

Carbon-Fiber Structural Batteries: From Multifunctional Integration to Retained Reliability

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Abstract

Carbon-fiber structural batteries represent a class of multifunctional energy-storage systems that integrate electrochemical energy storage with mechanical load-bearing capability. Unlike conventional batteries, which are mainly evaluated based on cell-level energy density, structural batteries provide new opportunities for system-level weight reduction by reducing inactive structural mass, improving space utilization, and enabling distributed energy storage within integrated structures. In recent years, substantial progress has been achieved in carbon-fiber electrodes, structural electrolytes, laminated devices, electrolyte topology engineering, and fully carbon-fiber structural batteries. Nevertheless, most reported advances have been demonstrated under relatively ideal static testing conditions, while maintaining multifunctional performance under manufacturing and long-term service conditions remains a critical challenge. This review systematically examines the development of carbon-fiber structural batteries from a reliability perspective. First, the system-level motivations and technological evolution are introduced, and existing architectures are categorized according to their integration depth and degree of multifunctional coupling. Carbon-fiber electrodes are then discussed with emphasis on balancing capacity, ion transport, cycling stability, mechanical property retention, interfacial robustness, and manufacturing scalability. Furthermore, structural electrolytes are reviewed from the viewpoint of topology-enabled regulation of ion transport and load transfer, with particular focus on the intrinsic trade-off between ionic conductivity and mechanical modulus. In addition, manufacturing routes and device architectures are analyzed from the perspective of multifunctionality-degrading defects, including voids, dry regions, coating cracks, weak interfaces, and current-collector discontinuities. Finally, retained multifunctionality is used as a reliability-oriented evaluation criterion to examine the preservation of electrochemical, mechanical, interfacial, and safety functions, with particular emphasis on the carbon-fiber-specific failure chain linking interfacial and manufacturing heterogeneities to multifunctionality-degrading defects, coupled-field localization, and damage propagation. This review emphasizes that reliable carbon-fiber structural batteries require application-specific and coordinated optimization of materials, interfaces, electrolyte topology, coupled degradation behavior, and validation protocols.

Keywords: carbon-fiber structural batteries; structural power composites; retained multifunctionality; carbon-fiber electrodes; structural electrolytes

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1. Introduction

The motivation for structural batteries is closely linked to the mass and volume penalties of conventional energy-storage integration. General reviews by Danzi et al. and Jin et al. have described structural batteries as a route to combine energy storage with load-bearing function, rather than treating the battery as a separate payload [1,2]. This issue is especially relevant for vehicles, aircraft, unmanned systems, satellites, robotic platforms, and distributed electronics, where the battery package competes with frames, casings, thermal management units, and supporting structures for limited mass and volume. In such systems, conventional rechargeable batteries mainly supply electrochemical energy, while the surrounding structure carries mechanical load. The result is a degree of functional separation that structural batteries are designed to reduce [1–5].

This system-level argument also explains why structural batteries should not be judged only by cell-level gravimetric energy density. Asp and Greenhalgh introduced the broader concept of structural power composites, in which energy-storage or energy-harvesting functions are integrated into materials that also contribute mechanically [3]. Later work on structural battery composites further developed this idea by treating the electrochemical cell as part of the composite architecture rather than as an externally attached component [4]. From this perspective, a structural battery with a lower cell-level energy density than a commercial lithium-ion cell may still be valuable if it replaces passive structural mass, reduces additional packaging, or improves volume utilization at the system level [3,4].

Several integration routes have been developed from this idea. Embedded-cell approaches place lithium-ion cells within composite laminates or sandwich structures and can improve packaging efficiency, although the electrochemical and structural functions remain partly separated [6,7]. Material-level structural battery composites aim for deeper coupling by allowing carbon fibers, structural electrolytes, and composite matrices to participate directly in both electrochemical and mechanical functions [2,4,5]. Related structural electrochemical systems and shape-conformable power supplies further broaden the design space by emphasizing device chemistry, geometry, and application-specific integration [8,9].

Existing reviews have, therefore, covered the field from different but complementary perspectives: general structural battery materials and devices [1,2], structural power composite concepts [3,4], lithium-based structural batteries [5], embedded-cell and energy-storage composite designs [6,7], structural electrochemical systems [8,9], safety and reporting protocols [10,11], and aeronautic applications [12]. More recently, Chaudhary et al. discussed structural batteries from concept to deployment, emphasizing system-level integration, multifunctional durability, manufacturing, safety, and application-oriented implementation [13].

These studies have established the conceptual foundation of structural batteries and clarified their potential for system-level mass saving. The recent perspective by Chaudhary et al. [13] further emphasizes the transition beyond proof-of-concept multifunctionality toward manufacturing, durability, safety, and deployment. These general reliability- and deployment-oriented considerations are, therefore, not claimed here as new concepts. The specific focus of the present review is instead on how these challenges manifest in carbon-fiber structural batteries, particularly through carbon-fiber electrode interfaces, structural electrolyte topology, manufacturing-induced multifunctionality-degrading defects, and coupled degradation. For carbon-fiber structural batteries, the key question is not only whether energy storage and load bearing can be combined, but whether both functions can be retained during electrochemical cycling, mechanical deformation, manufacturing, impact, thermal variation, and long-

term service. This distinction is critical because a structural battery is expected to operate as part of a load-bearing structure rather than as a protected standalone cell.

Table 1 compares representative reviews and perspectives on general structural batteries, structural power composites, lithium structural batteries, embedded battery composites, structural electrochemical systems, safety/reporting protocols, and application-oriented structural batteries. Compared with previous reviews, the present review focuses specifically on carbon-fiber structural batteries and reorganizes the field around carbon-fiber electrode interfaces, structural electrolyte topology, manufacturing-induced multifunctionality-degrading defects, coupled degradation, safety, and retained multifunctionality [1–14]. In this context, the general transition toward durability and deployment is recognized as an established direction of the field [13], whereas the present review places particular emphasis on the carbon-fiber-specific coupling among interfaces, electrolyte topology, multifunctionality-degrading defects, and degradation pathways.

Table 1. Positioning of this review relative to representative reviews and perspectives on structural batteries.

Literature Category	Representative References	Main Focus	Remaining Gap Addressed in This Review	Refs.
General structural battery reviews	Danzi et al.; Jin et al.	Materials, devices, and general challenges	Limited focus on carbon-fiber-specific interfaces, electrolyte topology, and retained multifunctionality	[1,2]
Structural power composite framework	Asp and Greenhalgh; Asp et al.	Structural power composites and structural battery composites	Needs updated discussion of recent carbon-fiber electrodes, electrolytes, and manufacturing reliability	[3,4]
Lithium structural battery reviews	Yang et al.	Lithium-based structural batteries and development history	Does not specifically organize carbon-fiber structural batteries around reliability-oriented design	[5]
Embedded battery and energy-storage composite reviews	Galos et al.; Zhou et al.	Embedded cells and structural energy-storage composites	Embedded systems are often partly decoupled from material-level multifunctionality	[6,7]
Structural electrochemical system perspectives	Navarro-Suárez and Shaffer; Hopkins et al.	Device chemistry and high-performance structural energy storage	Requires translation into carbon-fiber interphase and electrolyte topology design	[8,9]
Safety and reporting perspectives	Kalnaus et al.; Greenhalgh et al.	Safety and standardized reporting	This review integrates safety and reporting into retained multifunctionality	[10,11]
Application-oriented reviews	Kühnelt et al.	Aeronautic structural batteries	Needs deeper discussion of carbon-fiber electrodes, defects, and coupled degradation	[12]
Deployment-oriented perspective	Chaudhary et al.	Concept-to-deployment transition, durability, manufacturing, safety, and practical implementation	Broad structural battery perspective; limited carbon-fiber-specific organization around electrode interfaces, electrolyte topology, multifunctionality-degrading defects, and coupled failure mechanisms	[13]
Present review	This review	Carbon-fiber structural batteries, interfaces, electrolyte topology, manufacturing, and reliability	Focuses on carbon-fiber-specific interfaces, electrolyte topology, manufacturing-induced multifunctionality-degrading defects, coupled degradation, and the retention of electrochemical, mechanical, interfacial, and safety performance	—

In this review, retained reliability refers to the ability of carbon-fiber structural batteries to maintain useful electrochemical, mechanical, interfacial, and safety functions after manufacturing, electrochemical cycling, mechanical loading, damage, thermal variation, and service-relevant exposure. This term is used as a reliability-oriented umbrella concept rather than as a separate material property. Within this review, retained multifunctionality is defined as the preservation of electrochemical output, mechanical integrity, interfacial stability, and safety under coupled electrochemical, mechanical, thermal, and manufacturing-induced stresses. This perspective shifts the focus from initial demonstrations of capacity and stiffness toward the durability of coupled ion-transport, electron-transport, load-transfer, and interfacial networks.

The system context and carbon-fiber-specific analytical focus of this review are summarized in Figure 1. Rather than treating energy-storage, load-bearing, electrode interfaces, electrolyte topology, and manufacturing defects as separate topics, the framework emphasizes their coupling within the same carbon-fiber composite body. At the system level, carbon-fiber structural batteries aim to reduce inactive mass and occupied volume by replacing passive structural components with load-bearing energy-storage laminates. At the material level, carbon fibers, active-material coatings, structural electrolytes, current-collection pathways, and polymer matrices form a multifunctional composite in which ion pathways, electron pathways, mechanical load paths, and electrochemo-mechanical interfaces coexist. This coupling gives carbon-fiber structural batteries their multifunctional value, but it also makes them sensitive to interfacial, topological, and manufacturing heterogeneities.

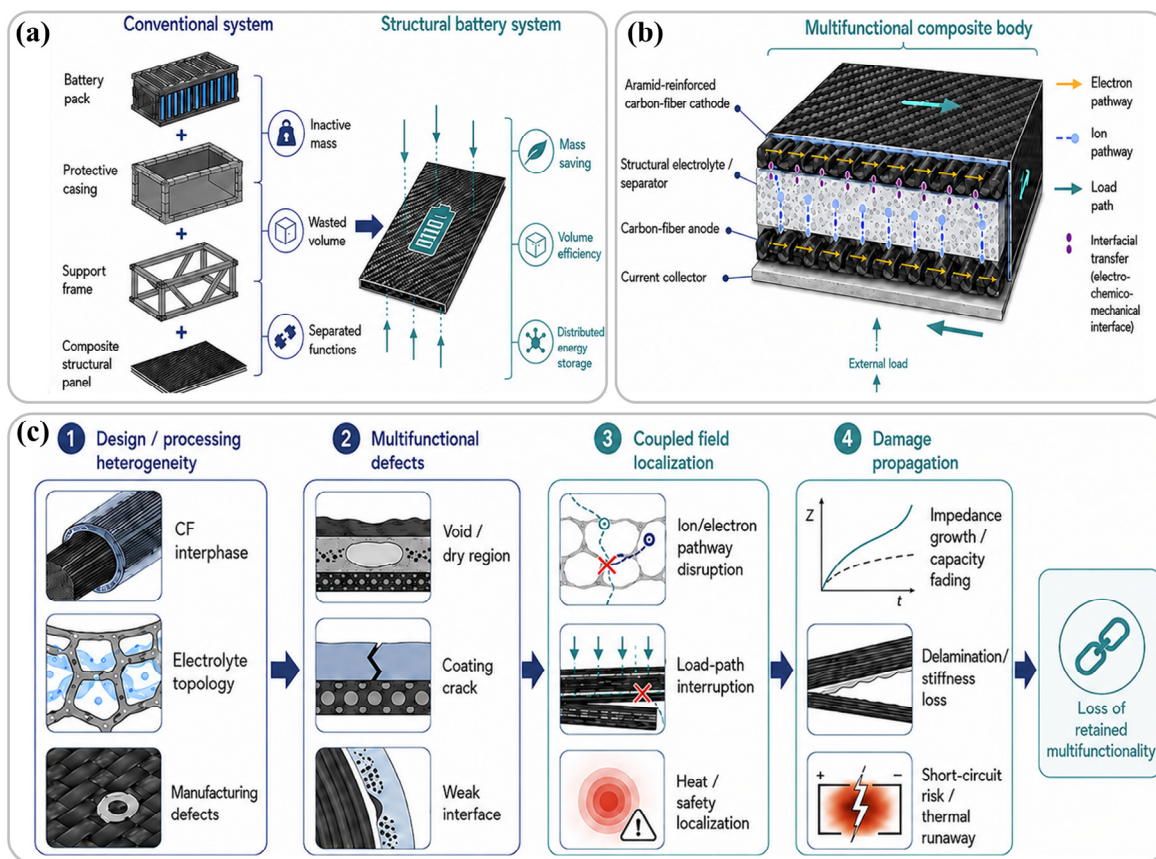


Figure 1. System context, multifunctional coupling, and failure mechanism focus of carbon-fiber structural batteries. (a) System-level comparison between conventional battery systems and

integrated structural battery systems. **(b)** Schematic of a carbon-fiber structural battery as a multifunctional composite body, where carbon-fiber electrodes, active-material coatings, structural electrolytes, current collectors, and polymer matrices jointly provide electron transport, ion transport, load transfer, and interfacial coupling. **(c)** Failure mechanism chain from design/processing heterogeneity to multifunctionality-degrading defects, coupled field localization, damage propagation, and loss of retained multifunctionality.

This mechanism-oriented perspective clarifies the central argument of the present review: carbon-fiber structural batteries should not be assessed only by their initial energy density, capacity, modulus, or strength. A device that appears multifunctional immediately after fabrication may lose practical value if electrochemical cycling, mechanical loading, thermal variation, or manufacturing-induced defects disrupt the coupled ion, electron, load-transfer, and interfacial networks. Therefore, retained multifunctionality is used throughout this review as a reliability-oriented criterion for judging whether a carbon-fiber structural battery can preserve useful electrochemical, mechanical, interfacial, and safety functions after manufacturing and service-relevant exposure. It is not intended here as a new general concept-to-deployment framework, but as a criterion for organizing and assessing performance retention in carbon-fiber structural batteries.

1.1. Scope and Literature Selection

This review focuses on carbon-fiber structural batteries, defined here as structural battery systems in which carbon fibers contribute essentially to both mechanical reinforcement and electrochemical or electronic function. This definition distinguishes carbon-fiber structural batteries from batteries that are merely enclosed in carbon-fiber housings or attached to composite structures. In the systems considered here, carbon fibers may serve as load-bearing reinforcements, electron-conducting networks, current-collecting pathways, lithium-hosting negative electrodes, or mechanically continuous scaffolds for active-material coatings. Accordingly, the scope includes pristine carbon-fiber negative electrodes, active-material-coated carbon-fiber positive electrodes, electrochemically modified carbon-fiber fabrics, carbon-fiber electrode laminae, carbon-fiber-reinforced structural battery composites, and structural electrolytes integrated with carbon-fiber architectures.

The literature discussed in this review was selected to represent five interconnected aspects of carbon-fiber structural batteries: structural battery and structural power composite concepts, carbon-fiber electrode materials and electro-chemo-mechanical interfaces, structural electrolytes and topology-controlled ion transport, structural architectures and manufacturing routes, and coupled degradation, safety, modeling, and reporting protocols. Particular emphasis is placed on studies that report both electrochemical and mechanical properties, because such studies provide the most direct evidence for multifunctional performance. Studies that further examine cycling stability, mechanical loading, interfacial evolution, manufacturing defects, post-damage behavior, or standardized reporting are treated as especially relevant to retained multifunctionality [10,11].

The literature survey was guided by searches in major scientific databases, including Web of Science, Scopus, Google Scholar, and publisher databases. Search terms included structural battery, carbon-fiber structural battery, structural power composite, carbon-fiber electrode, structural electrolyte, multifunctional battery composite, load-bearing energy storage, structural lithium-ion battery, structural zinc battery, and carbon-fiber-reinforced battery composite. Foundational studies were included to establish the conceptual and historical development of the field, whereas recent studies were selected

to capture advances in carbon-fiber electrodes, structural electrolytes, manufacturing strategies, reliability testing, and application-oriented structural integration.

The inclusion criteria were as follows. First, the study should involve a structural energy-storage system in which mechanical and electrochemical functions are integrated at the material, lamina, laminate, or component level. Second, carbon fibers should play a direct structural and electrochemical or electronic role rather than acting only as an external casing or passive support. Third, the work should provide information relevant to multifunctional performance, such as capacity, energy density, Coulombic efficiency, cycling stability, modulus, strength, stiffness, interfacial adhesion, damage tolerance, or safety behavior. Fourth, studies on structural electrolytes, embedded cells, structural supercapacitors, or related multifunctional electrochemical systems were included selectively when they offered transferable insights into electrolyte integration, interface design, current collection, manufacturing, coupled testing, or failure analysis.

1.2. Concept and Classification of Carbon-Fiber Structural Batteries

At present, the design of structural batteries is usually divided into system-level integration and material-level integration. System-level integration mainly utilizes relatively mature battery technology and established processing methods to embed traditional or improved battery cells into load-bearing composite structures. For example, embedded thin-film lithium batteries, integrated composite batteries, and multifunctional sandwich structures all indicate that electrochemical devices can be integrated into structural laminates or panels [6,7,15–18]. However, in this design, electrochemical and mechanical functions are still separated, with embedded batteries used for energy storage and composite materials used for load bearing. As a result, although this approach can improve packaging efficiency, it may also introduce stiffness mismatch, local stress concentration, thermal management problems, and damage sensitivity around the embedded cell.

Material-level integration represents a more strongly coupled form of multifunctionality. In this approach, the constituents of the composite are not only structural elements but also active participants in the electrochemical operation. Carbon fibers may serve as load-bearing reinforcements, current collectors, electron-conducting networks, lithium-hosting negative electrodes, or scaffolds for positive-electrode coatings. Structural electrolytes may function simultaneously as ion-conducting media, separators, polymer matrices, and load-transfer phases [2,4,5]. This “battery-as-composite” concept is fundamentally different from a “battery-in-composite” design because structural and electrochemical functions are coupled within the same material architecture.

Carbon-fiber structural batteries are particularly important because carbon fibers combine low density, high specific stiffness, high tensile strength, electrical conductivity, and compatibility with composite manufacturing. Recent free-form carbon-fiber structural batteries further show that carbon-fiber-based energy-storage structures can be shaped toward curved or application-specific geometries, suggesting a route toward distributed energy storage in load-bearing surfaces [14]. This shape-conformable design direction is especially relevant for aerospace structures, unmanned aerial vehicles, robotic shells, and vehicle components where structural volume is limited and conventional battery modules are difficult to integrate efficiently [12,14].

The development of carbon-fiber structural batteries can be understood from historical, architectural, and research-focus perspectives, as summarized in Figure 2. Early studies mainly focused on the feasibility of integrating electrochemical energy storage into load-bearing structures. Later work gradually moved from embedded-cell and sandwich configurations toward material-level systems in which carbon fibers and structural electrolytes participate directly in both electrochemical and mechanical functions. More

recent studies have extended this direction toward free-form, shape-conformable, and high-performance carbon-fiber structural batteries, where manufacturing reliability, coupled degradation, and service retention become increasingly important [14,19–22].

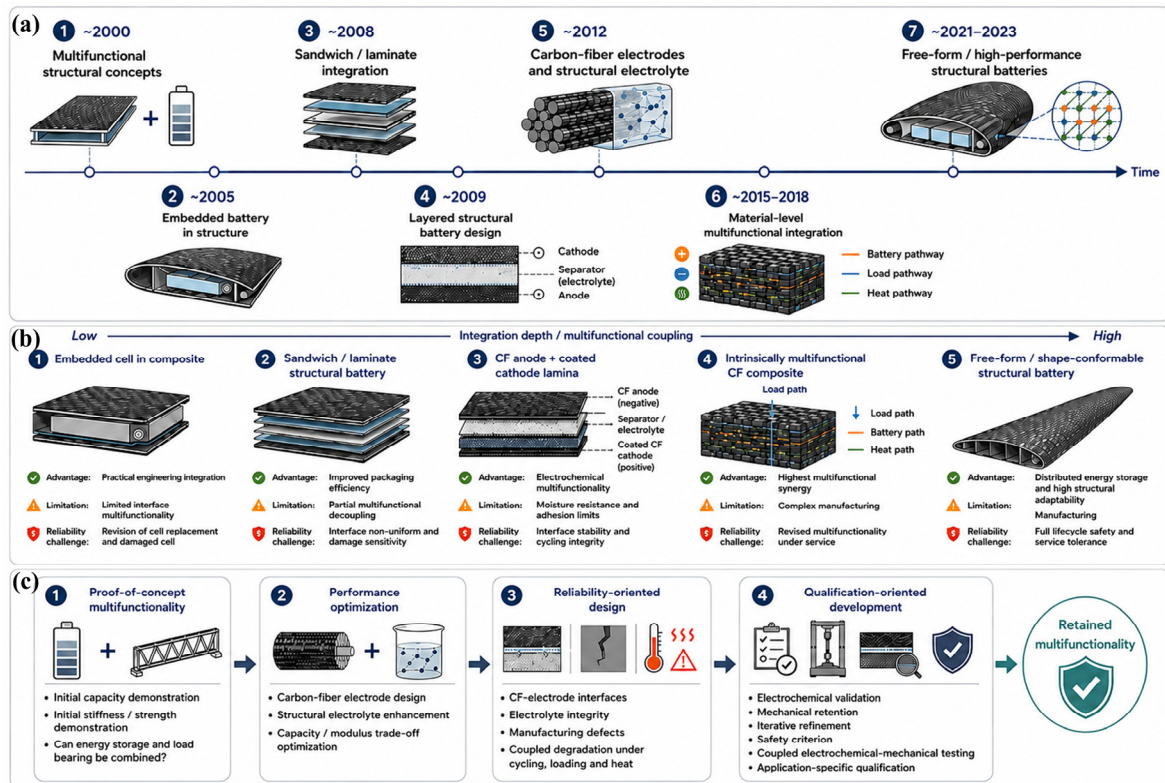


Figure 2. Historical evolution, technical routes, and research focus shift of carbon-fiber structural batteries. (a) Historical development from early multifunctional structural concepts to material-level carbon-fiber structural batteries and free-form/high-performance systems. (b) Representative technical routes classified by integration depth and multifunctional coupling, including embedded cells, sandwich/laminate batteries, carbon-fiber electrode laminae, intrinsically multifunctional composites, and free-form structural batteries. (c) Research focus shift from proof-of-concept multifunctionality to performance optimization, reliability-oriented design, and qualification-oriented development.

As illustrated in Figure 2, the development of structural batteries has evolved from packaging-level integration toward material-level multifunctional composites. Embedded systems remain relevant because they provide practical engineering routes for integrating near-commercial battery cells into load-bearing structures. However, their material-level multifunctional efficiency is limited if the battery and the structure remain largely decoupled. In contrast, carbon-fiber structural batteries attempt to integrate load-bearing fibers, active materials, structural electrolytes, and current-collection pathways into continuous multifunctional networks. The key challenge is, therefore, not simply to place electrochemical components inside a composite, but to design a composite body in which load paths, electron pathways, ion pathways, and damage-tolerant interfaces coexist.

1.3. Multifunctional Efficiency and System-Level Motivation

The motivation for structural batteries is sometimes misinterpreted as an attempt to directly outperform commercial lithium-ion cells in gravimetric energy density. This is not the most appropriate benchmark. In lightweight engineering systems, the relevant

question is whether the structural battery improves the mass and volume efficiency of the complete structure. A device with moderate cell-level energy density may still be valuable if it replaces passive structural mass, reduces packaging components, and contributes to stiffness, strength, or shape stability [1–5].

A useful structural battery should, therefore, be evaluated by multifunctional performance. If electrochemical performance is improved at the cost of nearly eliminating stiffness or strength, the device approaches a conventional battery. Conversely, designs with excellent mechanical properties but poor ion transport or limited cycling stability are more like simple composite materials. Therefore, carbon-fiber structural batteries should be evaluated using both electrochemical metrics, such as energy density and areal capacity, and mechanical metrics, including stiffness, strength, toughness, damage tolerance, safety, manufacturability, and long-term durability. Both energy-storage and load-bearing functions must be maintained at practically useful levels [3,9–11].

The appropriate balance among these properties depends strongly on the intended application. For electric-vehicle components, crash resistance, manufacturability, repairability, and thermal safety may be the most important concerns. For aerospace panels, greater emphasis is usually placed on stiffness, fatigue resistance, vibration tolerance, and mass reduction. Satellite structures may prioritize dimensional stability, vacuum compatibility, and long-term reliability. Robotic and unmanned aerial systems may prioritize shape conformity, distributed energy storage, and repeated deformation tolerance. Therefore, a carbon-fiber structural battery should not be assessed as a generic battery cell, but as an application-specific structural energy-storage component [12,14].

Representative demonstrations support this system-level motivation. Early multifunctional structural battery designs established the feasibility of integrating energy storage into load-bearing components [15]. Embedded thin-film lithium cells and integrated composite batteries demonstrated practical routes for packaging energy-storage devices within structural laminates [16–18]. Carbon-fiber-reinforced structural lithium-ion battery composites have been explored for aerospace-oriented systems, such as CubeSat power integration, where structural mass and energy-storage mass are tightly constrained [19]. Structural ceramic batteries based on inorganic waterglass binders further showed that rigid, mechanically robust binders can contribute to both cell integrity and structural function [20]. More recently, intrinsically coupled structural battery composites have demonstrated improved multifunctional performance by using carbon fibers and structural electrolytes as active electrochemical and mechanical constituents [21,22].

These studies demonstrate the potential of structural batteries but also reveal a major limitation of the current literature: most studies report only initial capacity, stiffness, or strength, whereas quantitative data on the retention of these properties after electrochemical cycling, mechanical loading, machining-induced stress, and damage exposure. Closing this gap is essential for moving from multifunctional demonstration to engineering qualification. In this context, the research focus shift shown in Figure 2c is important: the field has moved from asking whether energy storage and load bearing can be combined toward asking whether both functions can be maintained under realistic operating and manufacturing conditions. However, throughout this review, studies reporting only initial or component-level multifunctional performance are distinguished from those that directly demonstrate post-cycling, post-loading, damage-exposed, or coupled-condition performance retention.

1.4. Failure Mechanism Chain Limiting Retained Multifunctionality

The key barriers to retained multifunctionality in carbon-fiber structural batteries are often described as four technical bottlenecks: carbon-fiber electrode interfaces, structural

electrolyte topology, manufacturing control, and coupled degradation/safety. However, these factors should not be treated as independent challenges. In a load-bearing electrochemical composite, they are connected through a failure mechanism chain in which local heterogeneities evolve into multifunctionality-degrading defects, defects localize electrochemical and mechanical fields, localized fields drive coupled damage propagation, and accumulated damage finally causes the loss of electrochemical output, mechanical integrity, interfacial stability, and safety tolerance.

As summarized in Figure 1c, interfacial, electrolyte topology, and manufacturing heterogeneities first generate multifunctionality-degrading defects, such as voids, dry regions, coating cracks, and weak interfaces. These defects localize electrochemical, mechanical, and thermal fields, causing ion/electron pathway disruption, load-path interruption, and safety-relevant heat localization. The resulting impedance growth, capacity fading, delamination, stiffness loss, and short-circuit or thermal-safety risk eventually lead to the loss of retained multifunctionality. Degradation can then further worsen wetting, contact, current distribution, and stress fields.

This cascade begins with design and processing heterogeneity. Carbon-fiber structural batteries combine carbon-fiber reinforcements, active-material coatings, structural electrolytes, separators, current collectors, and composite matrices within a single device architecture. Each constituent must satisfy more than one function. Carbon fibers must carry load while providing electronic conduction, current collection, lithium storage, or active-material support. Structural electrolytes must provide ion conduction, electrical separation, interfacial adhesion, and load transfer. Manufacturing must produce uniform coating, sufficient electrolyte infiltration, controlled fiber alignment, low void content, stable interfaces, and reliable current-collector placement. Any nonuniformity in these regions can initiate coupled failure.

The first critical stage is the formation of multifunctionality-degrading defects. In conventional batteries, a local defect may mainly affect electrochemical transport or electrical isolation. In conventional composites, a defect may mainly affect load transfer or crack initiation. In structural batteries, the same defect can simultaneously damage electrochemical, mechanical, and interfacial functions. A void can act as both a crack-initiation site and an ionic transport barrier. A dry region can reduce interfacial adhesion while increasing local impedance. A resin-rich region can interrupt load transfer and restrict ion access. A coating crack can reduce active-material utilization while creating stress concentration. A weak carbon-fiber/electrolyte interface can cause both contact loss and delamination. Defects in carbon-fiber structural batteries should, therefore, be understood as multifunctionality-degrading defects rather than as purely mechanical or electrochemical imperfections.

These multifunctionality-degrading defects then cause coupled-field localization. Poor electrolyte wetting, disconnected ion-conducting domains, or blocked through-thickness pathways increase ionic resistance and create local electrolyte starvation. Coating cracks, fiber/electrode debonding, or current-collector discontinuities disrupt electron pathways and generate nonuniform current distribution. Voids, wrinkles, weak interfaces, and delamination concentrate stress and weaken interlaminar load transfer. As electrochemical cycling proceeds, local impedance growth can intensify current-density heterogeneity and heat generation. Under mechanical loading, stress concentration can enlarge interfacial cracks and disturb electrode/electrolyte contact. Ion transport, electron transport, stress distribution, and heat generation, therefore, become locally coupled rather than independently distributed.

Once electrochemical and mechanical fields are localized, degradation can accelerate through positive feedback. Local impedance growth reduces active-material utilization and accelerates capacity fading. Contact loss increases polarization and may promote

parasitic interfacial reactions. This coupling explains why structural batteries cannot be qualified by separate battery tests and composite tests alone [10,11].

The final outcome of this failure mechanism chain is the loss of retained multifunctionality. Capacity, Coulombic efficiency, rate capability, stiffness, strength, interfacial adhesion, dimensional stability, and safety margin may all decline through the same damage pathway. A structural battery may, therefore, show acceptable initial energy density and modulus but fail to remain useful if its ion pathways, electron pathways, load paths, and interfaces are not stable under manufacturing and service-relevant exposure. This is the fundamental distinction between initial multifunctionality and retained multifunctionality. In this review, retained multifunctionality is not interpreted as an arithmetic average of electrochemical, mechanical, interfacial, and safety retention. These functions are non-compensatory when they are critical to the intended application. For example, high-capacity retention cannot compensate for unacceptable loss of stiffness, interfacial integrity, electrical isolation, or safety. Accordingly, loss of multifunctionality is considered to occur when any application-critical function falls below its required acceptance level after a defined manufacturing or service-relevant exposure. The specific acceptance levels are necessarily application dependent and should be reported together with the corresponding test conditions.

This mechanism-oriented view defines the reliability challenge addressed throughout this review. Accordingly, the term “demonstrated reliability” is reserved here for studies that directly evaluate performance retention after relevant cycling, mechanical loading, damage, or coupled exposure. Studies reporting only initial multifunctional properties are treated as proof-of-concept or indications of multifunctional potential. Carbon-fiber electrode interfaces are discussed in Section 2 because they determine the stability of electron pathways, active-material anchoring, electrolyte contact, and interfacial load transfer. Structural electrolytes are discussed in Section 3 because their topology governs the coexistence of ion-conducting pathways and load-bearing skeletons. Structural architectures and manufacturing routes are discussed in Section 4 because they convert material-level multifunctionality into device-scale performance while introducing or suppressing multifunctionality-degrading defects. Finally, the conclusions and outlook emphasize coupled electrochemical–mechanical testing, safety evaluation, standardized reporting, and application-specific qualification because retained multifunctionality can only be demonstrated when electrochemical, mechanical, interfacial, and safety functions are evaluated together.

2. Carbon-Fiber Electrodes and Interphase Engineering

Carbon fibers are the key multifunctional component in carbon-fiber structural batteries. In conventional carbon-fiber-reinforced polymer composites, they are mainly used to provide stiffness, tensile strength, and continuous load-transfer pathways. In structural batteries, however, their function extends beyond mechanical reinforcement. Depending on the cell design, carbon fibers may also act as current collectors, electron-conducting networks, lithium-hosting negative electrodes, or continuous scaffolds for active-material coatings [22,23]. This dual role distinguishes them from conventional metal current collectors and from passive reinforcing fibers in ordinary composites. Because the same fibrous network is involved in both electrochemical operation and mechanical load transfer, the carbon-fiber surface becomes a critical electro-chemo-mechanical interface.

The behavior of carbon-fiber electrodes is influenced by several coupled factors, including fiber microstructure, degree of graphitization, surface chemistry, sizing layer, defect density, electrolyte accessibility, active-material adhesion, and interfacial load transfer. PAN-based carbon fibers contain partially ordered and turbostratic carbon

domains that can reversibly host lithium ions. However, their usable capacity and cycling stability are strongly affected by the fiber type, electrode configuration, surface condition, and local transport environment [24–27]. At the same time, lithiation, cycling, chemical modification, coating deposition, and interphase formation may influence fiber strength or interfacial bonding. Carbon-fiber electrode design, therefore, cannot be reduced to maximizing electrochemical capacity. A structurally useful electrode must maintain ion accessibility, electronic conduction, coating adhesion, interfacial load transfer, and mechanical integrity simultaneously.

The central argument of this section is that carbon-fiber structural electrodes should be designed as interfacial systems rather than as isolated active materials. For pristine fibers, the key issue is how lithium storage and tensile retention can coexist. For coated fibers, it is how active materials can be anchored without forming brittle, delaminating, or transport-limited layers. For electrode laminae, it is how fiber packing, electrolyte penetration, current collection, and load transfer can be coordinated at the laminate scale. These issues are discussed below from fiber-level lithiation to lamina-level electrode design, active-material coating, chemically engineered interphases, electrode/electrolyte contact, comparative electrode assessment, and design principles for durable carbon-fiber structural electrodes.

2.1. Carbon Fibers as Multifunctional Negative Electrodes

The use of carbon fibers as negative electrodes is one of the earliest foundations of carbon-fiber structural batteries. PAN-based carbon fibers can intercalate lithium ions and, therefore, provide electrochemical storage while retaining their reinforcing function [24]. This dual role is attractive because it can reduce the need for separate graphite electrodes and metallic current collectors, thereby improving material-level multifunctionality. In principle, the same fiber network can carry mechanical load, conduct electrons, and participate in charge storage.

However, carbon fibers are not equivalent to conventional graphite particles. Graphite electrodes are optimized primarily for lithium intercalation, particle packing, binder distribution, and electrolyte wetting. Carbon fibers are optimized primarily for mechanical reinforcement, and their electrochemical activity depends on microstructural ordering, accessible edge sites, surface area, electrolyte contact, and fiber orientation. Early studies on PAN-based carbon-fiber negative electrodes have shown that lithium insertion is feasible, but its capacity, Coulombic efficiency, and rate performance largely depend on the fiber type and electrode configuration [24].

Subsequent work demonstrated that electrochemical cycling can affect tensile properties, while lithium intercalation can alter the mechanical response of carbon fibers [25,26]. These findings are central to structural battery design because the electrode is also part of the load-bearing network.

High-precision coulometry of commercial PAN-based carbon fibers further confirmed that carbon fibers can be evaluated as electrochemical electrodes with measurable irreversible losses, parasitic reactions, and cycling behavior [27]. These measurements are important because even small irreversible losses or interfacial reactions can become relevant when the same electrode surface also has to transfer mechanical load. From a structural point of view, the main advantage of carbon-fiber negative electrodes is that they preserve continuous load paths.

2.2. From Single Fibers to Electrode Laminae

Single-fiber and tow-level tests are useful for studying lithium storage in carbon fibers. Practical structural batteries, however, must operate at the lamina or laminate scale. At this level, a carbon-fiber electrode must provide fiber alignment, electrolyte access,

electronic connection, current collection, and load transfer at the same time. This makes its design different from that of conventional slurry-coated electrodes. In ordinary batteries, porosity, binder content, and coating thickness are mainly adjusted for electrochemical performance. In structural electrodes, these same parameters also affect stiffness, strength, interlaminar bonding, and damage tolerance.

Solid-polymer-electrolyte-coated carbon fibers were among the early attempts to combine ion transport with fibrous reinforcement [28]. Such coatings can improve local ionic contact and enable microscale or fiber-based battery designs. The coating, however, must remain thin, continuous, chemically stable, and compatible with fiber deformation. Otherwise, it may reduce fiber packing density, increase interfacial resistance, or form a weak layer within the composite.

At the lamina level, unidirectional carbon-fiber electrodes have shown that electrochemical activity can coexist with stiffness and strength along the fiber direction [29]. Therefore, these electrodes should not be judged only by voltage profiles or capacity. Fiber-direction stiffness, lamina thickness, interfacial bonding, and retained mechanical contribution are also important. Several trade-offs appear at this scale: dense fiber beds improve stiffness but hinder electrolyte infiltration, thicker electrodes increase areal capacity but restrict ion access, and current collectors improve electronic connection but add inactive mass and local stress concentration.

Recent all-carbon-fiber structural batteries further illustrate the importance of lamina-level and cell-level design by using carbon fibers as both reinforcement and electrode components [22]. Such demonstrations move the field beyond isolated fiber electrochemistry toward true structural battery composites. Nevertheless, the gap between fiber-level storage and laminate-level retained multifunctionality remains substantial. Future lamina studies should report capacity and cycling stability together with fiber volume fraction, electrolyte uptake, active-material loading, thickness uniformity, interlaminar adhesion, tensile or flexural retention, and post-cycling damage morphology.

2.3. Active-Material Coatings on Carbon Fibers

Pristine carbon fibers can function as negative electrodes, but most positive-electrode functions require additional active materials. Lithium iron phosphate, transition-metal oxides, and other active phases have, therefore, been deposited onto carbon fibers to create structural cathodes or hybrid electrode scaffolds. The coating must satisfy four requirements simultaneously: it must store ions, remain electronically connected to the carbon fiber, allow ion access through the structural electrolyte, and resist cracking or delamination under mechanical deformation.

Electrophoretic deposition has been widely used because carbon fibers are conductive and can serve directly as deposition substrates. LiFePO_4 -coated carbon-fiber electrodes demonstrated that cathode materials can be deposited onto carbon fibers for structural lithium-ion batteries [30]. In these systems, carbon fibers act as both mechanical reinforcement and conductive scaffolds, while the deposited LiFePO_4 provides positive-electrode capacity. However, LiFePO_4 coatings also introduce an important trade-off. Increasing the active-material loading can raise the capacity, but an overly thick coating may become brittle, lengthen the ion-diffusion path, build up interfacial stress, and increase the risk of delamination. Coating design, therefore, has to balance active-material utilization with mechanical durability.

Conductive additives offer another way to improve coated carbon-fiber cathodes. LiFePO_4 /graphene oxide coatings on carbon fibers have shown that additive engineering can enhance coating connectivity and improve electrochemical utilization [31]. In these electrodes, conductive additives can help bridge active particles with the carbon-fiber surface.

Surface activation is equally important for improving coating adhesion, as oxidative treatment can introduce polar functional groups on the surface of carbon fibers, thereby increasing surface energy, improving wettability, and enhancing the anchoring effect of active materials on the fiber surface. Sutrisnoh et al. showed that different oxidation treatments can alter the surface chemical composition and morphology of carbon fibers, thereby affecting the electrophoretic deposition process and cathode performance [32]. Subsequent work further linked carbon-fiber cathode performance to multifunctional behavior, emphasizing that surface chemistry, coating morphology, electrochemical output, and mechanical contribution should be considered as interrelated factors [33]. It should be noted that surface activation should be carefully controlled rather than simply maximized, because excessive oxidation may improve wettability, but it may also introduce surface defects and even reduce the tensile strength of carbon fibers.

Graphene additives have also been explored for more environmentally friendly positive electrode designs in structural batteries [34], while the cost-effective LiFePO_4 -coated carbon-fiber cathode further demonstrates that economically feasible electrode processing methods are closely related to the development of actual structural batteries [35]. However, low-cost or environmentally friendly manufacturing alone is not sufficient to meet the application needs of structural batteries, as scalable coating processes must also be able to maintain coating uniformity at the scale of long fibers or fabrics, while being compatible with structural electrolytes, withstanding consolidation pressure during composite processing, and maintaining stability under repeated mechanical loads. Therefore, coating design should not be viewed solely as a material synthesis issue but should be considered simultaneously as a manufacturing feasibility and service reliability issue.

The interfacial logic of the carbon-fiber electrode design is summarized in Figure 3. Chemically derived coatings, such as MOF-derived oxide layers, can create continuous conductive interphases and more robust active-material anchoring, but they also introduce risks associated with volume change, coating stress, and long-term interface evolution.

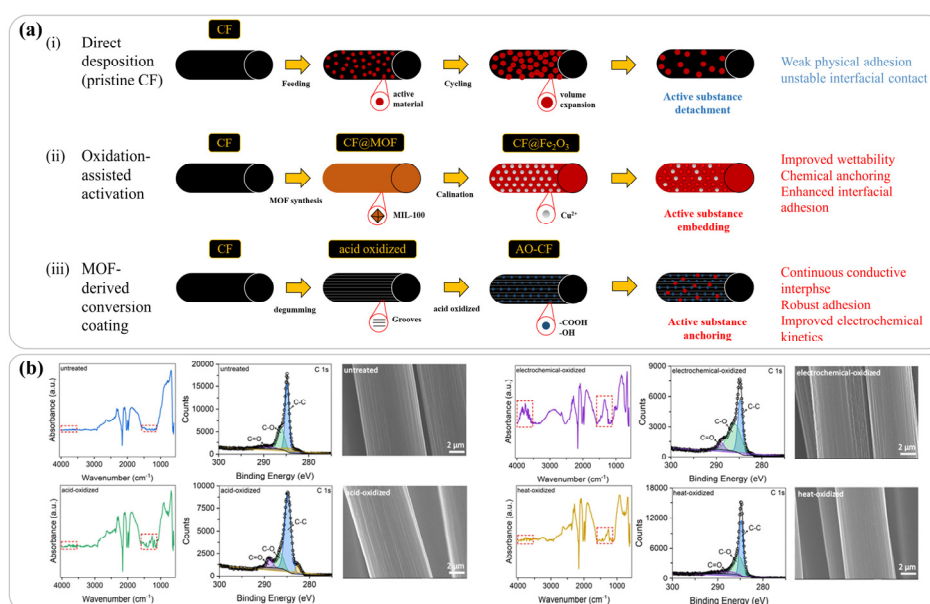


Figure 3. Carbon-fiber electrode and interface engineering. (a) Representative routes for carbon-fiber surface modification and active-material anchoring, including pristine fiber deposition, oxidative activation, and chemically derived active coatings [32,36]. (b) FTIR spectra, high-resolution XPS C 1s spectra, and SEM images of AS4C 3k carbon fibers before and after oxidative

surface treatments. Adapted with permission from ref. [32]. Copyright 2023 Advanced Engineering Materials. In panel (a), yellow arrows indicate processing steps; red outlines identify active-material anchoring, and in panel (b), curve colors distinguish treatment conditions while red dashed boxes highlight spectral regions.

2.4. Chemically Engineered Interphases

The limitations of simple particle deposition have motivated the development of chemically engineered interphases. In an ideal carbon-fiber structural electrode, the interface between the fiber, active material, conductive additive, and electrolyte should not behave as a weak boundary. Ideally, this interface should behave as a continuous electro-chemo-mechanical transition zone, allowing load transfer, electron conduction, ion access, and local stress accommodation to occur within the same region. This view is important because structural battery failure often starts at the interface rather than in the bulk fiber or active material. Loss of contact, coating fracture, electrolyte starvation, and interfacial debonding can all disrupt both electrochemical operation and mechanical load transfer.

MOF-derived coatings are one example of this chemically engineered electrode architecture. Cu-doped MOF-derived α -Fe₂O₃ coatings on carbon-fiber fabrics have been investigated as anode materials for possible lithium-ion and sodium-ion structural batteries [36]. Compared with randomly deposited particles, MOF-derived coatings can provide better control over morphology, porosity, and composition. At the same time, conversion-type oxides bring their own reliability issues, including volume change, low intrinsic conductivity, and interfacial stress during cycling. For this reason, these coatings should not be assessed only by specific capacity. Coating adhesion, impedance evolution, mechanical retention, post-cycling morphology, and deformation stability are also needed to judge their structural battery relevance.

Interface reinforcement offers another route to improve durability. Coupled carbon-fiber structural battery composites with reinforced interfaces have shown that interphases designed for both mechanical and electrochemical functions can improve multifunctional performance [37]. In-situ-interface-engineered solid polymer electrolytes also show that electrode/electrolyte contact can be adjusted during processing to improve mechanical robustness and electrochemical compatibility [38]. Together, these studies suggest that the carbon-fiber electrode interface should be designed together with the structural electrolyte, rather than treated as a separate surface modification problem. Treating fiber surface modification and electrolyte design as separate problems is unlikely to produce durable structural electrodes.

Long-term interfacial evolution is especially important for negative carbon-fiber electrodes. Surface films, electrolyte decomposition products, interphase growth, and contact degradation can change both impedance and load transfer during cycling. Studies of negative carbon-fiber structural electrodes show that interface evolution can govern long-term performance [39]. This means that initial coating morphology or initial impedance is insufficient for judging electrode quality. Structural electrodes should be assessed by how their interfaces evolve under repeated electrochemical cycling, mechanical loading, and combined cycling/loading conditions.

2.5. Comparative Assessment of Carbon-Fiber Electrode Strategies

The electrode strategies discussed above differ in their maturity, electrochemical contribution, mechanical risk, and processing complexity. Pristine carbon fibers offer the most direct form of multifunctionality, but their capacity and rate performance are limited by fiber microstructure and ion-access conditions. Active-material coatings can increase electrode capacity, but they also introduce risks of insufficient adhesion, coating fracture,

and increased ion-transport resistance. To improve interfacial bonding, surface activation is often used to enhance the wettability of carbon fibers and strengthen the anchoring effect of active materials. However, excessive treatment may weaken the intrinsic mechanical properties of the fibers. In contrast, chemically derived coatings offer greater control over morphology and composition, but such coatings still need to withstand volume changes and external mechanical deformations generated during electrochemical cycling processes. Enhanced interfaces and in situ construction of interfaces provide promising pathways for improving mechanical/electrochemical compatibility, but their long-term stability under coupled loading still needs further verification.

Table 2 systematically summarizes the main carbon-fiber electrode design strategies in structural batteries, including raw carbon-fiber anodes, solid polymer-electrolyte-coated carbon fibers, carbon-fiber sheet electrodes, LiFePO₄-coated carbon-fiber cathodes, graphene-assisted coatings, oxidation surface activation, MOF-derived oxide coatings, reinforced or in situ engineering interfaces, and carbon-fiber electrodes in alternative ion systems. For each strategy, the table further lists representative examples, main advantages, key limitations, and relevant references [24–43].

Table 2. Carbon-fiber electrode and interphase strategies for structural batteries.

Strategy	Representative Examples	Key Advantage	Main Limitation	Refs.
Pristine CF anodes	PAN-based carbon fibers	Intrinsic reinforcement/electrode dual function	Limited capacity and rate capability; possible mechanical changes after lithiation/cycling	[24–27]
SPE-coated CFs	Polymer-electrolyte-coated fibers	Improved local ion access	Coating continuity and mechanical compatibility	[28]
CF lamina electrodes	UD carbon-fiber electrode laminae	Lamina-level multifunctionality	Electrolyte infiltration, current collection, and interfacial adhesion	[29,40]
LiFePO ₄ -coated CF cathodes	EPD or coating-based LFP on CFs	Structural positive electrodes	Coating adhesion, cracking, and ion accessibility	[30,32,33,35]
Graphene-assisted coatings	LFP/GO or graphene-modified CF electrodes	Improved electronic connectivity	Additive anchoring and possible ion-transport blockage	[31,34]
Oxidative surface activation	Chemically or electrochemically treated CFs	Better wetting and active-material anchoring	Over-oxidation may damage fibers or reduce tensile retention	[32,33]
MOF-derived oxide coatings	Cu-doped α -Fe ₂ O ₃ on CF fabric	Tunable active coatings and porous morphology	Volume change, low conductivity, and interfacial stress	[36]
Reinforced/in situ interphases	Reinforced CF/electrolyte interfaces	Improved interface durability	Processing complexity and long-term validation	[37–39]
Alternative-ion CF electrodes	Zn and Na structural batteries	Extends chemistry beyond Li-ion	Chemistry-specific interface instability	[41,42]

To provide a more direct quantitative comparison of representative carbon-fiber electrode designs, Table 3 summarizes recently reported electrochemical metrics, including specific capacity, Coulombic efficiency, rate capability, and cycling stability [44–49]. The reported values should be interpreted with caution because the studies differ in carbon-fiber architecture, active-material loading, electrolyte chemistry, half-cell or full-cell configuration, C-rate, and capacity normalization basis. Therefore, Table 3 is intended to show representative experimentally demonstrated performance ranges rather than establish a strict numerical ranking among electrode strategies.

Table 3. Representative electrochemical performance of carbon-fiber electrodes and carbon-fiber-based structural battery configurations reported in recent primary studies.

Electrode Design	Specific Capacity	Coulombic Efficiency	Rate Performance	Cycling Stability	Test Configuration	Ref.
LFP/rGO/CF cathode	122 mAh g ⁻¹ (0.05C); 101 mAh g ⁻¹ (0.1C)	≈90%	0.05–2C; recovery at 0.1C	99.6%/100 cycles (0.1C)	Li half-cell; active-mass basis	[44]
Reclaimed CF/LFP cathode	54 mAh g ⁻¹ (1st cycle, 0.1C)	High; exact value NR	62.0→9.7 mAh g ⁻¹ (C/100→1C)	74.5%/350 cycles	Li half-cell	[45]
LFP/CF-graphite/CF SBC	122 mAh g ⁻¹ (LFP) (0.3C)	NR	122/111/90 mAh g ⁻¹ at 0.3/0.5/1C	91.9%/100 cycles	Full SBC	[46]
PC1100 CF anode	678 mAh g ⁻¹ (1st, 0.05C); 240 mAh g ⁻¹ (0.1C)	99.86% (50th)	Higher than T800 across tested rates	Stable to 125 cycles	Li half-cell	[47]
LFP/CNT/PVP/CF cathode	134.41 mAh g ⁻¹ (0.1C)	≈98%	>90% recovery after rate test	96%/200 cycles (0.5C)	Li half-cell	[48]
LFP/CF-LTO/CF SBC	≈114→83 mAh g ⁻¹ (0– 100 cycles, 0.1C)	>99% during stable cycling	115→98 mAh g ⁻¹ (0.1→1C)	≈73%/100 cycles	Full SBC; LFP basis	[49]

NR, not reported; SBC, structural battery composite.

The semi-quantitative comparison in Figure 4 presents the performance trade-offs between different carbon-fiber electrode designs from a more intuitive perspective. For the original carbon-fiber anode, its continuous fiber network is preserved, thus it has certain advantages in maintaining mechanical properties and process scalability, but its capacity contribution and ion accessibility are still limited. In contrast, surface-activated carbon fibers can improve electrode performance by improving wettability and enhancing interfacial stability, but excessive activation may also weaken the mechanical retention ability of the fibers. Coating cathodes with active materials and auxiliary coatings with conductive additives often help to increase capacity and improve rate behavior, but their cycling stability still largely depends on the integrity of the coating and the stability of the electrode/electrolyte interface contact. MOF-derived or oxide-coated carbon fibers may further provide higher capacity but are also more susceptible to risks, such as volume changes, interface stress accumulation, and processing complexity. Strengthening interfaces and in situ engineering interfaces are particularly noteworthy because they directly address key issues, such as adhesion, contact stability, and electrochemical mechanical compatibility. However, their scalable preparation capabilities and long-term durability under coupled loads still need further verification.

The scores in Figure 4 are intended as an ordinal semi-quantitative comparison rather than a statistical ranking. A score of 1 represents very limited performance or strong limitations, 2 represents relatively low performance, 3 represents intermediate performance, 4 represents relatively high performance, and 5 represents the strongest performance among the strategies compared. For capacity contribution, rate/ion access, and cycling retention, the ratings were assigned primarily from representative quantitative data and trends reported in the cited literature. Mechanical retention and interfacial robustness were assessed from reported mechanical property changes, adhesion/interface stability, and observed degradation behavior, whereas manufacturing scalability was evaluated from process complexity, number of processing steps, material compatibility, and demonstrated scale of fabrication. Where directly comparable quantitative data were unavailable, the scores represent a qualitative synthesis of the reported literature rather than a numerical meta-analysis.

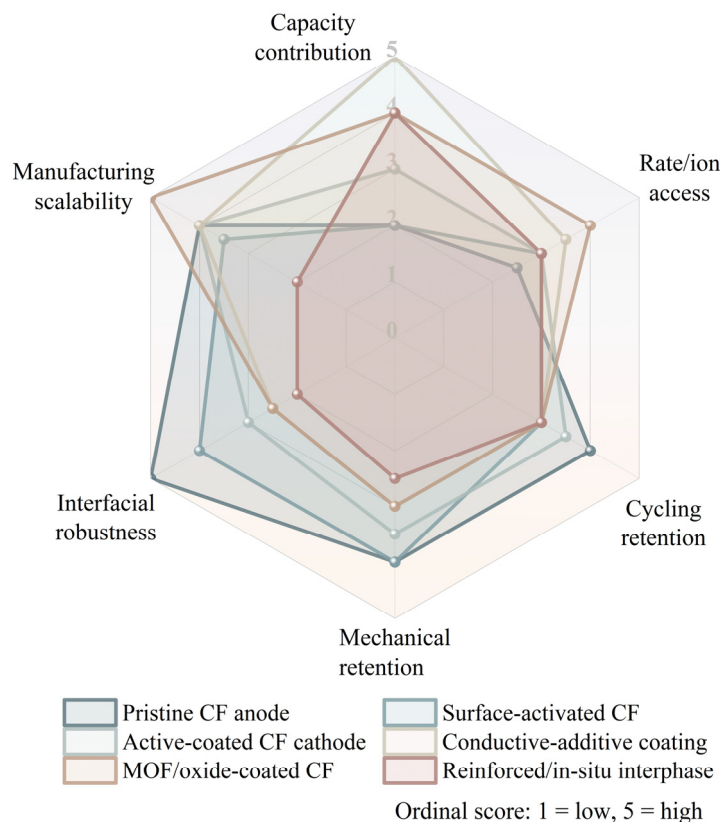


Figure 4. Semi-quantitative multifunctional comparison of carbon-fiber electrode strategies. Scores represent relative ordinal ratings (1 = very limited; 5 = strongest) based on representative literature data and reported trends, as described in the text.

No single electrode strategy currently satisfies all requirements for structural batteries. Pristine fibers offer the most intrinsic form of multifunctionality, but their electrochemical output is limited. Coated fibers can increase capacity, but they also introduce interfacial fragility. Reinforced and in situ engineered interphases improve durability, although they usually add processing complexity. Alternative-ion chemistries further expand the design space, while bringing new compatibility issues. Future carbon-fiber electrodes, therefore, need to be developed through coupled optimization of electrochemical performance, mechanical retention, interfacial stability, and manufacturability, rather than through isolated material modification.

2.6. Design Principles for Durable Carbon-Fiber Structural Electrodes

The surface activation of carbon fibers should be carefully controlled rather than simply maximized. Mild oxidation, coupling layers, or chemically compatible surface treatments can improve wetting and anchoring of active materials. However, excessive oxidation may damage the fiber surface and reduce tensile strength. Therefore, a balance point should be sought for surface chemistry, roughness, oxygen content, coating adhesion, and tensile retention.

Higher active-material loading does not necessarily result in better structural battery performance. Although increased loading can improve areal capacity, excessive coating thickness or brittleness can lengthen Li-ion diffusion pathways, increase internal stress, and promote interfacial delamination. Therefore, structural batteries should pay attention to parameters such as areal loading and coating thickness.

Conductive additives should also be incorporated into the coating network when needed, and their structural value lies in the ability of the battery to maintain electronic pathways under deformation, solidification, and cycling. Oxidized graphene, graphene, carbon black, or other conductive materials can improve electronic pathways. Their role is to maintain electronic connectivity, particularly when coatings undergo deformation, consolidation, or electrochemical cycling.

Electrode performance should be reported using metrics that reflect retained multifunctionality rather than only initial electrochemical activity. For pristine carbon fibers, capacity and Coulombic efficiency should be reported together with tensile retention, surface state, and post-cycling morphology. For coated carbon fibers, specific capacity should be accompanied by active-material loading, coating thickness, adhesion, impedance evolution, and mechanical retention. For electrode laminae, capacity and rate capability should be interpreted together with fiber volume fraction, electrolyte uptake, current-collection geometry, and interlaminar strength. Such reporting is necessary because carbon-fiber electrodes are not isolated active materials—they are load-bearing electrochemical interfaces embedded within structural composites.

The carbon-fiber electrode interface is the region where structural batteries either retain or lose multifunctionality. The next stage of progress will depend on quantitative links among fiber microstructure, surface chemistry, coating architecture, electrolyte contact, transport resistance, and mechanical degradation. Future carbon-fiber structural electrodes should, therefore, move beyond empirical coating demonstrations toward predictive electro-chemo-mechanical interface engineering. This interface-centered view provides the foundation for Section 3, where the structural electrolyte is discussed as the second critical multifunctional network that must simultaneously support ion transport and load transfer.

3. Structural Electrolytes: Topology-Controlled Ion Transport and Load Transfer

Structural electrolytes are among the most demanding components in carbon-fiber structural batteries. In conventional lithium-ion batteries, electrolytes are primarily optimized for ionic conductivity, electrochemical stability, separator compatibility, and electrode wetting. In structural batteries, the electrolyte must also transfer load, maintain dimensional stability, provide interfacial adhesion, tolerate deformation, and resist damage propagation. It may simultaneously function as an ion conductor, separator, binder, polymer matrix, and interfacial phase between carbon-fiber electrodes. These combined requirements create an inherent material–design conflict: ion transport is generally favored by high segmental mobility and liquid-rich or compliant polymer domains, whereas efficient load transfer requires rigid interfaces and well-connected load-bearing networks. Related gel polymer electrolyte studies further show that ion transport can be regulated through deliberately engineered polymer–filler interactions. For example, a three-dimensional PFPE-containing polymer network combined with Li_2O fillers was shown to generate space-charge-layer effects and synergistically enhance Li^+ transport [50]. Although this electrolyte was developed for lithium-metal batteries rather than structural batteries, the result illustrates how polymer network chemistry and inorganic fillers can be used to regulate ion transport at the molecular and interfacial levels.

The challenge is, therefore, not merely to achieve acceptable conductivity and modulus, but to organize the electrolyte into a multiphase architecture in which both the ion-conducting phase and the load-bearing skeleton remain continuous. Early structural lithium-ion battery electrolytes based on reaction-induced phase separation demonstrated that polymer-rich and electrolyte-rich domains can coexist within the same material. Later, bicontinuous electrolytes produced by thermally initiated polymerization once again

demonstrated that the continuous phase separation network can maintain ion conductivity and structural stiffness. These studies established the foundation for topology-controlled structural electrolytes: conductivity and stiffness are not only bulk material properties, but also consequences of spatially organized ion-transport and load-transfer networks.

In carbon-fiber structural batteries, this topology problem is amplified by the fibrous electrode architecture. The electrolyte must wet carbon-fiber surfaces, penetrate fiber bundles or laminae, maintain electrical separation between electrodes, adhere to active coatings, and transfer interlaminar stress. A free-standing electrolyte film with acceptable conductivity may perform poorly inside a dense carbon-fiber laminate if ion-conducting domains become blocked, compressed, disconnected, or poorly bonded. Structural electrolyte performance should, therefore, be evaluated in relation to electrode architecture, manufacturing pressure, electrolyte infiltration, and laminate-level transport pathways.

The topology roadmap of representative structural battery electrolytes is summarized in Figure 5. The field has evolved from stochastic bicontinuous phase-separated electrolytes toward topology-aware networks, reinforced composite electrolytes, architected skeletons, gel-in-resin systems, mechanically interlocked structures, and fire-resistant cocontinuous matrices. This evolution reflects a broader shift from chemistry-driven electrolyte formulation toward architecture-controlled ion/load pathway design.

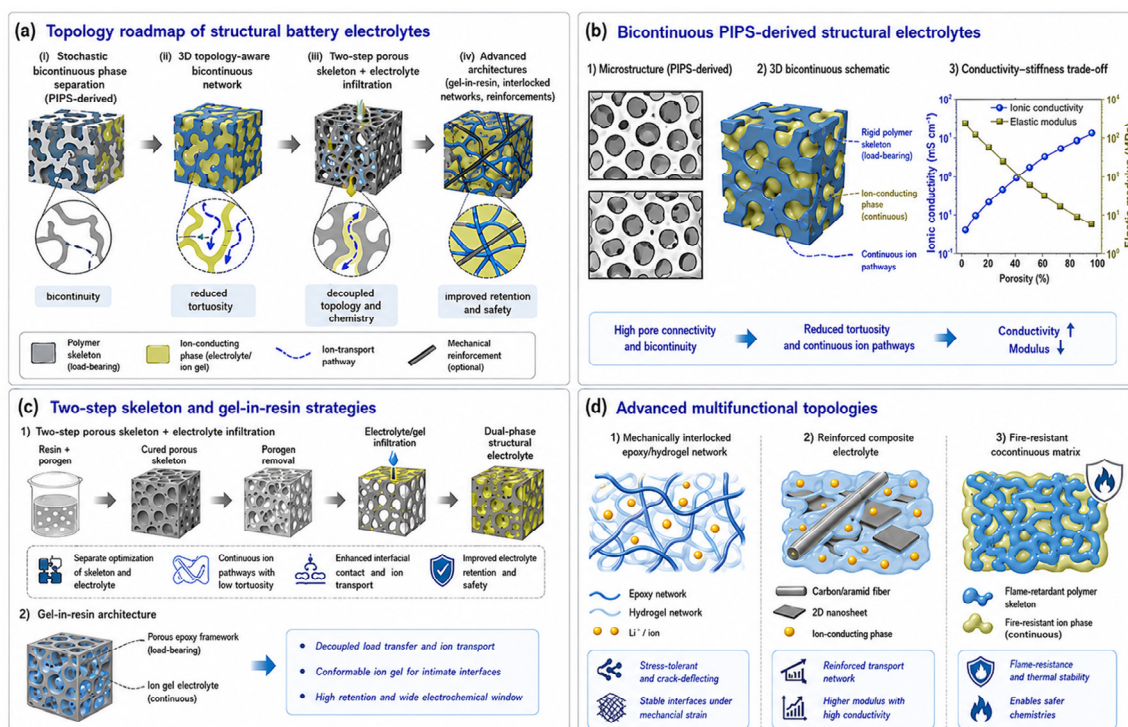


Figure 5. Topology-controlled structural battery electrolytes. (a) Roadmap from PIPS-derived bicontinuous electrolytes to topology-aware networks, skeleton-infiltration structures, and advanced multifunctional architectures. (b) Schematic PIPS-derived bicontinuous electrolytes, showing representative porous microstructures, 3D ion/load-bearing pathways, and the conductivity–stiffness trade-off. (c) Two-step skeleton and gel-in-resin strategies for decoupling mechanical support and ion transport. (d) Advanced mechanically interlocked, reinforced, and fire-resistant electrolyte topologies for improved transport, mechanical stability, retention, and safety. Schematically redrawn and summarized based on Refs. [51–62].

3.1. Bicontinuous Electrolytes and Phase-Separated Networks

Polymerization-induced phase separation is one of the most widely used strategies for structural battery electrolytes. During curing or polymerization, an initially homogeneous precursor can separate into mechanically rigid polymer-rich domains and ion-conducting electrolyte-rich domains. If both phases remain continuous, the electrolyte can provide simultaneous ion transport and load transfer. This concept is attractive because phase separation can be integrated with polymer processing, allowing structural and electrochemical functions to form within the same material.

Ihrner et al. demonstrated structural lithium-ion battery electrolytes prepared by reaction-induced phase separation, showing that bicontinuous morphology can provide both ionic conductivity and mechanical stiffness [51]. Schneider et al. used thermally initiated polymerization to develop bicontinuous electrolytes, showing that phase continuity is necessary for multifunctional performance [52]. These studies show that the structural electrolyte should not be treated as a simple homogeneous mixture of battery electrolyte and mixed resin. This is better understood as a spatially organized network in which one phase mainly provides ion transport and the other contributes more to mechanical support.

Bicontinuous electrolytes are attractive for their relatively simple processing logic. By adjusting the monomer composition, salt content, solvent fraction, curing conditions, and phase separation kinetics, researchers can tune the volume fraction and continuity of the ion-conducting and load-bearing phases. However, this advantage also leads to a limitation: the final morphology is highly sensitive to processing conditions. In thick laminates or densely packed areas of fibers, the ion-conducting domains may become tortuous or discontinuous, while the mechanically rigid domains may be fragmented or insufficiently bonded. As a result, small differences in processing can lead to noticeable changes in conductivity, modulus, interface adhesion, and cycle behavior.

Therefore, recent research has focused more on three-dimensional topology rather than relying solely on qualitative morphological observations. Three-dimensional reconstruction and computational analysis of structural battery composite electrolytes have shown that ion conductivity and mechanical response are closely related to phase coupling, curvature, volume fraction, and spatial distribution. This point is important because two electrolytes with a similar common composition can behave very differently if their ion-conducting domains are connected in one case, and isolated in the other. Phase separation alone is insufficient to ensure retained multifunctionality—the resulting network must remain connected after curing, electrochemical cycling, and mechanical deformation.

Porosity-controlled and confined liquid-phase systems extend this bicontinuous design strategy [54–59]. When a liquid or gel electrolyte is confined within a polymer network, ion mobility can be improved while part of the structural support is retained. The difficulty is that a higher liquid-rich fraction often lowers stiffness, dimensional stability, and damage tolerance. A key design question is, therefore, how much mobile phase can be introduced before load transfer, electrolyte retention, interfacial adhesion, or safety becomes compromised.

3.2. Architected Skeletons and Decoupled Ion/Load Pathways

A more controlled strategy is to build an architected skeleton first and then introduce the ion-conducting phase into its pore network. This route partly separates skeleton formation from electrolyte selection, allowing load-transfer pathways and ion-transport pathways to be adjusted more independently. Compared with stochastic phase separation, architected skeletons provide better control over pore connectivity, pore size, skeleton continuity, and electrolyte distribution. At a smaller length scale, related gel polymer

electrolyte research has also demonstrated that confined pore environments can be deliberately used to regulate ion migration. In a TMTD-confined MIL-101(Cr) gel polymer electrolyte, undercoordinated metal sites immobilized anions while the confined TMTD provided Li^+ -coordinating environments and interconnected migration pathways, producing a transient coordination relay for fast and selective Li^+ transport [63]. Although this MOF-based electrolyte is not a load-bearing structural electrolyte, it provides transferable mechanistic insight into how confinement, pore chemistry, and interconnected transport pathways can be jointly engineered.

Tree-root-inspired structural electrolytes are a useful example of this architecture-based design. Liu et al. developed a structural electrolyte for laminated carbon-fiber-reinforced composites by introducing a morphology inspired by tree-root networks [60]. Unlike conventional systems based on random phase separation, this design enables more hierarchical and directional transport pathways. The interconnected ion-conducting network improves electrode utilization. Meanwhile, the continuous polymer skeleton helps preserve mechanical load-bearing capability during structural battery operation.

Skeleton-regulated bicontinuous electrolytes further highlight the importance of electrolyte topology engineering. Li et al. achieved structural electrolytes with high ionic conductivity and mechanical performance by tailoring bicontinuous architectures through controlled skeleton construction [61]. Their results demonstrate that the conductivity–modulus trade-off can be partially alleviated when electrolyte topology is deliberately engineered rather than simply generated through physical mixing. Several structural parameters are critical in this process, including pore connectivity, pore size distribution, skeleton thickness, electrolyte retention capability, and phase compatibility.

The major advantage of architected skeletons lies in their ability to directly regulate ion-transport and load-transfer pathways. Rather than depending on spontaneous phase separation, the skeleton can be designed to maintain mechanical continuity. The infiltrated ion-conducting phase can then be optimized according to ionic conductivity requirements and electrode wettability. This design strategy is particularly attractive for carbon-fiber structural batteries, where electrolyte infiltration, fiber packing efficiency, and through-thickness transport remain major limitations for achieving improved performance.

However, architected skeletons also introduce additional manufacturing challenges. During consolidation, pore structures may shrink or collapse. Electrolyte infiltration can become heterogeneous, and the designed transport pathways may be blocked by active-material coatings, separator layers, or densely packed fibers. As a result, a skeleton architecture that performs well as an individual material may not fully retain its advantages after laminate processing. Therefore, architected electrolytes should be evaluated in fully integrated carbon-fiber structural cells. Particular attention should be given to through-thickness conductivity, interlaminar adhesion, electrolyte distribution, mechanical property retention after cycling, and post-consolidation morphology.

3.3. Gel-in-Resin and Mechanically Interlocked Electrolyte Architectures

Gel-in-resin electrolytes provide another strategy for balancing ion transport and mechanical load transfer. In these systems, a gel-based ion-conducting phase is embedded within a mechanically supporting resin framework. The gel phase enhances ion mobility and improves electrode wettability, while the resin phase provides stiffness, structural stability, and load-transfer capability. This configuration avoids the requirement for a single homogeneous polymer to simultaneously achieve high ionic conductivity and high mechanical modulus.

He et al. developed multifunctional gel-in-resin electrolytes for lithium-ion structural battery composites and demonstrated that both electrochemical and mechanical

properties can be enhanced by integrating a gel ion-conducting phase with a structural resin phase [62]. A key feature of this design is that the gel phase does not function as an independent soft electrolyte. Instead, it is confined within a structural framework, which improves electrolyte retention and preserves mechanical integrity while maintaining efficient ion transport.

Mechanically interlocked electrolyte architectures further extend this concept. Chen et al. reported a solid–solid bicontinuous epoxy/water-in-salt hydrogel structural electrolyte for zinc–lithium hybrid structural batteries [64]. In this architecture, the epoxy phase serves as the load-bearing skeleton, whereas the hydrogel or water-in-salt phase provides ionic conduction. Mechanical interlocking improves phase adhesion and deformation tolerance. Although aqueous and hybrid systems differ from conventional lithium-ion structural batteries, they still provide useful topology principles for carbon-fiber structural batteries, including phase continuity, mechanical interlocking, electrolyte retention, and strain tolerance.

The remaining concern is long-term stability. Gel and hydrogel systems can be sensitive to swelling, drying, creep, freezing, environmental exposure, or phase instability. For lithium-based systems, the electrochemical stability window and compatibility with electrode materials are especially important. Gel-in-resin and interlocked architectures should, therefore, be assessed by retained multifunctionality, not only by their initial conductivity or modulus. Useful metrics include conductivity after cycling, modulus after electrolyte aging, mechanical retention under fatigue, interfacial stability after bending, and performance after thermal exposure. Temperature-dependent ion transport also deserves explicit attention. In a related sodium-ion capacitor system, multi-ether solvation engineering was shown to reduce the Na^+ desolvation barrier and promote a Na_2O -rich inorganic interphase, thereby improving interfacial ion-transport kinetics and enabling operation at subzero temperatures [65]. Although the carrier ion and device chemistry differ from lithium-based structural batteries, this result emphasizes that electrolyte qualification should consider temperature-dependent solvation and interphase transport rather than room-temperature ionic conductivity alone.

3.4. Safer Electrolyte Topologies

Because structural batteries may encounter complex service conditions, including bending, impact, compression, vibration, fatigue loading, and temperature variations during practical operation, safety concerns have become increasingly important. In particular, damage to the electrolyte may interrupt ion-transport pathways, potentially resulting in internal short circuits, electrolyte leakage, localized overheating, or accelerated degradation of electrochemical performance. Therefore, the design of structural electrolytes should not be limited to improving ionic conductivity and mechanical stiffness, but should also consider thermal stability, flame retardancy, damage tolerance, and predictable failure mechanisms as integrated design requirements. Electrolyte chemistry can also play an important role in suppressing interfacial degradation. Evidence from related battery chemistries shows that electrolyte additives can modify ion-solvation structures, promote protective interphase formation, regulate interfacial ion distributions, and suppress dendritic growth and parasitic reactions [66]. Although these mechanisms were reviewed primarily for aqueous zinc-ion batteries, they illustrate the broader principle that electrolyte composition can actively regulate electrode/electrolyte interfacial stability rather than merely provide bulk ionic conduction.

The high electronic conductivity of carbon fibers introduces an additional safety constraint in structural electrolyte regions because unintended fiber-to-fiber contact may create electronic leakage or internal short circuits. Such failures can arise from stray carbon fibers, separator puncture, or migration of conductive particles during processing.

Randall et al. observed shorting associated with carbon-black migration and carbon-fiber penetration in all-fiber structural full cells, while Park et al. showed that carbon-fiber fragments generated during stitching could bridge opposite electrodes when only a glass-fiber separator was used. Adding PP/PE/PP insulating separator layers effectively suppressed these shorts [45,67]. Therefore, carbon-fiber-containing electrolyte architectures should maintain a continuous and mechanically robust electronically insulating phase, prevent fiber bridging and conductive-particle migration, and preserve separator integrity during consolidation and mechanical loading. These measures must be balanced against ion transport and interlaminar load transfer.

From the perspective of safety design, Phenoplast-based structural electrolytes provide a representative approach. Sha et al. developed a structural electrolyte with high ionic conductivity and fire resistance by combining the phenolic resin skeleton with the ionic conduction component [68], thus responding to the common problems in liquid-rich or gel-rich electrolytes to a certain extent: increased ionic conductivity in liquid-rich or gel-rich systems may be accompanied by greater flammability, leakage risk, or reduced thermal stability. By introducing fire-resistant polymer networks or using safer ion-conducting phases, structural electrolytes can better adapt to the impact and thermal abuse conditions that may occur in load-bearing applications.

From a broader material system perspective, polymer-based electrolytes with high mechanical strength are being used in the development of multifunctional structural batteries [69]. At the same time, research on solid-state electrolytes has provided a richer material foundation for structural batteries, including polymers, ceramics, composite materials, and mixed electrolytes, which typically have higher safety and mechanical stability [70]. However, traditional solid electrolytes cannot be directly applied to structural batteries without adjustment. The reason is that electrolyte requirements in structural batteries extend beyond ionic conductivity and electrochemical stability. They also involve interfacial adhesion with carbon fibers, compatibility with composite curing processes, mechanical load-transfer capability, and the retention of performance after electrochemical cycling and structural deformation.

Epoxy-based multifunctional solid polymer electrolytes are particularly relevant because epoxy networks are widely used in structural composites [71]. If epoxy-based electrolytes can provide sufficient ion transport while retaining stiffness and adhesion, they may bridge conventional composite matrices and battery electrolytes. Mechanical characterization of structural battery electrolytes is, therefore, essential for connecting electrolyte chemistry to composite-level performance [72]. Conductivity values alone provide an incomplete picture of electrolyte suitability if modulus, fracture behavior, adhesion, creep, and fatigue resistance are not reported.

3.5. Conductivity–Modulus Trade-Off

The electrolyte strategies discussed above show that structural electrolyte performance is governed by topology–property relationships rather than by composition alone. PIPS and bicontinuous electrolytes are conceptually simple and have established the foundation of multifunctional electrolytes, but their morphology can be difficult to control. Reinforced composite electrolytes improve mechanical robustness but may increase tortuosity or inactive mass. Architected skeletons and gel-in-resin systems provide more deliberate decoupling of ion and load pathways, but require careful control of infiltration, phase retention, and long-term stability. Interlocked and fire-resistant electrolytes can enhance deformation tolerance and safety; however, their performance still requires more comprehensive validation in full-cell configurations under coupled electrochemical and mechanical loading conditions. The main structural electrolyte topologies and unresolved challenges are summarized in Table 4.

Table 4. Structural electrolyte topologies and unresolved challenges.

Topology	Design Concept	Main Benefit	Key Challenge	Refs.
PIPS/bicontinuous electrolytes	Phase-separated ion/load networks	Simple route to dual functionality	Stochastic morphology and tortuosity	[51,52]
Porosity-controlled hybrids	Confined liquid phase in polymer network	Tunable ion mobility	Conductivity–stiffness trade-off	[53–55]
Reinforced composite electrolytes	Nanofibril or composite reinforcement	Improved modulus and dimensional stability	Added tortuosity or inactive mass	[56–59]
Architected skeletons	Designed porous or root-like pathways	Better decoupling of ion/load transport	Infiltration, collapse, and reproducibility	[60,61]
Gel-in-resin systems	Gel phase embedded in rigid resin	Improved wetting and ion transport	Swelling, drying, creep, and aging	[62]
Interlocked electrolytes	Mechanically interlocked solid/gel phases	Better phase adhesion and strain tolerance	Process complexity and chemistry compatibility	[64]
Fire-resistant/high-strength electrolytes	Phenolic, epoxy, or mechanically robust polymer networks	Improved safety and structural support	Full-cell and coupled-loading validation	[68–72]

The conductivity–modulus map in Figure 6 illustrates the inherent trade-off between ionic conductivity and mechanical stiffness. Matrices rich in rigid polymer or resin usually have high mechanical modulus, but the ionic conductivity is limited. Electrolytes rich in gel or liquid provide enhanced ionic mobility at the expense of load-bearing capability. Most materials selected as structural electrolytes are located in the intermediate regime between the two, so an ideal structural battery electrolyte needs to be designed by ensuring sufficient ion transport and effective load transfer.

This trade-off also affects how structural electrolyte performance should be reported. For ion conductivity, the measurement temperature, test geometry, electrolyte state, and whether the test object is an independent electrolyte membrane or an electrolyte integrated into the battery structure should be clearly specified. For mechanical data, the reported modulus should be explicitly identified as Young's, storage, shear, tensile, or compressive modulus. In addition, adhesion, fracture toughness, creep behavior, and fatigue performance should also be included in the evaluation system, because structural electrolytes are not only ion conductors, but also structural media that undertake load transfer functions. Without this clear and consistent reporting method, performance comparisons between different studies can easily be misleading.

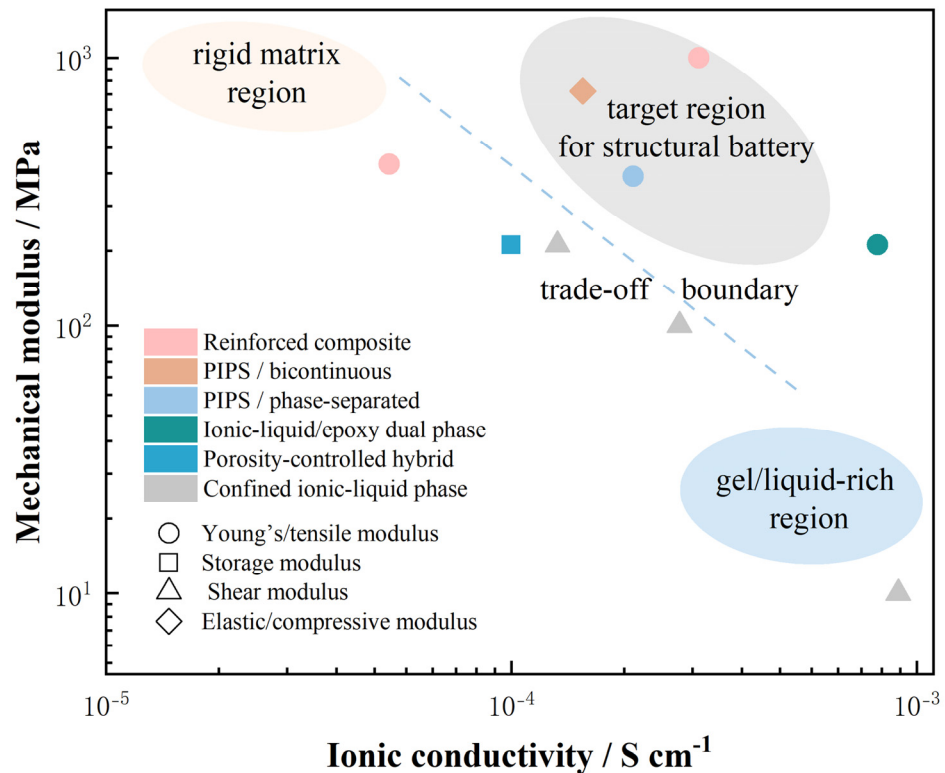


Figure 6. Conductivity–modulus trade-off map for representative structural battery electrolytes. (The plotted values are taken from the original literature and are not necessarily measured under identical temperature, electrolyte-state, or mechanical-test conditions, and the map is, therefore, intended to illustrate the overall trade-off rather than provide a strict performance ranking; the blue dashed line marks the approximate trade-off boundary).

3.6. Design Principles for Retained Electrolyte Multifunctionality

A more viable path for designing and developing future structural electrolytes is to maintain continuity in both the ion-conducting phase and the load-bearing phase. The isolated electrolyte-rich region limits the utilization of active materials, while the discontinuous polymer skeleton weakens load transfer. Therefore, dual continuity, permeability, and low-tortuosity pathways are the core of structural electrolyte design.

It is crucial that the electrolyte topology matches its corresponding carbon-fiber structure. Fiber packing, weaving geometry, coating thickness, and stack pressure all affect electrolyte distribution. An electrolyte that performs well as a free-standing material may still fail in a dense carbon-fiber laminate if it cannot penetrate fiber bundles and maintain through-thickness ion-transport pathways.

Electrode/electrolyte adhesion can also improve the mechanical performance of structural batteries. Poor adhesion can increase interfacial resistance and weaken load transfer. Structural batteries may experience bending, vibration, fatigue, impact, compression, and thermal changes in practical applications, so characterizing their fracture behavior, aging stability, fatigue retention, and other aspects under service conditions is particularly important. Moderate-modulus electrolytes with stable adhesion are often more practical than high-modulus electrolytes that are prone to brittle fracture.

Safety and qualification should be considered from the early stage of electrolyte design. Liquid-rich or gel-rich phases may improve conductivity, but they can also increase leakage, flammability, or thermal instability. Fire-resistant, solid-state, or hybrid topologies can improve safety, but they still need validation in full structural cells.

Structural electrolytes are the topology-controlled network through which ion transport and load transfer are reconciled. Their performance cannot be judged by ionic conductivity or mechanical modulus alone. The most promising electrolytes are those that preserve ion connectivity, mechanical continuity, interfacial adhesion, and safety after manufacturing, cycling, and deformation. This topology-centered view connects directly to Section 4, where structural architectures and manufacturing routes determine whether material-level electrolyte and electrode designs can be translated into reliable device-scale carbon-fiber structural batteries.

4. Structural Architectures and Manufacturing Strategies

The material-level discussions in Sections 2 and 3 show that carbon-fiber structural batteries rely on two coupled multifunctional networks: carbon-fiber electrodes that provide mechanical reinforcement and electrochemical function, and structural electrolytes that provide ion transport, electrical separation, interfacial adhesion, and load transfer. However, promising fiber-level electrodes and electrolyte films do not automatically translate into reliable structural battery components. Device-level performance depends on whether these constituents can be integrated into architectures that preserve mechanical continuity, electronic connectivity, ionic accessibility, interfacial stability, and manufacturing reproducibility.

In structural batteries, architecture is more than the physical arrangement of electrodes, separators, electrolytes, and current collectors. It controls how mechanical load paths, electronic pathways, ion-transport networks, and damage-tolerant interfaces are connected throughout the device. Manufacturing is equally important because processing determines fiber volume fraction, void content, electrolyte distribution, coating integrity, separator placement, current-collector geometry, residual stress, and interlaminar bonding. These factors decide whether the final device behaves as a true multifunctional composite or as a fragile electrochemical stack enclosed in a composite structure.

The architectural development of carbon-fiber structural batteries has followed several routes, including embedded-cell composites, laminated structural batteries, free-form and shape-conformable devices, coextruded or printed structures, woven carbon-fiber batteries, structure–function-integrated carbon-fiber-reinforced plastics, and high-loading dry-processing strategies [6,14,16–19,73–79]. These routes address different integration needs, but they also introduce different types of defects and scale-up challenges. For this reason, architecture and manufacturing should be considered as primary design variables rather than final assembly steps.

A major difficulty is that structural battery manufacturing must satisfy the requirements of both composite processing and battery fabrication. Composite processing usually seeks high fiber volume fraction, low void content, strong interlaminar bonding, and continuous load paths. Battery fabrication, in contrast, requires effective electrolyte wetting, high active-material utilization, controlled electrode thickness, stable electrical isolation, and low interfacial resistance. A successful carbon-fiber structural battery architecture has to reconcile these requirements within the same processed component.

4.1. Architectural Evolution from Embedded Cells to Battery-As-Composite Structures

Early structural battery architectures mainly followed a system-level integration strategy, in which thin-film or pouch-type energy-storage cells were embedded into composite laminates or sandwich structures [6,16–18]. This approach is important because it provides a relatively direct way to combine battery function with load-bearing components. Its practical appeal lies in the use of relatively mature cell chemistries and established composite-processing methods. For near-term applications, embedded-cell

structures may still be useful because they can improve packaging efficiency while relying on commercial or near-commercial battery formats.

However, embedded-cell architectures are only partly multifunctional. The battery stores energy, while the surrounding composite mainly carries load. This separation simplifies the electrochemical design, but it also introduces mechanical discontinuities, stiffness mismatch, local stress concentration, and damage sensitivity around the embedded cells. The battery region may become a weak interlaminar zone, and mechanical damage in the surrounding composite may directly affect electrical performance. Embedded-cell systems are, therefore, useful transitional architectures, but they do not fully realize the material-level potential of carbon-fiber structural batteries.

Material-level structural batteries attempt to reduce this separation by making the electrode, electrolyte, and reinforcement network structurally active. In these architectures, carbon fibers no longer serve merely as shells, support frames, or conductive additives; instead, they participate directly in electrochemical processes while carrying mechanical loads. Similarly, structural electrolytes no longer serve merely as separators or electrolyte-containing phases, they also contribute directly to load transfer and laminate integrity. This transition from a “battery-in-composite” to a “battery-as-composite” architecture captures the central logic of material-level structural battery integration [2,4,5,14,21,22].

Structural battery architecture requires coordinated continuity of four coupled networks: mechanical, electronic, ionic, and interfacial. Mechanical networks rely on fibers, matrix, and interlayer regions to achieve load transfer. Electronic networks must effectively connect carbon-fiber electrodes to the current collector while avoiding excessive resistance loss or local current concentration. At the same time, the ionic network must provide continuous ion-transport pathways between the positive and negative electrodes through structural electrolytes, while the interfacial network must maintain adhesion, electrical isolation, and damage tolerance. Due to the fact that these four types of networks are not independent of each other, once any one of them fails, the stability and overall battery performance of the other networks may also be affected. For example, delamination can interrupt both load transfer and electrode/electrolyte contact, electrolyte-poor regions can increase impedance while weakening interlaminar bonding, and current-collector discontinuities can produce local stress and uneven electrochemical utilization.

The representative manufacturing routes shown in Figure 7 illustrate how carbon-fiber structural batteries have moved from component-level preparation toward full-cell structural integration. Resin-assisted fabrication, dry lay-up, electrolyte precursor infiltration, hot pressing, vacuum infusion, and laminate consolidation provide different ways to combine carbon-fiber electrodes, structural electrolytes, separators, and current collectors. These routes are not interchangeable: each creates a different process–structure–property relationship [80–82].

The figure summarizes typical manufacturing routes, including resin-assisted processing, dry lay-up and full-cell assembly, electrolyte precursor infiltration, hot pressing, vacuum infusion, and laminate consolidation. These processes affect coating integrity, electrolyte distribution, interlaminar bonding, current-collector placement, and defect formation, thereby linking materials design with device-level retained multifunctionality [14,73,74].

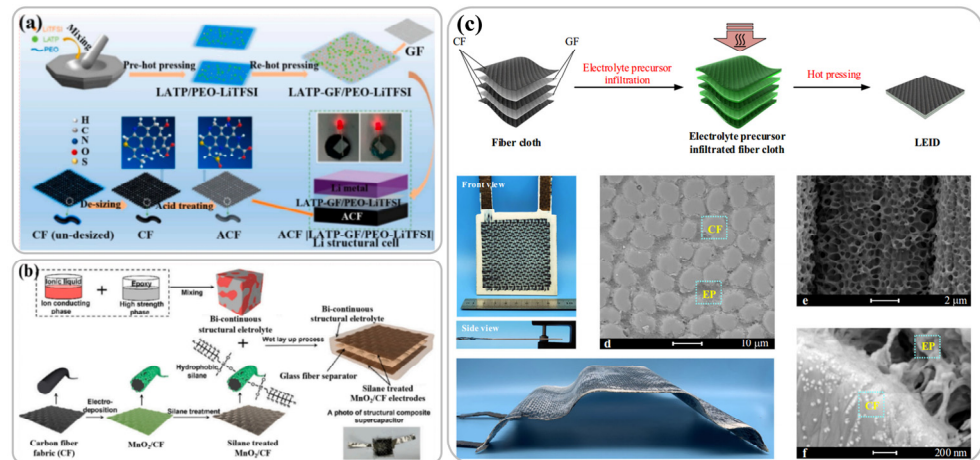


Figure 7. Structural architectures and device-level integration of structural batteries. (a) Schematic illustration of the fabrication of an LAMP-GF/PEO-LiTFSI structural electrolyte by hot pressing and an ACF|LAMP-GF/PEO-LiTFSI|Li structural cell. Reproduced with permission from ref. [81]. Copyright 2021 American Chemical Society. (b) Preparation of a resin-based structural electrolyte. Reproduced with permission from ref. [80]. Copyright 2022 American Chemical Society. (c) Schematic of fabrication using a hot-press prepreg process. Open Access article [82]. Reproduced with permission under a Creative Commons Attribution 4.0 International License.

4.2. Laminated Structural Batteries

Laminated structural batteries are a natural extension of established composite manufacturing routes, and its typical structure is usually composed of stacked carbon-fiber electrodes, structural electrolyte or separator layers, current collectors, and load-bearing composite panels or matrices. Due to its ability to integrate with common composite material processes such as dry lay-up, resin impregnation, vacuum-assisted infusion, curing, and hot pressing, this configuration has strong appeal in terms of manufacturing compatibility [14,19,73,74].

The main advantage of laminated structure is that it provides a practical path for the integration of structural and electrochemical functions in planar components. In this configuration, the carbon-fiber layer can bear in-plane loads and provide electronic conduction channels. Structural electrolytes are responsible for ion transport in the thickness direction and also achieve electrical isolation between electrodes. The current collector can be arranged at the edge or surface of the laminated structure, and the entire device can also be designed in the form of panels, shells, or load-bearing plates according to application requirements. Therefore, laminated structural batteries have a high correlation with aerospace panels, satellite structures, vehicle components, and other planar load-bearing components.

However, laminated structural batteries are highly sensitive to interlayer defects because their through-thickness direction must simultaneously support ion transport, electrical isolation, electrolyte wetting, and interlaminar load transfer. If electrolyte infiltration is insufficient, local dry zones may form inside the structure, thereby increasing impedance and weakening interlayer bonding. If the resin content is too high, it may also create areas that hinder ion transport. At the same time, excessively thick or brittle electrode coatings can easily cause stress concentration and delamination, while improper arrangement or misalignment of current collectors may also lead to local stress concentration and uneven current distribution. These defects may be less consequential when electrochemical and mechanical functions are evaluated separately, but in

laminated structural batteries they directly affect coupled device performance and reliability.

The curing and solidification process is also a core element in the design of laminated structural batteries, as laminated structural batteries are essentially multifunctional composite materials that have been cured and formed, rather than just simple electrochemical stacking. During this process, curing chemistry directly affects the formation of polymer networks, electrolyte distribution, interface construction, residual stress accumulation, and ultimately mechanical integrity. Therefore, curing kinetics should not be considered as a secondary detail in subsequent processing, but should be considered as part of structural battery design. Architectures based on macroporous epoxy with vertical ion channels further demonstrate how laminate-level ion transport can be improved by deliberately designing through-thickness pathways [74]. Such approaches are relevant because dense carbon-fiber laminae may restrict ion transport even when they provide good stiffness.

For retained multifunctionality, laminated structural batteries should be tested beyond initial capacity and modulus. Relevant tests include post-cycling tensile or flexural properties, electrochemical performance after bending or compression, interlaminar shear retention, impedance evolution under load, and damage morphology after coupled cycling/loading. Without such coupled evaluation, laminated devices may appear promising as initial multifunctional composites but fail to demonstrate durable structural battery function.

4.3. Free-Form and Shape-Conformable Structural Batteries

Many practical structures are not flat laminates. Aircraft components, unmanned aerial vehicle wings, robotic shells, wearable systems, and vehicle body parts may require curved, folded, or shape-conformable energy-storage elements. Free-form structural batteries address this requirement by integrating energy storage into carbon-fiber fabrics, flexible laminates, or formable composite structures. In these systems, geometry becomes part of the electrochemical and mechanical design rather than a passive packaging constraint [14].

The free-form carbon-fiber structural battery route shown in Figure 7 reflects this design direction, which is to achieve nonplanar shape construction of carbon-fiber-based devices while maintaining electrochemical function through electrolyte precursor infiltration and the hot-pressing process [14]. The important value of this structural form is that the energy-storage function can be distributed on the surface of the structure or inside the load-bearing components, rather than being concentrated in rigid, standalone battery modules. For aerospace, robotics, and vehicle systems, this design has particular potential for application, as there are often available curved structural spaces in these systems, and traditional battery modules are difficult to achieve efficient integration in such spaces.

However, shape conformity introduces failure modes that are not fully captured by flat-cell testing. During the molding process, fiber bundles may undergo movement, bending, wrinkling, or local misalignment. Meanwhile, due to the influence of curvature, pressure distribution, and local fiber accumulation on electrolyte infiltration, electrolyte-rich and electrolyte-poor regions may form inside the material. Similarly, the current collection path may also exhibit uneven distribution near the electrode tab, edge, or curved area, while the active material coating may be affected by bending-induced stress and experience local debonding. Therefore, free-form structure batteries cannot rely solely on the flexibility of the material itself, but require coordinated design of fiber structure, electrolyte rheological properties, molding temperature, consolidation pressure, active coating flexibility, and current-collector geometry.

The core principle of free-form structural design is to maintain the continuity of the multifunctional network even after forming. Specifically, the load-bearing fibers need to remain continuous in the curved area, the electron transport path must be stably connected to the current collector, the ion-transport pathways must be kept unobstructed through the structural electrolyte, and the interface must be able to withstand the strain generated during bending or forming processes. Material flexibility alone is insufficient to ensure the reliability of free-form structural batteries. The key issue is whether the complete multifunctional network can maintain continuity, stability, and effectiveness after forming, cycling, and mechanical loading.

4.4. Coextruded and Printed Structural Batteries

Unlike traditional lamination processes that are more suitable for planar component fabrication, additive manufacturing can form customized three-dimensional shapes, continuous fiber paths, and locally adjustable electrode/electrolyte distributions, providing greater design freedom in geometry and functional layout of structural batteries. Therefore, this type of method has strong application appeal in the fields of lightweight lattice structures, distributed energy-storage networks, customized load-bearing components, and complex geometric structure batteries.

The coextrusion of continuous carbon-fiber microbatteries provides a representative additive manufacturing strategy for structural batteries [75]. In this method, carbon-fiber reinforcement, electrode materials, and ion-conducting phases can be synergistically arranged into continuous filaments or patterned structures, thereby achieving simultaneous control of fiber paths, electrode spacing, electrolyte distribution, and external geometry during the manufacturing process. Its main advantage lies in its high degree of design freedom, which also provides new possibilities for integrating structural batteries into complex configurations that are difficult to prepare using traditional lamination processes.

However, printed and coextruded structural batteries still face significant manufacturing challenges, where the rheological properties of ink or slurry must be able to support both continuous and stable deposition processes, as well as maintain the stability of fiber arrangement and interface contact during the forming process. Porosity must also be tightly controlled, as voids not only weaken the mechanical strength of the structure, but may also hinder ion transport. The interlayer bonding must be strong enough to ensure effective load transfer and maintain necessary electrical isolation. Drying, curing, and consolidation may generate shrinkage, residual stress, or delamination. The printed architecture must also maintain sufficient electronic conductivity and ionic accessibility across the device.

Additive manufacturing should, therefore, not be viewed simply as a way to create arbitrary shapes. For structural batteries, printing must produce continuous and well-bonded multifunctional networks. A printed carbon-fiber pathway must carry load and conduct electrons. A printed electrolyte must connect electrodes while maintaining separation and adhesion. Printed interfaces must resist crack formation during cycling and mechanical loading. Without these conditions, the printed device may show geometric novelty but limited retained multifunctionality.

Advanced device demonstrations based on coextrusion, 3D printing, and woven carbon-fiber structural batteries are summarized in Figure 8. These examples show the field moving from flat proof-of-concept laminates toward programmable and application-oriented architectures. They also make clear that manufacturing complexity increases rapidly as geometry becomes more realistic.

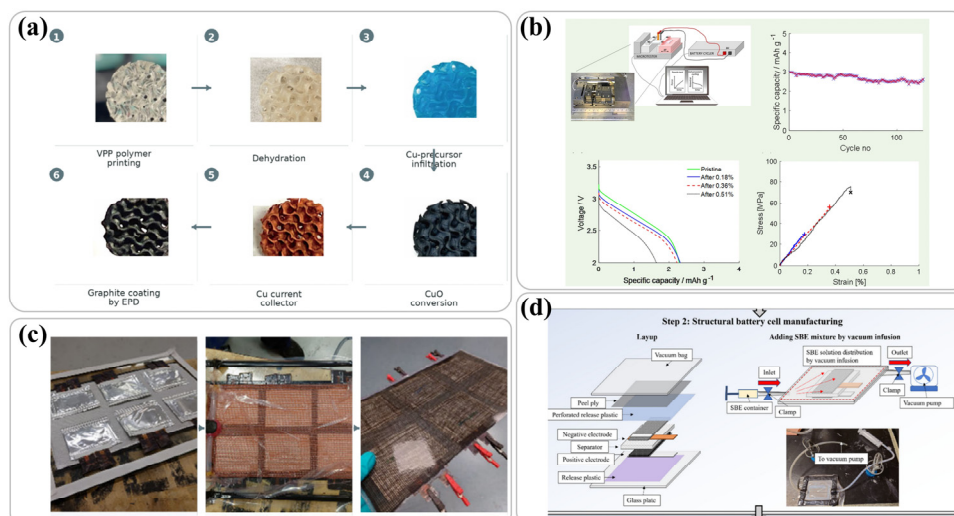


Figure 8. Representative manufacturing routes and coupled performance validation of structural batteries. (a) Additive fabrication of a three-dimensional copper current collector and graphite-coated electrode. Open Access article [83]. Adapted with permission under a Creative Commons Attribution 4.0 International License. (b) Electro-chemo-mechanical testing and performance evaluation of a structural battery composite cell. Open Access article [84]. Adapted with permission under a Creative Commons Attribution 4.0 International License. (c) Multicell structural battery laminate manufacture by vacuum infusion. Open Access article [85]. Adapted with permission under a Creative Commons Attribution 4.0 International License. (d) Structural battery cell manufacture by layer-by-layer lay-up and structural electrolyte vacuum infusion. Open Access article [85]. Adapted with permission under a Creative Commons Attribution 4.0 International License.

The figure summarizes representative coextruded, printed, and woven carbon-fiber structural battery demonstrations. These architectures enable programmable geometry, continuous fiber pathways, textile integration, and mechanical testing under electrochemical operation. They also highlight unresolved issues in rheology control, porosity, interlayer bonding, electrolyte infiltration, coating uniformity, and coupled electrochemical–mechanical retention [83–85].

4.5. Manufacturing Defects and Process–Structure–Property Relationships

In structural batteries, the same defects can also block ion transport, increase local impedance, disrupt electronic pathways, weaken current collection, and accelerate capacity fading. Structural battery defects should, therefore, be understood as multifunctionality-degrading defects.

A void may act as both a crack-initiation site and an ionic transport barrier. Poor bonding between the active-material coating and carbon fiber can reduce both electrochemical utilization and interfacial load transfer. The formation of resin-rich regions may increase ion transport resistance while reducing local stiffness. Similarly, localized dry areas often lead to poor interfacial adhesion and electrochemical contact, while fiber waviness may weaken compressive strength and simultaneously alter electron transport pathways. If further stratification occurs, load transfer and electrode/electrolyte interface contact will be interrupted. The defects in the manufacturing of structural batteries cannot be understood solely from a single performance perspective but must be analyzed in the context of the coupled process structure performance relationship.

In traditional batteries, current collectors are typically electronic conductivity, electrochemical stability, mass, and manufacturability. However, in carbon-fiber

structural batteries, they must also be current-collector design and must additionally account for laminate architecture, mechanical loading, electrical joining, and damage tolerance simultaneously. Improper placement of the current collector can lead to local stiffness mismatch, stress concentration, edge delamination, uneven current density, and local heating. Related multifunctional electrochemical architectures provide another perspective on current-collector integration. Three-dimensional graphene paper has been demonstrated to combine electrode and current-collection functions within a metal-free thin-film supercapacitor architecture, while also enabling electrical interconnection for tandem device assembly [86]. Although such supercapacitors are not load-bearing structural batteries, the component-integration principle is relevant to structural energy storage because reducing separate current collectors and interconnects may decrease inactive mass and simplify electrical integration, provided that mechanical and safety requirements can still be satisfied. Quality control is crucial for reducing multifunctionality-degrading defects. The manufacturing of structural batteries should not only test the electrochemical capacity and mechanical strength, but also the dynamic changes in pore content, electrolyte absorption, coating thickness distribution, active material loading, and interfacial adhesion.

Meanwhile, larger and more geometrically complex components are more difficult to manufacture, as they make manual assembly and local adjustment increasingly impractical. This requires that the thickness of the laminated board, electrolyte distribution, electrode alignment, current-collector placement, and electrical isolation must be synchronized throughout the entire system during design.

Manufacturing scalability remains a central challenge, although recent studies indicate that the conflict between battery processing and composite manufacturing can be partially alleviated. Conventional lithium-based structural batteries may require moisture-sensitive electrolyte handling and carefully controlled curing, whereas composite fabrication involves impregnation, consolidation, and thermal or photochemical curing. Recent work has demonstrated prepreg-inspired full-cell assembly under ambient conditions without a glovebox or dry room [45], scalable dry-processing routes for high-loading carbon-fiber structural electrodes [79], and photocurable structural battery systems compatible with established composite fabrication methods [41]. Nevertheless, a 2026 manufacturing-scale analysis concluded that current structural battery composite production remains best suited to low-volume, highly customized applications because of process sensitivity, labor-intensive workflows, high material costs, and limited recyclability [87]. Future scale-up should, therefore, emphasize automated deposition and lay-up, reproducible infiltration and curing, process-yield control, and compatibility between electrochemical and composite-processing windows. Manufacturing approaches developed for other integrated electrochemical electrodes may provide additional processing concepts. For example, laser-induced hydrothermal processing has been used to directly fabricate binder-free integrated electrodes, achieving a substantially higher production rate and lower energy consumption than conventional hydrothermal processing [88]. Although demonstrated for electrocatalytic rather than structural battery electrodes, this approach illustrates the potential of localized, rapid, and energy-efficient processing for future scalable electrode integration.

Techno-economic and end-of-life assessment remains less mature than electrochemical and mechanical development. Recent manufacturing analyses still identify high initial investment, labor-intensive processing, expensive materials, and limited recyclability as major barriers to large-scale structural battery production [87]. At the same time, circular-material strategies are beginning to move beyond conceptual proposals: reclaimed carbon-fiber textiles have been successfully reused as electrodes in structural full cells [45], and recycled carbon-fiber felts have recently been incorporated

into all-carbon-fiber structural battery architectures while retaining electrochemical function after mechanical impact [89]. Component-level recovery of structural battery electrolytes has also demonstrated substantial material recovery and potential cost reduction [90]. However, a comprehensive techno-economic assessment of complete carbon-fiber structural batteries—including automation, yield, cycle time, quality control, repair, disassembly, and material-recovery efficiency—remains unavailable. Future industrial evaluation should, therefore, integrate manufacturing cost and end-of-life recovery with the system-level mass and volume savings provided by structural integration.

4.6. Comparative Assessment of Structural Battery Architectures and Manufacturing Routes

The architectural development of carbon-fiber structural batteries indicates that no single manufacturing route is universally optimal. From an integration perspective, embedded-cell systems provide a relatively direct route toward structural battery implementation because they can incorporate mature or near-commercial battery cells into load-bearing composite structures. However, these systems remain closer to a “battery-in-composite” architecture, and the degree of material-level multifunctional coupling is, therefore, limited. Laminated structural batteries are highly compatible with established composite manufacturing processes, but they are particularly sensitive to interlaminar defects and insufficient electrolyte infiltration. Free-form architectures offer greater geometric adaptability, although their performance depends strongly on controlling fiber misalignment, electrolyte heterogeneity, and other forming-induced nonuniformities. Coextruded and printed structural batteries enable programmable control over geometry and material distribution, but they remain at an early stage of development and are highly sensitive to rheology, porosity, and interfacial defects. Woven carbon-fiber batteries provide textile-like drapability and scalable fiber architectures, yet coating uniformity and electrolyte infiltration at tow crossovers remain difficult to control. Structure–function-integrated composites and high-loading dry-processing strategies may further improve system-level mass efficiency, but their ion-transport characteristics, interfacial durability, and mechanical property retention still require more comprehensive validation. The main architectural and manufacturing trade-offs are summarized in Table 5.

Table 5. Structural battery architectures and manufacturing considerations.

Architecture	Manufacturing Route	Main Advantage	Key Risk	Refs.
Embedded-cell composites	Cell embedding in laminates or sandwich structures	Near-term integration using mature cell technologies	Stiffness mismatch and damage around embedded cells	[6,15–18]
Laminated structural batteries	Dry lay-up, infusion, curing, or hot pressing	Compatibility with composite processing	Interlaminar defects and electrolyte starvation	
Free-form batteries	Infiltration and hot pressing of CF fabrics	Shape-conformable energy storage	Fiber misalignment and nonuniform ion/current pathways	[14]
Coextruded/printed batteries	Continuous-fiber coextrusion or additive deposition	Programmable geometry and fiber paths	Rheology, porosity, and interlayer bonding	[75]
Woven CF batteries	Textile architecture with printed electrolyte	Drapability and multiaxial reinforcement	Nonuniform coating and infiltration at tow crossovers	[76]

Structure–function-integrated CFRPs	Integrated composite construction	Improved structural robustness and functional integration	Interface durability and electrochemical stability	[77,78]
High-loading dry processing	Dry electrode/composite processing	Potential system-level mass savings	Transport limitation and brittle high-loading electrodes	[79]
Reliability-oriented validation	Coupled electrochemical/mechanical testing	Links manufacturing quality to retained multifunctionality	Lack of standardized protocols	[9,10]

Structural battery architectures should preserve continuous mechanical load paths and avoid weak interlayers or stress concentrations introduced by electrochemical integration. At the same time, the ion-transport pathways must be fully accessible throughout the thickness direction of the device and on the electrode surface. In other words, high fiber volume fraction or high active-material loading can only truly translate into structural and electrochemical performance advantages when electrolyte transport can still be effectively guaranteed. Current collection should avoid local overheating, current-density nonuniformity, galvanic incompatibility, and excessive inactive mass. Manufacturing should minimize multifunctionality-degrading defects, such as voids, coating cracks, electrolyte-poor regions, current-collector discontinuities, and interfacial debonding. Device-level testing should combine electrochemical cycling with relevant mechanical loading modes.

Table 6 summarizes representative quantitative benchmarks for carbon-fiber structural batteries, including energy density, modulus, and available electrochemical and mechanical retention data. Because test conditions and normalization bases differ among studies, the values indicate reported performance ranges rather than a strict ranking.

Table 6. Quantitative benchmarking of representative carbon-fiber structural batteries.

Study	Energy Density (Wh kg ⁻¹)	Mass Basis	Modulus (GPa)	Capacity Retention	Stiffness Retention	Ref.
Asp et al. (2021)	23.6	Total cell	25.4	NR	NR	[21]
Jiang et al. (2023)	5.6	Total battery	4.6	NR	NR	[91]
Bouton et al. (2024)	33.4	Cell	38	NR	NR	[92]
Chaudhary et al. (2024)	30	Total cell	76	≈100% (1000 cycles)	85.5%	[22]
Liu et al. (2025)	28.0	Whole device	29.7 *	90.5% (1000 cycles)	NR	[38]
Park et al. (2026)	42.2	Total structure	14.7 *	77% (500 cycles)	NR	[67]
Yang et al. (2026)	127	Cell	3.2	NR	NR	[79]
Hu et al. (2026)	19.8	Total SBC	43.8	NR	NR	[93]
Jiang et al. (2026)	2.0	Total battery	27 ± 10	NR	NR	[94]
Han et al. (2026)	45.8	Cell core †	13.04	≈73% (100 cycles)	NR	[49]

NR, not reported. * Flexural modulus for [38,67]. All other values are tensile or Young's modulus, as reported. † Outer CF/epoxy encapsulation was excluded from the mass basis in ref. [49]. The 85.5% stiffness retention in ref. [22] and ≈73% capacity retention in ref. [49] were calculated from the reported before–after values.

The quantitative trade-offs are further visualized in Figure 9. Figure 9a maps gravimetric energy density against mechanical modulus to illustrate the currently reported multifunctional performance space, whereas Figure 9b compares capacity

retention with cycle number and distinguishes studies that provide matched quantitative post-cycling stiffness data from those reporting electrochemical retention alone.

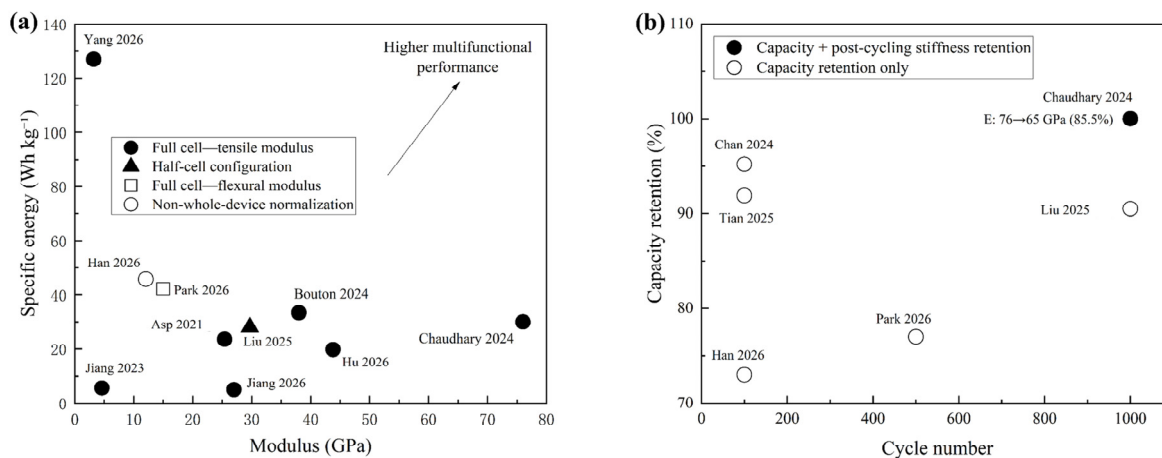


Figure 9. Quantitative performance mapping of representative carbon-fiber structural batteries. (a) Energy density versus mechanical modulus. (b) Capacity retention versus cycle number, with filled symbols indicating available post-cycling stiffness retention data. Data sources: Refs. [21,22,38,46,49,59,67,79,91–94].

Figure 9a compares reported energy density and mechanical modulus, whereas Figure 9b compares cycling durability and identifies studies that additionally report post-cycling stiffness retention. Due to differences in battery chemistry, mass normalization basis, modulus definition, C-rate, and cycling protocol across studies, these charts aim to illustrate performance boundaries and gaps in reporting, rather than provide a strict ranking.

The comparison reveals a broad trade-off between electrochemical energy storage and structural stiffness rather than a single dominant design. Recent high-loading approaches extend the upper energy-density boundary but generally remain at relatively low modulus, whereas highly stiff all-carbon-fiber configurations occupy a lower specific-energy range. More importantly, Figure 9b shows that electrochemical capacity retention is reported substantially more often than matched post-cycling stiffness retention. Quantitative mechanical retention after extended full-cell cycling, therefore, remains sparsely documented, despite short-term electrode-level studies showing that stiffness can be largely retained after cycling [22,29,39]. This reporting gap limits rigorous assessment of retained multifunctionality and supports the need for coupled electrochemical–mechanical validation under clearly defined service-relevant conditions.

Structural battery architectures convert material-level multifunctionality into device-level performance. Carbon-fiber electrodes and structural electrolytes may show promising properties as individual components, but their practical value depends on whether manufacturing can integrate them into continuous, defect-tolerant, and scalable structures. The examples discussed in this section demonstrate progress in laminated, free-form, woven, coextruded, printed, high-loading, and structure–function-integrated structural batteries. They also show that interfacial stability, electrolyte distribution, defect control, quality monitoring, current collection, and coupled testing remain central unresolved challenges. These issues provide the basis for the final section, where retained multifunctionality, coupled degradation, safety, standardization, and application-oriented qualification are discussed.

5. Conclusions and Outlook

5.1. Conclusions

Carbon-fiber structural batteries have developed from embedded-cell concepts toward material-level multifunctional composites in which carbon fibers, active-material coatings, structural electrolytes, current collectors, and polymer matrices are integrated into load-bearing energy-storage structures. Their value should be assessed from a system-level perspective rather than by cell-level energy density alone, because their main advantage lies in replacing passive structural mass, reducing redundant packaging, and enabling distributed energy storage within load-bearing components.

Consistent with recent deployment-oriented perspectives [13], the key challenge is increasingly the retention of multifunctional performance beyond initial demonstrations. The present review specifically examines this challenge from a carbon-fiber-specific perspective, emphasizing electrode and interphase behavior, structural electrolyte topology, manufacturing-induced multifunctionality-degrading defects, and coupled degradation. Early studies demonstrated the feasibility of combining energy storage and load bearing in composite-like structures, while recent work has advanced carbon-fiber electrodes, active-material-coated fiber cathodes, structural electrolytes, laminated batteries, free-form devices, woven architectures, printed/coextruded systems, high-loading processing, and all-carbon-fiber structural battery composites.

For carbon-fiber electrodes, performance retention is largely determined by the stability of the electrochemical–mechanical interface. Pristine carbon fibers inherently provide a multifunctional platform, as they can simultaneously function as reinforcement, electron-conducting pathways, current collectors, and lithium-storage hosts. Nevertheless, their electrochemical contribution remains constrained by the intrinsic microstructure of the fibers and limited electrolyte accessibility. Introducing active-material coatings onto carbon-fiber surfaces can effectively increase electrode capacity, but it may also introduce issues, such as coating cracking, weakened interfacial adhesion, volume-change-induced stress, and restricted ion transport. Therefore, strategies including surface activation, conductive additives, MOF-derived coatings, and in-situ-engineered interfaces can only provide real value for structural batteries when they enhance electrochemical performance while preserving the mechanical integrity and load-bearing capability of carbon fibers.

For structural electrolytes, the primary challenge is to achieve a balance between ionic conductivity and mechanical modulus. In general, ion transport is favored in soft, gel-rich, or liquid-rich phases, whereas efficient load transfer depends on rigid and continuous polymer networks. Accordingly, PIPS-derived bicontinuous electrolytes, reinforced composite electrolytes, architected skeletons, resin–gel structures, mechanically interlocked networks, and fire-resistant matrices share a common objective: constructing continuous ion-conducting pathways and load-bearing frameworks within a single material system. Therefore, the most promising structural electrolytes are not necessarily those with the highest value of an individual performance parameter, but those that can maintain ion connectivity, mechanical support, interfacial adhesion, and safety throughout electrochemical cycling and mechanical deformation.

At the device level, architecture and manufacturing determine whether material-level multifunctionality can be translated into retained performance. Laminated, free-form, woven, printed, coextruded, and high-loading architectures each offer a different route toward structural battery integration, but they also bring different defect risks. Voids, dry regions, coating cracks, electrolyte-poor zones, fiber misalignment, interfacial debonding, and current-collector discontinuities can occur during processing or service. Once formed, these defects may simultaneously disturb ion transport, electron conduction,

load transfer, interfacial adhesion, and thermal safety. Reliable carbon-fiber structural batteries, therefore, require coordinated control of materials, interfaces, electrolyte topology, manufacturing quality, and coupled degradation.

5.2. Outlook

Future work should prioritize the retention of coupled electrochemical, mechanical, interfacial, and safety performance over isolated property maximization. A higher active-material loading can raise capacity, but it may also make coatings more brittle, increase ion-transport resistance, and promote delamination. More electrolytes can improve wetting and ionic conductivity, while reducing modulus, strength, and damage tolerance. Increasing the fiber volume fraction can improve stiffness, but it may also restrict electrolyte infiltration and active-material utilization. Future studies should, therefore, report electrochemical retention, mechanical retention, interfacial retention, and safety retention together with active-material loading, fiber volume fraction, electrolyte content, laminate thickness, normalization basis, and testing configuration [10,11]. Such reporting should also distinguish initial proof-of-concept performance from directly demonstrated retention after electrochemical cycling, mechanical loading, damage, or coupled exposure. The corresponding future research priorities are summarized in Figure 10.

Coupled degradation and service-relevant testing should become central to future evaluation. Carbon-fiber structural batteries are exposed to electrochemical cycling, bending, compression, vibration, impact, fatigue, and thermal variation. These conditions can generate thermal stress, diffusion-induced stress, state-of-charge-dependent mechanical changes, matrix cracking, fiber/electrolyte debonding, coating damage, delamination, and internal short-circuit risks [95–108]. Therefore, structural batteries should not be qualified by separate battery tests and composite tests alone. More representative protocols should combine cycling with mechanical loading, mechanical testing at controlled state of charge, impact before and after cycling, cycling after controlled damage, and thermal or abuse exposure under load.

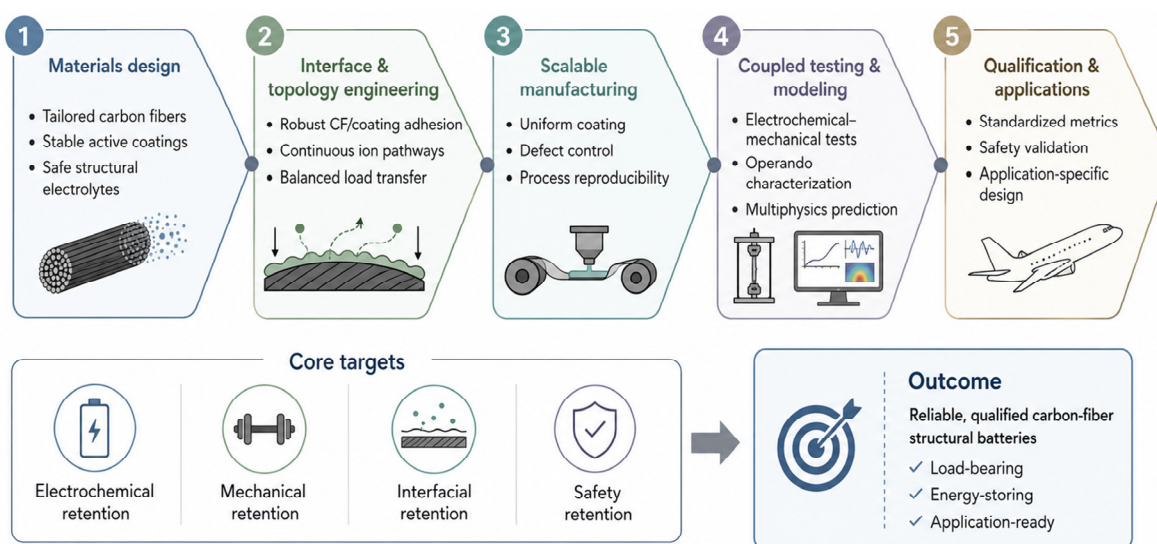


Figure 10. Future research priorities for carbon-fiber structural batteries. This roadmap highlights materials and interface design, electrolyte topology, scalable manufacturing, coupled testing and modeling, and application-oriented qualification. The central targets are electrochemical, mechanical, interfacial, and safety performance retention.

Operando characterization and multiphysics modeling are also needed to reveal how ion transport, electron conduction, stress evolution, heat generation, and damage propagation interact. Models of structural battery composites, electrode expansion, and electro-chemo-mechanical coupling can help connect material properties with laminate-level behavior [109–112]. To make these models genuinely useful for structural battery design, their predictions should be validated against measurable indicators, including impedance increase, strain evolution, interfacial delamination, coating failure, local current distribution, temperature rise, and mechanical property retention after cycling. Integrating modeling analysis with in situ monitoring, operational condition measurements, or post-mortem characterization can provide deeper insight into degradation processes and failure mechanisms. Such an approach can enhance the credibility of lifetime prediction and accelerate the development of reliability-oriented structural batteries.

However, current multiphysics models remain limited by uncertain interfacial parameters, simplified geometries and constitutive assumptions, and incomplete validation across relevant length and time scales [109–112]. Operando methods also face limitations in spatial and temporal resolution, access to buried interfaces, and compatibility with mechanically loaded structural cells. Model predictions and operando observations should, therefore, be interpreted together with controlled ex situ and post-mortem measurements rather than as standalone evidence of service-life reliability.

Scalable manufacturing remains one of the key challenges hindering the practical implementation of carbon-fiber structural batteries. Many laboratory-scale prototypes currently rely on manual lay-up, highly controlled coating procedures, and optimized curing conditions, and are generally limited to small specimens with relatively simple geometries. However, engineering-scale components require manufacturing processes capable of maintaining stable, uniform, and reproducible quality across larger areas and more complex structural configurations. Future manufacturing should control fiber alignment, coating thickness, active-material loading, electrolyte infiltration, void content, separator placement, current-collector geometry, cure kinetics, and electrical isolation [73–79,113–115]. Quality-control methods, such as tomography, ultrasonic inspection, thermal imaging, impedance mapping, and statistical sample testing, will be needed to link processing defects with retained multifunctionality. Industrial evaluation should additionally report process yield, cycle time, automation level, manufacturing cost, and end-of-life recovery efficiency so that system-level mass savings can be assessed against production and recycling burdens [45,87,89,90].

A similar distinction between component-level performance and system-level benefit is encountered in other integrated energy technologies. For example, thermophotovoltaic heat-recovery research evaluates not only individual emitter and photovoltaic-cell performance but also system-level energy-conversion efficiency and practical integration under application-relevant thermal conditions [116]. Although the underlying energy-conversion mechanism is different, this systems-engineering perspective reinforces the importance of evaluating structural batteries at the integrated component or platform level rather than through isolated material metrics alone.

Finally, qualification should be application specific. Aerospace panels, satellites, unmanned aerial vehicles, robotic shells, marine structures, and vehicle components impose different requirements on stiffness, fatigue resistance, impact tolerance, thermal stability, repairability, and safety [12,14,108]. Experience from batteries designed for extreme service environments reinforces this point. Deep-sea lithium-battery development, for example, requires materials selection informed by electro-chemo-mechanical considerations together with environment-specific component modification, testing, and battery management strategies to address high-pressure, low-temperature,

and other severe operating conditions [117]. Although these systems are not structural batteries, they demonstrate why qualification protocols should be defined according to the actual coupled environmental, mechanical, and electrochemical conditions of the intended application. Related structural electrochemical systems, including structural supercapacitors and multifunctional current-collector designs, can also provide useful lessons for electrode architecture, electrolyte integration, current collection, and mechanical–electrochemical evaluation [118–124]. For carbon-fiber structural batteries, the final criterion should be whether they provide a reliable system-level benefit under the load cases and safety requirements of the intended application.

In summary, carbon-fiber structural batteries are unlikely to progress through improvements in materials, interfaces, electrolytes, architectures, manufacturing, testing, or qualification alone. These aspects need to be developed together. High-capacity coatings, high-conductivity electrolytes, and lightweight architectures are valuable only when their functions are retained after manufacturing and service exposure. Retained multifunctionality is, therefore, used here as a practical evaluation criterion for assessing whether application-critical electrochemical, mechanical, interfacial, and safety functions are preserved after manufacturing and service exposure. Within this criterion, the contribution of this review is the carbon-fiber-specific synthesis of interfaces, electrolyte topology, manufacturing-induced defects, and coupled degradation mechanisms that govern such performance retention.

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