CRASHWORTHY BATTERY INTEGRATION FOR A MEDIUM-LIFT HYBRID-ELECTRIC HELICOPTER

Erik Wegener, German Aerospace Center (DLR) Institute of Structures and Design, Stuttgart, Germany
Matthias Waimer, German Aerospace Center (DLR) Institute of Structures and Design, Stuttgart, Germany
Paul Schatrow, German Aerospace Center (DLR) Institute of Structures and Design, Stuttgart, Germany

Abstract

This paper presents current research on the development of crashworthy battery integration in medium-lift helicopter airframes. First, an overview of regulatory requirements is presented, followed by an examination of battery installation areas, integration categories, and safety concepts such as "Safety Cell" and "Mechanical Overload." Guidelines for Crash-Resistant Battery Systems (CRBS) are formulated based on existing Crash-Resistant Fuel Systems (CRFS) standards. The study then focuses on crucial technology bricks required for implementing crashworthy battery integration within the framework for the "Mechanical Overload" concept. A sample suggestion for crashworthy battery pod design using these technology bricks is included. The paper concludes by introducing methodologies for evaluating crashworthiness designs. This includes the use of battery surrogate models, methodologies to investigate the integration concept on the airframe and an overview of relevant load cases to consider.

1. NOTATION

Acronyms:

BatMac	Battery Macro Model
CRBS	Crash-Resistant Battery System
CRFS	Crash-Resistant Fuel System
DLR	German Aerospace Center
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Administration
FE	Finite Element
MOC	Means of Compliance
MTOM	Maximum Take-Off Mass
NASA	National Aeronautics and Space Administration
SC-VTOL	Special Condition-VTOL (EASA)
eVTOL	Electric Vertical Take-Off and Landing
VTOL	Vertical Take-Off and Landing

2. INTRODUCTION

The transportation sector, including the aviation industry, is actively working on innovative solutions to decrease CO2 emissions and support global climate objectives. One innovative approach to reduce emissions for medium-lift helicopters is the introduction of hybrid-electric drivetrains into the propulsion architecture. Naturally, hybrid electric propulsion requires new energy storage systems compared to conventional fuel systems that are highly sophisticated in today's helicopter technology.

In the past, the Federal Aviation Administration (FAA) launched the development of Crash-Resistant Fuel Systems (CRFS) in aviation applications by designing and introducing crash-resistant fuel tank features into the market, like self-sealing breakaway valves. The timeline of these efforts, dating back to the 1940s, is detailed in Ref. 1. Throughout the following decades, research expanded to include the introduction of innovative bladder materials (Ref. 2, Ref. 3), self-sealing breakaway valves (Ref. 4), attachment mechanisms (Ref. 4) and the realization of various drop tests (Ref. 3, Ref. 4, Ref. 5, Ref. 6). Key contributors besides the FAA included the U.S. Army, U.S Air Force and the National Aeronautics and Space Administration (NASA). The development efforts resulted in the establishment of multiple criteria for the design and integration of CRFS, analyzed in more detail in Chapter 3.4.

Military applications played the primary role in advancing CRFS technologies in this time period. By 1994, it was concluded that no further scientific breakthroughs were required to implement CRFS in civil aviation (Ref. 7). The FAA responded by adding new amendments to airworthiness standards Part 27 and Part 29, integrating successful military rotorcraft strategies with reduced requirements to suit the less severe crash environments in civil aviation. Similar adjustments were made in the European Union Aviation Safety Agency's (EASA) airworthiness standards CS-27 and CS-29.

Adopting battery technology for energy storage introduces challenges in crashworthiness. Balancing the integration of additional components, while minimizing their impact on post-crash hazards for occupants and individuals on ground is crucial to achieving a safety level equivalent to traditional propulsion architectures.

This paper covers the necessary requirements and methodologies for integrating batteries into the current propulsion architecture of medium-lift helicopters. Capitalizing on insights from conventional fuel tank technology, the aim is to effectively facilitate the adoption of battery technology in aviation operations.

3. CRASHWORTHINESS

The design of an energy storage system is crucial for a helicopter to achieve its design objectives and operate safely across the entire flight envelope. In addition, a crash-resistant energy storage system must adhere to specific criteria to prevent or minimize hazards in the event of a crash. Modern CRFS are required to withstand crash impacts and conditions considered severe but survivable for occupants, which may include significant structural damage. With the progress in crash survivability technologies, such as improved seats and restraints, systems enabling passengers to endure severe crashes that might otherwise destroy the aircraft have become crucial. Therefore, it is essential that the energy storage system is designed to meet these strict requirements.

3.1. Authority Regulations

To the authors knowledge, EASA currently lacks a standardized regulatory framework specifically dedicated to hybrid-electric propulsion systems for Vertical Take-Off and Landing (VTOL) applications. Consequently, all relevant EASA certification regulations have been thoroughly reviewed, including CS-27 (Ref. 8), CS-29 (Ref. 9), Special Condition E-19 for Electric / Hybrid Propulsion System (Ref. 10), and Special Condition for VTOL (SC-VTOL) (Ref. 11).

CS-29, the regulation for large and medium-lift rotorcraft serves as the foundation for the requirements discussed in this paper. Although SC-VTOL specifically targets electric VTOL (eVTOL) configurations rather than helicopters, the authors anticipate that EASA will extend the application of SC-VTOL requirements to hybrid-electric helicopters in the future. For the purpose of developing crash-safe battery integration concepts, the following key aspects can be extracted from SC-VTOL's requirements, which, in many instances, originate from CS-27 and CS-29:

Emergency Landing Conditions

Regulation CS-29.561(d) (Ref. 9) mandate that the fuselage structure surrounding internal fuel tanks located beneath the passenger floor level must be engineered to withstand specific ultimate inertia load factors. This requirement ensures the structure is capable of preventing potential ruptures of the fuel tanks due to loads applied on this area.

In addition, SC-VTOL under MOC VTOL.2270(b)(1) (Ref. 11) specifies that battery integration below the cabin floor may result in the underbody design being considered "non-traditional". In such instances, separate demonstration must be provided that the updated underbody structure features damping properties to limit acceleration to below 30 g in impact scenarios, as outlined in CS27.562(b)(1) (Ref. 8). Note, that the equivalent for large rotorcraft CS-29.562(b)(1) (Ref. 9) depicts the same requirements. Consequently, considerable effort must be expected in the approval process.

Energy Storage Crash Resistance

As outlined in MOC VTOL.2325(a)(4) (Issue 2) (Ref. 11), batteries installed as energy storage units are required to undergo a drop test with charged batteries from a height of 15.2 m. The primary objective of this test is to confirm the safety of the batteries post-crash, specifically ensuring that no leakage or fire ensues. However, if such incidents do occur, the test aims to demonstrate that they can be effectively controlled and contained for at least 15 min.

Therefore, crash-resistant battery integration concepts must guarantee robustness and safety under such testing conditions. This requirement is reflective of the standards described in CS-29.952 (Ref. 9) concerning the crash resistance of fuel systems. It emphasizes a similar level of safety applied to traditional fuel systems and newer battery energy storage implementations.

Energy Retention Capability in an Emergency Landing

According to MOC VTOL.2430(a)(6) (Issue 2) (Ref. 11) the drop test, as outlined in the previous paragraph, is also required to be conducted on water. It is crucial to demonstrate that the batteries' electrical energy poses no hazard post-impact with water, ensuring the safety of the occupants and any individuals in the water.

The presented research work focuses on "Limited Overwater Operations". Given this mission requirement, the specific drop test on water can be performed from a reduced height of only 6 m (Ref. 12).

3.2. Battery Integration Concepts

Developments in electromobility are already well-advanced in the automotive industry, where crash safety is also a critical concern. Currently, the "Safety Cell" concept is widespread in the automotive industry. This concepts' design principles aim to prevent battery penetration and deformation during a crash through the use of very stiff surrounding structures. However, this approach results in added weight, which is not ideal for the typically lightweight requirements of aviation applications.

Emerging developments are focusing on allowing penetration into the battery, thereby permitting “Mechanical Overload”. The main advantages of this approach include:

- Significant weight reduction due to less rigid structures
- Smaller battery volume through denser cell packaging within the battery module
- Increased flexibility in installation space, enabling battery integration even in crash-prone areas

In conclusion, two distinct concepts for battery integration can be identified. The first, termed the "Safety Cell" concept, is a conservatively safe approach that integrates the battery based on the safety cell principle, prohibiting any mechanical overloading. This concept oftentimes includes installing the battery outside the crash zone. The second approach, called the "Mechanical Overload" concept, is a more progressive yet still safe approach that permits mechanical overloading. Implementing this concept involves a thorough analysis of the battery and its integration into the surrounding structure. It further includes measures for safe containment of potential battery thermal runaways. Specific means of battery protection and containment for a “Mechanical Overload” design are documented in Chapter 4.

3.3. Battery Integration Areas

Figure 1 categorizes potential battery pack integration areas on a helicopter based on the type of loads expected in the event of a crash that may lead to a thermal runaway of the battery. These loads include accelerations, localized penetrations and mechanical deformations.

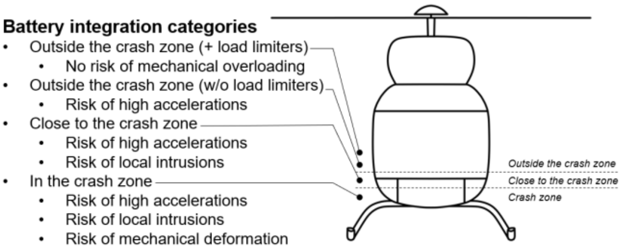

Figure 1: Categories for crash-resistant battery integration in helicopters

A hybrid-electric drive system requires two distinct energy storage systems: a fuel tank and a battery. In the context of crash load scenarios, different integration combinations can be outlined and evaluated. Examples of these combinations are depicted in Figure 2. Several criteria must be considered during the evaluation, including:

- Regulatory aspects (e.g. CS-29.561(d) (Ref. 9))
- Expected design changes compared to traditional integration methods
- Interaction with the surrounding structure
- Crash energy absorption management
- Robustness with regard to off-axis crash loads
- Occupant evacuation
- Firefighting
- Interaction of fire load and ignition source

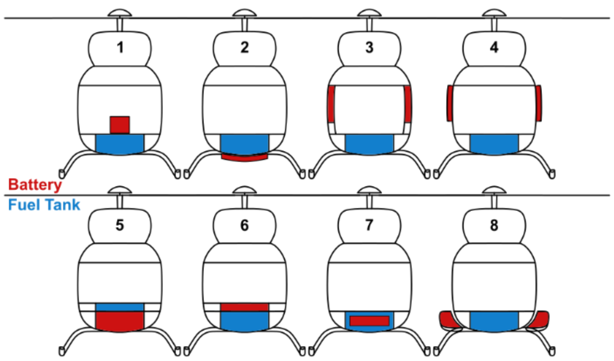

Figure 2: Example integration options for hybrid energy storage systems

One of the most promising approaches identified for the "Safety Cell" concept and visualized in Figure 2 version 6 involves integrating the battery within a double floor. In this configuration, the battery is placed above the underbody structure, preserving a conventional subfloor design to ensure sufficient crash protection for the battery. Although this integration method is seen as safe and conservative, it may entail trade-offs in cabin volume, particularly impacting cabin height, or necessitate a design with elevated airframe specifications.

A promising method within the "Mechanical Overload" safety concept can be seen in Figure 2 version 8 and involves integrating the battery outside the airframe and alongside the underbody structure. In this setup, the battery is positioned in the primary crash zone while the underbody structure retains a traditional design.

Because of the advantages mentioned in the last section, the “Mechanical Overload” safety concept is investigated in more detail in this paper. Chapter 4 in particular documents the necessary technology bricks for this integration concept.

3.4. Crash-Resistant Battery Systems (CRBS)

The Energy Storage Crash Resistant Drop Test, described in Chapter 3.1, serves as a demonstration that a designed energy storage system is capable of sustaining both the static and crash-dynamic loads while maintaining post-crash safety. This procedure entails dropping the system from a 15.2 m height onto a non-deforming impact surface while the tank is housed within a structure that replicates the features of its installation area. Minimizing post-crash risks, either by reducing the hazard's magnitude or by isolating it from occupants and emergency exits, is crucial.

Generic guidelines for Crash-Resistant Energy Storage Systems have been developed by the authors of this paper. The guidelines build upon insights from traditional Crash-Resistant Fuel Systems (CRFS) (Ref. 13) and were then adapted to the emerging field of Crash-Resistant Battery Systems (CRBS). Figure 3 shows a chart of these crash-resistance guidelines, which are described in more detail in following paragraphs. Note that a precise categorization of the guideline sections proves challenging, because the content partly overlaps.

The main objectives of the guidelines are to prevent post-crash hazards related to the energy storage, focusing on preventing leakage for fuel systems and preventing or containing thermal runaways for battery systems.

Before designing the energy storage system in detail, the spatial arrangement of the energy storage system relative to the crash zone, the occupants and evacuation paths should be considered. This involves evaluating the installation area relative to the crash zone, as performed in Chapter 3.3, including weighing concept options of “Safety Cell” versus “Mechanical Overload”. Furthermore, it requires considerations about the spatial separation of the energy storage systems’ components and occupants using measures such as bulkheads, vent pipes, containment layers, among others.

Afterwards, the design of an energy storage system should follow the systems design approach, where each component must be seen as part of a larger system of other products or systems. Components are typically designed to withstand normal flight and operational loads. To improve their crashworthiness, they either are redesigned with a crash-resistance focus, the surrounding structures are reinforced to shield the components, or both strategies are employed. The complex dynamics of crash events often necessitate a combination of the measures above for optimal effectiveness.

Not discussed in the guidelines are further energy storage crash safety measures such as service-disconnects and rescue maps for emergency responders.

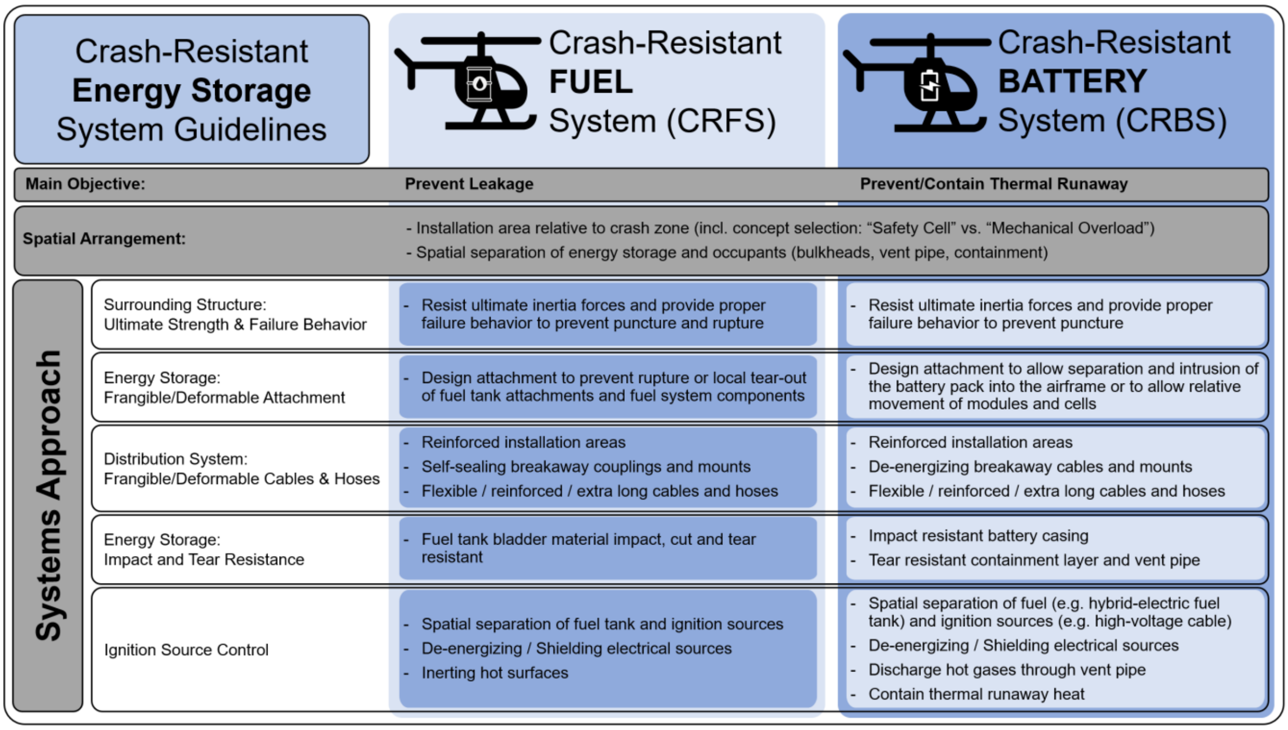

Figure 3: Crash-Resistant Energy Storage System Guidelines

Surrounding Structure: Ultimate Strength & Failure Behavior

Essential for the integrity of the system is the crash-resistance of integration structure in close proximity to the energy storage system to resist ultimate inertia load factors. Specific values depend on the exact location of the energy storage relative to the occupants and are detailed in CS-29.952(b) (see Chapter 3.1). Simultaneously, the integration structure must provide appropriate failure behavior to avert potential hazards due to puncture or rupture of the energy storage system.

Energy System: Frangible/Deformable Attachment

In a crash scenario, components of the energy storage system are frequently exposed to significant stress as they are attached to parts of the aircraft structure that are being torn apart or displaced over long distances. Ensuring a safe separation from these displacing structures can be achieved through the application of frangible or deformable attachments. Such mechanisms allow the entire energy storage system and its individual components to detach from the surrounding aircraft structure and to move relatively from each other, safeguarding the energy storage system's integrity throughout the event.

Distribution System: Frangible/Deformable Cables & Hoses

Critical internal infrastructure, including pipes and cables, may require specialized protection within the airframe's structure. Wherever additional structural reinforcements are impractical or unwanted due to concerns about weight increase, the implementation of frangible mounts and deformable infrastructure is advised. Frangible mounts would enable the movement of the infrastructure and surrounding structure relative to each other, allowing for deformation during crash scenarios. Deformable internal infrastructure with additional length can aid in preserving their integrity and preventing disconnections or tear-offs.

Moreover, integrating a de-energizing or self-sealing mechanism that triggers if cables or pipes become detached from their plugs or break, can also prevent more hazardous situations.

Energy Storage: Impact and Tear Resistance

Impact and tear resistance are critical attributes for an energy storage system to safely contain its contents under severe conditions. It is crucial for the system to not only provide resistance against the initial impact or breach but also to provide resistance against any punctures or tears that might occur.

Beyond merely holding its contents, the system must also offer protection against sharp, foreign objects that could penetrate its exterior. While not always common, impacts on uneven surfaces or obstacles on ground could lead to localized damage, threatening the integrity of the system.

Ignition Source Control

Spatially separating hazardous elements, such as ignition sources and fuel, can greatly improve crash safety. Specifically, for hybrid-electric systems the spatial arrangement of fuel and high-voltage system can be crucial for crash safety.

Moreover, controlling ignition sources oftentimes involves incorporating mechanisms for de-energization and shielding electrical sources, such as wires and electronic components. Energized components being torn apart during a crash event can easily become ignition sources.

Finally, shielding hot surfaces and discharging hot gases could also contribute significantly to enhancing safety measures within these systems.

4. TECHNOLOGY BRICKS FOR THE "MECHANICAL OVERLOAD" INTEGRATION CONCEPT

In the previous chapter, the requirements and specifications for energy storage systems were discussed. For scenarios where the battery might undergo significant stress and deformations, such as those envisaged in the "Mechanical Overload" integration concept, additional battery-specific safety measures are recommended. This chapter covers these technology bricks in more detail, with the objective of either reducing structural stress and deformations, or ensuring containment integrity under extensive deformation conditions. The guidelines from Section 3.4 can help to cover all relevant issues related to crashworthiness.

4.1. Crash Absorber

Given the position of the battery in the crash zone, it may be subjected to extremely high accelerations in the event of a crash. To limit these accelerations within acceptable levels, additional load attenuating structures like crash absorbers are essential. Two types of absorbers can be considered: discrete and volumetric absorbers.

Discrete absorbers are characterized by localized load transfers and typically feature high mass-specific energy absorption. However, as shown in Figure 4, they require a rigid housing to transfer the concentrated absorber loads into the battery. Additionally, there is a risk of penetration of the battery module by the discrete absorber.

In contrast, volumetric absorbers, such as honeycomb structures, provide full-surface load transfer of crash loads into the battery module, although at the expense of mass-specific energy absorption. The risk of battery penetration by these absorbers is significantly reduced due to the full-surface load transfer and the failure characteristics of volumetric absorbers. Additionally, volumetric absorbers provide better protection against penetration by external bodies, as they typically compact with increasing compression distance and can act as protective shields. Lastly, volumetric dampers demonstrate superior crash characteristics when encountering soft impact surfaces or water, thanks to their spatial expansion.

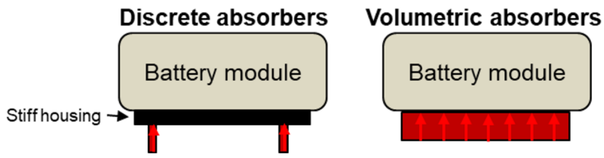

Figure 4: Basic battery absorber concepts

4.2. Containment

The "containment" aspect focuses on finding materials and design solutions that can encapsulate the energy storage system to withstand and contain a potential battery thermal runaway post-crash for a minimum of 15 min. Material or component requirements, informed by regulatory specifications in Section 3.1, can be defined as follows:

- Withstand temperatures up to 1000°C for 15 min
- Airtight (and watertight) seal under crash-induced stress and deformations
- Electrical insulation
- Resistance to wear and tear
- Resistance to penetration

As an external battery pod installation potentially coincides with cabin evacuation paths, heat containment requires special attention to prevent hot outer pod surfaces in case of a thermal runaway.

4.3. Vent Pipe

Battery containment can be implemented at the cell, module, or pack levels. Across these solutions, venting is essential and can be facilitated through a designated "vent pipe" that directs hot and potentially toxic gases away from the cabin and evacuation paths. This venting mechanism is crucial for preventing overpressure within the battery system and for dissipating heat away from the battery modules. Such thermal management is crucial in preventing a thermally induced chain reaction that may result from the thermal runaway of individual cells.

A single, continuous vent pipe, illustrated in Figure 5 (I), poses challenges for elongated battery pods as it increases the risk of vent pipe damage and containment integrity issues under crash-induced loads. This scenario can lead to heat concentration and vent pipe blockage, necessitating additional containment layers. Alternatively, implementing multiple shorter vent pipes with various outlets, shown in Figure 5 (II), could significantly reduce the risk of vent pipe rupture during crashes. It is crucial to avoid positioning these outlets close to evacuation paths, which must always remain clear of hot and toxic gases. The most flexible solution is a deformable vent pipe system, depicted in Figure 5 (III), capable of adapting to large crash deformations while ensuring consistent discharge of hot battery gases. This design minimizes the need for structural modifications and secondary containment, resulting in a positive impact on the overall battery weight. Additionally, this design allows individual battery modules to detach from each other, aiming to preserve the integrity of each module.

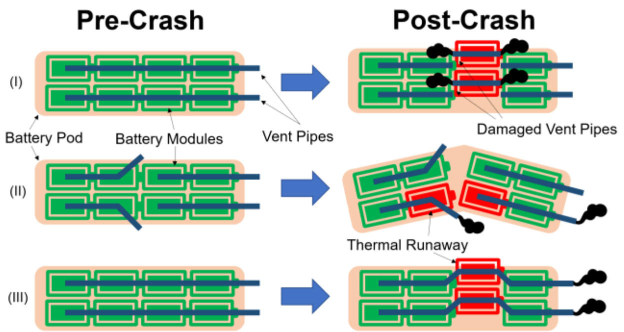

Figure 5: Containment and Vent Pipe in Battery Pod Pre- and Post-Crash

Vent pipes must be strategically positioned and oriented to guarantee that in the event of a crash, they remain uncrushed and unobstructed, thus preventing potential blockages.

In instances of a battery thermal runaway leading to significant heat spikes, positioning vent pipes containing hot gases near primary structural elements is only viable if additional measures, like heat shields, are integrated. However, these enhancements add extra weight to the system.

4.4. Surrounding Airframe Structure

CS-29.561(d) (refer to Section 3.1) establishes the crash factors and loads that the integration structure below the passenger floor level must withstand to maintain structural integrity. Compliance with this requirement is crucial to maintain mass retention and prevent the disintegrating of the battery storage system into a hazardous heavy mass object.

Depending on the battery installation area, structural reinforcements to the existing primary structure may be required to ensure that the survivable cabin volume for the occupants is preserved under battery mass inertia loads.

4.5. Separation and Intrusion Mechanism

Placing the battery pack externally on a helicopter and inside the crash zone could lead to interactions between the battery and the airframe structure during a crash. While such interactions are unlikely to occur in regulatory compliance tests that only focus on small roll angles around 0°, they become more critical for robustness purposes at larger roll angles. In these instances, designing the battery module to detach from the airframe upon impact, as shown in Figure 6 on the left, can prevent the batteries from being crushed under the helicopter's weight. This method only minimally affects the traditional airframe design. However, accurately controlling this separation mechanism during real-world crash scenarios presents notable challenges.

To increase robustness in scenarios involving larger roll angles, an alternative concept is illustrated in Figure 6 on the right. It addresses both the separation and potential intrusion of the battery module into the airframe. Allowing structural interaction between the battery pod and the helicopter airframe will designate the helicopter's subfloor box as a potential intrusion zone. This strategy aligns with traditional helicopter crashworthiness design principles, where the underbody structure acts as a crush zone to absorb and dissipate impact energy during a crash.

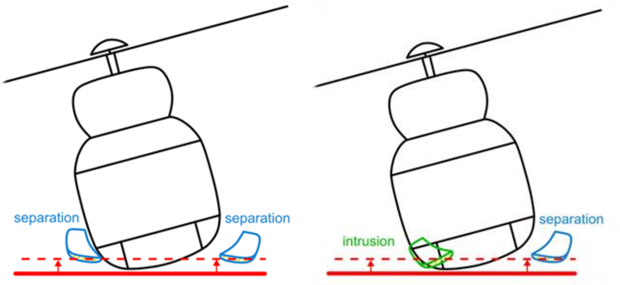

Figure 6: Helicopter structural interaction - battery pod: pure separation mechanism (left), separation mechanism and permitted intrusion (right)

Understanding the interaction between the battery pod and the airframe in such off-axis conditions is crucial as it influences the airframe, the survivable volume and thereby affecting the occupants' survival chances. When permitting interaction between the battery pod and the airframe, it is important to avoid placing rigid components of the battery pod near primary structures of the airframe, such as frames. This precaution intends to minimize the risk of significant interaction and subsequent deformation in these structures and therefore assists in preserving the survivable volume for occupants and reduces the risk to the energy storage system.

4.6. Case Study for Technology Brick Integration

In an exemplary case study, the technology bricks previously described have been combined into a single energy storage system. The use case is an external battery bod positioned alongside the helicopter subfloor structure. This pod is specifically designed for the purpose of a hybrid-electric medium-lift helicopter, demonstrating an innovative approach to energy storage integration in aviation. Figure 7 offers a visual representation of the chosen design.

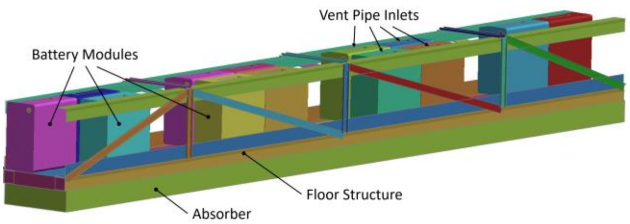

Figure 7: Battery Pod Design Concept

The pod's primary structure was designed following traditional crashworthiness design principles for helicopter subfloor structures. It incorporates a stiff load-bearing "floor" structure positioned between the battery modules above and the absorber structure below. The load-bearing "floor" structure provides structural integrity under crash conditions. Furthermore, it provides additional stroke distance for the battery modules and hence reduces risks of battery module penetrations. The primary structure is purposely positioned underneath the battery modules to maintain a safe distance from the heat pipes located on top in order to mitigate the risk of heat-induced damage.

The load-carrying "floor" structure also provides the structural connection between the battery modules and the helicopter airframe via three attachment points. Two of these points are located at the airframe's front and rear main frames. A third attachment point is suggested at the location of the landing gear's front subfloor bulkhead.

The configuration of battery modules and the spacing within the battery pod have been selected to prevent any critical crash interactions between the battery modules and hard points of the helicopter airframe, as seen in Figure 8. This configuration enables the battery pod to intrude into the airframe's subfloor structure during a crash scenario without compromising the safety of the occupants.

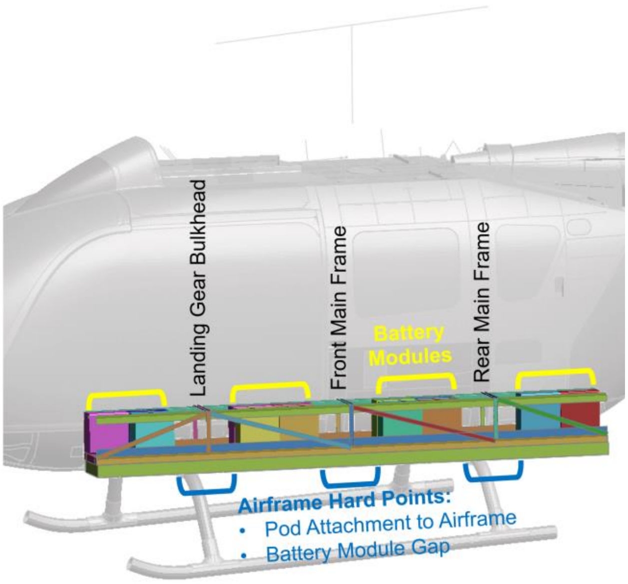

Figure 8: Battery Pod attached to Airframe

A volumetric absorber has been selected for this case study. This absorber type shall enhance the impact resistance of the battery pod by compensating localized irregularities of the impact surface, such as large stones.

In this case study, the battery containment is directly incorporated in the battery module housing, designed to sustain the conditions of a thermal runaway event for a minimum of 15 min. The battery module housing also serves as additional impact resistance due to its sturdy shell.

The orientation of the battery modules is primarily determined by the positioning of the vent pipe. In potential off-axis crash scenarios, the lower and side surfaces of the battery modules are expected to be highly involved in crash deformations of the pod structure. Vent pipes located on these surfaces risk damage, potentially compromising their function. To ensure that emergency exits remain free of smoke and toxic gases, the vent pipe is positioned at the top of the battery modules. Utilizing a single longitudinally running vent pipe necessitates the vent pipe to be flexible enough to maintain its integrity despite larger crash deformations of the battery pod and between the battery modules. Flexible tubes made from heat-resistant fabric material with sufficient strength properties are being considered, along with an "accordion" pipe design, to facilitate extensive vent pipe elongations. Note, that the vent pipe has not been modelled in the figures above.

The assessment of this concept is part of ongoing research work.

5. METHODS

The authority requirements outlined in Section 3.1 necessitate the demonstration of compliance by conducting a physical crash test. Alongside physical tests, finite element (FE) analyses are instrumental in formulating robust integration strategies for crash safety. Throughout different development phases, FE methodologies of varying degrees of detail and efficiency are required. These methods must be capable of accurately representing the battery behavior (see Section 5.1) as well its structural integration into the airframe (see Section 5.2).

5.1. Surrogate Battery Models

In initial design stages, fast yet adequately accurate techniques are required, whereas detailed design phases demand more precise yet complex approaches. As a result, surrogate battery models can be employed at several development stages for both physical testing and numerical simulation. Only the final validation crash test requires the use of actual, and most critically, charged batteries.

Examining batteries at the module level achieves a balance between assessing the effects of entire battery packs and investigating individual battery cells. The approach promises to be effective in understanding thermal runaway events and battery pod integration concepts, while not disregarding the significant impact of the small-sized battery cells.

Figure 9 illustrates surrogate battery models with varying degrees of detail in both numerical and physical dimensions within a building block. At the most fundamental level, merely the battery mass is represented. Subsequent levels progressively incorporate inertia, stiffness, and ultimately, battery-specific characteristics, including electrical and thermal properties.

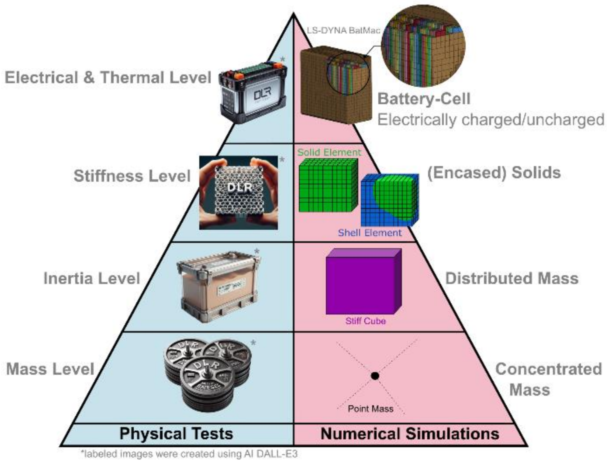

Figure 9: Surrogate battery models with different degrees of detail within the Building Block

The different fidelity levels of battery surrogate models require corresponding quantitative pass/fail criteria that enable the prediction of thermal runaway in the actual battery. Those criteria may be based on parameters such as internal energy, maximum local deformation, accelerations at the battery module level or other. The definition of pass/fail criteria for low-fidelity surrogate models remains an active area of research.

High-fidelity surrogate models for full-scale applications such as the LS-DYNA Battery Macro (BatMac) Model shown in Figure 10 are more advanced. This numerical surrogate model can simulate electric and thermal properties along with the structural characteristics of layered pouch cells. This architecture allows for the prediction of thermal runaway in batteries at each individual pouch cells. Further details can be found in Ref. 14.

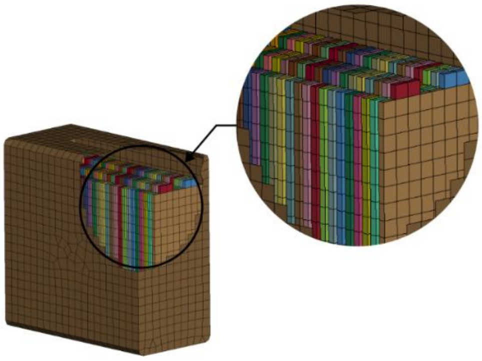

Figure 10: LS-DYNA Battery Macro (BatMac) Modelling Approach

5.2. Battery Integration Study

Studying the integration of the battery into the structural environment typically involves integrating the battery inside the airframe structure. However, in the concept of this paper, it means integrating the battery modules first into the battery pod as seen in Figure 7, which is then integrated as an attachment into the airframe as seen in Figure 8.

Therefore, a two-step approach is selected, starting with an evaluation of the pod structure itself with numerical simulations, where battery packaging, absorber design and the primary structure can be assessed for crashworthiness. This initial step includes considering robustness load cases to enhance the battery pod's performance under realistic crash conditions. In the next step, the analysis expands to the entire helicopter airframe with attached battery pod. This phase investigates the full-vehicle crash kinematics and structural interaction between the pod and the airframe. Combining this two-step approach with surrogate battery models, as discussed in the Section 5.1, can help to advance from efficient to more detailed studies progressively.

5.3. Load Cases

Mandatory load cases can be derived from regulatory requirements depicted in Section 3.1. The drop test mentioned must be executed from a height of 15.2 m. This results in a vertical velocity at impact of 17.3 m/s. The impact surface must be flat and non-deforming. To allow "Limited Overwater Operations" a specific water drop test must be performed from a reduced height of only 6 m. Additionally, the batteries must be charged to its most critical condition expected during a crash and enclosed in a surrounding structure representative of the installation area. The final impact should be ±10° with regards to the horizontal axis. And finally, the risk of fire, harmful fluids and toxic gases must be contained for at least 15 min in non-occupied areas and outside the evacuation paths.

Beyond this mandatory load case, other load cases can be consulted to increase the understanding of the integration design and improve robustness. They are listed in the following paragraphs.

Investigating qualitative criteria outlined in the CRBS guidelines in Section 3.4 can provide insights into whether the concept would align with recommended best practices.

While vertical velocities are generally considered more critical than horizontal velocities, it is crucial to also consider crash loads that result in horizontal loads. These horizontal forces can also significantly contribute to the overall kinetic energy of the system that must be dissipated during a crash.

While the impact surface is typically assumed to be flat and rigid, examining the effects of softer soil types and slanted impact surfaces could offer valuable scientific insights.

The effect of the airframe's orientation in relation to the impact surface on crash dynamics needs detailed exploration. Specifically, analyzing large pitch, yaw, and particularly the roll angle is crucial. Its impact on the interaction between the battery pod and airframe significantly affects the overall crash performance of the system.

An ideal study also considers the impact of localized contact points between the impact surface and the airframe of the battery pod, such as simulating small to large stones at crash sites using rigid boxes to evaluate their effect on the system's crash dynamics. Additionally, introducing pointed penetrators in test scenarios can offer insights into the potential consequences of sharp foreign objects colliding with the energy storage system.

6. CONCLUDING REMARKS

The integration of Crash-Resistant Energy Storage Systems based on batteries within the crash zone is expected to be achievable by adhering to the guidelines developed in Chapter 3.4:

1. Spatial Arrangement: The location of the energy storage system relative to the crash zone and to occupants and evacuation paths must be considered, including weighing integration concepts of "Safety Cell" versus "Mechanical Overload".

2. Surrounding Structure: Ultimate Strength & Failure Behavior: The integration structure must be able to resist ultimate inertia load factors and provide proper failure behavior to prevent puncture and rupture.

3. Energy Storage: Frangible/Deformable Attachment: Structural attachments should allow for separation and limited intrusion between the energy system and surrounding structure.

4. Distribution System: Frangible/Deformable Cables & Hoses: Internal infrastructure should be reinforced and protected with additional structure. Alternatively, they can be designed to be deformable (with extra length). Additionally, using frangible mounts and de-energizing mechanisms is advantageous.

5. Energy Storage: Impact and Tear Resistance: The system must offer impact and tear resistance against sharp, foreign objects to prevent localized punctures and its propagation.

6. Ignition Source Control: Creating spatial separation between hazardous elements, incorporating de-energizing mechanisms, shielding electrical sources and managing temperature peaks throughout the system can help control ignition sources.

Chapter 4 outlines concrete technology bricks that align with these guidelines for battery pods mounted on medium-lift hybrid-electric helicopters:

1. Volumetric crash absorber.

2. An airtight (and watertight), electrically isolating, impact and tear resistant containment layer designed to withstand temperatures of up to 1000°C for 15 min.

3. Single, flexible vent pipe to facilitate discharge of hot and toxic gases and keep emergency exits clear.

4. Separation and intrusion mechanism for off-axis crash scenarios.

Methods for developing crash-resistant energy storage systems can be found in Chapter 5 and include:

1. Use of surrogate battery models for tests and simulations customized for various development stages.

2. A methodology for evaluating battery integration across two stages: battery pod and attachment of the battery pod to the airframe.

3. Mandatory drop test evaluation and supplementary load cases for robustness assessment.

Author contact:

Erik Wegener erik.wegener@dlr.de

Matthias Waimer matthias.waimer@dlr.de

Paul Schatrow paul.schatrow@dlr.de

7. ACKNOWLEDGMENTS

Parts of the research leading to these results were accomplished in the framework of the 6th Aeronautical Research Program of the German Federal Ministry of Economic Affairs and Climate Action (BMWK) under grant 20M2114C, as part of the LuFo-VI-2 project NEUTRON. The authors wish to thank Michael Geiss, Sascha Schneider, Marc Nothen, Stefan Böhnel, Martin Blacha and Johannes Röthinger from Airbus Helicopters for great collaboration in this research project.

8. REFERENCES

1. Robertson S. H., Johnson D. S., Hall D. S., and Rimson I. J., "A Study of Helicopter Crash-Resistant Fuel Systems," U.S. Department of Transportation Final Report DOT/FAA/AR-01/76, 2002.

2. Bennett C. V., and Schroers R. J., "Impact Tests of Flexible Nonmetallic Aircraft Fuel Tanks Installed in Two Categories of Simulated Wing Structures," CAA Technical Development Report No. 291, 1957.

3. Robertson, S. Harry, and Turnbow J. W., "Aircraft Fuel Tank Design Criteria," USAAVLABS Technical Report AvSER 65-17, 1966.

4. Johnson N. B., Rogers J. H., and Cook R. L., "Aircraft Fuel Systems Design Study," USAAVLABS Technical Report 67-33, 1967.

5. Robertson, and H S., "Development of a Crash-Resistant Flammable Fluids System for the UH-1A Helicopter," USAAVLABS Technical Report 68-82, 1969.

6. Cook Richard L., and Donald E. Goebel, "Evaluation of the UH-1D/H Helicopter Crashworthy Fuel System in a Crash Environment," USAAMRDL Technical Report 71-47, 1971.

7. Coltman J. W., "Rotorcraft Crashworthy Airframe and Fuel System Technology Development Program," FAA Final Report DOT/FAA/CT-91/7, 1994.

8. European Union Aviation Safety Agency, "Certification Specifications, Acceptable Means of Compliance and Guidance Material for Small Rotorcraft (CS-27) (Amendment 10)," EASA, February 2023.

9. European Union Aviation Safety Agency, "Certification Specifications, Acceptable Means of Compliance and Guidance Material for Large Rotorcraft (CS-29) Amendment 11," EASA, December 2023.

10. European Union Aviation Safety Agency, "SC E-19 Electric / Hybrid Propulsion System," EASA, 7th April 2021.

11. European Union Aviation Safety Agency, "MOC SC-VTOL (Issue 2)," EASA, 12th May 2021.

12. Lewis E., "Ditching, Emergency Flotation and Limited Overwater Operations," Rotorcraft and VTOL Symposium 2020 (Virtual Event), 12th November 2020.

13. Aircraft Crash Survival Design Guide, Volume V - Aircraft Postcrash Survival," USAVSCOM Final Report TR-89-D-22E, 1989.

14. L'Eplattenier P., and Çaldichoury I., "BatMac: A battery Macro Model to simulate a Full Battery in an Electric or Hybrid Car Crash using LS-DYNA," 12th European LS-DYNA Conference 2019 Proceedings, Koblenz, Germany, May 2019.