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RESEARCH

Paving the Way for the Electrified Future of Flight: Safety Criteria Development for Integrating Structural Batteries in Aircraft

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Abstract
Within the global push towards environmental sustainability, the aviation industry is increasingly investigating electrification as a potential solution to reduce emissions and combat climate change. However, traditional battery integration faces significant drawbacks due to their limited energy and power densities, which negatively impact aircraft weight and performance. In this scenario, structural batteries are gaining interest, since they combine energy storage and load-bearing capabilities in multifunctional material structures, thus potentially eliminating barriers to the electrification of the air transport sector. While this novel technology holds immense potential, its integration raises new and unique airworthiness concerns. The present activity aims to support the development of aircraft certification requirements for structural batteries. Recognizing the dual nature of this technology, the proposed approach seeks to maintain or even enhance the current level of safety in both normal and emergency flight conditions.

Keywords Structural batteries · Multifunctional materials · Airworthiness requirements · Certification by analysis

1 Introduction

Current air transport systems face the critical challenge of reconciling environmental sustainability with continued economic growth [1]. This pressing need has been recognized by European policymakers, resulting in the development of comprehensive strategy roadmaps and sustained long-term research efforts. The European Green Deal of 2019 [2] established the ambitious goal of achieving climate neutrality across all sectors of the EU economy, including air transport, by 2050. This represents a significant increase in environmental targets compared to previous initiatives.

One of the central strategies to achieve in-flight emission reduction of greenhouse gases (GHGs) and pollutants is the increased utilization of electrical energy onboard aircraft. This applies to both non-propulsive and propulsive functions, giving rise to the concepts of “More Electric Aircraft” (MEA), “Hybrid Electric Aircraft” (HEA), and “All-Electric Aircraft” (AEA).

HEA solutions hold considerable promise [3, 4], offering the potential for low- or even zero-emission flight. In addition, they enable the exploration of novel air transportation missions, enhance safety through distributed systems, and offer improved design flexibility due to innovative solutions like distributed electric propulsion (DEP) [5]. These cutting-edge concepts are being actively investigated across diverse aviation sectors, ranging from twin-aisle passenger jets to urban air mobility vehicles with vertical take-off and landing capabilities.

While several all-electric aircraft designs have been developed and flown [6], the currently operational models primarily represent electrified versions of existing gliders or very light machines. Examples include the Lange Aviation Antares 20E and 23E, the Pipistrel Taurus Electro G2, the Yuneec International E43, and the Pipistrel Alpha Electro.

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The hybrid-electric propulsion scenario remains even less populated, with no commercially available designs to date. Nevertheless, ongoing research holds significant promise for future advancements in this application field.

Despite the improved efficiency of modern electric motors compared to internal combustion engines (ICEs) in converting stored energy to mechanical power, the primary limitation for electric aircraft remains the energy density of batteries. Particularly in aviation, current battery technology falls short in terms of energy-to-mass and energy-to-volume ratios [7], significantly impacting the aircraft's maximum take-off weight and consequently its payload or size. However, ongoing research efforts aimed at enhancing these performance metrics have enabled the design and flight of electric aircraft, including both prototypes and production models, primarily in the ultralight and general aviation categories [8].

A notable example is the Pipistrel Velis Electro, belonging to the very light aircraft category and the only commercially certified all-electric aircraft to date. Analysis of its certification process provides valuable insights for ensuring the airworthiness of battery packs in electric aircraft [9].

Nevertheless, several challenges hinder the widespread adoption of hybrid-electric aircraft. These include the limited weight performance of current energy storage devices, the lack of regulatory frameworks for novel mobility concepts, and uncertainties regarding future market demand. Regardless of the chosen aircraft configuration, HEAs reliant on conventional batteries face the inherent weight penalty associated with storing the required electrical power. This added battery mass triggers a detrimental "snowball effect" on the overall aircraft weight: increased demand for electric power necessitates more batteries, further elevating the Maximum Take-Off Weight (MTOW).

One promising approach to mitigate this effect and its negative impact on weight convergence involves the concept of structural batteries (SBs). Developed since the late 1990s, SBs are hybrid, multifunctional composite materials that combine the capability of storing electrical energy (similar to conventional lithium-ion batteries) with the ability to bear structural loads. This integration eliminates the weight penalty associated with conventional batteries, as the SBs simultaneously fulfill both roles. While traditional battery packs solely provide electrical energy, SBs extend beyond this function by creating a robust structure that reinforces the aircraft body.

The research scenario involving structural batteries and their potential impact on the aeronautical field is rapidly expanding. Adam et al. [10] estimated that integrating SBs as energy storage devices within aircraft structures could achieve a range extension of 11–66%, assuming ideal conditions and full substitution within 10–40% of the aircraft's MTOW. Recent research has increasingly focused on understanding the trade-offs between mechanical and energy storage performance. For instance, Schutzeichel et al. [11] characterized the electrochemical properties of carbon fibers as structural anodes, while Leijonmarck et al. [12] investigated their use as negative electrodes in Li-ion batteries embedded in a cathode-doped matrix material. Shirshova et al. [13] conducted a systematic analysis of bi-continuous liquid-epoxy systems for developing stiff structural solid electrolytes.

These studies pave the way for optimizing the multifunctional capabilities of relevant structures. Scholz et al. [14] demonstrated that structural batteries with a minimum energy density of one-third to one-half of conventional batteries could replace entire propulsive batteries for small all-electric aircraft.

Karadotcheva et al. [15] investigated the potential of structural batteries to improve fuel efficiency and reduce GHG emissions in various A320-like aircraft configurations.

Despite optimistic forecasts, several research challenges remain. These include material configuration and functionalization, optimization strategies to balance structural and electrochemical properties, environmentally friendly manufacturing processes, large-scale production methods, and life cycle analysis.

Furthermore, a critical challenge lies in the lack of certification standard for this novel technology. This study aims to establish a viable route for defining safety criteria for SBs by leveraging relevant regulations for conventional batteries and composite structures while incorporating the performance-based approach advocated by certification entities. A comprehensive overview of the current state-of-the-art and relevant literature is provided, along with a reasonable strategy for developing future SB certification criteria.

2 Structural Batteries State of the Art

Structural batteries represent a promising solution for enhancing the electrical energy storage capabilities of aircraft. These multifunctional components, fabricated similarly to composite materials already employed in many aircraft, hold the potential to replace stress-bearing parts typically constructed from metal alloys or carbon fibers. Through this multifunctionality, the weight penalty associated with conventional battery packs on board the aircraft can be mitigated, as the structural batteries simultaneously store electrical energy and bear structural loads.

Two key parameters are used in the literature [16] to characterize this technology, the integration degree, and the functionalization scale. The integration degree quantifies the proportion of the battery integrated into the structure, while the functionalization scale refers to the physical dimensions of the elements enabling multifunctionality.

Based on these parameters, structural batteries can be classified into multifunctional structures and multifunctional materials. In multifunctional structures, different materials within the structural battery perform single functions, even though the overall composite fulfills both energy storage and load-bearing functionalities. Conversely, in multifunctional materials, all constituents act simultaneously as load-bearing and energy-storing components. More in detail, SBs can be further classified in four types:

- Integrated conventional storage: achieved by embedding commercially available lithium batteries within dedicated structural elements. Weight savings are limited to the replacement of the battery enclosure with composite fiber laminates.
- Integrated thin-film energy storage: similar in approach to type-I but utilizing thin-film batteries embedded within the structural elements instead of conventional ones. This approach offers the advantage of minimizing battery impact on the mechanical properties of the composite structure, increasing on the other hand the total cost of the technology.
- Structural laminate capacitors: represent the transition from multifunctional structures to multifunctional materials, relying on the substitution of conventional battery components with load-bearing elements to achieve greater weight savings.
- Microscaled fiber capacitors: represent a further step towards multifunctional materials, with two proposed approaches in the literature, the coaxial and the layered ones. Despite research efforts, appreciable performance for this SB type has yet to be demonstrated.

Figure 1 presents examples of structural battery types based on the aforementioned classification criteria.

It is important to note that the key performance indicators (KPIs) of this technology, schematically shown in Fig. 2, exhibit trade-offs. Increased demands on the electrochemical side typically lead to diminished structural properties, and vice versa.

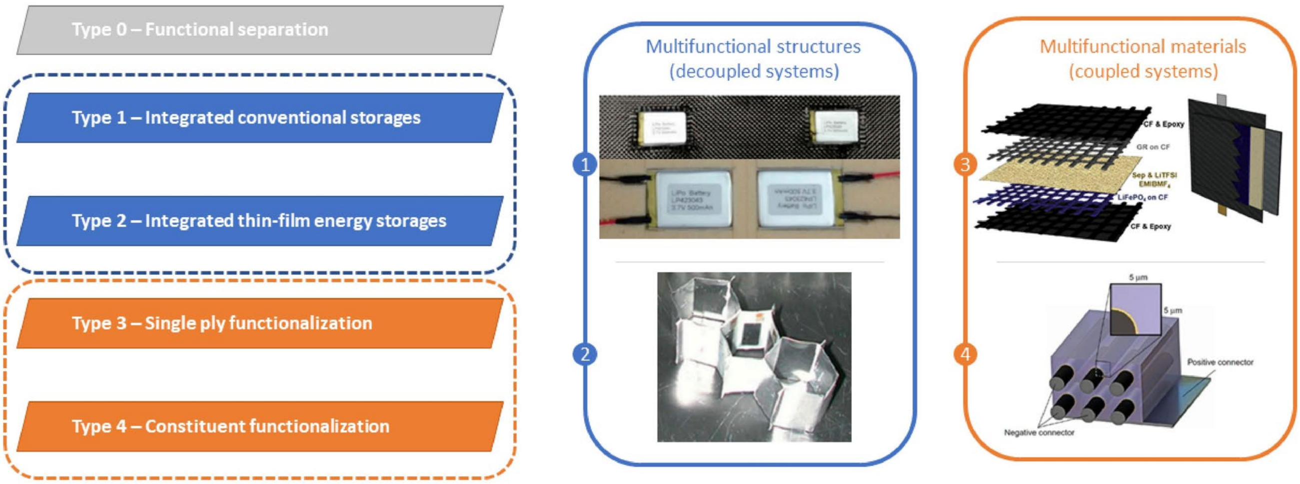

Fig. 1 Structural battery types: examples of integrated conventional storage, integrated thin-film energy storage, structural laminate capacitors, and microscaled fiber capacitors

Fig. 2 Structural and electrochemical KPIs for SBs

Table 1 Expected structural batteries mechanical properties compared with carbon fiber-reinforced polymer ones [22]

Property	CFRP	SB
Mass density [kg/m^3]	1600	1800
Tensile modulus [GPa]	70	70
Shear modulus [GPa]	5.2	5.0
Ultimate tensile strength 0° [MPa]	600	560
Ultimate compressive strength 0° [MPa]	570	280
Ultimate tensile strength 90° [MPa]	600	560
Ultimate compressive strength 90° [MPa]	570	280
Ultimate in-plane shear strength [MPa]	90	52
Ply thickness [mm]	0.200	0.275

Table 2 Expected structural batteries electrochemical properties compared with conventional ones [22]

Property	Conventional	SB
e_b[Wh/kg]	265	125
p_{b-peak}[W/kg]	2600	1200
p_b[W/kg]	900	400

Research on structural battery configurations encompasses diverse areas, including electrode material studies [17], development of ionically conductive matrix materials that maintain rigidity [18, 19], assembly techniques, scale-up processes, demonstration projects, multiphysics modeling, design optimization, and applications. Potential applications extend beyond aircraft structures, encompassing casings for mobile phones, laptops [20], and even structural components in automobiles, all offering the benefit of significant weight savings.

The selection of composite materials for this novel technology stems from their advantageous properties, the good lithium-ion conductivity and the ability to withstand loads, characteristics that have already driven their exponential adoption in aircraft structures in recent years.

Tables 1 and 2 provide a concise comparison of anticipated structural battery properties against the established properties of carbon fiber laminates from a structural perspective and conventional lithium-ion batteries from the electrochemical side. This comparative analysis enables a focused evaluation of the strengths and weaknesses of structural batteries as a potential technology for integration within aircraft structures.

Several integration strategies have been proposed for SBs integration in aircraft. Nguyen et al. [21] explored the feasibility of embedding SBs in the cabin floor panel of an A220-like aircraft, demonstrating their potential to power in-flight entertainment systems. Riboldi et al. [22] proposed a detailed preliminary design for a CS-23 hybrid-electric general aviation aircraft incorporating SBs. This design envisioned utilizing SB panels across 75% of the fuselage structure and select wing components, such as ventral skin panels and leading/trailing edges, where compressive loads are reduced.

It is crucial to acknowledge that the current maturity level of SB technology precludes its application within primary aircraft surfaces due to stringent certification requirements. Consequently, a viable near-term strategy involves integrating SBs in secondary surfaces like floor and overhead panels, where achieving aeronautical certification is more feasible. This approach would allow for initial demonstrations and pave the way for future advancements towards broader SB integration in the airframe.

3 Certification Requirements for Composite Materials

The rapid development and aerospace applications of composite materials, subject to stringent safety requirements, have necessitated the meticulous characterization of these materials. Unlike readily available and well-characterized metal alloys commonly used in aerospace, composite materials are often manufactured concurrently with the structural components themselves. This results in a wider variability of mechanical properties due to the selected fiber, type of resin, production processes and environmental conditions. Consequently, certification requirements for composite structures are notably stricter than those for metallic ones. This disparity arises from the fundamental objective of maintaining equivalent safety levels in aeronautical applications regardless of the chosen material.

The first step for certification of any advanced material and process is the material and process control. It is the most critical phase since the materials and processes must be defined and stable. Three are the items needed to check:

- The feedstock material must be certified. For composites, this is more than just laminate materials, meaning that also core, adhesive, and non-fly away materials need to be certified. Specifically, for structural batteries certified materials must be available, the carbon fiber, the matrix material, and the adopted electrolyte to make the structural battery capable of storing electrical energy.
- The process adopted to convert the feedstock material to a part has to be stable and repeatable.
- The final part material must ensure that the required chemical, physical and mechanical properties are achieved. With a particular reference to structural batteries, their interaction with surrounding structures must be accounted.

In this context standardization, organizations and shared databases become increasingly important. The most widely used standard for verifying the airworthiness of a composite material is the FAR part 25 from Federal Aviation Administration (FAA) [23]. In addition, the AGATE [24] and NCAMP [25] programs are two databases that provide a list of composite materials certified according to FAR part 25 regulations.

Once material and process control is correctly finalized, the airworthiness certification must be carried out, with respect to the Advisory Circular (AC) 20-107 [26]. This document emphasizes the need for targeted experimental tests to determine the mechanical properties of the investigated structures with:

- Static testing: evaluates structural resistance by subjecting it to 150% of the Design Limit Load (DLL), effectively simulating the Ultimate Load.
- Fatigue testing: assesses resistance to degradation and breakage due to cyclic loading. Frequencies are typically low (5–10 Hz) to avoid excessive specimen heating. Cyclic loads can be applied with constant amplitude or follow load spectra resembling real operating conditions.
- Damage tolerance and impact resistance: quantifies the specimen's capacity to withstand impact and penetration. Specimens are subjected to impactors of varying sizes and materials.

Considering that structural batteries partially or entirely incorporate carbonaceous materials and fabrication methods similar to carbon fiber-reinforced polymer (CFRP) structures, it becomes evident that a rigorous assessment of their structural performance necessitates applying the same testing approach as that specified for CFRP structures.

4 Certification Requirements for Lithium Batteries

Current certification requirements for battery installations in large airplanes are outlined in Certification Specification (CS) 25.1353(c). However, these regulations, based on the Joint Aviation Requirements (JAR)/CS 25 airworthiness code, lack specific standards or guidance for lithium batteries. Moreover, their content remains largely unchanged from the initial JAR code and fails to adequately address several critical failure, operational, and maintenance aspects unique to lithium batteries, potentially compromising safety and reliability. Recognizing this inadequacy, the Federal Aviation Administration (FAA) advocated for standardized test methods to facilitate certification of new aircraft designs incorporating permanently installed rechargeable lithium-ion batteries. In this context, AC 20-184 [27] establishes special conditions for applicants with such designs, providing comprehensive certification standards. While primarily intended for non-rechargeable lithium batteries, this document serves as a valuable reference for structural battery certification due to their shared lithium-based nature and consequent susceptibility to similar failure modes, including over-charging/discharging, toxic gas release, short circuits, and lightning strikes.

Extensive research efforts have explored the link of electrical and structural performance in conventional batteries, employing both experimental and numerical approaches. In Ref. [28], dynamic abuse tests on pouch and elliptic Li-ion cells, with and without liquid electrolyte, at varying intrusion velocities are exhibited. Further advancements at the component level are documented in Refs. [29, 30], which comprehensively evaluate the mechanical failure mechanisms of both cylindrical and pouch cell components. These findings are crucial, as dynamic intrusion represents a major failure mode for batteries.

Significant attention is focused on predicting battery behavior during such events to enhance safety. A multiphysics model presented in Ref. [31] comprehensively couples mechanical, battery, short-circuit, exothermic, and thermal models to analyze the response of a cylindrical cell under abuse loads. Both numerical and experimental studies consistently observe a characteristic after impact occurs: a sudden voltage drop accompanied by a rapid temperature rise. While Ref. [32] attributes the short circuit to severe battery deformation, Refs. [33–35] link it to separator failure. These results and models not only improve the understanding of lithium-ion battery failure behavior but also offer valuable insights for developing physics-based safety design tools for battery structures under mechanical abuse. Such advancements contribute significantly to the safe integration of structural batteries in the aeronautical field.

5 Viable Route for SBs Certification

The integration of structural batteries into aeronautical structures poses a significant challenge from a certification perspective. Regulatory agencies effort is very important to ensure airworthiness without compromising safety. The European Aviation Safety Agency (EASA) is embracing a performance-based approach [36] to expedite the incorporation of innovative technologies like structural batteries into the aviation industry. This approach prioritizes safety while offering flexibility for industry players to leverage potential safety benefits through innovative design.

This approach is especially aimed at new generation structures, that fall under the category of advanced manufacturing, meaning the ones in which the material is made concurrently with the part. This approach completely differs from the normative-based one, giving more design flexibility for novel technologies to be introduced in the aviation sector, prior demonstration their performance.

The European community actively supports this shift through numerous Horizon 2020 projects. Examples are the ACACIAS (Advanced Concepts for Aero-Structures with Integrated Antenna and Sensors) project, focused primarily on the realization of a fuselage panel with integrated sensors and wiring for reduction of cabin noise and a smart winglet with integrated blade antenna [37]; similarly, the MORPHO (Manufacturing, Overhaul, Repair for Prognosis Health Overreach) project, which proposes to embed printed fiber-optical sensors in aircraft engine fan blades, thus providing them with cognitive capabilities while they are manufactured [38]; the DOMMINIO (Digital method for imprOved Manufacturing of next generation MultIfuNctIOnal airframe parts) project, aimed to develop innovative fiber-based piezoresistive strain sensors employed to incorporate novel continuous carbon nanotubes in the laminate [39].

These projects exemplify how structural battery certification can be harmonized with the new performance-based approach. However, until a comprehensive understanding of structural performance across various scenarios is achieved, a conservative approach is recommended. This involves employing well-established engineering methods with point design substantiation, followed by a more rigorous building block approach as applications expand. Within this framework, a composite laminate with integrated SBs can be treated as a delaminated laminate, leveraging existing regulatory guidelines. Crucially, this approach must comply with both structural and electrical requirements through:

- Structural aspects: damage tolerance, fatigue assessment, strength assessment, detailed design, and fabrication must demonstrate the absence of catastrophic failure due to fatigue, defects, environmental deterioration, or accidental damage throughout the aircraft's operational life.
- System-structure interaction: for aircraft equipped with systems impacting structural performance, the influence of these systems and their potential failure modes must be considered during airworthiness evaluations to ensure the structural integrity of the aircraft [40].

6 Conclusions

Structural batteries have emerged as a promising solution for enhancing onboard electrical energy storage capacity within aircraft structures. This holds the potential for significant advancements in several key areas, including increased range, expanded payload capacity, and reduced greenhouse gas emissions.

This study conducted a comprehensive review of the current state-of-the-art in structural battery technology, focusing on their potential benefits and the critical challenge of certification.

An overview about the current regulatory scenario has been delivered, focusing on existing regulations that could serve as a foundational framework for developing specific certification criteria for SBs, acknowledging their dual nature as both structural and electrical components. Moreover, the development of physics-based safety design tools tailored specifically for battery structures was identified as a crucial contribution to ensuring the safe and successful integration of SBs within the aeronautical field.

Ultimately, by overcoming these challenges and achieving successful integration, SBs have the potential to revolutionize aircraft design, paving the way for a future of cleaner, more efficient and longer haul flights.

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Data Availability No datasets were generated or analyzed during the current study.

Declarations

Conflict of Interest The authors declare no conflict of interest.

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