Structural batteries challenges for emerging technologies in aviation

Gennaro Di Mauro[1,a], Michele Guida[1,b,*], Gerardo Olivares[2,c], Luis Manuel Gomez[2,d]

[1]Department of Industrial Engineering, Università degli Studi di Napoli Federico II

[2]National Institute for Aviation Research (NIAR), Wichita State University, Kansas, USA

[a]gennaro.dimauro@unina.it, [b]michele.guida@unina.it; [c]gerardo.olivares@wichita.edu, [d]luismanuel@niar.wichita.edu

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Abstract. In a global context where modern societies need to move towards greater environmental sustainability, ambitious targets to limit pollutant emissions and combat climate change have been set out. Concerning the aviation sector, research centers and industries are carrying out new aircraft designs with increased use of electrical energy onboard aircraft both for non-propulsive and propulsive purposes, leading to the concepts of More Electric Aircraft (MEA), Hybrid Electric Aircraft (HEA) and All-Electric Aircraft (AEA). Despite the expected flight emissions reduction, new potential air transportation missions, safer flights, and enhanced design flexibility, there are some drawbacks hindering the trend to HEA solutions, strictly bounded to the limited performance of traditional battery systems. The reference is to low energy and power densities, which impact on aircraft weight and flight performances. A new technology, namely structural battery, combining energy storage and load-bearing capacity in multifunctional material structures, is now under investigation since capable to mitigate or even eliminate barriers to the electrification of air transport sector. Although, the deployment of this technology raises relevant questions regarding airworthiness requirements, which need to be applied when considering such multifunctional materials. The purpose of the presented activity is to take a step towards the definition of aircraft certification requirements when dealing with structural batteries, considering them both as a structure and as a battery, to maintain unchanged or even improve the level of safety in all normal and emergency conditions.

Introduction

Aviation is a continuously growing sector that has seen an increase of 6% per year in passengers and goods transported since 1950 and it is estimated that this number will increase by a further 44% by 2050 [1]. The need for reduce the environmental impact of the sector with the help of eco-friendly initiatives, to achieve the objectives, set by the Paris agreements, which provide for the reduction of total CO2 emissions. The importance of such a change is evident considering the eventuality of continuing to use fossil fuels as a source of power, there would be a 17% increase in CO_2 compared to the current situation. Instead, in a different scenario, in which the electric alternative was able to acquire a greater application space, a 45% reduction in CO2 would be achieved compared to the levels present in 2005. Among the solutions identified aimed at reducing the environmental impact of aviation the hybrid electric, electric and solar energy aircraft are applied, [2], there are already certified aircraft projects and others are in the experimental stage, and it is interesting how these projects exclusively concern aircraft of categories glider, very light aircraft and unmanned.

The main reason for such a circumscription and, consequently, for the non-inclusion of larger and heavier aircraft, lies in two parameters: specific energy density and specific energy, [3]. The first concerns the amount of energy available per unit mass; while the second is the amount of energy that can be contained in each volume. The batteries currently used are the lithium ones as they guarantee a reduced volume and mass compared to the competitors. By comparing the lithium batteries available on the market with the fossil fuels currently in use, such as kerosene and diesel, the parameters suggest that, with the same specific energy density, the batteries would weigh about 50 times more than their fossil alternatives. At the same time, for the same specific energy, batteries would occupy about 18 times the volume of their fossil alternatives. At this point, one wonders how to overcome these physical limitations. A potential solution, object of this thesis work, is represented by multifunctional materials, [6]. The latter are materials capable of fulfilling several functions simultaneously: in our case reference will be made to the structural batteries, which, as mentioned above, perform both a structural and energy storing function at the same time. This work deals with the most interesting points concerning the applications of Structural Batteries in the aeronautical field, [4]. The main environmental issues and the objectives that push aviation towards a 'green' perspective were discussed. Subsequently, a summary of the most relevant literature on the state of the art available regarding structural batteries was discussed. A focus on the mechanical point of view was made by discussing the main issues related to their manufacturing and certification requirements. The main current regulations issued by the FAA and EASA were discussed and a 'tailoring' between lithium-ion battery standards and composite material standards was discussed to find a certification process for this type of materials.

Material and Process Control

It is more important than ever to ensure that batteries are safe, strong, and dependable. However, the safety, performance, and longevity of a battery are only as excellent as the materials used to make them. *Electrodes, separators, current collectors, and electrolytes* must be extensively characterized and monitored from the moment they enter the production plant until they are incorporated into the finished product.

Solid electrode materials, it is well known that the parameters of the electrochemically active material have a substantial influence on the performance of battery electrodes. Following the formulation of the electrode, the components must be combined to produce a slurry or a dry blend. Relevant influencing variables include particle size, aggregate or agglomeration size, and particle size distributions of the different components. Furthermore, determining features such as powder rheological qualities or particle density and porosity can aid in tailoring the dry-mixing process. The characteristics of the powders are critical for functional and process-relevant factors. These include particle size distribution and mean particle size, particle shape, porosity, and specific surface area. They affect the flowability, dispersibility, and viscosity of the particles, as well as the sedimentation (stability) of the final slurry. The latter influences structural recovery after application, drying and calendering behaviour of the produced electrode layer, mechanical characteristics, and, lastly, the electrochemical parameters of the battery cell.

Electrode slurries, proper design and development of the mixing and coating procedures of the anode and cathode slurry is critical to battery performance. Knowing a slurry's rheological behaviour can also aid in the dimensioning of slurry pumps and anticipating slurry storage behaviour. The uniform thickness and density of the slurry layer are critical to ensuring the battery's lifetime, charge-discharge performance, and ion transfer rate - regardless of battery size. Finally, the proportion of solid particles in a slurry determines the quality and uniformity of the final coating.

Separators: A lithium-ion battery's separator is a thin, porous membrane that plays an important role in battery performance by avoiding a short circuit between the anode and cathode while permitting ion movement between them. Separators must be mechanically strong, stable in active battery conditions, and inert to other cell components while remaining porous enough to allow ion passage. The separator's through-pore size is an important characteristic for guaranteeing optimal battery performance since the holes must be tiny enough to prevent dendrites from growing across the separator while yet being large enough to allow ion movement between the cathode and anode. Larger pores or pin holes must also be searched for and avoided since they might contribute to short-circuit generation. Mechanical strength and structural qualities are another important criterion for separators. Measuring the amount of pre-tension necessary for the separator is critical for avoiding rupture or tearing during assembly as well as drooping after assembly.

Liquid electrolyte, lithium-ion electrolytes are essential in batteries because they allow charge transfer between the anode and cathode. Lithium-containing salts dissolved in an organic solvent are employed for this purpose. The salt lithium hexafluorophosphate (LiPF6) is most often utilized. Because of the reactivity of lithium in water, organic solvents serve as matrix in which lithium salts are embedded.

Raw material quality, adequate salt dissolving, and ion mobility are all critical elements to consider.

Performance-based regulations

Performance-based regulation is commonly regarded as a preferable way to regulation [7]. Rather than outlining the actions that regulated companies must take, performance-based regulation mandates the achievement of results and provides flexibility in how to reach them. Thus, assuming this approach is valid, it is possible, e.g., to treat a composite laminate in which a structural battery is integrated as a laminate in which a delamination has occurred evolving the current regulatory activities, and which meets the structural and electrical requirements considering that:

- regarding the structural aspect, the concept of damage tolerance and fatigue assessment of the structure, a strength assessment, detail design and fabrication shall demonstrate that catastrophic failure due to fatigue, manufacturing defects, deterioration, Environmental (ED) or Accidental Damage (AD) will be avoided for the operational life of the aircraft systems [13].
- regarding the aspect of the interaction between systems and structure, for aircraft equipped with systems that affect structural performance, either directly or because of a failure or malfunction, the influence of these systems and their failure conditions shall be considered when demonstrating compliance with airworthiness requirements, to evaluate the structural performance of airplanes equipped with these systems [13].

In addition to FAA requirements [11] and [12], the AGATE [9] and NCAMP [10] programs are two databases that provide a list of composite materials certified according to FAR part 25 regulations, reporting, in addition, the entire material certification procedure.

Certification Requirements for Composite Materials

One of the problems associated with this new technology concerns the certification process. This research activity seeks to carry out a 'tailoring' between the existing certification regulations of composite materials and lithium batteries, since the structural batteries, simultaneously fulfilling the functions of structural element and energy storing, must simultaneously comply with the two regulations.

For the structural airworthiness requirements, reference is made to the Advisory Circular 20-107 of the Federal Aviation Administration, which refers to the Code of Federal Regulation 14 parts 23, 25, 27 and 29.

In particular, the latter impose that the structure, regardless of the material it is made of, must be subjected to static tests, performed at 150% of the Design Limit Load, fatigue tests where the structure is subjected to cyclic loads with frequencies between 5 and 10 Hz, and impact tests and Damage Tolerance with impactors of different sizes.

At the first level (coupon level) we are interested in defining the mechanical properties of foil and laminate, thus defining the admissible ones.

The second level of analysis is dedicated to establishing the eligibility for critical structural details present in the project. The elements are still relatively simple structures, such as: glued or bolted joints, skin-stringer combinations, panels or laminates which in the design are loaded more in tension, compression and shear.

These elements are tested both at room temperature and in extreme environmental conditions, depending on the fatigue loads that could be encountered in real service conditions of the structure. Then the sub-component level analysis takes place in which are tested for example: wing panels reinforced by currents, simplified mobile surfaces, spars, ribs.
It is a generally unnecessary test that is only required when new materials are used in the project.

The last level of analysis is the full scale, which concerns the entire structure, which must be tested both statically and for durability and damage tolerance in different environmental conditions.

Focusing on the coupon level test, the legislation imposes the test execution methods and the selection of the samples to be tested (number, type and size). A-Basis type samples are distinguished with mechanical properties higher than 99% of the population with a confidence interval of at least 95% (for their determination, at least 55 different specimens are tested, obtained starting from 5 banks of material); B-Basis which have mechanical properties greater than 90% of the population with a confidence interval of 95% (for their determination at least 18 specimens obtained from 3 banks of material are tested).

The samples are tested according to regulations in various conditions and the tests are performed in compliance with the standards imposed by the American Society for Testing and Materials, which set out the test conditions, the methods of execution, the dimensions of the sample, the number of tests necessary and the conditions of acceptability of the test results.

From an energy storing point of view, the structural batteries must be certified according to Advisory Circular 20-174 which establishes the rules relating to safety, health monitoring, continuing airworthiness and maintenance of these devices.

Conclusions

In this report general considerations about certification requirements on composite material structures and the current trend of certification agencies to move towards a performance-based regulations have been addressed.

We are still a long way from certifying an aircraft of this type, the solutions currently available do indeed allow for 'full-electric' travel but at the expense of the aircraft's distance and duration ranges. In the meantime, other solutions are also being evaluated, such as integrating the batteries into the floor or within other constituent elements of the aircraft. In other fields of application such as the automotive one, research seems to have obtained better results, think of Tesla which has managed to integrate the battery pack into the powertrain or other solutions that provide for the integration of structural batteries into the vehicle body, [5]; clearly this is possible because on the ground it is not necessary to submit to the weight limits physically imposed by the aeronautical field.

Although the application of this technology, to date, is easier to apply for a field such as the automotive one, not subject to the physical and certification limitations imposed, however, in the aeronautical field, it is always necessary to continue to look to the future by pushing the research towards new frontiers and solutions.

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