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Structural Battery Composites for Small Electric Aircraft: A Materials-Focused Review of CF Structural Electrodes with Solid Polymer Electrolyte

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Abstract. The transition towards sustainable short-range electric aviation is urgently constrained by the mass penalties of conventional energy storage systems. With the rapid development of electric aviation technology, the development of new energy storage materials that combine high energy density with excellent mechanical properties has become an urgent need in the industry. This review focuses on carbon fiber (CF)-based structural battery composites, where CF acts as both a structural electrode and a load-bearing component, integrated with solid polymer electrolytes (SPEs), specifically for applications in unmanned aerial vehicles (UAVs) and 2–4-seater light aircraft. Comparative analysis reveals that while these multifunctional composites exhibit superior specific modulus and specific strength, their specific energy density remains a trade-off, often lower than that of standalone cells. Safety is enhanced by the non-volatile nature of SPEs, though effective thermal management remains critical to mitigate operational risks. The findings provide crucial insights for material selection and multifunctional design strategies, highlighting the potential of structural batteries to enable mass-efficient energy storage in next-generation lightweight electric airplanes.

Keywords: Structural battery composites, Carbon fiber electrode, Solid polymer electrolyte

1. Introduction

The rapid development of electric aviation - particularly urban air mobility (UAM) vehicles and unmanned aerial systems (UAS) - is forcing a rethink of how energy is stored and carried on board [1]. Conventional battery packs are typically treated as a passive payload, mounted as discrete systems that contribute substantially to take-off weight. This creates a self-reinforcing constraint: more mass demands more energy, while more energy usually means more battery mass, which in turn worsens the mass fraction and penalises range and payload [2]. Multifunctional materials offer a route out of this loop. In structural battery composites (SBCs), the energy-storing components are themselves load-bearing, allowing mass that would otherwise be “parasitic” to be repurposed as structure [3].

Despite impressive progress, there remains a pronounced gap in how the aerospace community evaluates and compares candidate SBC systems. Many studies report electrochemical and

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mechanical performance separately, often using inconsistent normalisation, test geometries, state-of-charge (SoC) windows, or environmental conditions, which makes it difficult to compare like-for-like or to judge aviation viability in a systems context [4]. This review targets that gap with a materials-focused analysis of carbon-fibre (CF) structural electrodes used together with solid polymer electrolytes (SPEs) in SBC laminates intended for small electric aircraft. We focus on CF because it is the dominant reinforcement in aerospace composites and can, with suitable surface state and pre-lithiation, act as an anode or current collector. We emphasise SPEs because they remove free liquid electrolyte (improving inherent safety and integration) and can also function as the structural matrix or interleaf.

This paper aims to conduct a systematic review study on structural battery composite materials (SBCs) applied to small electric aircraft. The focus of the research is on the laminated board system using carbon fiber (CF) as the structural electrode and solid polymer electrolyte (SPE) as the core electrolyte. In view of the current situation where research data in this field is scattered and testing standards are not unified, making it difficult to conduct effective comparisons and assess the aviation feasibility, this study is dedicated to establishing a unified evaluation framework closely related to aerospace applications. This framework will comprehensively consider four key dimensions: first, the structural efficiency of the material, measured by modulus of elasticity and strength ratio; second, its multi-functional performance, that is, the specific energy at the composite material level; third, safety and abuse tolerance; and finally, thermal management characteristics, including the heat transfer requirements under actual loads.

2. Materials systems and architectures

2.1. Carbon-fibre structural electrodes

In SBCs, the carbon fibres perform a dual role. They provide the principal load-bearing reinforcement of the laminate while also participating electrochemically - most commonly as an anode (after appropriate pre-lithiation/conditioning), or as a conductive current collector supporting a composite cathode layer [5-7]. Typical aerospace laminates employ a fibre volume fraction Vf of 45–60%, balancing stiffness/strength against the need to allocate volume to electrolyte and any electrochemically active phases. Surface chemistry matters twice over: it governs interfacial adhesion and stress transfer with the polymer phase, and interfacial impedance and solid–electrolyte interphase (SEI) properties that control charge transfer and stability. Tailored sizings and surface treatments (e.g., plasma, oxidative, grafted functional groups) have therefore been developed to raise interfacial shear strength without unduly increasing interfacial resistance [8].

2.2. Solid polymer electrolytes as multifunctional matrices

SPEs replace both the liquid electrolyte and the conventional epoxy matrix. The most studied systems are poly(ethylene oxide) (PEO) complexed with lithium salts such as LiTFSI or LiPF6 [9]. To mitigate the classical trade-off between ionic conductivity and mechanical stiffness, recent work has explored block copolymers [10] and ceramic-filled polymer electrolytes (e.g., Al2O3, LLZO, LAGP) that can raise modulus and reduce flammability while maintaining ion transport [11]. Typical ionic conductivities for PEO-based systems lie in the 10-4–10-3 S cm-1 range near 40–60 °C; mechanical properties vary widely with molecular weight, crystallinity, cross-linking, and filler type and loading [12]. Because the SPE often serves as the structural interleaf, its shear modulus and

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glass transition temperature (or melting/crystallisation behaviour) must be compatible with the laminate's service envelope.

2.3. Laminate architecture and load paths

A characteristic CF/SPE SBC is a multilayer laminate in which CF electrode plies alternate with SPE interleaves. Additional layers provide current collection (e.g., thin metal mesh/foil or conductive veil), environmental sealing, and electrical isolation from adjoining aircraft structure. Stiffness and strength are dominated by the CF plies, while through-thickness shear compliance and ion transport are governed by the SPE. The design challenge is to maintain adequate fibre-dominated load paths while ensuring low-resistance ionic pathways and stable interfaces. This architecture can be realised in skins (wing/fuselage), control surfaces, fairings, or internal panels where bending and in-plane loads dominate and where geometric area can be exploited for electrode area.

3. Materials selection and evaluation methodology

3.1. Normalisation and reporting

The Unified Performance Evaluation Framework for Carbon Fiber/Solid Polymer Electrolyte (CF/SPE) Structural Batteries is detailed in Table 1.

Table 1. Unified performance evaluation framework for CF/SPE structural batteries

Performance Metric	Units	Normalization Basis
Specific Modulus	GPa/(g cm^{-3})	Based on total composite density
Specific Strength	MPa/(g cm^{-3})	Based on total composite density
Specific Energy	Wh·kg^{-1}	Total mass based on multifunctional composites
Safety Performance	-	Qualitative/quantitative assessment
Thermal Conductivity	W/(m·K)	Directional measurements

Where possible, electrochemical data are re-expressed at the laminate level. Tests should specify temperature, C-rate, SoC window, and preconditioning. Mechanical tests should report lay-up, gauge length, environmental conditions, and test rate. For multifunctional coupons, coupled testing is strongly preferred to capture realistic degradation modes.

3.2. Carbon-fibre electrodes

High-modulus fibres enhance stiffness but can be more brittle; intermediate-modulus grades may offer a better balance with electrochemical cycling strains. Surface state and sizing: Plasma/oxidative treatments and bespoke sizings can lift interfacial shear strength and reduce contact resistance; however, overly resistive interphases penalise rate capability [8]. Pre-lithiation of CF anodes reduces initial irreversible capacity and stabilises SEI composition, improving coulombic efficiency and cycle life. Electrode architecture: Unidirectional vs woven fabrics, tow size, and areal weight all affect current distribution, strain compatibility, and crack paths.

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3.3. Solid polymer electrolytes

PEO remains common, but cross-linked networks, UV-curable systems, and block copolymers can raise modulus and thermal stability [10-15]. LiTFSI is typical; salt content tunes both conductivity and mechanical behaviour via plasticisation or crystallinity changes [9]. Ceramic fillers (Al_2O_3, SiO_2, BN, LLZO) can enhance modulus, suppress dendrites, increase k, and toughen the interleaf [11]. Plate-like BN is particularly useful for in-plane heat spreading. Solvent casting, hot pressing, or UV curing each affects phase morphology, adhesion, and porosity.

4. Results and discussion

4.1. Comparative performance landscap

Aggregating representative literature data within the above framework reveals consistent trade-offs between structural efficiency and energy storage:

Table 2. Specific performance metrics for aviation SBC applications [13-16]

System	Fiber Volume Fraction Vf (%)	SPE Composition	Specific Modulus (GPa/(g cm^{-3}))	Specific Strength (MPa/(g cm^{-3}))	Specific Energy (Wh·kg^{-1})	Safety/Thermal Characteristics
CF/PEO-LiTFSI	55	PEO-based electrolyte	75	0.9	24	No leakage risk; Limited thermal data available
CF(LFP)/PEO	50	PEO with Li-salt	65	0.7	32	Enhanced interfacial stability; Moderate thermal
CF/Photopolymer	60	UV-cured polymer	95	1.0	12	High mechanical modulus; Brittle
CF/PEO+Filler	45	Composite electrolyte	50	0.6	38	Improved ionic conductivity;
Aerospace CFRP	60	Epoxy matrix	100	1.2	0	Benchmark for structural performance
Commercial Li-ion	-	Liquid electrolyte	-	-	200-250	Benchmark for energy density

As shown in table 2, two immediate points follow. First, present CF/SPE SBCs achieve approximately 50–90% of the specific stiffness and strength of aerospace CFRP while delivering laminate-level specific energies of roughly 12–38 Wh kg-1 - well below dedicated Li-ion packs. Second, those headline numbers hide system-level benefits: SBCs can displace both battery mass and the structural mass otherwise required to carry that battery.

4.2. Mass efficiency and aircraft-system implications

A useful systems yardstick is: MSBC < Mstructure + Mbattery + Mmounts+wiring, evaluated for an aircraft meeting identical performance and safety constraints. Even with w' ≈ 20–Wh kg-1, SBCs can win on mass when (i) large wetted areas exist (wings, skins) that are already structurally necessary; (ii) battery mounting/containment structures are heavy; and (iii) wiring harness length is reduced by distributing energy storage in situ within load-bearing members. Particularly for mass-

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constrained UAVs and e-STOL/VTOL vehicles with short-range missions, the ability to “pay once” for structure and energy storage can dominate the arithmetic.

From a design standpoint, SBC integration influences centre-of-gravity management, crashworthiness, lightning protection, and maintainability. Distributing energy across structural skins reduces the risk of single-point failure but complicates isolation and fault detection.

4.3. Interface-dominated performance and failure modes

The CF/SPE interface largely controls both load transfer and electrochemistry. The competing requirements - high interfacial shear strength for mechanics versus low interfacial impedance for rate capability - create a classic multi-objective optimisation [17]. Too strong and too brittle an interface can localise strains and promote interfacial cracking under cycling or thermal excursions; too compliant or poorly bonded, and the laminate loses stiffness and delaminates under shear.

Failure modes observed or anticipated include: (i) interfacial debonding initiating at stress concentrations (fastener holes, ply drops); (ii) micro-cracking of the SPE interleaf leading to increased internal resistance; (iii) dendrite-like filament growth across defects under high local fields (mitigated by ceramic fillers and mechanically stiff interphases); and (iv) mechanically induced SEI disruption with concomitant gas generation and swelling. Interface engineering - via tailored sizings, nano-scale interlayers (e.g., grafted polymers, ultrathin ceramic coatings), and controlled roughness - offers routes to raise both interfacial shear strength and suppress charge-transfer resistance. Promising approaches combine covalent bonding sites with percolated ionic domains, ensuring simultaneous stress transfer and ion mobility.

4.4. Thermal management requirements

SPEs eliminate free liquid electrolyte, reducing leakage and improving inherent abuse tolerance. However, most SPEs have low through-plane thermal conductivity, which risks hot-spot formation at moderate to high C-rates [18]. In-plane k_\parallel is elevated by CF, but heat must still cross the SPE interleaf to reach heat sinks. For operating currents above about C/2, many architectures will require designed-in heat paths: e.g., BN-filled SPEs to raise k; thin, thermally conductive veils bridging between CF plies; or embedded heat spreaders that do not overly compromise electrical isolation. Because temperature also modulates ionic conductivity (beneficial up to a point) and mechanical stiffness (potentially detrimental near softening), thermal and structural design must be co-optimised from the outset.

4.5. Durability, ageing, and safety

Aviation service imposes cyclic mechanical loads, temperature swings, humidity exposure, and occasional impacts. These occur simultaneously with the electrochemical cycle. The durable design may require the search for a solid electrolyte with stable modulus and minimal creep within the 0 - 60°C range; in addition, the material needs to be able to resist hydrolysis/oxidation and maintain a low impedance interface, as well as have cathode chemicals that inhibit oxygen release and are compatible with volume changes, and a strong electrical isolation strategy to prevent fault propagation after being impacted or flooded. Safety assessment should extend beyond single-cell abuse to coupon- and sub-component-level testing under combined load and charge/discharge, with pass/fail criteria that include structural residual strength as well as thermal runaway metrics.

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4.6. Manufacturability and repairability

Manufacturing CF/SPE SBCs at scale raises familiar composite challenges (voids, fibre alignment, surface preparation) alongside battery-specific ones (moisture sensitivity, salt distribution, residual solvent). UV-curable or hot-press processes that integrate with existing composite lines are attractive [15]. Quality assurance must verify both structural integrity (NDT of porosity/delaminations) and electrochemical functionality (impedance mapping). Repair in the field is non-trivial: scarf repairs that restore load paths may not restore ionic pathways, and vice versa. For near-term applications, modular replacement at the sub-panel level is likely more practical than on-wing repair, with health-monitoring features used to schedule replacement.

4.7. Certification and test pathways for multifunctional materials

Because SBCs combine functions, certification cannot simply bolt together existing structural and battery standards. This system begins at the material and test specimen level, where coupled electromechanical performance tests (including tensile, compressive, shear, and fatigue experiments) need to be conducted under representative charging and discharging rates and temperatures to simulate the multi-field coupling effects in real working conditions. After the tests, the residual performance needs to be evaluated, and special abuse tests on the charged test specimens are conducted t determine the failure boundary and safety threshold. Subsequently, the verification moves up to the component level, where bending and torsion tests under cyclic loads are carried out for sub-components (such as wing skin panels), while electrical isolation checks, lightning simulation, and impact damage tolerance assessment are also conducted in parallel to verify the integrity of the functional-structural integrated components. Finally, at the system level, integrated packaging tests including thermal baking, water intrusion tests, and assessment of internal failure propagation barriers are performed to comprehensively evaluate the durability, safety, and reliability of the entire system in harsh environments. This complete verification process, spanning materials, components, and systems, is crucial for evaluating the multi-functional performance of structural batteries and promoting their engineering applications. Throughout, diagnostics such as embedded strain/temperature/impedance sensing can provide evidence for prognostics-based maintenance and support certification arguments.

4.8. Application-specific feasibility

For UAVs and two- to four-seat short-range aircraft, CF/SPE SBCs already present a compelling value proposition. These platforms usually have the following characteristics: Firstly, the absolute energy consumption required by the platforms is relatively low, and they have a large surface area suitable for distributed storage; Secondly, they can achieve significant benefits in significantly reducing the weight of installation and protection; Finally, their service life requirements are not as strict as those for vehicle usage cycles. In UAM/VTOL craft, the peak-power demands of hover are more severe; SBCs may contribute as structural “energy reservoirs” paired with a smaller high-power buffer pack, easing thermal loads and enabling graceful degradation. Even in these cases, careful thermal design and robust isolation are mandatory.

5. Conclusions

Carbon-fibre structural battery composites with solid polymer electrolytes are a promising route to meaningful mass reduction in electric aviation. Although current laminate-level specific energies

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(≈12–38 Wh kg^{-1}) are far below those of standalone Li-ion packs (≈200–250 Wh kg^{-1}), SBCs can win at the aircraft level by displacing both battery and structural mass while simplifying mounting and wiring. Present CF/SPE systems offer 50–90% of the specific stiffness and strength of aerospace CFRP, with significant headroom remaining through interface and electrolyte design.

Three focused research thrusts would accelerate adoption. Tailored sizings and nano-interlayers that increase interfacial shear strength while maintaining low charge-transfer resistance; mechanically robust SEIs for CF anodes; controlled roughness to distribute shear without localising fields. SPEs and interleaves that combine higher through-thickness conductivity with adequate shear modulus; embedded heat-spreading pathways that preserve electrical isolation; validated thermal models linked to flight profiles, demonstrating safe operation at ≥C/2 without hot-spots. Standardised, coupled electro-mechanical tests at coupon and element level; integrated damage-tolerance/abuse protocols; and embedded diagnostics to support condition-based maintenance. Agreement on aerospace-relevant normalisation will reduce ambiguity and speed airworthiness assessments.

With these advances, CF/SPE SBCs could enable lighter, simpler, and safer small electric aircraft - particularly UAVs and short-range piloted platforms - within the coming decade. Their greatest value will be realised when materials choices, laminate architecture, thermal pathways, and certification strategy are co-designed as a single system rather than treated as add-ons to a conventional airframe-plus-battery paradigm.

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