materials used for composite manufacturing would significantly affect the manufacturing process. For example, for additive manufacturing of polymeric composites, the printability of the constituents should be compatible with the material feeding, deposition, adhesion, and polymerisation processes.

Among reinforced composites, the continuous fibre-reinforced polymer (CFRP) composite is a type of FRP composite materials which have a reinforced polymer matrix by continuous or long fibre filaments and result in anisotropic behaviour of the material. The speciality of continuous fibre over short is its ability to significantly enhance the mechanical properties of the composite such as high tensile stiffness and strength, fatigue resistance, efficient load transfer, and weight reduction. Typically, since the highest values of tensile strength and stiffness are exhibited in the direction parallel to the orientation of the fibre [11], characterising the orientation of the fibres is a crucial element of the design considerations for these composites. However, the traditional manufacturing methodologies used for the synthesis of CFRP composites have incorporated practical limitations on tailoring the orientation of fibres, especially in the local domain, and as a result are considered to be an area of research in recent years.

Some of the conventional manufacturing methods for CFRPs include hand lay-up, filament winding, compression moulding, pultrusion, prepreg out-of-autoclave curing, resin transfer moulding, autoclave moulding, wet lay-up with vacuum bagging, and automated fibre placement [12]. Due to the nature of these processes, fibres are introduced mainly as fabrics, tapes, or tows with predefined architectures and consolidated onto a tool surface. As a result, changing fibre direction typically requires cutting and stacking discrete plies or steering tows along the toolpath. These operations are negatively constrained by drape or shear limits, wrinkling or bridging possibilities, special tooling and curing requirements, which restrict the implementation of local orientation of fibres. Therefore, achieving continuously varying fibre paths or truly free-form local fibre steering is a challenge in conventional CFRP manufacturing, particularly for complex geometries.

These limitations adversely affect the structural integrity of the material and/or limitations in achieving the required performance from the composite design process [22]. Compared with these conventional technologies, the additive manufacturing of CFRP composites stands out by its flexibility and freedom in manufacturing, and the hope to tackle the gaps of traditional manufacturing techniques. Because of its capacity in fibre placement at user-defined targets and the possibility of multidirectional anisotropy, design considerations can be allocated to local material points within the components. Furthermore, it predominantly alleviates the need for post-processing of the fabricated component by directly fabricating the final geometry of the components. However, there are still several manufacturing challenges in the additive manufacturing of CFRP composites that require research attention in order to make these technologies suitable for industrial applications, and in this review paper, we aim to highlight these challenges.

Although additive manufacturing technologies for composite materials have been available for the past decade, there are still several gaps that need further investigation and research. Some of the fields to be addressed include optimisation of printing parameters, which enhance structural integrity, material compatibility studies that can provide various functionalities, recyclability, and re-manufacturing and new standardised testing methodologies for 3D-printed composites. The other major gaps are the lack of enough experimental knowledge about the properties of additive manufactured CFRP composites and the gaps in the development of advanced simulation models, which encompass the standardisation of fibre orientation in 3D-printed continuous fibre-reinforced composites.

To make these gaps easier to follow, this review is organised using a process–structure–property view of additive manufactured CFRP composites. In other words, we first look at how the manufacturing and tool-path choices (such as deposition temperature, consolidation/compaction, and fibre placement strategy) shape the microstructure and typical process-induced defects (e.g. voids, interfacial quality, fibre waviness, and discontinuities between rasters). Then those features are used to investigate the mechanical response, including anisotropy and variation, which are often reported in studies. Thus, we discussed what level of modelling and experimental validation is available, ranging from analytical and homogenisation approaches to filament scale FEM and data-driven models. Furthermore, we tried to make a link between testing consistency and standardisation, as prerequisites toward reliable design allowable, and ultimately, certification. With this structure, this review connects manufacturing routes to measurable structure and performance, and then to modelling approaches and indicators of industrial readiness.

This review aims to provide comprehensive insight into current trends and advances in the fast-growing field of the additive manufacturing of continuous fibre-reinforced composites and compare them with conventional methodologies. In this study, we have reviewed the literature published in the last decade, reflecting the rapid growth period in the additive manufacturing of CFRP composites. We also explored design considerations, mechanical characterisation methods, and numerical simulation techniques, contributing to the development of guidelines for fibre orientation to ensure optimal performance and consistency of 3D-printed CFRP composite materials. In addition, we will explore the applications of 3D-printed continuous fibre composites in various industries and review existing studies on the recyclability of these materials. Despite rapid advances in fused filament fabrication (FFF) for additive manufacturing of continuous fibre composites, optimising the fibre orientation remains critical and currently lacks a standardised procedure. This review also aims to guide the reader through the methodologies and processes essential to developing a standardised procedure to optimise fibre orientation that will enable full utilisation of this technology, unlocking new possibilities in the field.

The structure of this review paper is as follows: Section 2 represents a review of additive manufacturing technologies for the fabrication of CFRP composites compared with conventional methods, Sections 3 and 4 comprehensively review the characterisation of 3D-printed CFRP composite materials and the numerical simulations and computational frameworks for these materials, respectively. Thus, the applications of 3D-printed CFRP composites and their acceptability in industrial applications are reviewed in Section 5, and the sustainability and end-of-life pathways of these composites are explored in Section 6. Finally, based on all the limitations, challenges and potentials of this fast-growing manufacturing technology, the future directions and the areas that need further research are discussed and concluded in Section 7.

2 | Additive Manufacturing Technologies for CFRP Composite Materials

To investigate recent advances in additive manufacturing technologies for the fabrication of continuous fibre-reinforced polymer (CFRP) composites, it is necessary first to briefly review the conventional manufacturing methods that have been historically employed in this field. This will provide the foundation for understanding the evolution of composite manufacturing and will enable a systematic comparison between traditional and emerging approaches in terms of material architecture, processing parameters, and the resulting structural performance.

Several traditional technologies are widely adopted in industries for the manufacturing of CFRP composites. These methodologies are commonly used for the fabrication of different composites with various matrices and reinforcements. Some of the commercially adopted technologies include, but are not limited to: Wet Lay-up, Resin Transfer Moulding (RTM), Prepreg Lamination in an autoclave, Filament Winding, Pultrusion, and Compression Moulding, as illustrated in Figure 1. As presented in Figure 1a, Wet Lay-up is the most manual process to fabricate composites that involves combining dry fibres and uncured resin in an open mould. Resin transfer moulding (RTM), as shown in Figure 1b, is a process that involves a closed mould and dry fibres or pre-prepared materials that will be soaked in resin. This method could be used for simple composite fabrication as well as advanced out-of-autoclave composite manufacturing for aerospace components. In addition, the prepreg lamination process in an autoclave is schematically presented in Figure 1c, where the prepreg laminates cure under precisely controlled temperature and pressure. Figure 1d–f also demonstrates three other important commercial technologies of filament winding, pultrusion, and compression moulding, respectively, which are used to fabricate CFRP composite tubes and profiles. A comprehensive classification of CFRP manufacturing methods based on various parameters can be seen in Table 1.

Thus, to accommodate the need for a manufacturing technique that provides more freedom to align the fibres in CFRP composites, several innovations and researches have been conducted on additive manufacturing of these specific materials in the last ten years and there are now several technologies available in commercial medium or in research laboratories for this purpose. Some of these techniques are material extrusion (ME)/fused filament fabrication (FFF), laminated object manufacturing (LOM), and automated fibre placement (AFP) [12] as shown in Figure 2. Laminated object manufacturing (LOM), as schematically illustrated in Figure 2a, is a rapid prototyping technique by which several pre-cut adhesive-coated laminates (prepregs) of various contours are stacked on top of each other to form a required shape and then later bonded through the post-processing stage [39]. This is one of the first additive manufacturing processes that has been adopted for the fabrication of CFRP composites. In addition, automated fibre placement, as presented in Figure 2b, uses a robotic arm to deposit CFRP composite layers in a mould. The method could be used to generate semi-complex shapes as the robot arm could deposit the composite layers onto moulds with complex shapes. Finally, in the fused filament fabrication technique (FFF) as shown in Figure 2c, the matrix polymeric material is melted using a heat source and then extruded through a nozzle or orifice to be deposited on a surface and mixed with the continuous fibre deposited to form the added layer. A comprehensive classification of these additive manufacturing technologies for CFRP fabrication can be seen in Table 2.

Each of the additive manufacturing techniques for CFRP composites as presented in Table 2 own different levels of manufacturing maturity and industrial readiness. For example, automated fibre placement is a production-grade, computer-controlled

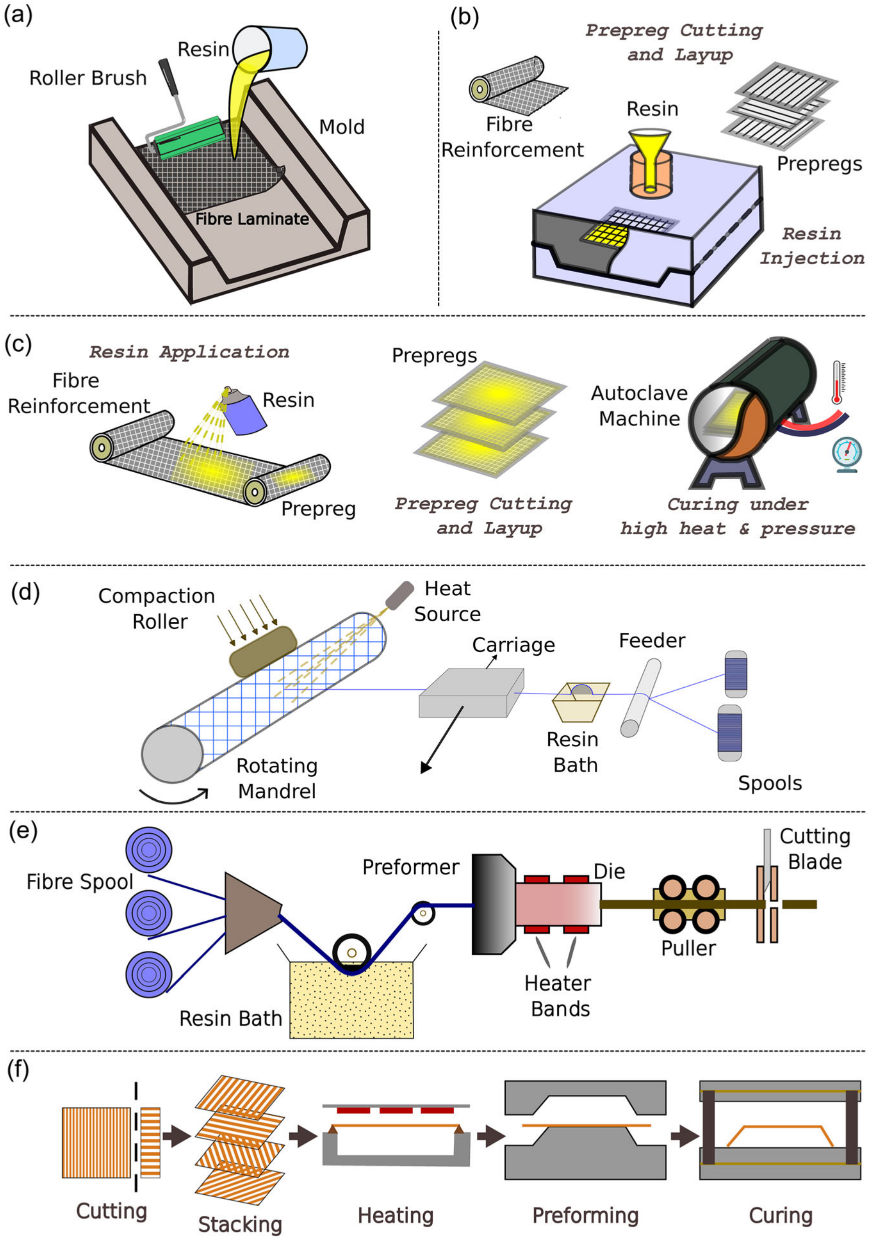

FIGURE 1 | Conventional manufacturing methods for composite materials. (a) Wet layup: manual resin impregnation of dry reinforcement in an open mould. (b) Resin Transfer Moulding: resin injected into a closed mould containing a dry preform. (c) Prepreg Lamination in an autoclave: pre-impregnated plies cured under heat and pressure. (d) Filament winding: continuous tows wound under tension onto a rotating mandrel. Adapted from [23], copyright (2021, The authors and MDPI). (e) Pultrusion: fibres pulled through impregnation and a heated die to form a constant profile. Adapted from [24], copyright (2024, Elsevier B.V.). (f) Compression moulding: plies consolidated in a heated matched-die under pressure. Adapted from [25], copyright (2024, The authors and MDPI).

deposition method with extensive industrial adoption in high-performance composite manufacturing. It is supported by a substantial body of work on process planning, defect formation, in situ inspection, and qualification readiness for safety-critical structures [23, 35, 36]. Sheet lamination approaches, including laminated object manufacturing and ultrasound-assisted laminate bonding, are predominantly at laboratory and pilot scale, and their broader industrial uptake is limited by inter-laminar bonding robustness, processing throughput, and geometric constraints associated with laminate stacking [40, 48, 49]. Material extrusion with continuous fibre co-extrusion has progressed to commercially implemented platforms and is supported by extensive experimental validation. The performance of the material fabricated with this method remains sensitive to fibre impregnation quality, void formation, and attainable fibre volume fraction relative to established prepreg-autoclave routes, which positions the approach between pilot-scale and early industrial adoption depending on the application [41, 42, 50]. Chopped-fibre extrusion and large-format pellet-based deposition are more mature in industrial settings for tooling and large composite structures, where deposition rate, build volume, and cost effectiveness are prioritised over aerospace-grade consolidation and defect control [43]. Powder bed fusion routes that process carbon-fibre-filled thermoplastics are widely used in industrial polymer additive

TABLE 1 | Classification of CFRP manufacturing methods by parameters (traditional/automated lay-up).

Method	Matrix	Impregnation (class)	Mechanism	Tooling needed/ post-processing	References
Traditional/automated lay-up					
Hand lay-up + vacuum bagging	Thermoset	IN SITU	Chemical curing	Tooling required/ thermal treatment, machining	[26]
Prepreg (autoclave)	Thermoset	Pre-impregnated	Chemical curing	Tooling required/ pressure-cure, machining	[27]
Prepreg (OOA oven)	Thermoset	Pre-impregnated	Chemical curing	Tooling required/ thermal treatment, machining	[28]
Resin transfer moulding (RTM)/vacuum-assisted RTM (VARTM)	Thermoset	IN SITU	Chemical curing	Tooling required/ thermal treatment, machining	[29]
Compression moulding	Thermoset	Pre-compounded chopped	Chemical curing/thermal fusion	Tooling required/ machining	[30]
Thermoplastic laminate consolidation/hot press	Thermoplastic	Pre-impregnated	Thermal fusion	Tooling required/ machining	[31]
Thermoforming/stamp forming	Thermoplastic	Pre-impregnated	Thermal fusion	Tooling required/ machining	[32]
Filament winding (wet/ towpreg)	Thermoset/ thermoplastic	IN SITU/pre-impregnated	Chemical curing/thermal fusion	Tooling required/ pressure-cure	[23]
Pultrusion	Thermoset/ thermoplastic	IN SITU/pre-impregnated	Chemical curing/thermal fusion	Tooling required/ minimal finishing	[33]
Automated tape laying (ATL)	Thermoset	Pre-impregnated	Chemical curing	Tooling required/ pressure-cure, machining	[34]
Automated fibre placement (AFP, thermoset)	Thermoset	Pre-impregnated	Chemical curing	Tooling required/ pressure-cure, machining	[35]
Automated fibre placement (AFP, thermoplastic) laser/IR-assisted	Thermoplastic	Pre-impregnated	Thermal fusion	Tooling required/ machining	[36]
Tailored fibre placement (TFP) + infusion	Thermoplastic	IN SITU	Chemical curing	Tooling required/ thermal treatment	[29]

manufacturing for repeatable production of discontinuously reinforced composite components with good dimensional stability. These processes therefore form an established industrial baseline for carbon-fibre-filled polymer parts rather than continuous-fibre architectures [44]. Vat photopolymerisation with filled resins has also reached industrial deployment for high-resolution polymer components, although reinforcement is typically discontinuous and continuous-fibre load paths are uncommon in these systems [45]. Emerging routes that enable true 3D fibre steering, such as CF3D and nonplanar robotic deposition of thermoplastic continuous fibre, remain at early maturity. Current studies focus on in situ heating, compaction, and process control to improve consolidation consistency and to build the evidence base required for qualification and scalable production [46, 47].

To provide a concise baseline for the discussion, Table 3 summarises key differences between conventional CFRP manufacturing processes and AM-based methods for fabrication of CFRP composites. The comparison covers parameters that directly influence manufacturing feasibility and performance, including fibre orientation/steering capability, achievable fibre volume fraction, dominant defect mechanisms, tooling requirements, scalability/automation, geometric complexity, and industrial readiness level. This summary clarifies the motivations for AM (toolpath-driven fibre placement) while also highlighting current limitations (consolidation quality, defect variability, and qualification readiness). The detailed process classification frameworks for conventional and additive routes are then presented in Tables 1 and 2, respectively.

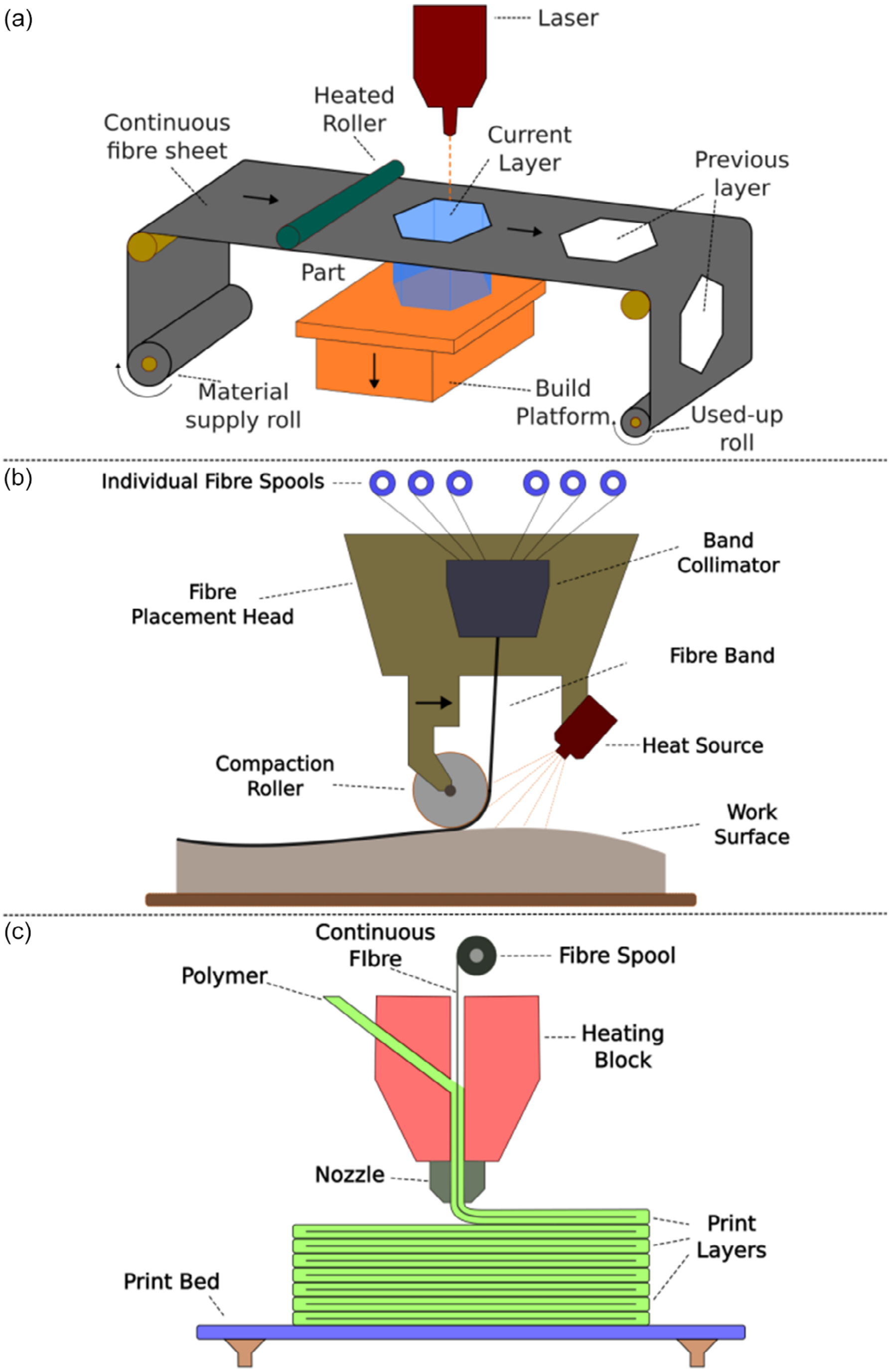

FIGURE 2 | Additive manufacturing methods used for fabrication of CFRP composites: (a) Laminated object manufacturing (LOM). Adapted from [37], copyright (2017, Elsevier Ltd.). (b) Automated fibre placement (AFP). Adapted from [38], copyright (2021, Elsevier Ltd.). (c) Fused filament fabrication (FFF).

2.1 | Parameters Governing CFRP Additive Manufacturing

To better understand the new domain of CFRP additive manufacturing, it is essential to first describe the key parameters that influence these technologies. In fact, it is an interrelated domain that influences the selection of materials, structure, process, and hardware. For example, a material compatible for a specific manufacturing process might not satisfy the proposed structural demands of the composite or vice versa. Therefore, the governing parameters, as summarised in Table 4 and comprehensively evaluated in this section, are material selection for matrix and reinforcement, structural patterns, pre-processing, and fabrication hardware.

2.1.1 | Material Selection for Matrix and Fibre

When it comes to material selection, the printability of the material is a primary factor which will influence the process design aspect. The term printability refers to the smooth carriage of the material through the hardware system of the printer from material loading to the print site, and then embedding the

TABLE 2 | Classification of CFRP manufacturing methods by parameters (additive manufacturing).

Method	Matrix	Impregnation (class)	Mechanism	Tooling needed/post-processing	References
Additive manufacturing (AM)					
Laminated object manufacturing/sheet lamination	Thermoset/ thermoplastic	Adhesive lamination/pre-impregnated)	Adhesive/ chemical bonding	Flat bed/machining	[40]
Fused filament fabrication (FFF) co-extrusion	Thermoplastic	IN SITU	Thermal fusion	Flat bed/thermal treatment, machining	[41]
FFF/FGF (Fused granular fabrication) chopped carbon fibre	Thermoplastic	Precompounded chopped	Thermal fusion	Flat bed/minimal machining	[42]
Large-format AM/big area AM, pellet)	Thermoplastic	Precompounded chopped	Thermal fusion	Flat bed/machining	[43]
Selective laser sintering (SLS)/ multi jet fusion (MJF, CF-filled)	Thermoplastic	Precompounded chopped	Thermal fusion	Flat bed/surface machining, thermal treatment	[44]
Stereolithography (SLA)/digital light processing (DLP, filled resins)	Thermoset	Predispersed fillers)	Ultraviolet/ electron beam	Flat bed/post-cure, machining	[45]
Continuous Fibre 3D (CF3D) UV-curable continuous fibre	Thermoset	IN SITU	Ultraviolet	Flat bed/post-cure	[46]
Robotic multi-axis thermoplastic continuous fibre	Thermoplastic	IN SITU/pre-impregnated	Thermal fusion	Tooling/flat bed/ thermal treatment	[47]

material to the print bed layer by layer. Furthermore, the mechanical, electrical, thermal and chemical properties of both the fibre and matrix materials are taken into account to produce the desired functionality of the CFRP composite. As stated previously, the main strength element of the composite is contributed by the fibre reinforcement material, where the matrix material makes the most volume of the composite. The ideal concept of reinforcing instead of using the stronger material for the entire composite refers back to the idea behind the composites itself, which is the use of different properties of two materials to satisfy a specific functionality. For example, here the point of interest can be the material property of the matrix material, which lacks structural strength, and that can be provided by the fibre material being embedded within the matrix. In addition, the point of interest can be the material property of the fibre material that lacks in flexibility and volume (limited by a high cost), which could be resolved by the addition of matrix material around it. The arrangements can be done in infinite ways as per the user requirements, and there is no requisite for a specific material to be used only as reinforcement or matrix. Table 5 summarises the practical criteria used to select matrix material and continuous fibre reinforcement for additive manufactured CFRP composites, considering both processing constraints and performance goals.

Some commonly used reinforcement materials are fibres of carbon, Kevlar, glass, and natural fibres. Continuous carbon fibre is the most widely used reinforcement in additive manufactured CFRP due to its high stiffness and thermal stability. However, printability depends on the matrix-specific sizing of the fibre that promotes fibre impregnation and interfacial bonding in extrusion or UV-curing-based routes [41, 79–81]. Glass fibre is known for its reliability with thermoplastics such as PA and PETG and is cost-effective. Although the fibre itself is not hygroscopic, the moisture in the polymer feedstock and 3D-printed parts must be controlled to avoid porosity and property loss [42, 82, 83]. Aramid fibre (Kevlar) offers low density and high impact resistance, but can exhibit weaker adhesion to the fibre matrix without a tailored size or surface activation, which may reduce interlaminar strength compared to carbon or glass fibres [56, 83, 84]. Natural fibres (e.g. flax, jute) have lower thermal stability and higher moisture uptake; therefore, they pair best with low-temperature thermoplastics (PLA, TPU) or photo-curable resins and benefit from pre-drying and simple surface treatments (e.g. alkali/silane) to improve bonding [85, 86]. Chopped carbon-fibre or glass-fibre feedstocks can enhance stiffness and dimensional stability in extrusion-based processes but provide limited load transfer compared with continuous fibres due to orientation and interfacial constraints [42]. In general, reinforcement printability is governed by the compatibility between the sizing of the fibre and the chemistry of the matrix, the thermal stability in the chosen process, the moisture control, and the ability of the process to achieve sufficient impregnation and consolidation at the fibre scale [41, 79]. The key reinforcement fibres employed in additive-manufactured CFRP composites, together with their main advantages and disadvantages, are outlined in Table 6.

The fibres could also be categorised based on their states and whether they are treated or not. The treated fibre has undergone treatment processes that include chemical or physical modifications. These modifications add additional features to the fibres such as strength, adhesion, alteration in the crystalline structure, addition of a protective layer, hydrophobic nature, thermal resistance, etc. [87–90]. One of the common treatment on long fibres

TABLE 3 | Comparison between conventional CFRP manufacturing processes and AM-based methods for fabrication of CFRP composites.

Comparison dimension	Conventional CFRP (e.g. lay-up, RTM, prepreg, winding, pultrusion, AFP/ATL)	AM-based CFRP (e.g. material extrusion co-extrusion, CF3D, robotic deposition, lamination)
Conventional vs. additive CFRP fabrication		
Fibre steering/local orientation control	• Ply-based architecture (discrete layup angles) • Local steering constrained by drape/shear and wrinkling risk • Limited by minimum tow radius and tooling/compaction constraints	• Toolpath-driven placement enables higher local tailoring • Constrained by bead width and minimum turn radius • Start/stop events can introduce discontinuities
Achievable fibre volume fraction (FVF)	• Typically high for prepreg/autoclave and optimised RTM • Mature process control supports repeatability	• Often moderate and process-dependent • Limited by impregnation/consolidation and print architecture
Dominant defect mechanisms	• Infusion-related voids and resin-rich zones • Ply waviness and wrinkling/bridging • Generally mature defect control at production scale	• Inter-bead porosity and imperfect impregnation • Fibre waviness at turns and raster discontinuities • Higher variability reported across studies/routes
Tooling dependence	• High reliance on moulds/tools • Consolidation infrastructure (pressure/temperature control) required	• Lower tooling for near-net shapes • Fixtures and post-processing may still be required (route-dependent)
Geometric complexity/part integration	• Complex parts feasible but often require complex tooling • Design changes can be costly (tooling/layup changes)	• High geometric freedom and potential for functional integration • Near-net fabrication achievable for selected architectures
Scalability/automation	• High automation possible (e.g. AFP/ATL) • Still ply/tow deposition onto tooling; changeover can be intensive	• Digitally driven workflows enable rapid iteration • Scalability depends on process class (e.g. LFAM vs. precision deposition)
Surface finish/dimensional accuracy	• Typically better and more consistent for production tooling routes • Established finishing practices	• Often lower as-printed finish • Machining/finishing may be needed to meet tolerances and surface quality
Qualification/certification maturity	• High maturity with established allowables and certification pathways • Broad industrial experience for many applications	• Emerging qualification readiness • Limited by variability, defect control, and evolving standardisation

that is used in the additive manufacturing of CFRP composites is the impregnation of fibres.

The impregnation of fibres generally refers to the incorporation of a polymer material into the fibre arrangements to facilitate the manufacturing of a CFRP composite. It is the infusion of a resin or plastic material (can be the same as matrix material or not) into the gaps between fibres inside a strand or filament, in a controlled and fixed ratio that would not affect the matrix material distribution in the composite. This impregnation process can be performed before the main manufacturing step referred to as pre-impregnation [91] or it could be performed during the manufacturing process named co-extrusion technique [92]. Furthermore, impregnation could also be implemented through the use of commingled fibres where polymer strands are placed along the reinforcement filaments and bonds together during the time of extrusion [93]. These three types of fibre impregnation are illustrated in Figure 3. These impregnation materials can be partially or fully cured at the infusion stage and then later undergo post-processes. The main uses of impregnating fibres include (i) the precise distribution of the fibre strands according to the design when laid by the print head, (ii) better adhesion properties, and (iii) uniform load transfer among the fibres. As these fibres are very flexible, there is a high chance of forming clumps while printing, and the pre-impregnation helps in steady layup of the fibre. In addition, it also helps to smooth and clean fibre handling throughout the printing process. It also adds a layer of protection to the filaments from environmental and mechanical damage that can occur while handling. Meanwhile, it also reduces the interfibular friction within the reinforcement and to some extent augments the mechanical properties of the fibre. The different pre-impregnated fibres available commercially are carbon, fibreglass, and Kevlar with a common resin substrate such as polyamide or epoxy [94–96].

The counterpart of the fibre is the matrix material that provides support and creates an environment for the placement of reinforcement fibres. It is in some ways similar to the support structure that is used in 3D printing of over-hanging parts but not removed upon the completion of the printing process. Instead, in CFRP composites, the matrix materials contribute to some of the key functionalities of the composite in the application environment. The major factors influencing the selection of matrix materials are the thermal, physical, and chemical properties of the material in conjunction to its suitability with the adopted reinforcement fibre. As it encompasses and surrounds the fibres

TABLE 4 | Design aspects with influencing factors in additive manufacturing of CFRP.

Aspect	Type	Influencing factors
Material selection of matrix and fibre	Matrix selection [51, 52]	Thermal
		Physical
		Chemical
	Reinforcement selection [13, 16, 53–56]	High strength
		Electrical conductivity
		Thermal conductivity
Structural design strategies for fibre infills	Cellular design [57–61]	Cell shapes
		Spatial arrangement
		Cell geometry parameters
	Topological design [62–70]	Design material distribution
		Process planning
Manufacturing process considerations	Preparation	Digital modelling
		Material preparation
	3D printing	Layer by layer deposition
		Parameter control
	Post-Processing	Surface machining
		Curing
	Parameter optimisation [48, 71–78]	Nozzle temperature
		Filament feed rate
		Fibre tension
		Printing speed
3D printing hardware considerations	Single nozzle	Separate material placement
		In situ fibre placement
	Multinozzle	Layered nozzle systems
		Multihead nozzle systems
	Degree of freedom	Three-axis system
		Multi-axis system

from all directions, from the structural point of view it acts as a load transferring medium from external agencies to the fibres. In addition, it also protects the fibres from being prone to other conditions such as moisture, impact, and other chemical reactions. The other aspect of the matrix material is that it generates a bonding surface for the reinforcement fibre which would help to maintain the structure and alignment of the fibre in place within the composite; otherwise, it would have been affected under loading conditions due to the flexible and delicate nature of it.

Matrix materials that are commonly used in additive manufactured CFRP include polyurethanes (TPU), polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), nylon, polyethylene terephthalate glycol (PETG), polyether-ether-ketone (PEEK), onyx, polyetherimide (PEI; e.g.-ULTEM 9085), and epoxy [12]. Low-temperature thermoplastics such as PLA and PETG are readily printable and form reliable interlayer bonds, but their service temperature is limited. ABS and PC offer greater heat resistance and toughness; however, they are prone to warpage, which can be mitigated by enclosed heated build chambers [42]. Nylon (PA) provides good strength and toughness, but is highly hygroscopic and therefore requires thorough drying of the feedstock (and fibres) to avoid porosity and weak interlayer interfaces [82]. TPU processes at relatively low temperatures with good adhesion, although its low modulus can complicate dimensional control and fibre placement [42]. High-temperature matrices such as PEEK and PEI/Ultem deliver superior thermal and mechanical performance, but require high nozzle and chamber temperatures and often supplementary laser/IR heating to achieve complete fibre impregnation and interfacial bonding [97, 98]. Chopped carbon-fibre filled PA (e.g. Onyx) prints similarly to PA but with increased stiffness and is often used as a base for embedding continuous fibres [56]. Epoxy/UV-curable systems can be deposited at room or moderate temperatures and then post-cured to reach final properties [46]. Across all matrices, printability is governed by the available thermal processing window, the viscosity of the melt and the impregnation behaviour of the fibre, moisture management (particularly for PA), and sufficient process energy to minimise voids and achieve robust interlayer strength [42]. Table 7 summarises the commonly used matrix materials in additive-manufactured CFRP composites along with their key advantages and disadvantages.

TABLE 5 | Selection guidelines for matrix and continuous-fibre reinforcement in additive manufactured CFRP composites.

Selection criterion	Matrix selection (thermoplastic/thermoset)	Reinforcement selection (continuous fibres)
Printer/process capability	• Choose matrix by process class (thermal fusion vs. UV/chemical cure) • Limited nozzle/chamber temperatures: use lower-melt matrices (e.g. PA, PLA, PETG) • High-temperature hardware available: use high-performance thermoplastics (e.g. PAEK-family)	• Match continuous tow feed to the route (co-extrusion, on-tool placement, etc.). ' • Tight radii and frequent start/stop increase waviness and discontinuities
Service temperature and chemicals	• High temperature/harsh chemicals: select thermally/chemically stable matrices • General-purpose environments: engineering thermoplastics may suffice	• Carbon fibre supports stiffness retention at elevated temperatures (architecture-dependent) • Ensure fibre/matrix compatibility for wetting/impregnation and interface integrity
Moisture sensitivity and porosity	• Hygroscopic matrices (e.g. many PAs): dry and store properly to reduce porosity • If dimensional stability matters: prefer lower-moisture-uptake matrices	• Moisture + poor consolidation increases inter-bead porosity and interface variability • Prefer fibre/matrix pairs with proven bonding and stable load transfer
Stiffness/strength priority	• Use matrices that enable strong load transfer and reliable consolidation • Ensure bonding in the processing window (critical for continuous fibre)	• Continuous carbon fibre for maximum stiffness/strength • Fibre sizing/chemistry controls interface quality and realised strength
Impact/toughness priority	• Prefer toughened/ductile matrices for energy absorption • Anneal/post-cure if required (route-dependent)	• For impact-critical parts, reduce waviness and improve interlaminar integrity • If aramid is used, manage interface/bonding (sizing/surface treatments may be needed)
Cost/availability	• Commodity/engineering matrices reduce cost • High-performance matrices raise cost and require high-temperature hardware	• Carbon fibre: higher performance, higher cost • Glass fibre can reduce cost where conductivity is not required and stiffness targets are moderate
Functional/multifunctional targets	• Keep processability when adding functional additives (viscosity/curing/flow) • Use matrices compatible with hybrid architectures when needed	• Continuous carbon fibres may enable electrical/thermal functionality (route-dependent) • Hybrid continuous-fibre strategies can tailor properties but increase complexity
Recyclability and end-of-life	• Thermoplastics offer more direct remelting/reprocessing pathways than thermosets • Consider separation and reuse constraints when selecting matrix type	• Continuous fibres are difficult to recover intact; prioritise reuse/re-manufacture • Many recycling routes disrupt fibre continuity,limiting direct re-use as continuous reinforcement

The performance of CFRPs depends not only on the intrinsic properties of the fibres and matrix but also on the compatibility between them. Effective fibre-matrix adhesion ensures efficient load transfer, maintains fibre alignment, and prevents premature de-bonding or fibre pull-out under service conditions. This compatibility is typically achieved through surface treatments or fibre sizing designed to improve wettability with the chosen resin system. In additive manufacturing of CFRPs, for example, post-print epoxy infusion has been shown to significantly enhance fibre impregnation and interfacial bonding in curved printed structures [99]. Similarly, plasma oxidation and sizing treatments increase the surface activity of carbon fibres, improving adhesion to thermoplastic matrices during 3D printing [100]. More recently, graphene-enhanced epoxy prepregs have demonstrated improved interlayer bonding and compatibility in Additive manufactured CFRP laminates [101]. Furthermore, thermal–mechanical compatibility is equally important, as mismatched coefficients of thermal expansion between the fibres and the matrix can induce residual stresses and microcracks during curing or in service, which can reduce the durability and performance of 3D-printed composites [95].

Another significant parameter in material selection, especially for matrix material, is the post printing process of the composite. This mainly contemplates how the matrix material cures to attain its structural integrity after the printing process. From the polymeric materials perspective, thermoplastics are materials that soften and melt upon application of heat and solidify upon cooling, as seen in the fusion deposition modelling process. These polymers are known for their flexibility, and this is also a reversible process, but the quality of the polymer could degrade. Meanwhile, thermosetting polymers follow an irreversible process. They are mostly available in liquid and powder forms

TABLE 6 | Commonly used reinforcement fibres in additive-manufactured CFRP composites.

Reinforcement material	Type	Advantages	Disadvantages
Carbon fibre	Synthetic fibre	High stiffness and tensile strength; excellent thermal stability; well-suited for continuous fibre extrusion and UV-curing routes	Requires matrix-specific sizing for proper impregnation; high cost compared to glass or natural fibres
Glass fibre	Synthetic fibre	Cost-effective; reliable with thermoplastics such as PA, PETG; good strength and chemical resistance	Sensitive to moisture in polymer feedstock; void formation if drying not controlled
Aramid (Kevlar)	Synthetic organic fibre	Low density; excellent impact and abrasion resistance	Weaker interfacial adhesion without tailored sizing or surface activation; reduced interlaminar strength compared to carbon or glass
Natural fibres (e.g. flax, jute)	Biobased fibre	Low cost; renewable; compatible with low-temperature thermoplastics (PLA, TPU) or photo-curable resins	High moisture absorption; low thermal stability; needs pre-drying and surface treatments for bonding
Chopped carbon or glass fibres	Short, discontinuous fibres (filler)	Enhances stiffness and dimensional stability in extrusion-based printing	Limited load transfer; poor fibre alignment; weaker interfaces than continuous fibres

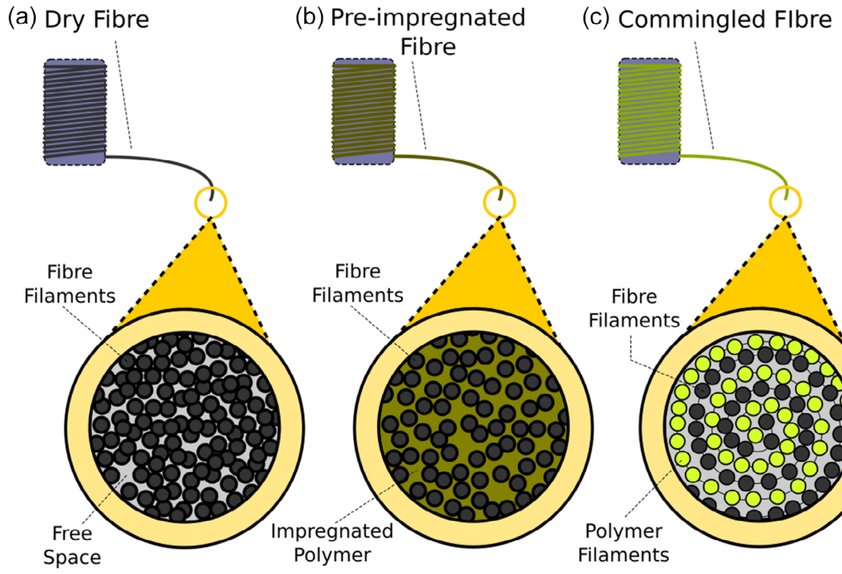

FIGURE 3 | Different types of feed-in fibres used in CFRP manufacturing: (a) dry fibre, (b) pre-impregnated fibre, and (c) commingled fibre.

and specifically need a curing process that solidifies and tempers to a rigid and infusible structure following the process. This makes the thermosetting material suitable for high strength and thermal applications. Therefore, because of their powdered or liquid form, the thermosetting polymers are used mainly for selective laser sintering (SLS) and stereolithography (SLA) processes. The curing of the material can either happen completely during the laser sintering or partially, which will again need a post-sintering process in the case of SLS. When it comes to SLA, curing is facilitated by the application of ultraviolet light on the thermoset resin. The continuous fibre manufacturing through SLS is at a very immature stage, but efforts are put into retrofitting an additional fibre laying component or use of prepreg sheets integrated into the powder bed. Prepreg sheets or dispersed continuous fibres within the resin are the methods adopted in SLA. However, both methods are limited by their inability to generate complex structures as well as their inefficiency in fibre steering.

2.1.2 | Structural Design Strategies for Fibre Infills

As discussed earlier, reinforcement fibres provide the major source of structural strength of CFRP composites. Meanwhile, additive manufacturing technology offers the exceptional advantage of a free-form methodology that can benefit the placement of fibres within the component and, as a result, provides the opportunity for structural improvisation. This has led to the freedom of adapting various design configurations in the structural aspect, such as cellular design and topological design. The cellular structural design contemplates the arrangement of cells (where fibres form the beams or boundaries of the cell) and pores (the space

TABLE 7 | Commonly used matrix materials in additive-manufactured CFRP composites.

Matrix material	Type	Advantages	Disadvantages
PLA	Thermoplastic	Low cost; easy printability; good interlayer bonding	Low service temperature; brittle; poor toughness
PETG	Thermoplastic	Good adhesion; low warpage; transparent grades available	Limited high-temperature performance
ABS	Thermoplastic	Higher heat resistance; reasonable toughness	Warping and shrinkage; requires heated chamber
PC	Thermoplastic	Excellent strength and thermal stability	High viscosity; prone to warpage; poor flow
Nylon (PA6/PA12)	Thermoplastic	Good toughness; impact and fatigue resistance	Highly hygroscopic; needs drying to prevent voids
TPU	Thermoplastic elastomer	High flexibility; good interlayer adhesion	Low modulus; poor dimensional stability
PEEK	High-performance thermoplastic	Superior strength, stiffness, and heat resistance	Requires high nozzle and chamber temperature; difficult impregnation
PEI (Ultem)	High-performance thermoplastic	Excellent thermal stability; high modulus	Expensive; processing challenges similar to PEEK
Onyx (PA + short CF)	Composite thermoplastic	Increased stiffness; compatible with continuous fibre reinforcement	Limited elongation; anisotropic surface finish
Epoxy/UV-curable	Thermoset	Excellent adhesion; low printing temperature; tuneable cross-linking	Requires post-curing; relatively brittle compared to thermoplastics

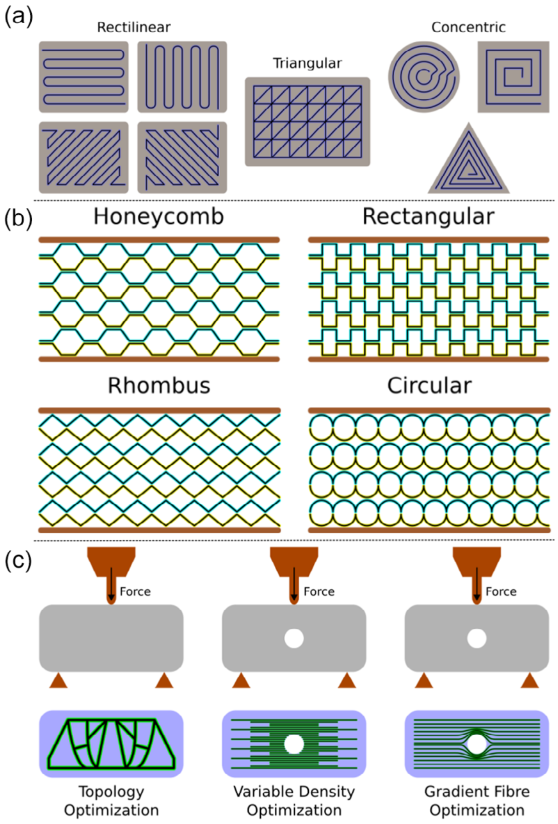

FIGURE 4 | Different structures in CFRP: (a) infill patterns, (b) cellular structures, and (c) topological designs.

formed between the cells forming interconnected voids), which follows a pattern. In cellular structural design, the underlying factors are the number of layers, geometrical parameters such as cell length, wall thickness, and beam (fibre) orientation angles. Here, depending on the mechanical advantages of the cells formed, the structural performance of the overall composite is altered. Some of the cellular approaches that can be found in the literature, as well as available 3D printers, are honeycomb, trapezoidal, circle, rhombus, corrugated structures, and other infill patterns such as straight line, contour, zig–zag and hybrid contour [102–106], which are visually presented in Figure 4a,b.

Although cellular and infill-based architectures can achieve favourable stiffness-to-weight ratios by aligning material and fibres along efficient load paths, these advantages come with distinct structural compromises. Decreasing the relative density typically lowers the mass, but it also decreases the ultimate load capacity and damage tolerance, since there are fewer continuous fibre pathways available to resist crack propagation and span defects. For many patterns, overall stiffness is controlled more by bending of the cell walls than by axial stretching, which increases compliance and makes the structure more prone to local buckling under compression. Strength and fatigue resistance may also be constrained by stress concentrations at nodes, corners, and regions where the path turns, as fibre curvature and adjacent resin-rich pockets hinder efficient load transfer. These issues are amplified in additive manufactured architectures because inter-bead interfaces and interlayer bonds can act as preferred failure pathways, especially when the infill pattern causes frequent start/stop points or breaks in continuous fibre deposition. Consequently, cellular and infill architectures should be evaluated as a trade-off between competing objectives, in which improvements in specific stiffness or energy absorption must be weighed against potential losses in strength, fatigue performance, and resistance to impact or delamination.

When we look at the topological design aspect of structural elements, optimising solutions to produce a superior fibre layout is considered the outlier. The topology optimisation process includes two interrelated processes where one is realising parameter values of interest within the structure such as stress levels, displacement, stiffness, and other required mechanical properties, whereas the other is determining the various attributes of matrix and fibres like type, size, shape, and distribution suitable for obtaining the desired performance by the composite. The two processes can be performed sequentially or concurrently, depending on the chosen approach. In topological design, major considerations are given to attributes such as local fibre orientation (straight or curvilinear), parallel or overlapping arrangements, fill densities, and volume fraction. Figure 4c demonstrated the topology optimisation process by controlling the orientation of the fibres as well as the variable density optimisation and the gradient fibre optimisation by controlling the density of the fibres in the local domains of a component. An illustrative example of topology optimisation applied to continuous fibre composites is shown in Figure 5. In this example, Boddeti et al. [107] optimised a plate-with-hole geometry to minimise compliance under load, using both the volume fraction of the fibre and the orientation of the local fibre as design variables. The resulting design exhibits spatially varying fibre densities and smoothly varying orientations, which are then compiled into a set of manufacturable fibre paths suitable for continuous deposition.

In practice, topology optimisation produces continuous spatial fields, such as fibre orientation and local reinforcement density, whereas continuous-fibre additive manufacturing operates with discrete and physically feasible deposition paths. Bridging this gap introduces manufacturability constraints that can shift the final design away from the ideal case. First, fibre paths must comply with geometric limits set by the deposition head, including a minimum turning radius, a finite bead width, and restrictions on overlap and local overfill, all of which cap the attainable local fibre concentration. Second, continuous fibre deposition is highly sensitive to path continuity and the number of start/stop events, since interruptions can cause fibre breaks, resin-rich pockets, and local defects that impair load transfer. Third, the geometry of the part itself introduces process constraints such as access to the layers, allowed overhang angles, and the need for supports that may hinder the placement of curvilinear reinforcements in mechanically critical regions identified by the optimisation. Finally, factors related to consolidation, such as available compaction pressure, thermal history during printing, and quality of impregnation, govern how accurately the intended fibre layout is achieved without porosity or weak bonding between adjacent beads. Consequently, a practical design approach couples topology optimisation with deposition-aware path planning or embeds manufacturing constraints directly into the optimisation problem, ensuring that the resulting fibre layouts are both structurally efficient and physically printable.

2.1.3 | Manufacturing Process Considerations

There are different methodologies that can be adopted in the manufacturing of a continuous fibre reinforced polymer. This includes conventional methods such as resin transfer moulding,

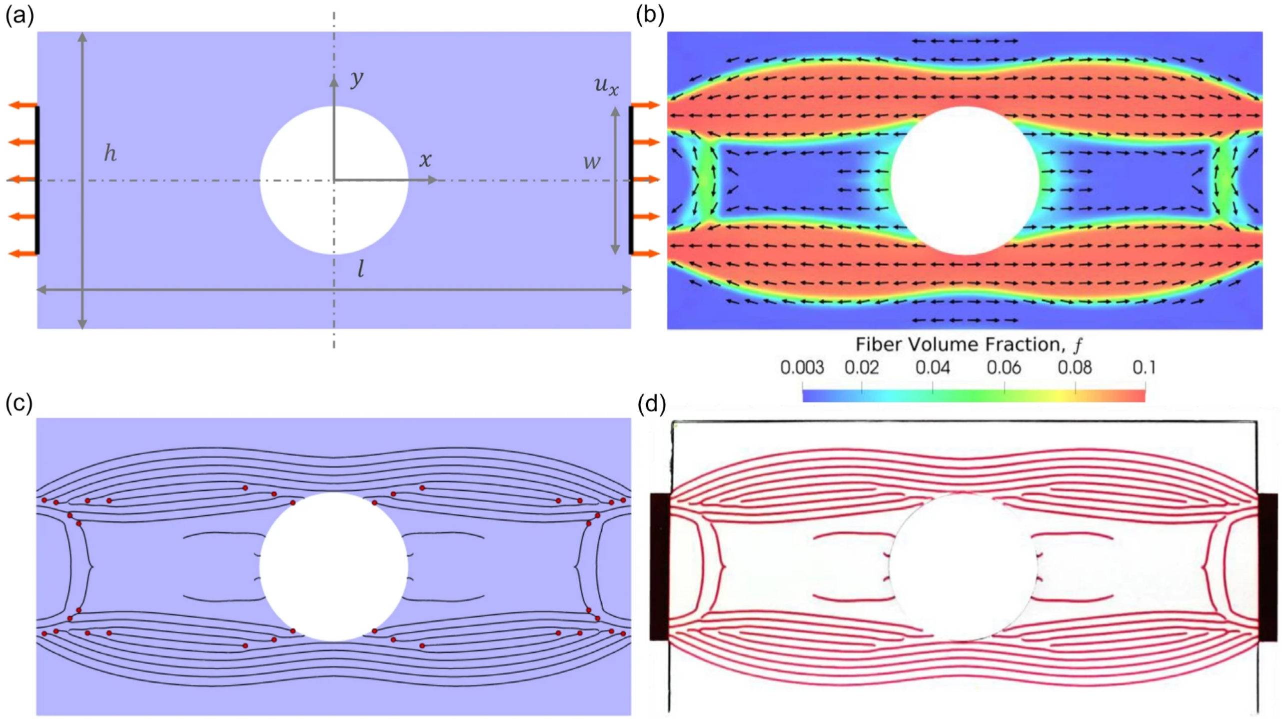

FIGURE 5 | Topology optimisation of a composite plate structure with a hole. (a) Problem setup with the design and geometrical parameters. (b) Optimised design with spatially varying fibre volume fractions and optimised fibre orientations. (c) Results after applying topological optimisation algorithm. (d) Visualisation of the 3D printed sample [107]. Reproduced with permission. Copyright 2020, Springer Nature Ltd.

filament winding, pultrusion, compression moulding, or prepreg-lamination to more advanced techniques such as automated fibre placement and automated tape laying, along with the recent extrusion deposition modelling. The extrusion deposition technique offers flexibility in manufacturing and enables rapid prototyping that eliminates the need for moulds and tooling, which also results in less material waste. However, less precision, lower surface finish, and slower production rate for large-scale production are limitations of the extrusion deposition technique that need to be re-examined in the future. The processes in the modelling of the fusion deposition of a continuous fibre reinforced polymer can be categorised into four different sections, including design, material preparation, 3D-printing, and post-printing, and are illustrated as a step-by-step algorithm in Figure 6.

The initial step of the 3D-Printing process of composite material comprises of digital modelling and material preparation. The digital model defines the geometry, dimensions, and composition of the fibre and matrix material in each layer of the composite. It starts with the creation of a 3D computer-aided design (CAD) model of the component. Then, the CAD model is fed into the slicer, a tool used by the 3D printer to generate the G-codes for the different layers to be printed. The G-codes are then shared with the printer's control system, which will move the print head through the specified location of interest over the print bed. The digital model represents the coordinates for the designed product in a Euclidean space that is then matched to the coordinates of the printed bed. Parameters to be adjusted, such as the fibre layup direction, matrix infill, and their corresponding ratios, are designed and controlled using the built-in software assigned along with the printer used.

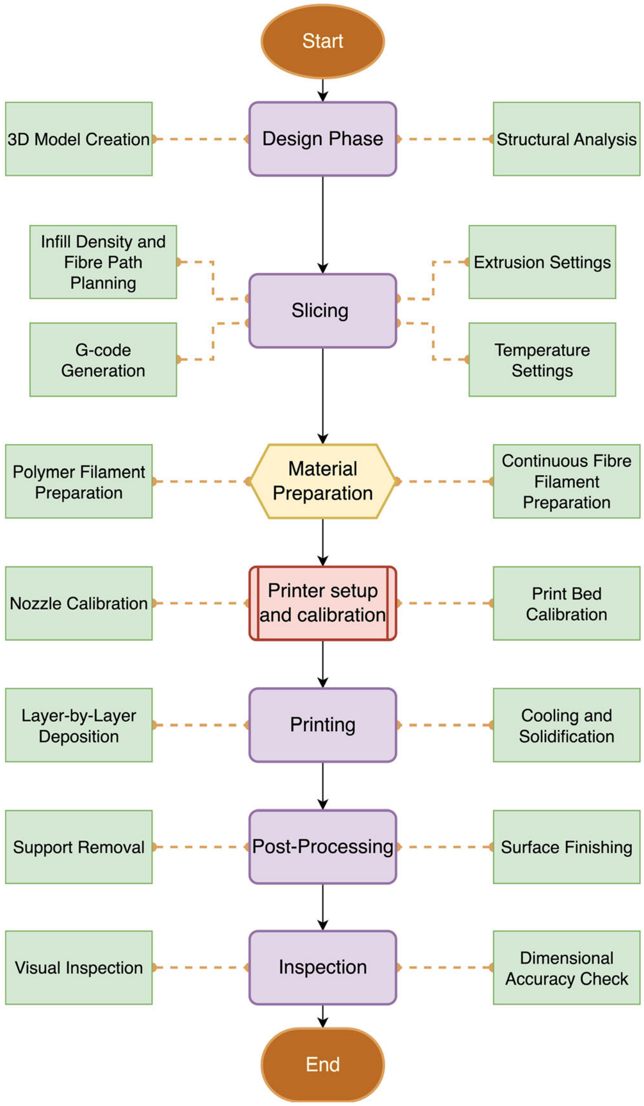

FIGURE 6 | Process flow for fusion deposition modelling of continuous fibre reinforced polymer.

The next step is the preparation of the material, which comprises the preparation of fibre filaments and matrix material compatible with easy passage through the 3D-printing system. As stated in the material selection section, fibre filaments have to be impregnated with resin material for uniform distribution and protection of the fibre filaments when passed through the system. Impregnation can be achieved in different ways [108–112], which can be broadly viewed as interconnected approaches of pre-impregnation and in-situ extrusion mechanisms. An option is to use available stock impregnated filament rovers as feed material or commingled fibres, which already contain the matrix as presented in Figure 7a. The other is the method by which the resin is impregnated in pure fibre material prior to the extrusion process, either inside the nozzle as shown in Figure 7b. Another way of impregnation is possible by deposited fibres and matrix separately and combined directly on the surface of the growing component. This configuration resembles conventional fibre-placement processes and increases machine complexity, since additional axes are needed to coordinate deposition and fibre orientation. Although it enables for embedding in situ, it also carries the highest risk of impregnation defects and adhesion problems between the fibre and the matrix, as shown in Figure 7c.

Several underlying parameters govern the printability of the material, such as nozzle temperature, layer thickness, filament feed rate, fibre tension, printing speed, etc. The set values for these parameters are subject to change concerning changes in material or structural constraints. In some cases, the 3D-printing process can be accompanied by the post-printing process, especially the curing process. It is highly dependent on the type of matrix material that is used for composite printing. The extrusion deposition modelling is known for producing components without the usage of machining elements, but in certain cases, the surfaces have to be machined to obtain smooth texture requirements. Furthermore, the support structures must be removed after the completion of part manufacturing, which might also result in further surface machining. The curing process occurs immediately after the material exits the printer nozzle due to natural cooling for thermoplastic matrix materials. In certain cases, in situ consolidation techniques, such as controlled thermal environment, compaction pressure, or deposition speed, are employed to promote bonding and minimise defects in continuous fibre composites [50, 113, 114]. In certain cases, the printed composite is exposed to additional curing process before or after surface finishing to attain further chemical reactions that intensify the bond between particles, especially for thermosetting polymers.

2.1.4 | 3D Printing Hardware for CFRP Composites

There are several technologies available on the market for the additive manufacturing of polymer materials, but there are

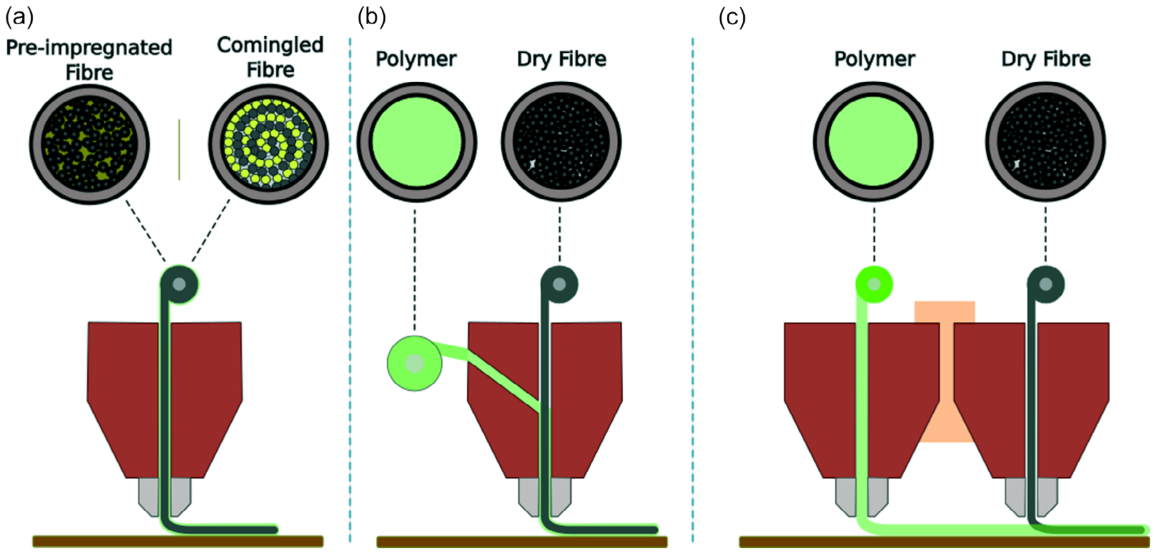

FIGURE 7 | Impregnation and extrusion principles: (a) stock impregnated filaments and extrusion, (b) impregnation during extrusion, and (c) impregnation in situ after extrusion.

not many that specialise in the manufacturing of composite materials. Looking at the commercial availability of 3D printers, there are basically two categories of them: closed-source printers and open-source printers. The main idea behind this classification is that closed-source printers do not provide the users with the freedom of accessibility to the design and hardware components of the 3D printer. Users must limit themselves to the design options provided by the equipment manufacturer. However, open-source printers give users the access to tools that enable them to retrofit various components such as different printing heads, rotary cylinder print beds, compaction rollers, etc.

When we narrow the field to continuous fibre-reinforced polymeric composites, which include two or more different materials, a significant difference can be observed in the number of nozzles used in the print head. There are single-nozzle and multinozzle configurations for printing continuous fibre-reinforced composites. In the single-nozzle type, as shown in Figure 8a, the fibre and the matrix are co-extruded through the same nozzle, which requires precise control of the feed to ensure effective impregnation and deposition, while dual or multiple nozzle systems provide separate feed paths for the fibre and polymer matrix, which facilitates higher fibre volume fractions and greater process flexibility, as reported in recent reviews of continuous carbon fibre print heads [112]. Dual nozzle types, as schematically illustrated in Figure 8b, are generally used, one for the fibre filaments and the other for the matrix material. Multiple nozzles larger than two nozzles, as illustrated in Figure 8c, can be used in cases of more materials in the composite. Another development is in the degree of freedom of printing that became possible with the integration of additional axes [86] to the usual rectilinear setup or robotic arms retro-fitted with print-head or print-bed as their end-effectors [115], while most commercial ones use the XYZ system in printing. The degrees of freedom in additive manufacturing of CFRP composites are presented schematically in Figure 9a,c, and their advancements can be seen in Figure 9b,d.

2.2 | Commercial CFRP Composite 3D Printers

In recent years, a diverse range of commercial additive manufacturing systems capable of depositing continuous fibres have emerged, spanning from compact desktop printers to large multi-axis robotic platforms. These systems exploit thermoplastic or thermoset matrices and are compatible with high-performance fibres such as carbon, glass, aramid, and basalt. Several leading industrial pioneers have introduced advanced solutions, as mentioned in Table 8. Anisoprint offers Composer A4/A3, Composer Nova, and industrial ProM IS 500, all of which implement Composite Fibre Co-extrusion (CFC) with in-nozzle impregnation of dry fibre. This approach provides flexibility in the combination of carbon or basalt fibres with a wide range of thermoplastics, including high-temperature matrices such as PEEK and PEI in the industrial platform.

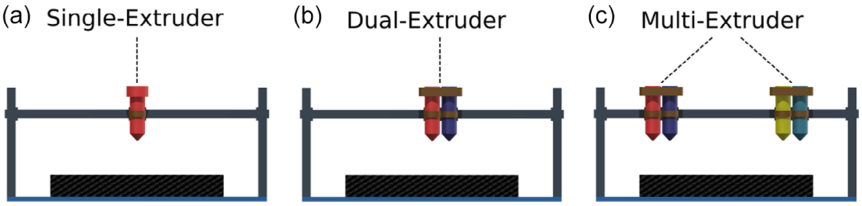

FIGURE 8 | Extrusion head types: (a) single-extruder head for both fibre and matrix, (b) dual-extruder head for fibre and matrix each, and (c) multi-extruder heads for multiple fibre and matrix materials.

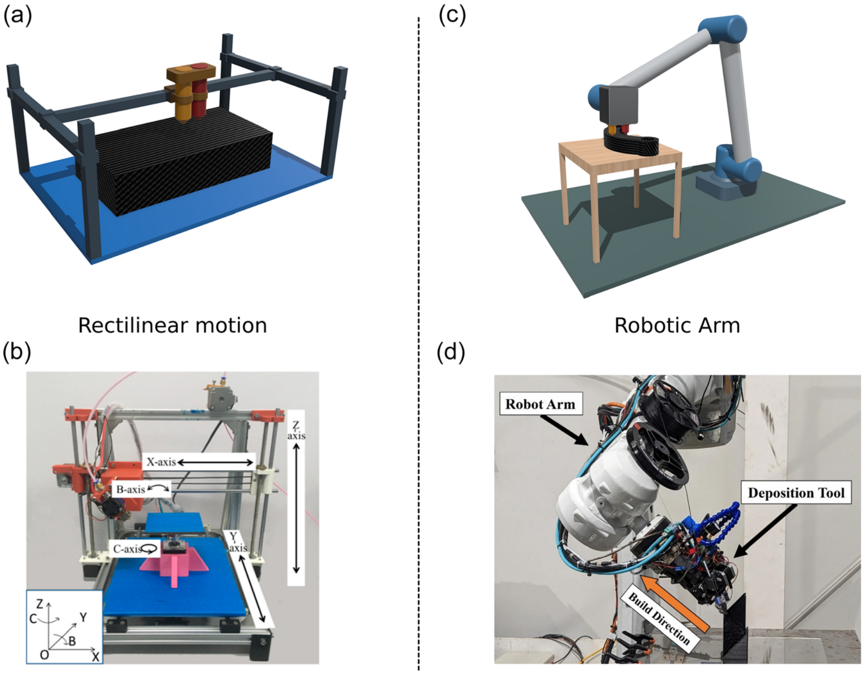

FIGURE 9 | Advancements in Degrees of Freedom: (a) common rectilinear 3 degree-of-freedom printer configuration. (b) Five-axis 3D printer [86]. Reproduced with permission. Copyright 2020, The authors and MDPI. (c) Robotic arm configuration with higher degrees of freedom. (d) Six degree-of-freedom robotic arm retrofitted with deposition tool [115]. Reproduced with permission. Copyright 2025, Springer Nature Ltd.

Desktop metal offers the Fibre LT and Fibre HT platforms, which has fused filament fabrication (FFF) along with micro-automated fibre placement (μAFP) to embed continuous carbon or glass fibre tapes within thermoplastic matrices. 9T Labs has developed the Red Series, which combines a Build Module for fibre placement with a Fusion Module for consolidation, implementing their additive fusion technology (AFT). Their system significantly reduces porosity and improves fibre–matrix bonding by applying pressure and heat during the fusion step. This enables the fabrication of structural carbon fibre–reinforced parts in high-performance thermoplastic matrixes such as polyetherketoneketone (PEKK). Markforged commercialises a range of desktop and industrial systems including the Mark Two, X7, and FX20, all of which employ continuous fibre reinforcement (CFR) using pre-impregnated fibre tows. These printers embed carbon, glass, or aramid (Kevlar) fibres into thermoplastic matrices such as Nylon, Onyx, and high-temperature polymers such as ULTEM 9085, allowing lightweight parts with high specific strength and stiffness.

Moi Composites employs its Continuous Fibre Manufacturing (CFM) system, in which multi-axis robots deposit continuous fibres impregnated with UV-curable thermoset resin to create complex, mould-less composite structures reinforced with carbon, glass, or basalt fibres. Furthermore, Addcomposites offers the SCF3D (Structural Continuous Fibre 3D Printing) system. This robotic printhead solution for Structural Continuous Fibre 3D Printing is compatible with thermoplastics such as PA, PEEK, and polyaryletherketone (PAEK), allowing carbon and glass fibre reinforcement in large-format composite parts. In addition, Continuous Composites has developed CF3D, a robotic platform that deposits dry fibre impregnated with photo-curable resin and achieves in situ consolidation through UV curing, allowing rapid fabrication of thermoset composite structures reinforced with carbon or glass fibres.

Orbital Composites provides the Orbital series (e-, S, and F), which uses multirobot extrusion systems equipped with coaxial continuous fibre deposition. These scalable platforms are designed for large-format manufacturing of thermoplastic and thermoset composites reinforced with carbon or glass fibres. Furthermore, CEAD has developed the CFAM Prime, a large-format additive manufacturing system that combines pellet extrusion with continuous addition of fibre. This platform enables the production of structural thermoplastic composites reinforced with carbon or glass fibres on scales up to 4 × 2 × 1.5 m.

In general, while these industries represent the current leaders in the commercial continuous fibre additive manufacturing, many other enterprises and research groups are actively developing systems, reflecting the strong and growing interest in this domain. Table 8 represents a detailed summary of all commercial solutions of additive manufacturing technologies for CFRP composites to facilitate the comparison of different products in terms of various parameters.

The availability of several commercial platforms indicates that additive manufacturing of continuous fibre-reinforced composites has progressed beyond purely laboratory-scale demonstrations. However, the level of technological maturity differs between platform categories. Desktop continuous-fibre extrusion systems are generally the most mature in practice and are commonly employed for prototyping and low-volume manufacture of fixtures and lightweight components, where process repeatability and integration into existing workflows are relatively well established. In contrast, industrial high-temperature thermoplastic systems and hybrid approaches (printing combined with

TABLE 8 | Overview of selected commercial continuous-fibre additive manufacturing (AM) systems, their product lines, build envelope, process technologies, and material compatibility (compiled from publicly available manufacturer specifications).

Brand	Product	Build envelope	Process/tech	Matrix class	Typical fibres
Anisoprint	Composer A4/ A3	A4: 297 × 210 × 148 A3: 460 × 297 × 210 mm	Composite Fibre Co-extrusion (CFC), in-nozzle impregnation	Max. Temp—270°C (PLA, PETG, PA, PC, ABS, TPU)	Carbon (1.5 K), basalt
	Composer Nova	400 × 300 × 150 mm	CFC (new generation)	Max. Temp—320°C (Thermoplastic)	Carbon (1 K, 3 K), basalt, glass
	ProM IS 500	600 × 420 × 300 mm	Dual-nozzle CFC, industrial	Max. Temp—410°C (PEI, PEEK, PEKK, PSU, PPSU, PESU)	Carbon (1K, 3K)
Desktop metal	Fibre HT/LT	(FFF): 310 × 240 × 270 (µAFP): 290 × 210 × 270 mm	Microautomated fibre placement (+ FFF)	Nylon (LT), PEEK/PEKK (HT)	Carbon, glass
9T Labs	Red Series (Build + Fusion Modules)	—	Additive fusion technology (AFT): print + consolidate	PEKK	Carbon
Markforged	Mark Two	320 × 132 × 154 mm	Continuous fibre reinforcement (CFR)	Nylon, Onyx, TPU, PLA	Carbon, Kevlar, glass
	X7	330 × 270 × 200 mm	CFR (industrial)	Nylon, Onyx, TPU, PLA	Carbon, Kevlar, glass
	FX20	525 × 400 × 400 mm	CFR	PEI, PEKK, Onyx	Carbon, glass, aramid
Moi Composites	CFM System	—	Multi-axis continuous fibre + UV-curable resin	Thermoset	Glass
Addcomposites	SCF3D	—	Robotic structural continuous fibre 3D printing	PA, PEEK, PAEK	Carbon, glass
Continuous composites	CF3D Enterprise	—	Robotic—dry fibre + in situ UV curing	Thermoset	Carbon, glass
Orbital composites	Orbital series: e-, S, F	(S): up to 2.25 × 2.25 × 2.25 m	Multirobot extrusion with coaxial fibre	Thermoplastic/thermoset	Carbon, glass
CEAD	CFAM Prime	4 × 2 × 1.5 m	Pellet extrusion + continuous fibre add-on	Thermoplastic	Carbon, glass

consolidation) target superior structural performance and fewer defects, but they are more heavily reliant on robust material and process control, as well as stable consolidation conditions. Multiaxis robotic deposition and large-format systems expand the achievable geometries and part dimensions even further, yet their industrial viability is still constrained by challenges in deposition stability, dependable in situ consolidation, and scalable quality assurance and traceability.

The commercial technologies available mentioned above provide several advantages such as (i) availability of cost-effective on-site manufacturing solutions, (ii) acquisition of complex geometries and designs, and (iii) offering a high degree of control over fibre placement and orientation within the part. However, there are still significant limitations and challenges related to this industry that need to be addressed to provide a robust solution for CFRP composite manufacturing. Some but not all of these limitations include the following: (i) the range of compatible continuous fibre and matrix materials is still limited, (ii) available printers are restricted in terms of the part size, (iii) the fabricated parts have fallen short in surface finish quality and dimensional accuracy, (iv) the low quality fibre dispersion, incurring uneven fibre distribution and defects or voids inside the layers, and (v) the low quality of impregnation of matrix material within the fibres before deposition that causes not very strong bond between the polymer and fibre. Furthermore, the dedicated software used by individual manufacturers does not provide much freedom for users in defining critical printing parameters, which limits the optimisation of fibre placement in different parts.

3 | Mechanical Characterisation of AM-Based CFRP

Characterisation of additive manufactured continuous fibre reinforced polymers is essential for establishing their viability in structural applications. Unlike conventional composites, the performance of additive manufactured CFRP composites is governed not only by the intrinsic properties of the fibre and matrix but also by the spatial distribution of fibres, interfacial bonding, layer-wise consolidation, and process-induced defects such as voids or fibre waviness. Mechanical characterisation provides the foundation for component design by quantifying stiffness, strength, and failure mechanisms in directions dictated by fibre orientation and print path strategies. The resulting data are essential for benchmarking and validating analytical and numerical models; for establishing the link between process parameters, microstructural features, and final properties; and for clarifying how local heterogeneities such as voids, fibre waviness, or resin-rich regions affect the overall structural performance of additive manufactured CFRP composites. In addition, rigorous characterisation enables a reliable comparison with traditionally manufactured composites, supporting the adoption of these novel CFRP composites in safety-critical sectors where certification, durability, and reproducibility are crucial.

The mechanical characterisation of composites, and in particular additive manufactured CFRP composites, is commonly structured around standardised testing protocols that evaluate their anisotropic response under different loading conditions. Benchmark properties such as tensile, compression, shear, and flexural behaviour are assessed through widely adopted standards (e.g., ASTM D3039, D3410, D2344, and D790), which provide comparable datasets for design and validation against conventionally manufactured laminates. Complementary methods that address damage resistance, such as impact testing (ASTM D6110), hardness testing (ASTM D4762), and fracture toughness (ASTM D5528), are increasingly used to capture the role of fibre–matrix interfaces, void content, and interlayer adhesion in determining structural reliability. A summary of these destructive test categories, their associated standards, and representative applications in additive manufactured CFRP composites is presented in Table 9.

Furthermore, time- and environmental-dependent characterisations are essential for assessing the long-term durability of additive manufactured CFRP composites. Fatigue testing (ASTM D3479) provides insight into the performance of cyclic loading, where factors such as fibre orientation, layer interfaces, and void distribution strongly influence endurance limits compared to traditional laminates. Creep testing, commonly performed using ASTM D638 (Type IV), evaluates deformation under sustained loading at elevated temperatures and is particularly relevant for thermoplastic matrices used in extrusion-based printing.

In addition to mechanical durability, spatially resolved characterisation methods are critical for quantifying fibre orientation, fibre volume fraction, and void content as crucial parameters that dictate anisotropy and failure modes in printed composites. Nondestructive testing (NDT) approaches, including X-ray and micro-CT imaging, ultrasonic testing, optical and electron microscopy, and thermography, are increasingly applied to composite materials to capture process-induced heterogeneities and validate print path strategies. These categories of analysis, together with their associated standards and applications, are summarised in Table 9.

Although numerous studies present properties based on established composite coupon standards, applying these standards directly to additive manufactured continuous-fibre composites is not always straightforward. The most commonly used standards were originally developed for consolidated laminates that exhibit a clearly defined load-bearing cross section, consistent thickness, and relatively low geometric variability. In CFRPs with material expansion, the load-bearing behaviour is governed by discrete fibre tows embedded in the printed polymer matrix, where notable variations in thickness, fibre placement tied to the tool-path, and void content may occur [124]. These features can influence both the measured mechanical behaviour and the observed failure modes, even when the nominal specimen size meets conventional standard specifications. In practice, standard coupon geometries are sometimes obtained by first printing plates and then cutting specimens to the required dimensions or by applying post-processing steps such as compaction to adjust the fibre volume fraction before specimen extraction. However, these procedures can introduce edge damage or locally disrupt the fibre architecture, potentially shifting failure initiation away from the intended gauge region. The design of grips and end-tabs is also challenging, since surface roughness and stiffness differences between fibre-rich and polymer-rich areas can lead to premature failures originating at the grips or tabs [103, 138].

Therefore, a number of studies highlight the importance of carefully specifying specimen geometries and tabbing strategies for

TABLE 9 | Standardised methods for destructive and nondestructive characterisation of continuous fibre reinforced polymers (CFRPs), with examples of ASTM standards and typical applications in additive manufactured composites.

Test type	Characterisation aspect	Tests	Example standards	References
Destructive tests	Universal property tests	Tensile testing	ASTM D3039; ISO 527	[57, 78, 116–122]
		Compression testing	ASTM D3410	[57, 58, 117]
		Shear testing	ASTM D2344	[116, 117]
		Flexural testing	ASTM D790	[57, 78, 119–121]
	Damage and failure	Impact testing	ASTM D6110	[57]
		Hardness testing	ASTM D4762	[117]
		Fracture toughness testing	ASTM D5528	[116]
	Durability and performance	Fatigue testing	ASTM D3479	[116]
		Creep resistance testing	ASTM D638 (Type IV)	[58]
Nondestructive tests	Fibre orientation and void fraction (spatial arrangement)	X-ray/CT scan /µCT	—	[123–127]
		Ultrasound testing	—	[128, 129]
		Optical microscopy/ scanning electron microscopy	—	[130–136]
		Thermography	—	[137]

additive manufactured continuous-fibre systems [79, 95, 117]. Even when established tensile, compression, flexural, or shear standards are applied, the definition of the effective cross-sectional area can be unclear for infill-based architectures, and relying on the nominal width and thickness can lead to an overestimation of the load-bearing area. Consequently, many studies perform repeated gauge measurements at several positions and supplement mechanical tests with microstructural analyses of void content and fibre distribution [123]. As a result, these issues increase data scatter and undermine the comparability between studies, especially when different standards or polymer-only standards are used. To make this connection and enhance comparability between published datasets, Table 10 presents an overview of common processing factors that can influence the standardisation of characterisation procedures, along with their typical microstructural signatures and the mechanical properties they most strongly affect [50, 139].

The NDT evaluations mentioned above, together with destructive tests, as presented in Table 9, have been adopted in several research investigations and studies to understand how manufacturing strategies affect the properties of additive manufactured CFRP composites. Parmiggiani et al. [140] varied the number of continuous carbon fibre (CCF) layers within Onyx laminates, reaching fibre volume fractions up to 52%. They reported tensile strengths between 24 and 566 MPa, showing that the strength scales with the reinforcement content and layer configuration. Todoroki et al. [138] kept the fibre content constant at around 30% but altered the fibre orientations of 0°, 45°, and 90°. Their results ranged from 19 to 701 MPa in strength and from 2.3 to 60.9 GPa in elastic modulus. This highlighted the pronounced anisotropy of additive manufactured CFRP composites and confirmed that fibre alignment is the primary factor controlling tensile behaviour. Saeed et al. [120] extended these observations to fully filled specimens, where favourable configurations produced tensile strengths between 597 and 768 MPa and an elastic modulus close to 80 GPa. These results show that printed composites can approach the lower bound of aerospace-grade laminates. Bendine et al. [116] explored the effect of fill density, ranging from 13% to 50%, and reported strengths between 207 and 738 MPa. This work provided a clear demonstration of how the process-controlled reinforcement content governs the scaling of properties. In addition to tensile studies, Zeng et al. [57] examined the flexural behaviour of additive manufactured composites and showed that bending stiffness is highly sensitive to the orientation of the fibre and the path used for deposition. Together, these investigations illustrate how the orientation, fibre fraction, and infill settings define the accessible mechanical envelope of additive manufactured CFRP composites.

In addition, durability and microstructural characterisations have been investigated through several studies. Saeed et al. [120] reported fatigue behaviour under different fibre orientations, showing that endurance limits are governed by fibre alignment and interfacial quality. Their results emphasise the need for standardised fatigue protocols such as ASTM D3479 to establish durability benchmarks for 3D-printed composites. Sommacal et al. [123] applied X-ray micro-CT to quantify the voids and the fibre distribution in CF/PEEK specimens, while Wang et al. [124] used in situ micro-CT before and after the testing to identify fracture initiation sites. Luo et al. [131] analysed the fracture surfaces using SEM and reported asymmetric failure patterns linked to fibre–matrix de-bonding. Ochana et al. [137] compared thermography and sheargraphy for defect detection and found that thermography was more effective for subsurface flaws. Lee et al. [129] applied laser ultrasonics for defect

TABLE 10 | Compact process–microstructure–property mapping for AM-based CFRP characterisation.

Process factor	Microstructure signature	Property sensitivity
Thermal history	• Crystallinity/cure • Residual stress • Fusion quality	• Modulus drift; warpage. • Creep sensitivity
Deposition control	• Bead geometry • Voids; lack of fusion • Thickness variation	• Strength scatter • Fatigue scatter
Compaction and impregnation	• Wet-out level • Porosity level • Interface quality	• Ultimate tensile strength; inter-laminar shear strength; toughness. • Delamination tendency
Path continuity	• Fibre breaks/ends • Resin-rich zones • Local volume fraction(V_f) variation	• Strength drop • Fatigue hot spots
Fibre steering	• Waviness • Misalignment • Tow distortion	• Stiffness loss • Compression sensitivity
Interlayer strategy	• Bond variability. • Interface network. • Anisotropy	• Directional strength. • Splitting/delamination
Infill architecture	• Load-path density • Node stress raisers • Buckling modes	• Specific stiffness gain • Lower strength/toughness
Material condition	• Moisture effects • Degradation • Extra porosity	• Toughness loss • Higher scatter
Post-processing	• Void reduction • Bond improvement • Stress relief	• Higher strength • Lower scatter; stability

Notes: Typical measurements include micro-CT (micro-computed tomography) for porosity and fibre trajectories; optical/SEM (scanning electron) microscopy and fractography for interfaces and failure; ultrasound or thermography for bond quality; DIC (Digital Image Correlation) for strain localisation; DSC (differential scanning calorimetry)/DMA (dynamic mechanical analysis) for matrix state and thermal effects.

inspection and showed that it provided results comparable to micro-CT with greater potential for industrial use. These studies confirm that nondestructive evaluation is crucial for quantifying void content, detecting defects, and monitoring fibre orientation without damaging the specimen.

These experimental investigations collectively demonstrate that additive manufactured CFRP composites have the potential to achieve performance levels similar to those of conventionally manufactured laminates, provided that fibre alignment and reinforcement content are meticulously controlled. At the same time, durability studies remain limited, and large-scale validation of nondestructive techniques is still sparse. This highlights the need for more work to establish robust process–structure–property relationships and to expand standardised protocols beyond static testing. Such efforts are essential to move AM-CFRPs from laboratory-scale demonstrations toward certified structural applications.

4 | Numerical Simulation of Additive-Manufactured CFRP Composites

Computation approaches such as numerical simulations and/or optimisations are fundamental for product design and manufacturing fields, especially those related to composite materials, where there are several material parameters to be decided through the product development process. Using numerical simulations, engineering can efficiently explore the complex interactions and behaviours of materials under various conditions without the need for extensive physical experimentation. For example. Sakhaei et al. developed a full 3D large deformation higher-order finite element analysis that could model and predict the generation of micro defects and wrinkling during the composite formation process of an uncured composite material [22]. Furthermore, the ability to visualise material behaviour, optimise the properties of composites, adjust parameters, and explore intricate geometries that are difficult to fabricate or assess experimentally are crucial accessibilities from numerical simulations. Moreover, once simulation models are validated against empirical data, they become reliable tools for predicting the performance of new designs or loading conditions. This capability not only reduces the experimental burden but also opens avenues for optimisation studies, allowing engineers to test multiple hypotheses in controlled virtual environments. Techniques such as finite element analysis, homogenisation, multiscale modelling, and data-driven methods are commonly employed to improve the performance and application of polymeric composites.

Numerical simulations of CFRP composites can be performed at different scales depending on the length scale of the parameters under investigation [141]. For example, microscale Simulations [132, 133, 142–145] focus on lengths between about 1 and 50 μm, representing individual reinforcing filaments. Meso-scale simulations [139, 146, 147] cover characteristic lengths between 0.1 and 1 mm and capture the behaviour of filament bundles, inter-layer regions, and different orientations. Furthermore, macroscale analysis [142, 148–151] characterise the length range from a few millimetres to several metres, allowing investigation of the overall geometry and behaviour of structural components. In addition, multiscale modelling approaches [152, 153] integrate these levels by transferring information from lower scales to higher scales, often using homogenisation techniques, so that the point-wise material response can inform the macroscopic behaviour of the composite.

In recent years and with new advances in manufacturing of additive manufactured composite materials, various computational strategies have been developed to simulate the mechanical response of additive manufactured CFRP composites. These approaches are usually based on constitutive modelling, micromechanics modelling, finite element modelling, data-driven techniques, or a combination of these methods.

Constitutive models are central to the numerical simulation of additive manufactured CFRP composites, as they establish the relationship between the micro- to mesostructural features of printed layers and their macroscopic stress–strain behaviour. Such models are essential for capturing the layer-wise anisotropy, interfacial defects, and heterogeneity that distinguish printed structures from conventionally processed laminates. At the laminate scale, El Moumen et al. [154] discussed two representative strategies. The first strategy is classical laminate theory (CLT), where each printed ply is described by orthotropic elastic constants. The stiffness of each ply is then transformed into the global laminate axes according to the fibre orientation and stacking rules to simulate the overall laminate response. The second approach discussed by El Moumen et al. [154] is the MESOTEX model, which represents the meso-structural filament arrangement within a repeating unit that considers the anisotropy, imperfect bonding, and voids specific to 3D printing. This approach bridges filament-level features and laminate stiffness predictions, offering a more realistic description of additive manufactured laminates. Furthermore, Grieder et al. [155] introduced a process-aware constitutive formulation in which engineering constants evolve with temperature, crystallisation, and porosity during the consolidation of PA12 continuous-fibre laminates. Implemented through user subroutines and validated against the evolution of porosity and thickness, their approach demonstrated a pathway to translate the thermal history directly into laminate-level properties and residual stress predictions. In parallel, Hou et al. [156] established a fibre-volume-fraction dependent description for printed continuous fibre laminates, experimentally mapping stiffness and strength parameters into a plane-stress formulation. When integrated with CLT stacking rules and Hashin failure criteria, this model allowed the analysis of functionally graded laminates in ABAQUS by linking print-controlled fibre content to laminate-scale mechanical performance.

There are also several micromechanic based modelling of additive manufactured composite materials that link the behaviour of fibres, matrix, and their interfaces to the effective response of the composite. This is implemented by building a representative volume element (RVE) that reflects the printed architecture and then applying homogenisation to obtain overall properties. For example, Abdullahi et al. calibrated a rule-of-mixtures model to co-extruded roads and showed how the predicted modulus varies with fibre content and its distribution [157]. Hetrick et al. tested classical bounds and semi-empirical relations across fibre volume fraction and orientation, mapping where Voigt, Reuss, and Halpin–Tsai succeed or fail for printed laminates [158]. Heidari–Rarani et al. provided a comparative baseline for unidirectional plies that guided the selection of homogenisation schemes when transferring micromechanics to AM laminates [159]. Melenka et al. evaluated continuous fibre printed coupons and used a volume average stiffness workflow with layerwise properties, coordinate transforms and global averaging to predict tensile modulus, showing appropriate agreement at moderate to high fibre content [160]. Furthermore, Polyzos et al. develop a three scale framework that couples a micro RVE for fibre and matrix, a meso-scale void representation and a laminate level assembly, and introduce a concentric cylinder analytic model validated against numerical and experimental data [161].

Finite element modelling techniques and commercial software, as prominent tools within Computer-Aided Engineering (CAE) for composite design, have been extensively adopted for the analysis of additive manufactured CFRP composites recently. This adoption is attributed to their ability to accurately characterise the heterogeneous microstructure resulting from filament deposition, fibre-matrix interfacial interactions, and the distribution of voids. Unlike classical laminate models, FEM allows for direct incorporation of bead geometries, layer arrangements, and local anisotropy, thus capturing process-induced effects more realistically. In the recent literature, several FEM strategies have been reported for additive manufactured CFRP composites, where each of these strategies then has a specific strength. Van de Werken et al. [162] demonstrated that the assignment of orthotropic properties element-wise according to the fibre deposition paths provides a direct link between the print geometry and local anisotropy with a relatively modest mesh cost. Avanzini et al. [150] introduced the embedded element technique, in which fibres are modelled as beams embedded within a polymer matrix mesh, an efficient way to capture curved or intersecting fibre paths while retaining numerical stability. Dong [163] proposed a homogenised finite element framework based on Kerner and Hashin micromechanics models. This approach strikes a balance between computational efficiency and the ability to account for porosity and fibre distribution when predicting tensile and flexural properties. De Kergariou et al. [164] advanced the field by combining voxel-based, filament-scale finite elements with an evolutionary algorithm. This method enables highly detailed representation of fibre paths and optimisation of complex 3D and 4D architectures. Finally, Bendine et al. [116] focused on providing systematic experimental datasets and used FEM primarily as a validation tool, underlining the importance of experimental–numerical integration. Together, these studies show that FEM is not just a convenient numerical technique but a critical enabler to understand, predict, and optimise the performance of additive manufactured CFRP composites.

Data-driven modelling or AI-based models have recently gained momentum for material modelling and, as a result, additive manufactured CFRP composites. This is due to the claims that AI-based models can handle the complex and non-linear relationships between process parameters, microstructure, and mechanical performance more efficiently. Unlike conventional models, machine learning approaches rely directly on data, enabling fast predictions once trained and allowing efficient exploration of large design spaces. Considering the high momentum of progress in this area, several strategies have been reported in the literature, each highlighting a different strength. For example, Almeida and Gomes [153] combined machine learning with genetic algorithms to optimise continuous carbon fibre laminates, achieving a balance between inter-laminar strength and printing efficiency. Furthermore, Li et al. [165] introduced a neural-network-assisted multiscale optimisation framework, allowing concurrent design at the material, process, and structural levels. Monticeli et al. [166] used artificial neural networks together with response surface methodology to predict and optimise the flexural behaviour of FFF-based continuous CF/epoxy composites, demonstrating accurate mapping of multiple process parameters. Liu et al. [167] focused on continuous CF/PEEK systems and showed that machine learning can predict tensile strength effectively, providing a useful tool for aerospace applications where high-temperature performance is critical. In the same context, Jimenez–Martinez et al. [168] developed an ANN model for Onyx–Kevlar printed composites to predict fatigue-damage accumulation and temperature increase, illustrating the potential of data-driven models in the evaluation of service life. Dhage and Khedkar [169] combined the design-of-experiments with supervised learning to optimise impact energy in 3D-printed Onyx–Kevlar laminates, offering a practical route to parameter tuning. In summary, these methodologies can be used to enhance optimisation and service-life assessment, rendering them an invaluable contribution to constitutive, micromechanical, and finite element models in the analysis of additive manufactured CFRP composites.

To support method selection, Table 11 presents an integrated overview of the main numerical modelling approaches for additive manufactured CFRP composites. It connects each approach to its typical application scenarios, identifies the phenomena that can be captured with confidence, and clarifies the key assumptions and limitations underlying each framework. The table also demonstrates how multifidelity workflows can be constructed by pairing rapid laminate-level screening with targeted filament-scale or process-informed simulations when local defects, interfaces, or thermal history govern structural performance.

TABLE 11 | Modelling approaches for additive manufactured CFRP composites, highlighting typical applications, strengths, and limitations.

Modelling approach (scale)	Typical applications and strengths	Key limitations and assumptions
Laminate/CLT-type (macro)	• Fast screening of layups and fibre angles • Good for global stiffness and load paths • Useful for early design selection	• Homogenised plies; discrete toolpaths ignored • Defects and interfaces not resolved • Needs reliable effective ply properties
Mapped orthotropy FEM (macro)	• Component analysis with local fibre direction • Practical cost for complex geometries • Captures steering trends at part scale	• Orientation mapping can be implementation-sensitive • Still homogenised; gaps/overlaps not explicit • Limited prediction of local failure hotspots
Embedded fibre paths (meso–macro)	• Discrete fibre trajectories inside matrix FEM • Efficient compromise: realism vs. cost • Good for comparing reinforcement strategies	• Interface behaviour often simplified • Tow geometry idealised unless refined • Calibration needed for load transfer
Filament/voxel FEM (meso)	• Resolves bead geometry, gaps, overlaps • Captures local stress concentrations • Useful for failure initiation studies	• High cost; heavy pre-processing • Often limited to subregions or thin parts • Requires assumptions on bonding and pores
RVE/multiscale (micro–meso)	• Links microstructure to effective properties • Supports property prediction vs. process changes • Useful for uncertainty and sensitivity	• Representative geometry/data required • Periodicity assumptions may limit transfer • Interfaces are major uncertainty drivers
Process-aware (thermal/consolidation)	• Predicts bonding quality and defect tendency • Explains porosity and variability trends • Supports parameter optimisation	• Needs accurate material/process inputs • Validation is demanding • Coupling to mechanics adds complexity
Data-driven surrogates (any scale)	• Rapid design-space exploration • Inverse design and optimisation workflows • Useful when trained on validated data	• Generalisation outside training is uncertain • Sensitive to data quality and bias • Limited interpretability without constraints

Abbreviations: CLT = classical laminate theory; FEM = finite element method; RVE = representative volume element.

5 | Applications of Additive Manufactured CFRP Composites

CFRP composites exhibit a wide range of applications in multiple disciplines. These diverse functionalities arise from the synergistic interactions between their constituent components, namely the reinforcing fibre and the matrix material. With the integration of additive manufacturing technology that unlocks the freedom in the fabrication of complex structures through in situ fibre placement and impregnation technique, the scope of CFRP composite applications expands even further. There are several features, including material selection and distribution [134, 170], shape morphing [171, 172], sensing [173–176], and fibre manipulation and placement control [115, 177–179], that influence the functionalities and the core area of applications of additive manufactured CFRP composites.

In practice, the selection of fibre and matrix constituents is intrinsically associated with the necessary functionalities of a composite material. For energy storage, Thakur and Dong [180] demonstrated structural battery composites by co-printing continuous carbon fibres coated with a solid polymer electrolyte with a cathode-doped matrix. In this design, as illustrated in Figure 10a, the fibre provided both mechanical reinforcement and acted as a current collector. The use of additive co-extrusion allowed the integration of the two functions in a single step and allowed the cell geometry to be tailored to the intended application. Furthermore, Zeng et al. reported 4D printed shape memory polymer composites reinforced with continuous carbon fibres to combine a responsive polymer with fibre path programmability that results in efficient morphing behaviour [19]. As presented in Figure 10b, the fibres acted as embedded heating elements that allowed electrically triggered bending while also increasing the flexural resistance of the structure. Similarly, Xia et al. developed fibre reinforced liquid crystal elastomer actuators that responded to heat, light, and electricity with multidirectional deformation [181]. The fibre architecture, as shown in Figure 10c, was used to programme the actuator kinematics, demonstrating how the placement of the fibre through additive manufacturing can prescribe complex morphing modes that are attractive for soft robotic applications.

Sensing capabilities have also been demonstrated through printed continuous fibre structures. Ye et al. fabricated honeycomb lattices from PLA and TPU co-extruded with continuous carbon fibres, which showed stable resistance changes during cyclic compression [182]. The geometry of the lattice, as illustrated in Figure 10d, extended the sensing range, while the continuous fibre provided a reliable conductive pathway. This application could highlight the importance of continuous fibres in embedding the sensor directly during additive manufacturing. In a related study, the same research group reported tensile and compressive tests of additive manufactured CFRP composites and found that the resistance response correlated well with the applied strain [183]. This work, as shown in Figure 10e, discussed how continuous fibres enable strain sensing to be integrated into load bearing structures without the need for secondary processing. Furthermore, related to light-weighting, Zhang et al. combined experiments with predictive modelling to study deformation and failure in additive manufactured continuous fibre structures [184]. Their results, as presented in Figure 10f, showed how fibre placement strategies and printable corrugated geometries can be used to achieve higher specific performance while adjusting for process related defects, which is particularly relevant for aerospace and automotive applications.

6 | Sustainability and End-of-Life Pathways for Additive Manufactured CFRP Composites

Sustainability considerations for additive manufactured CFRP composites extend throughout the life cycle, including (i) impacts from material production (in particular fibre and resin fabrication); (ii) energy consumption and scrap generation during manufacturing; (iii) advantages in-use derived from weight reduction and extended service life; and (iv) end-of-life options, including reuse, re-manufacturing, and recycling. Within this broader context, we focus on recyclability as a key sustainability lever, while also evaluating it in conjunction with life-cycle assessment (LCA) indicators, process energy requirements, and material efficiency measures that together define overall environmental performance. The main dimensions of sustainability, the suggested quantitative metrics, and the actionable levers are compiled in Table 12.

Life-cycle assessment offers a systematic approach to comparing CFRP manufacturing pathways by establishing evaluation indicators such as global warming potential, cumulative energy demand, and material circularity. In the context of additive manufacturing, LCA outcomes are highly dependent on assumptions regarding production volume, machine utilisation, the extent of post-processing, and scrap generation. Consequently, even though comprehensive LCAs for additive manufactured CFRP composites are currently limited or show substantial variability, it is still important to consistently report the main impact drivers, including energy per component, the mass of discarded polymer/fibre, the use of solvents and auxiliary materials, and the degree of reuse achievable for recovered fibre [185]. More general AM sustainability/LCA frameworks and circular-economy approaches can be applied to position additive manufactured CFRP composites within these indicators while CFRP-specific datasets continue to develop [9, 186].

6.1 | Energy and Resource Demands

A key sustainability difference between additive manufacturing of CFRP and traditional composite fabrication lies in how process energy, tooling and post-processing demands, and material waste are balanced. Conventional high-performance CFRP manufacturing frequently depends on energy- and infrastructure-intensive stages, including controlled curing/consolidation and extensive trimming or machining [27]. In contrast, many additive manufacturing strategies minimise tooling requirements and can limit finishing operations by producing components close to net shape. Nevertheless, additive manufacturing of CFRP can be energy-inefficient at low production volumes. Extended build times, high nozzle or chamber temperatures (particularly for high-performance thermoplastics), and repeated start–stop sequences can raise the energy consumed per part when machine utilisation is low [187]. As a result, the idea of additive manufacturing as inherently more environmentally friendly is not always justified unless the specific production scenario is defined [188]. The sustainability

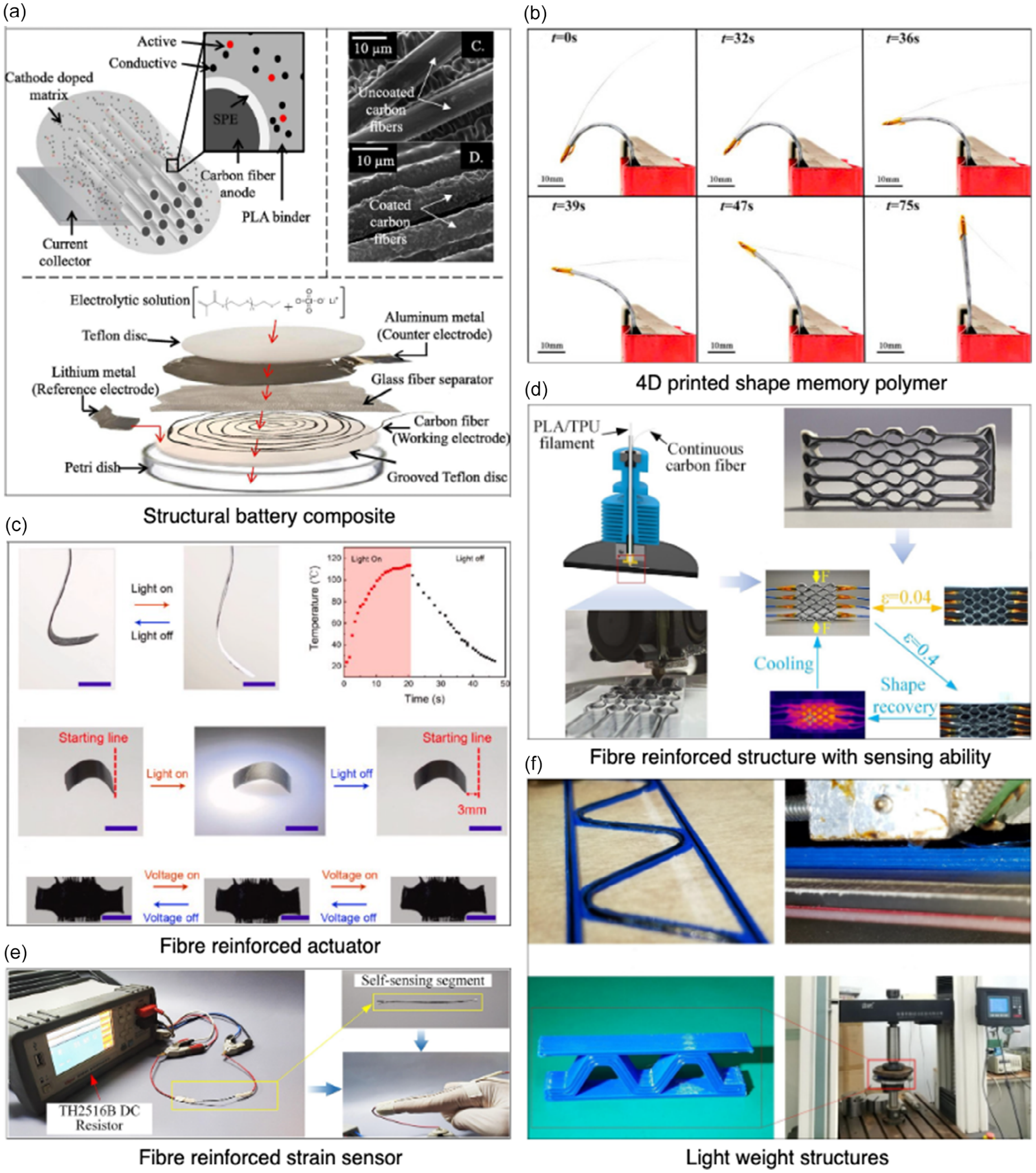

FIGURE 10 | Various applications of CFRP composites. (a) Structural battery composite [180]. Reproduced with permission. Copyright 2020, Elsevier Ltd. (b) 4D printed shape memory polymer [19]. Reproduced with permission. Copyright 2020, Elsevier Ltd. (c) Fibre reinforced actuator [181]. Reproduced with permission. Copyright 2023, Elsevier Ltd. (d) Fibre reinforced structure with sensing ability [182]. Reproduced with permission. Copyright 2022, Elsevier Ltd. (e) Fibre reinforced strain sensor [183]. Reproduced with permission. Copyright 2022, John Wiley & Sons Ltd. (f) Light weight structures [184]. Reproduced with permission. Copyright 2021, Elsevier Ltd.

advantages are most convincingly demonstrated when additive manufacturing significantly cuts scrap, removes the need for heavy tooling or autoclave-type processing, or enables part consolidation and lightweighting that dominate impacts during the use phase [7].

6.2 | Material Efficiency, Waste Streams, and Life Extension

Beyond energy considerations, the sustainability of additive manufacturing of CFRPs is heavily influenced by how efficiently materials are used. Common waste streams encompass purge

TABLE 12 | Sustainability scope for additive manufactured CFRP composites, highlighting key life-cycle aspects, what to quantify, and practical levers.

Life-cycle aspect	What to quantify and why	Primary levers and implications
LCA framing (system)	• Functional unit linked to performance (e.g., stiffness/strength targets) • System boundaries (cradle-to-gate vs cradle-to-grave) • Key indicators (e.g., GWP, energy demand, material circularity)	• Ensure fair baselines vs. conventional CFRP routes • Report utilisation, scrap, and post-processing explicitly • Avoid general claims without boundary definition
Manufacturing energy (process)	• Energy per part (machine power profile, heating, idle time) • Build-time dependence and throughput sensitivity • Post-processing energy (finishing, anneal, consolidation)	• Increase machine utilisation; reduce start– stop losses • Optimise thermal management and build strategy • Design for near-net-shape to reduce finishing
Material efficiency and waste (factory)	• Purge mass, failed builds, off-spec parts • Support/material losses (if applicable) • Trimming/machining waste vs conventional CFRP	• Design-for-AM to reduce supports and trial iterations • Robust feedstock handling (e.g., drying) to reduce defects • In situ monitoring to prevent scrap accumulation
Use-phase benefits (service)	• Lightweighting benefits (energy/fuel savings where relevant) • Durability and service life vs alternative materials • Part consolidation effects (assembly reduction)	• Tailor fibre paths to achieve stiffness/strength at lower mass • Consolidate parts to reduce fasteners and assembly steps • Balance performance gains against manufacturing energy
Life extension (circularity)	• Repairability (local reinforcement/patch strategies) • Remanufacture and reuse potential of subcomponents • Delay-to-replacement as a sustainability driver	• Design modular/replaceable sections for value retention • Enable repair workflows to defer new part production • Consider inspection and qualification requirements
End-of-life pathways (EoL)	• Fibre quality retention after recovery (length, surface, strength) • Matrix recovery feasibility and contamination • Downcycling vs high-value recovery yield	• Choose route by value retention: reuse/repair or recycle • Thermoplastic matrices can enable remelt/reshaping (if degradation controlled) • Thermosets typically require thermal/chemical matrix decomposition

Abbreviations: GWP = global warming potential; LCA = life-cycle assessment.

material, support structures (when needed), failed builds, off-spec components, and feedstock degraded by moisture. Minimising these losses calls for effective process monitoring, reliable material handling (including dry storage for hygroscopic matrices), and design-for-AM approaches that cut down on trial-and-error iterations. A second major lever is to extend the life of the product through repair and re-manufacturing [189]. AM-enabled repair and restoration strategies illustrate how localised material deposition can prolong service life and postpone replacement, often offset by impacts at the manufacturing-stage in many use cases [190]. Although repair research focusses mainly on metals, the same sustainability rationale holds for polymer and composite systems that design modular replacement, repairable structures, and subcomponent reuse, shifting the emphasis from "end-of-life management" to "life-cycle value retention" [8].

6.3 | Durability, Degradation, and Ageing

Additive manufactured CFRP components intended for real-world applications must likewise be evaluated with respect to environmental degradation and ageing, because sustainability is governed not only by recyclability but also by the preservation of properties and the extension of service life. In material-extrusion CFRP systems, moisture absorption (especially in hygroscopic matrices such as PA6/PA12), hygrothermal loading, exposure to saltwater or chemicals, UV radiation, and thermal cycling can modify matrix-dominated responses and compromise interface integrity, thereby intensifying AM-specific vulnerabilities including interlayer bonding quality, porosity, and raster/interface discontinuities. Recent studies have started to quantitatively assess these phenomena in additive manufactured continuous-fibre systems subjected to controlled environments (such as hygrothermal and saltwater ageing, long-term changes in flexural behaviour, and bond/property retention after consolidation). This work establishes preliminary durability benchmarks and underscores the importance of reporting ageing conditions together with the print-path and consolidation parameters [191–194].

6.4 | End-of-Life Recycling Routes for CFRP Composites

The increasing utilisation of CFRP composites has made the recycling of CFRP products a critical necessity, especially considering the importance and economic value of high-performance fibres. Most current recycling strategies focus on separating the matrix from the fibres while maintaining the integrity of the fibre. Figure 11 illustrates three representative routes for CFRP recycling and reusing. Mechanical recycling, as presented in Figure 11a, uses size reduction followed by separation. The process includes breaking the composite using various fragmentation methods, such as shredding, crushing, and milling, followed by segregation into powdered products (matrix-rich material) and fibrous products (fibre-rich material). This route is simple and scalable; however, the fibres become short and their surfaces are often damaged. Therefore, this approach is best suited for fillers or moulding compounds rather than for structural continuous-fibre parts. Ogi et al. [198] milled the cured CFRP into flake and powder fractions and compounded these with ABS to form test bars. The study reports improvements in stiffness due to the carbon fragments, while strength gains remain limited because the fibres are short and the interface is weaker. Pickering [199] describes the mechanical route from granulation and milling through classification into fibre-rich and matrix-rich streams. This process achieves high throughput at low cost, but the output is generally suitable for fillers or moulding compounds rather than recovery of continuous reinforcement. Furthermore, Palmer et al. [195] demonstrate an operational closed loop by grinding end-of-life thermoset composites and reprocessing the recycled material into new moulding compounds. The work shows that mechanically recycled material can re-enter manufacturing at scale for noncritical parts where short fibres are acceptable.

Thermosetting matrix recycling, as illustrated in Figure 11b, is aimed at higher-value recovery, since thermal and chemical processes can separate fibres while maintaining much of their strength. Yu et al. [196] introduced a vitrimer-based thermoset in which bond-exchange reactions allow almost complete resin recyclability and clean fibre release. The study shows that fibre properties are largely preserved and promises high-value recovery rather than down-cycling. Jody et al. [200] present an industrially orientated process that combines thermal decomposition with post-treatment to recover fibres from aerospace composite scrap. Furthermore, Pinero–Hernanz et al. [201] used near- and supercritical water to break down the epoxy and release the fibres. They obtained clean fibre surfaces and strong resin removal, which shows that this water-based route can give high-quality recovery. Liu et al. [202] used nitric acid to decompose the epoxy matrix and release the carbon fibres. Reclaimed

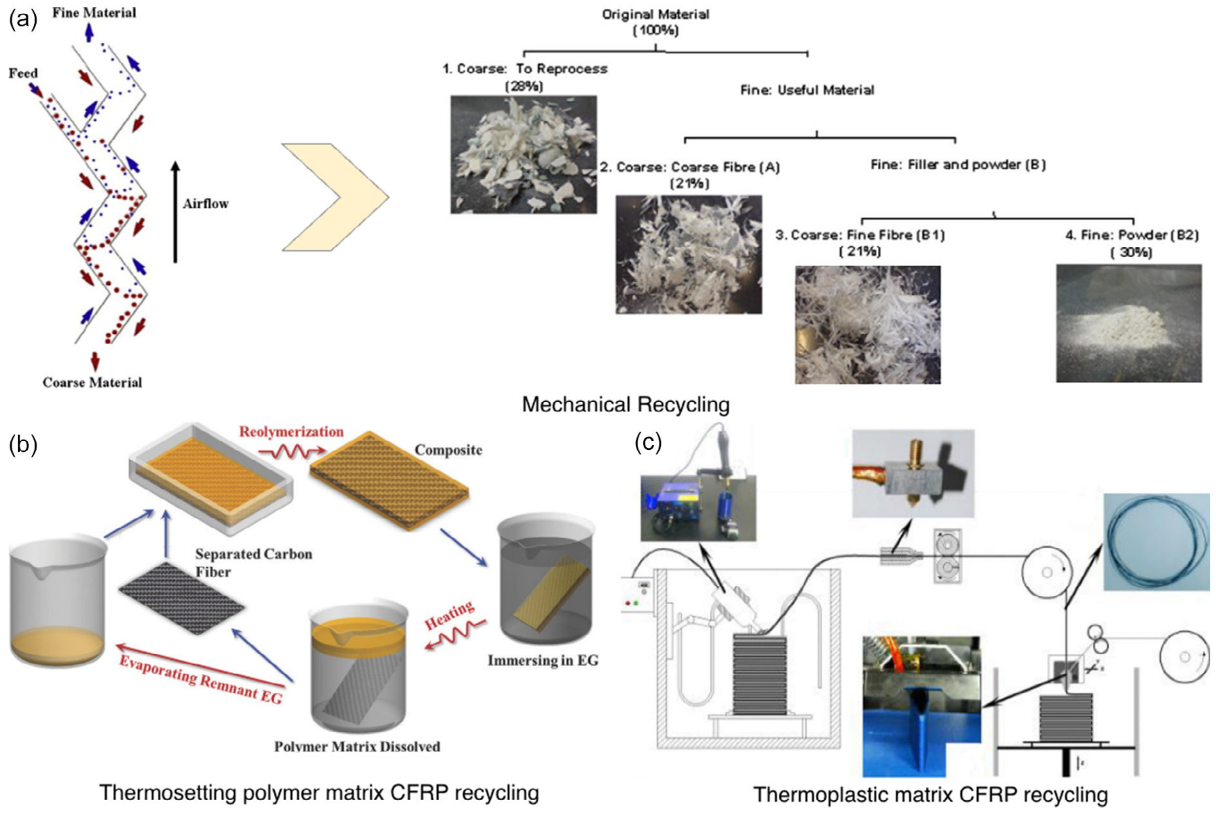

FIGURE 11 | Different recycling approaches in CFRP composites. (a) Mechanical Recycling [195]. Reproduced with permission. Copyright 2009, Elsevier Ltd. (b) Thermosetting polymer matrix CFRP recycling [196]. Reproduced with permission. Copyright 2016, John Wiley & Sons Ltd. (c) Thermoplastic polymer matrix CFRP recycling [197]. Reproduced with permission. Copyright 2017, Elsevier Ltd.

fibres showed substantial retention of tensile strength, supporting the reuse of fibres in secondary structural applications.

For thermoplastic matrix recycling, as shown in Figure 11c, a recent study has been conducted in which recycling and re-manufacturing was conducted on a CFRP composite based on poly-lactic acid [197]. In this study, localised remelting of the matrix material is performed while the reinforcing fibre is pulled out of the composite, resulting in the recovery of a continuous fibre filament impregnated with the re-solidified thermoplastic material. The fibre filament obtained is fed through a remoulding nozzle for smoothing, rolling up, and reuse in the next additive manufacturing process. The mechanical properties of the re-manufactured composites show promising results. Similarly, Zhang et al. [203] demonstrated a reverse tool-path thermal-radiation method for carbon fibres in the PEEK Matrix. They selectively softened the thermoplastic matrix along the printed path to peel and recover continuous fibre filaments for reusing. In conclusion, CFRP composite recycling has a clear future because it reduces waste, reduces material costs, and reduces supply risks for high-value fibres. However, more studies are needed to standardise fibre-quality metrics, surface conditioning, and printability, and to scale the most promising routes.

7 | Conclusions and Future Directions

This review brings together the current state of additive manufactured CFRP composites, covering processing technologies, characterisation methods, modelling approaches, and sustainability and end-of-life routes. With this comprehensive analysis, we have:

- Mapped the current technology landscape for additive manufacturing of CFRP composites and highlighted capability trade-offs that govern fibre steering, part scale, and performance,
- Synthesised mechanical characterisation and modelling approaches across various scales, clarifying typical use-cases and limitations for design and reliability assessment,
- Reframed end-of-life recycling within a broader sustainability scope, including life-cycle drivers, energy/waste considerations, and durability/ageing implications.

We have also discussed in-depth any limitations and gaps related to the manufacturing, characterisation, modelling, and sustainability of additive manufactured CFRP composites. The critical research gaps could be summarised as

- **Standardisation and certification:** insufficient qualification pathways for additive manufactured CFRP composites, including standardised documentation of process parameters and widely accepted testing/inspection procedures.
- **Quality assurance and defect control:** absence of a connection between in-situ monitoring and post-process inspection with defect acceptance criteria, limiting the ability to reduce variability in material properties.
- **Durability and ageing:** restricted, controlled-exposure datasets and limited predictive insight to underpin design allowables in actual service conditions.
- **Validated process-structure-property models:** inadequate and not fully validated simulation-driven design and optimisation frameworks for additive manufactured CFRP composites.

7.1 | Insights on Future of Additive Manufactured CFRP Composites

One of the main objectives in the development of CFRP composites is to utilise the tensile properties of continuous fibres by translating them into beneficial longitudinal and transverse properties within the material medium. This is achieved by controlling the fibre orientation and distribution, thereby dictating the anisotropy of the composite along various axes. Focussing on this detail, there are many other factors that add or subtract from the quality of this manufacturing system, and such few remarks and suggestions are presented in this section under four different banners.

7.1.1 | Composite Design

As clearly presented in the literature, the orientation and density of the fibres within the composite material greatly influence the performance of the material. Therefore,

i. A thorough understanding of the relationship between composite design parameters and mechanical properties is significantly important.
ii. Data-driven or AI-based approaches can be used to identify the optimal parameters needed for a particular design chosen by the user.

Furthermore, additive manufacturing of composites has been shown to have potential to replace conventional composite manufacturing methods in the future. Therefore,

iii. Standardising the design environment by generating a universal framework for CFRP design will be a future challenge.

7.1.2 | Materials and Process

Although significant progress has been made in the field of additive manufacturing of CFRP composites, there are still some manufacturing elements that negatively affect the quality of the additive manufactured samples such as void generation, poor inter-laminar adhesion, and vulnerability of fibre and polymer to moisture contents. Therefore,

i. Novel and more efficient techniques for pre-impregnation and in-nozzle impregnation of continuous fibre is needed.
ii. An active compaction method integrated with the additive manufacturing process could support the inter-laminar adhesion.
iii. Further research on the material front is needed for the development of filaments resistance to in-situ moisture.

Furthermore, FFF-produced composites exhibit lower fibre volume fractions compared to conventional techniques. This makes them less competitive, along with process-induced constraints such as gaps between adjacent fibre lines, overlaps within a layer, and twisting of fibres around the corners. Therefore, further developments are recommended in this respect in improving process parameters.

7.1.3 | Production Method

Most composite fibre 3D-printers are limited to a three-axis motion system, which allows the material to be deposition along a planar surface. Therefore, increasing the number of freedoms for the printing head would add another dimension to the composite design, especially while developing corrugated and lattice structures. Furthermore, equipping commercial composite 3D printers with in situ defect detection systems as was studied in the literature could create a meaningful impact on composite products without compromising the manufacturing speed.

7.1.4 | Optimisation

There is considerable ambiguity at the microstructural level, which requires a deeper understanding of failure theory at these scales to shed light on the reliability and lifespan of manufactured components. The process of measuring defects and assessing their influence on the quality of composites after production presents a complex challenge. It is crucial to utilise nondestructive testing techniques, such as ultrasonic testing and computed tomography, to analyse, and to evaluate the quality of high-performance components post-production.

Author Contributions

Cherian Thomas: conceptualisation (equal); data curation (lead); formal analysis (lead); investigation (equal); methodology (equal); visualization (lead); writing – original draft (lead). **Amir Hosein Sakhaei:** conceptualisation (equal); formal analysis (equal); funding acquisition (lead); methodology (equal); supervision (lead); writing – review and editing (lead).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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