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MECHANICAL CHARACTERIZATION OF A COMPOSITE STRUCTURAL BATTERY LAMINATE

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Abstract

Recently, ambitious targets have been set out in various branches of transportation sector to restrict pollutant emissions and to combat climate change and environmental degradation. In this frame, with specific reference to the aeronautic field, new designs including electric or hybrid-electric power-trains propulsion systems penalize battery characteristics, especially in terms of limited energy and power density performances, in turn imposing an increase of the machine weight. Structural batteries (SB) constitute an interesting technology, with the potential to alleviate such problems, since they can perform both load bearing and energy storing functions. In the literature, starting from a side-by-side combination of a structural element and a conventional battery (zero degree of integration) in a fully integrated system, in which the structural element also acts as an energy accumulator, structural batteries can be divided into two general categories: multifunctional structures and multifunctional materials. In the first case different materials within the structural battery perform a single function, however the overall composite is multifunctional, whereas in the latter all materials adopt multiple functions. Although higher mass savings are predicted for multifunctional materials, current research efforts show that multifunctional structures exhibit better overall performances.
Apart from the classification, the use of this technology raises relevant issues concerning airworthiness requirements that need to be applied when considering such multi-functional materials.

The purpose of this work is to overview the new problem of aircraft certification in presence of structural batteries. A focus on impact tests needed to prove damage tolerance of this technology is considered, also demonstrated through an experimental-numerical correlation on a test case.

Keywords: keywords: structural battery, multi-functionality, airworthiness

1. Introduction

Nowadays there are several reasons to study alternative propulsion systems. As reported in [2], civil aviation within Europe is responsible for 13.2% of CO_2 emissions in the transport sector. The European Aviation Environmental Report 2019 shows a relative increase of 16% in CO_2 emissions compared to the reference year of 2005 to 2017. A further increase of 42% is expected according to current models. Nitrogen oxide emissions also show drastic increases. Worldwide, the air traffic is estimated to be responsible for 2% of carbon dioxides emissions. Besides that, the amount of oil is limited and its price is progressively increasing. A resolution to these outcomes has been made by the European Flight path, which addresses ambitious environmental protection goals for civil aviation. By 2050, the technologies are expected to reduce:

- CO_2 emissions per passenger kilometer by 75%,
- nitrogen oxide emissions by 90%,
- noise emissions by 65%.

Clearly, all-electric and hybrid-electric aircraft represent the higher step towards environmental friendly air-transport. As of today, some all-electric aircraft have been designed and flown [3]. Most of them are basically electrified versions of existing gliders, others are very light machines, inspired by a corresponding conventionally-powered aircraft in the light-weight sport aircraft (LSA) category.
In general, among all available batteries on the market, lithium batteries are the preferred ones, since they have better performances in terms of energy density and volumetric energy density. This means that lithium batteries have the least weight and the smallest size for the same amount of energy stored, when compared with batteries using a different chemistry. In spite of that, the specific energy and the volumetric energy density of batteries today are exactly the limiting aspects for electrification in aircraft applications, especially when high-weight categories of aircraft are considered.

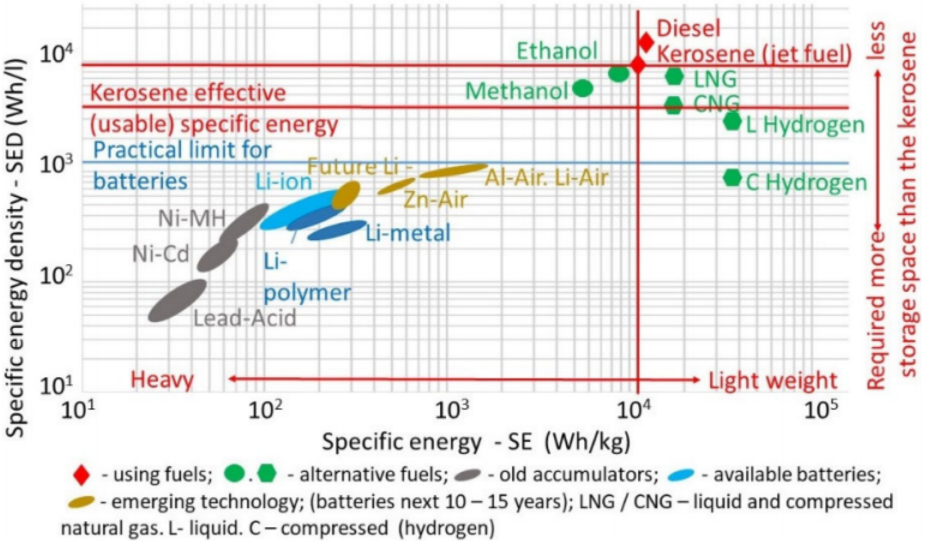

Figure 1 – Energetic comparison of the applicable fuels [7].

It can be seen from Figure 1 that even the most advanced current battery storage systems fall short of the traditional fuels such as Kerosene. Considering the same amount of energy, a battery system weighs about 60 times more and it is about 18 times bigger than a kerosene system. This is a core problem for application in aviation, especially for aircraft belonging to higher weight categories, in which the energy requirements increase more and more. Given such limitations, the all-electric aircraft might be successfully developed in the following cases:

- limited range is acceptable (25-50% compared to ICE aircraft);
- significantly increased battery specific energy levels;
- unconventional structures are developed;

Range limitation is currently the only feasible solution, even if it is not the most attractive one. Future, better batteries may provide more promising solution. Despite that, the battery developers estimate the availability of batteries with specific energy greater than $750\mathrm{Wh/kg}$ within the next 10-20 years. Until then, unconventional concepts could provide interesting solutions.

2. Structural Battery: a promising solution

Structural composites stand out as a possible solution to the problems mentioned before, since they are capable to perform both the load bearing and the energy storing functions. In literature two expressions are used to describe the functional integration characteristics of energy storages. Firstly, the scale of multifunctionalization, which refers to the physical dimensions of SB functionalized components. The second relevant expression is the degree of integration and it is used as a measure for the proportion by which a battery is integrated into a fiber-reinforced structure. These concepts are resumed in Figure 2, where SBs are classified in 4 categories. It is clear from the figure that the degree of integration and the scale are in an inverse relation: increasing the degree of energy storage integration requires a lower scale functionalization and vice versa [1].

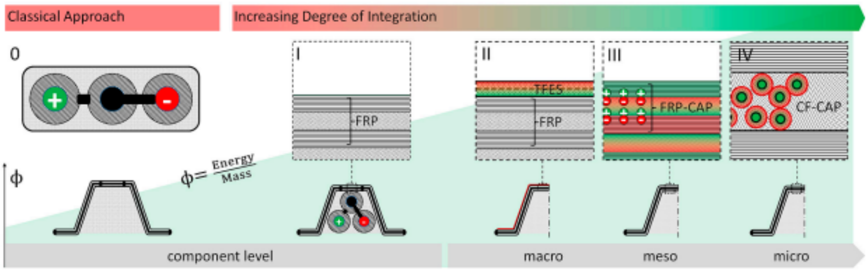

Figure 2 – SBs classification [1].

2.1 Integrated Conventional Storage (Type I)

The integration of commercial lithium batteries into a dedicated structural element, as shown in Figure 3, represents the lowest degree of multifunctionality. It was the first and remains the most widely investigated approach. Weight savings are achieved by replacing the battery cover with a reinforcing material like CFRP to get multifunctionality.

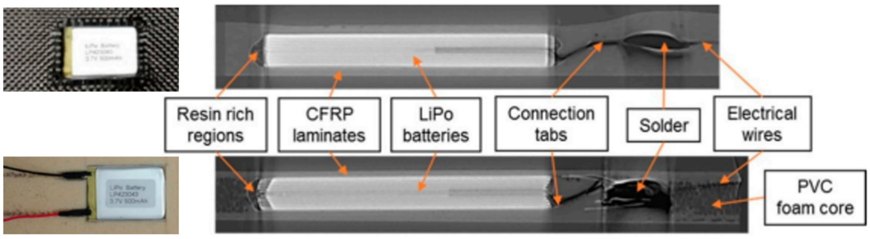

Figure 3 – Examples of type-I SBs: (top) composite laminate and (bottom) sandwich composite.

The mechanical and electrochemical performance depends on how many batteries are incorporated in the structure. A general trend is that the more batteries are incorporated, the higher the achieved energy density, but the lower the mechanical properties. This is to be expected, as some of the mechanically reinforcing material with high tensile modulus (around $50\mathrm{GPa}$) needs to be removed in order to fit the battery cells with low modulus (around $150\mathrm{MPa}$) in the structural composite. Therefore, the main challenge remains to find the right compromise between the reduction of mechanical properties and the achievable energy density. With type-I SB, energy densities of $20 \div 139\mathrm{Wh/kg}$ have been achieved. Attempts to increase the structural capabilities of this type of SB include modifications of the batteries themselves by introducing polymer rivets for stabilizing the battery layers [8].

2.2 Integrated Thin-film Energy Storage (Type II)

Integrating thin-film batteries into structural elements has the advantage of minimizing the impact of the battery on the mechanical properties of the composite structure. Examples of type-II concepts are shown in Figure 4.

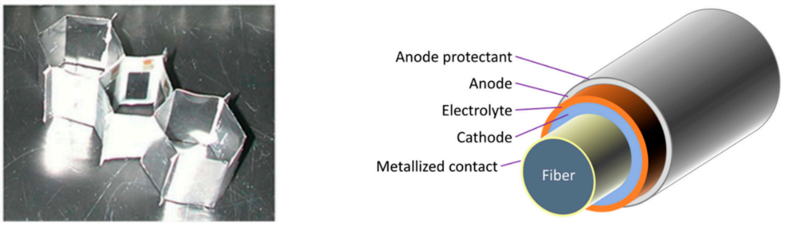

Figure 4 – Examples of type-II SB: planar (left) and coaxial (right) configurations.

Unfortunately, energy densities of only $35 \div 3500 \mu \mathrm{Wh/cm^2}$ have been reached with this approach. In addition, thin-film batteries are significantly more expensive than conventional cells, thus increasing the total cost of the structural composite.

2.3 Single-ply Functionalization (Type III)

Type-III structural batteries represent the first step toward true multifunctionalization. The idea behind this approach is to substitute the passive components of the conventional battery (i.e., the casing, current collectors, separator, and electrolyte), with load-bearing elements, as shown in Figure 5.

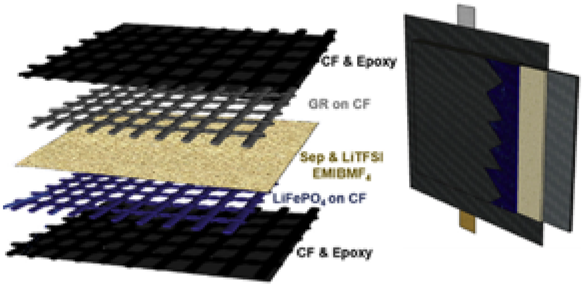

Figure 5 – Example of type-III SB.

For this type of SB, the cathode is usually prepared from conventional laminate electrodes or functionalizing carbon fibers with active materials like LiFePO$_4$. Carbon fibers can be also used for the anode, as they show similar performances to conventional graphitic materials. The separator can be obtained by a glass-fiber weave. Concerning the electrolyte, conventional liquid carbonates are still employed due to the lack of alternative highly conducting electrolytes with good mechanical and structural properties. Proposed solutions concern biphasic structural electrolytes that comprise a load-bearing component (e.g. epoxy-based resin) and an ionically conductive component (e.g. liquid electrolyte) [9]. Working type-III SBs have shown specific energies of between $12 \div 58 \mathrm{Wh/kg}$ and elastic or tensile modulus in the GPa range.

2.4 Constituent Multifunctionalization (Type IV)

For type-IV SBs two different setups are proposed, the coaxial and layered ones (Figure 6). The coaxial approach envisions a fiber-shaped battery, which is composed of a carbon fiber core onto which an electrolyte layer is deposited; afterward, the fibers are immersed into a matrix acting as the cathode material [10]. In the layered approach, carbon fibers act as the anode material as well, with coated carbon fibers acting as the cathode material. They are aligned to form electrode bands, separated by a thin layer of electrolyte [11].

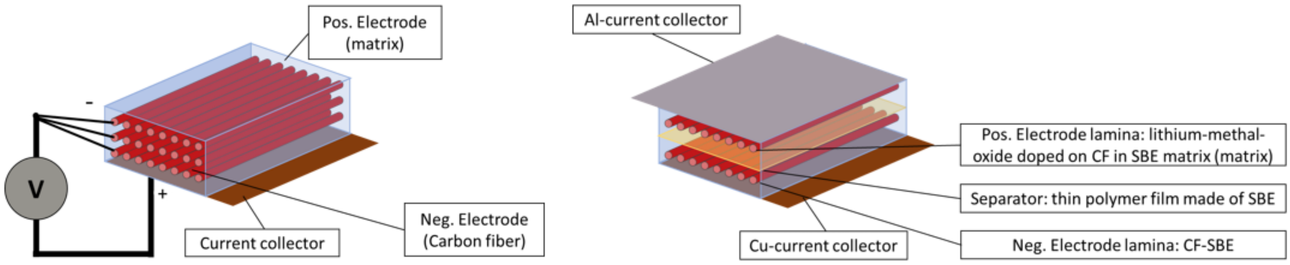

Figure 6 – Example of type-IV SB: coaxial (left), layered (right).

Unfortunately, no functional type-IV structural battery offering significant energy storage and load-bearing capabilities has yet been demonstrated.

3. Certification Requirements for SB

The rapid development of composite materials over the past three decades and their use in fields such as the aeronautical one, in which the safety requirements are particularly stringent, has given rise to the need for an accurate characterization of these materials. In 1978 the Federal Aviation Administration (FAA) issued the Advisory Circular (AC) 20-107 [4] on the certification of aeronautical structures in composite materials. This document specifies that the composite design must reach a safety level at least equal to that required by metal structures. The AC remarks the need to determine the mechanical properties of the material examined by conducting targeted experimental tests:

- static test, by subjecting the structure to 150% of Design Limit Load (DLL);
- fatigue tests on primary structures;
- damage tolerance compliance and impact resistance of primary structures.

This document represents a reference for SBs, since there are still no well-defined certification requirements about it. SBs, however, have also an energy-storing function, so they have to meet airworthiness requirements applied on aircraft batteries. About this, the reference document is the AC 20-184 [5]. This document provides guidance on how to obtain installation approval for rechargeable lithium battery systems on aircraft. Considering the above, the following paragraphs present a comprehensive overview of the tests that should be performed on structures made by SBs.

3.1 Static Tests

The structural static strength substantiation of a composite design should consider all critical load cases and associated failure modes. The strength of the composite structure should be established through a program of analysis and a series of tests conducted using specimens of varying levels of complexity. Often referred in industry as building block approach, these tests at the coupon, element, details, and sub-component levels can be used to address the issues of variability, environment, structural discontinuity (e.g., joints, cut-outs or other stress risers), damage, manufacturing defects, and design or process-specific details. Typically, tests progress from simple specimens to complex elements. In this way, the lessons learned from initial tests help avoiding early failures in more complex full scale tests, which are more costly to conduct. Most of the tests are conducted under static loads of traction, compression or shear. It is also possible to apply flexural loads, which stress the specimens to combined tension, compression and shear. The application of static loads can be either of short duration (few minutes), or prolonged for weeks and months. Detail and sub-component tests may be used to validate the ability of analysis methods to predict local strains and failure modes. The static strength substantiation program should also consider all critical loading conditions for all critical structure. This includes an assessment of residual strength and stiffness requirements after a predetermined length of service, which takes into account damage and other degradation due to the service period. When the detail, sub-component and component tests show that local strains are adequately predicted, and positive safety margins exist using a validated analysis everywhere on the structure, then proof of static strength is said to be substantiated using analysis supported by test evidence. Alternatively, in absence of sufficient building block test data and analysis validation, overloads are needed in the component test to gain proof of static strength for the structure using an approach referred to as substantiated by tests.

3.2 Damage Tolerance Evaluation

A damage threat assessment must be performed to determine possible locations, types, and sizes of damage considering environmental effects, intrinsic flaws, and foreign object impact or other accidental damage that may occur during manufacture, operation or maintenance. Some factors to consider in a damage threat assessment for a composite structure include part function, location on the airplane, past service data, accidental damage threats, environmental exposure, impact damage resistance, durability of assembled structural details and anomalous service or maintenance handling events that can overload or damage the part.

A complete damage tolerance evaluation should always include any available damage data collected from service plus an impact survey, which consists of impact tests performed on a representative structure subjected to boundary conditions characteristic of the real structure. Many different impact scenarios and locations should be considered in the survey, which has a goal of identifying the most critical impacts. When simulating impact scenarios at representative energy levels, blunt or sharp darts of different sizes and shapes should be selected to cause the most critical and least detectable damage, according to the load conditions. Until sufficient service experience exists to make good engineering judgments on energy and dart variables, impact surveys should consider a wide range of conceivable impacts, including runway or ground debris, tool drops, and vehicle collisions. This consideration is important in defining design criteria, inspection methods and intervals for maintenance. In particular, damages can be classified into different categories, mainly differing in size, each with associated detection methods and supports programs. Despite the classification, the main target is to make the structure able to withstand loads which are reasonably expected during a completion of the flight on which damage resulting from obvious discrete sources occur.

3.3 Fatigue Evaluation

Fatigue substantiation should be accomplished by component fatigue tests or by analysis supported by test evidence. Cyclic loads are used to measure resistance degradation and breakage due to loads varying over time. The frequency of application is generally low to avoid excessive heating of the specimens: in the case of composites it is $5 \div 10\text{Hz}$. The cyclic loads can be of constant amplitude or follow load spectra representative of particular operating conditions. It should be demonstrated during the fatigue tests that the stiffness properties have not changed beyond acceptable levels [4].

3.4 Regulations on Lithium batteries

The current requirements governing the installation of batteries in large aeroplanes does not adequately address several failure, operational, and maintenance characteristics of lithium batteries that could affect safety and reliability of battery installations. Until regulation are not released, the FAA issued special conditions for rechargeable lithium-based batteries:

1. The cells within the lithium battery system shall be designed to minimize the impact of self-sustained, uncontrolled increases in cell temperature or pressure, as a result of any foreseeable charging or discharging condition.
2. The lithium battery system shall be designed to minimize the impact of self-sustained, uncontrolled increases in temperature or pressure, as a result of any failure within the battery.
3. The battery system shall not emit any explosive or toxic gases, smoke or fluids during normal operation except through designed venting provisions.
4. Internal and external materials of the lithium batteries must meet the applicable certification flammability requirements of the installation.
5. No corrosive fluids or gases that may escape from any lithium battery may damage surrounding structure or any adjacent systems, equipment, or electrical wiring of the airplane.
6. Each lithium battery installation must have provisions to prevent any hazardous effect on structure or essential systems caused by the maximum amount of heat the battery can generate during a short circuit of the battery or of its individual cells.
7. Lithium battery installations must have a system to control the charging rate of the battery automatically, so as to prevent battery overheating or overcharging.
8. Any lithium battery installation must incorporate a monitoring and warning feature that will provide an indication whenever the state-of-charge has fallen below levels considered acceptable for dispatch of the airplane.
9. Maintenance requirements for measurements of battery capacity at appropriate intervals are needed to ensure that batteries will perform their intended function as long as the battery is installed in the airplane [5].

3.5 Test matrix definition for SB

In order to have a trace of the different kind of tests to perform on a composite structural battery, a test matrix is reported in Table 1, considering both structural and energy storing functions.

ID	Test	Ref.	Comments
1	Static	[4]	Structure subjected to 150% of DDL.
2	Fatigue	-	Low frequency, $5 \div 10\text{Hz}$.
3	Impact	-	Darts of various size and materials should be used.
4	Environmental qualification	[5]	These tests should consider: - equipment configuration, - installation-specific environment, - duration of exposure periods, - geographical locations and frequency of environmental occurrences.
5	System safety Assessment	-	These tests should consider: - the levels of hazard associated with the installation and the use, - no interference due to any failures of the battery, - system separation and zonal analysis, - protection against fire, smoke and electrical shock hazards.
6	Continued airworthiness	-	The following information are deemed: - specifics on batteries installation, - electrical wiring diagrams, schedule, inspection, removing and replacing parts, repairs, component manuals, - configuration control, - storage instructions, - manufacturer's maintenance, inspection and replacing instructions.
7	Maintenance	-	The following battery parameters are considered: - chemistry, - age, state of charge/health and mechanical integrity, - reliability of charging/monitoring systems.

Table 1 – Test Matrix for an Aircraft Structural Battery.

4. Numerical modeling and experimental data correlation for a SB impact test

The activity presented in this section is aimed at simulating the response of a clamped rectangular SB type I model, obtained by embedding a Teflon layer through the plies of a composite laminate, struck at low-velocity by a rigid projectile. A finite element model, based on the LS-DYNA software, is built and calibrated using the information gathered from experimental data.

4.1 Experimental Activity

The purpose of the tests was to verify the behavior of laminates after a controlled energy impact test. The focus was on the evaluation of differences between laminated panels with and without an embedded battery. To simulate the presence of the embedded battery from a mechanical point of view, a through-the-thickness discontinuity was needed, thus a Teflon layer has been inserted between the plies of the laminate during the manufacturing. A single panel was created, then cut in order to obtain 4 specimens: 2 of them with the embedded Teflon layer and the other two without it. A hand-lay-up process have been applied, impregnating the dry carbon fabric with epoxy resin, as depicted in Figure 7. In particular, a $200\text{g}/\text{m}^2$ plain fabric has been used, for a total of 12 plies. Once the lamination process was finished, the laminate was cured for 5 hours at controlled pressure and temperature, through, respectively, a vacuum pump and an oven. The obtained result is summarized in Figure 8.

Figure 7 – Hand-Lay-Up technology.

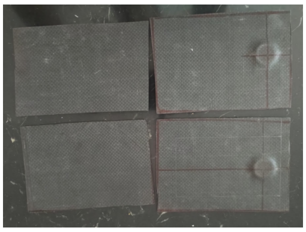

Figure 8 – Output of lamination process: two specimens with the embedded Teflon layer (right) and the other two without it (left).

Once realized, the specimens were subjected to impact tests, thanks to the availability of a small customized drop tower. Such facility consists of four rectified metal columns fixed on a metallic base. The columns are characterized by four tracks that ensure the guidance of a falling frame, equipped with eight steel wheels. A system obtained by a belt, a tensioner and a hook makes it possible to rise the falling frame ($13.6\ \mathrm{kg}$ minimum mass) to the desired height of impact ($1\ \mathrm{m}$ maximum).
The sample to be tested is fixed with the aid of a ground support. It consists of a metallic frame, which is characterized by a rectangular hole (whose dimensions are given by ASTM D7136 requirement [6]), enabling the deflection of the sample subjected to the impact test. In order to obtain the desired boundary conditions, four clamps are mounted on the ground frame to make it possible to lock the sample on the edges.
The drop tower is instrumented with a set of sensors which allow to measure various test parameters, in particular the force and the acceleration. A first piezoelectric sensor measures the moveable frame acceleration during its fall, while a second sensor is used to measure the acceleration on the impacted sample. In order to obtain the force released at the impact, a piezoelectric force sensor, embedded into the dart itself, is used. Figure 9 shows the general set-up for the performed tests.

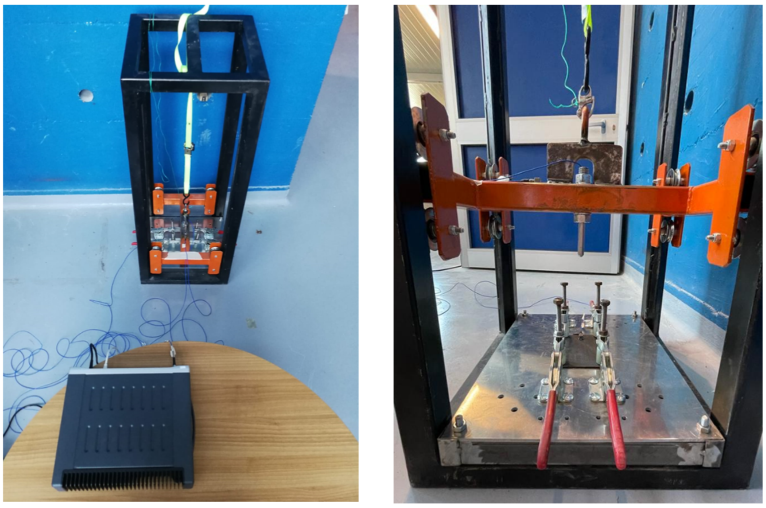

Figure 9 – Test set-up.

4.2 Modeling Procedure

The SB type-I model has been performed in LS-DYNA, taking into account the corresponding experimental test. The considered composite fiber is a plain weave with a cloth weight of $200\mathrm{g/m^2}$. The cured laminate has a thickness of $3.6\mathrm{mm}$ and a mass of about $0.056\mathrm{kg}$. By that information, a rectangular $150\mathrm{mm} \times 100\mathrm{mm}$ laminate ($3.6\mathrm{mm}$ thick) has been modeled. Each layer of the laminate has been meshed using solid squared elements. The dimensions of the mesh elements have been set in order to have a right compromise between computational time and accuracy of the expected results. The same considerations are valid also for the spherical dart meshing. The complete Finite Element model is shown in Figure 10.

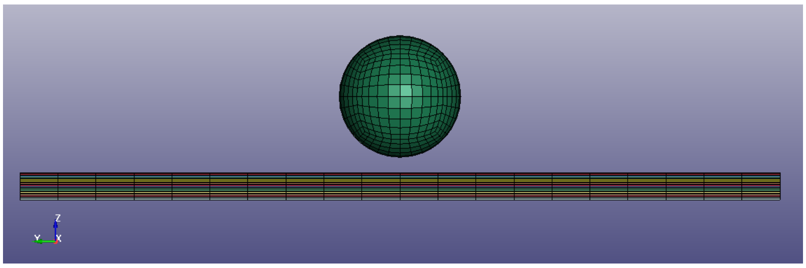

Figure 10 – Front view of the complete numerical model.

The laminate is clamped at the edges (standard ASTM D7136 [6] is followed), as shown in Figure 11, and the dart is given a mass of $13.4\mathrm{kg}$ (to account for the weight of the whole falling frame) and a velocity constant profile with $0.7\mathrm{m/s}$ magnitude.

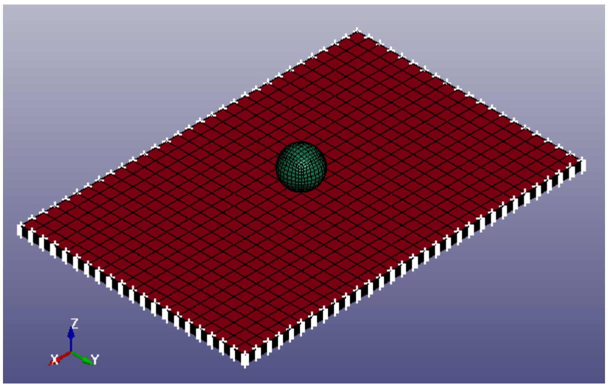

Figure 11 – Constraints applied on the edges of numerical model.

In order of having a safer model validation it was initially chosen to consider the structure without battery. Once the validation of the model was obtained, the adding of a Teflon layer simulating the presence of the battery has been performed. In particular, as shown in Figure 12, the solid element thus considered have been inserted between the 6th and 7th plies of the SB model.

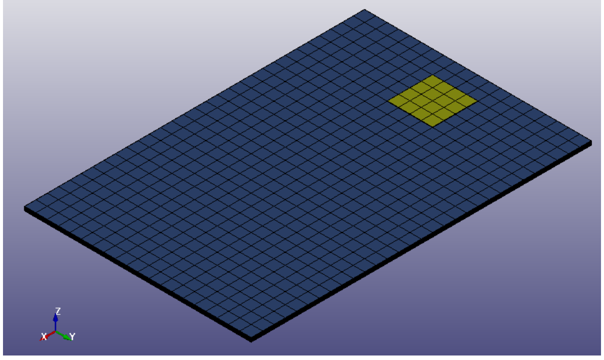

Figure 12 – Isometric view of numerical model for the laminate with embedded battery.

4.3 Experimental numerical correlation

In the considered application, the drop tower falling frame is dropped from a height of $3\mathrm{cm}$. Than, the experimental results have been compared with the numerical simulation outputs, both the acceleration evaluated on the specimen (Figure 13) and the force at the impact (Figure 14).

For the sake of completeness, notice that, the outputs of the experimental tests have been averaged and than treated by a Gaussian filter. Another aspect to take into account concerns the absence of an anti-rebound system for the drop tower, thus the outputs analysis is performed only on the first peak value for each curve. The summary of the data obtained from the experimental-numerical comparison are schematically reported in Table 2.

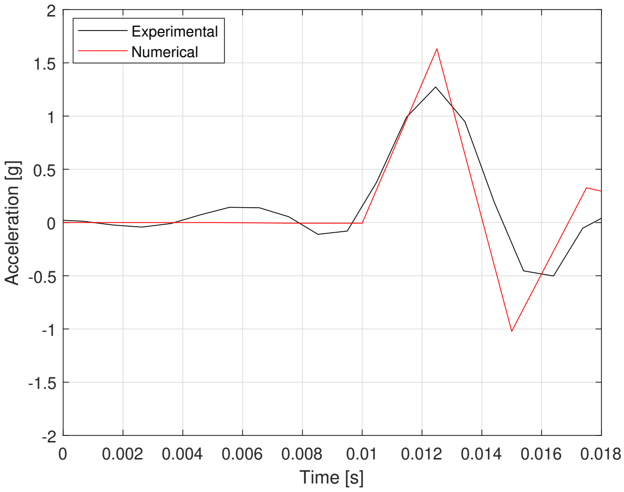

Figure 13 – Numerical-experimental comparison of acceleration on the specimen.

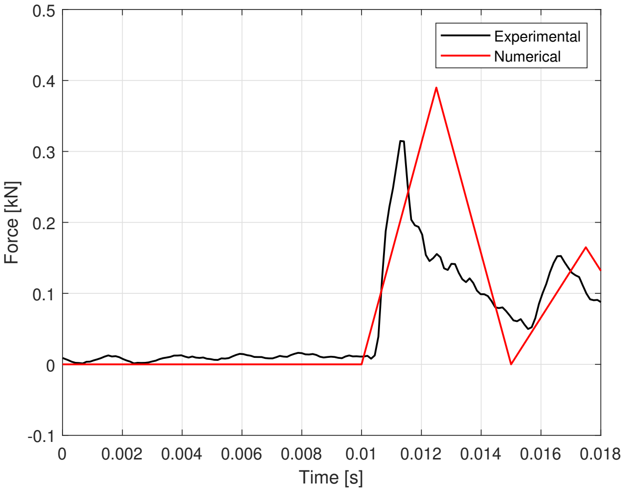

Figure 14 – Numerical-experimental comparison of force on the specimen at the impact.

Test	Peak acceleration [g]	Peak force [kN]
Experimental	1.3	0.31
Numerical	1.6	0.39
Difference %	18.7	20.5

Table 2 – Summary of numerical-experimental comparison.

Notice that the numerical model effectively reproduces the impact dynamics and time history of the impact force and acceleration, but the FE model is to be improved with more experimental tests. The main purpose of such a global analysis is to try to gain an understanding of the behavior of vibro-impacting systems and the situation, thanks to this preliminary experimental test, it is clear cut.

Besides that, a comparison between the two numerical considered tests has been performed. Figures 15 and 16 show the comparison between the z-dir. stresses for the two laminates performed by LS-DYNA post-processor. To notice is that such Figures were obtained by hiding plies from 1st up to 6th and displaying what was happening at the 7th ply, where the Teflon layer is located. It is clear that the introduction of the battery into the laminate determines the onset of stress concentration zones between the ply of the laminate with possible delamination creation.

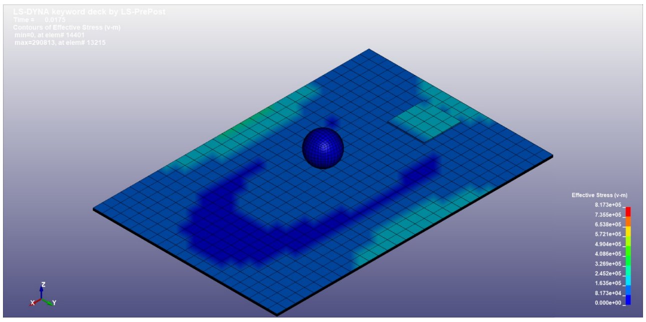

Figure 15 – z-dir. stresses comparison on the laminate with embedded battery.

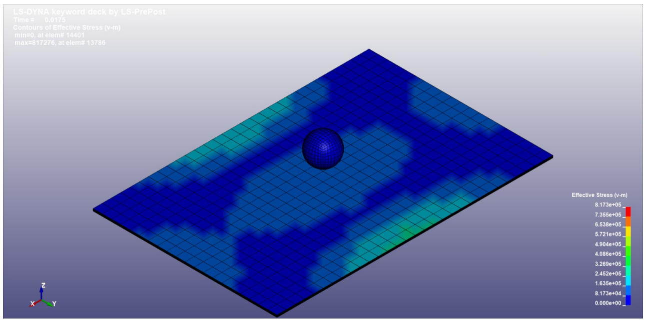

Figure 16 – z-dir. stresses comparison on the laminate without embedded battery.

5. Conclusions

The main points concerning applications of multifunctional SB in the aeronautic field, arising from the most relevant state-of-the-art literature available publications have been presented and discussed.

Structural batteries were analyzed according to several perspectives, ranging from the mechanical point of view and considering specific issues related to manufacturing processes of multifunctional composite structures and airworthiness, certification and safety requirements. Concerning that, a test matrix which gives an overview on such requirements has been proposed.

Among the several tests to be performed, impact tests were chosen in order to prove the damage tolerance of a both numerically and experimentally simulated SB. Despite some limitations, the performed analysis, especially from the numerical side, confirms that the most critical area for the SB type-I model is the one involving the embedded battery itself.

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