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Crashworthiness and Structural Durability of Lithium-Ion Battery Packs under Impact and Drop Scenarios

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Abstract: *The Increase of use of LIB systems in vehicles, electric operated consumer electronic products, and energy storage, the mechanical and crashworthiness of such systems is of considerable concern. This research focuses on the crashworthiness and structural integrity of Lithium-ion battery pack in different impact and drop tests in order to mimic real-world conditions such as vehicle crashes, falls, and mechanical treatments of batteries. The finite element analysis (FEA) is done at cell, module, and pack levels and adopted explicit dynamic solvers to determine the stress distribution, deformation patterns, and potential failure modes. The work takes into account different restrictions and velocities of the aircraft, as well as the sides at which it impacts: side, bottom, and corners. Casing structures, areas prone to the thermal runaway, and internal battery components are incorporated within the simulation the mechanical behavior and safety-related results. The experimental verification is performed to drop test and crash impact test with commercial 18650 and pouch cell based battery modules. These aspects involve peak acceleration, energy absorption capability, intrusion depth, and structural aspects aiming at identifying the ability of the structure to withstand an impact. The observations from the current development offer means of further future alterations in designing the protective structure for battery enclosure to reduce potentials of electric shock or heat build-up during mechanical stress. They contribute to the understanding of the safety requirements that should be incorporated in futuristic lithium-ion batteries as well as addressing how lithium-ion batteries can be made to be safe, especially for use in mobility and storage facilities.*

Keywords: Lithium ion battery, Electric vehicle, drop and impact test, crashworthiness, finite element analysis.

I. INTRODUCTION

LIBs are widely used in EVs and energy storage systems nowadays because of such beneficial characteristics as high energy density, lightweight design, long cycle life, and comparatively fast charging rate. These being so portable and flexible, they are good for use in applications that call for small batteries in consumer electronics up to the large-scale grid energy storage and electric vehicles. In electric vehicles, LIB packs are not only involved in the physical power of the vehicle but also the travelling distance, energy consumption, and eco-efficiency of the vehicle. Likewise, in the renewable energy systems, batteries play the role of energy storage systems to store the produced energy from the solar or wind for use during the period of high demand or low generation. These aspects can play a significant role for electric and other sustainable technologies in increasing their popularity and being trusted as safe and efficient if the lithium-ion battery packs are reliable, durable, and safe.

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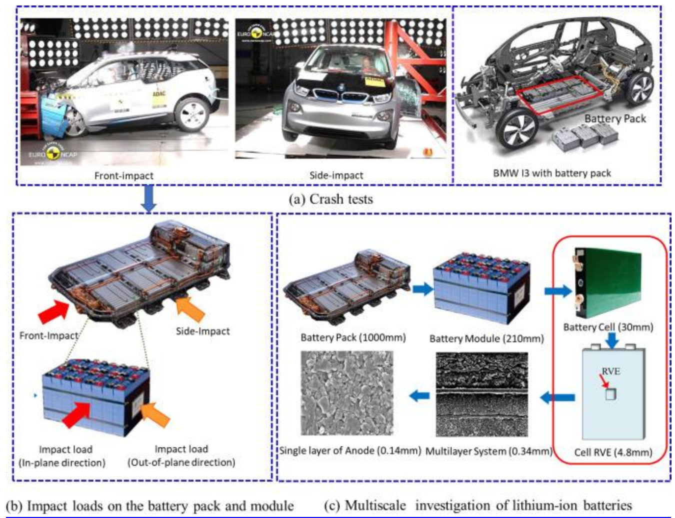

Figure 1: Dynamic crashing behaviours of prismatic lithium-ion battery cells

1.1 Problem Statement:

However, lithium-ion battery pack is quite sensitive to mechanical abuse thus; crashworthiness and structural durability are very important aspects to consider when designing the battery pack. Damage to the battery pack structure by impact, drop or crush situations which may result to internal shorting, leakage of electrolyte or thermal runaway, which has very dangerous consequences to users and those attending to crash incidences. Hence, battery packs are required to be capable of withstanding mechanical stress which accompany accidents, handling or transportation without resulting to structural failure or non-functioning. Apart from safety, structural durability is the ability to maintain the electrical performance and long useful life since it physically protects the electrode from misalignment at the mechanical level or the rupture of the separator. These attributes are critical especially in cars and aircraft industries where timeliness is mandatory despite harsh and unstable circumstances. Crash safety is not only a statutory and safety efficiency requirement but also a means of increasing customers' confidence in LIB-powered technologies and expanding the technology's market applicability.

1.2 Objectives of the Review and Scope of the Study

Hence, the purpose of this review is to provide an adequate stock on current literature about the crashworthiness and structural integrity of Li-ion batteries especially under impact and drop conditions. The development of this paper involves an effort to review the various experimental, numerical, and empirical studies performed on the mechanical response on LIB packs subjected to abusive conditions. It examines factors in structural design that related to its ability to withstand natural disasters, describes usual modes of failure, and assesses various measures for disaster mitigation and protective structures. Moreover, the review also discusses some new development made some modelling theories, material applications, and testing standards along with some limitation like difficulty in mimicking real-world crash situation and complexity in understanding Multiphysics effect. This paper aims at identifying research deficiencies and suggesting the focus for future research in order to provide an enhanced safety, durability, and compliance to regulation of lithium-ion battery systems that would be used in next generation electric and energy storage applications.

1.3 Methodology

This review paper has followed a structure guideline to understand the implication of impact and drop on the crashworthiness and structural durability of lithium-ion battery (LIB) packs. From this research, the literature was obtained using related keywords which included 'battery impact', 'crashworthiness', and 'drop testing', through IEEE Xplore, ScienceDirect, and Scopus. The sources were classified as experimental researches, numerical analyses,

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structural solutions, failure mechanisms and code provisions. An impact categorization structure was used to categorize the literature by impact type, battery format, structure and material, performance measures, and simulation techniques. All the retrieved data was analysed in order to identify methodological merits, demerits, and patterns in the studies. It allowed for the combination of existing literature flow, similarities, differences, and gaps' detection. Last but not the least, the study acknowledges some of the limiting factors and suggests some guidelines for future safe and robust designs of LIB pack.

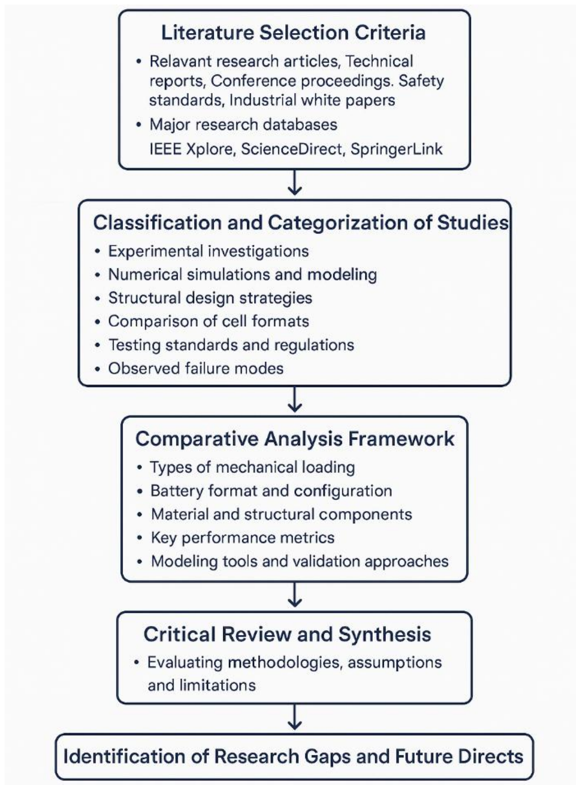

Figure 2: Methodology of the work

II. LITERATURE SURVEY

The structure of a lithium-ion battery (LIB) pack is a critical component in determining its mechanical stability and crashworthiness. A typical battery pack consists of numerous interconnected cells grouped into modules, which are then assembled into a complete pack with protective casings and support structures. Crashworthiness in this context refers to the ability of the battery pack to absorb mechanical energy during collisions or drops without compromising safety or performance. The design must balance energy density with mechanical protection, incorporating features like reinforcement frames, shock-absorbing layers, and thermal barriers. The structural layout directly affects the pack's ability to withstand impact loads, distribute stress, and prevent cascading failures. Therefore, understanding the fundamentals of LIB pack structures is essential for improving mechanical integrity and ensuring safety under mechanical abuse conditions. Lithium-ion battery cells are commonly manufactured in three major formats cylindrical, prismatic, and pouch each with unique structural and mechanical characteristics. Cylindrical cells, such as the 18650 or 21700 formats, are robust due to their symmetrical shape and metallic casing, offering good resistance to mechanical deformation and ease of thermal management. Prismatic cells feature a rectangular design and metal casing, providing a higher packing efficiency, but their flat surfaces may be more susceptible to bending and crushing under load. Pouch cells are the lightest and most flexible in design, utilizing polymer aluminium laminated enclosures. While they offer the highest volumetric efficiency, they are also the most vulnerable to external mechanical stress due to the absence of a rigid outer shell. The choice of cell format significantly influences the mechanical resilience and energy absorption characteristics of the battery pack during crash and drop scenarios. Battery modules are intermediate assemblies comprising multiple interconnected cells. These modules are then arranged within a protective housing to form a battery pack, which includes additional components such as busbars, thermal management systems, battery management systems (BMS), and protective casings. The module and pack construction process plays a critical role in determining the mechanical stability, thermal behavior, and electrical performance of the entire system. Structural considerations during assembly include cell spacing, mounting strategies, support frames, and load distribution paths. Crashworthy designs focus on modular compartmentalization to limit damage propagation during impact events. Effective construction practices enhance the mechanical integrity of the system, prevent localized damage from spreading, and contribute to thermal and electrical isolation in the event of structural failure. Materials used in LIB pack construction significantly affect their crash performance. Common materials include aluminium alloys for casings and structural frames due to their favourable strength-to-weight ratio and corrosion resistance, thermal insulation foams for heat shielding, and elastomeric polymers for vibration damping and impact absorption. Advanced materials such as carbon fibre composites and high-strength steels are increasingly being used in high-performance applications to enhance crash energy absorption while minimizing weight. Design practices often incorporate honeycomb structures, reinforced corner elements, and energy-dissipating spacers. The integration of materials with tailored mechanical properties into strategic areas of the battery pack can greatly enhance crashworthiness and structural durability, reducing the likelihood of catastrophic failure under extreme conditions. Mechanical protection mechanisms are essential in maintaining the structural integrity of LIB packs under abusive conditions. These mechanisms are designed to absorb and dissipate impact forces, prevent intrusion into active battery components, and isolate damaged sections. Protective layers such as crash cans, reinforced enclosures, shock-absorbing foams, and crumple zones are employed to mitigate damage. Additionally, structural partitions between modules can restrict the spread of thermal or mechanical damage. These mechanisms not only improve the survivability of the battery system in accidents but also play a critical role in maintaining passenger safety by reducing the risk of fire or explosion. Thus, incorporating robust mechanical protection strategies is fundamental to achieving crashworthiness in battery design.

III. IMPACT SCENARIOS: FRONTAL CRASH, SIDE IMPACT, REAR-END, AND ROLLOVER

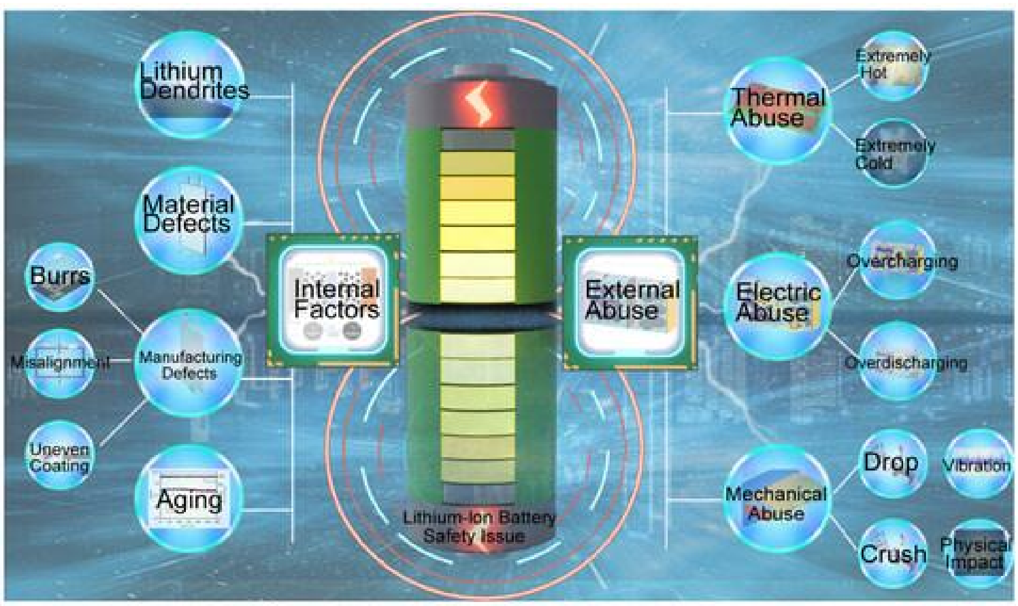

Figure 3: Classification of factors causing safety issues in lithium-ion power batteries.

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Lithium-ion battery packs in electric vehicles are subjected to a range of impact scenarios, each presenting unique mechanical challenges. Frontal crashes are among the most common and subject the front of the pack to high deceleration forces, often requiring reinforced crash structures. Side impacts are particularly dangerous as they can lead to deep intrusion into the battery enclosure, increasing the likelihood of cell deformation and short circuits. Rear-end collisions pose a risk of compressive loading along the vehicle's longitudinal axis, while rollovers can result in multi-directional stresses and complex deformation modes. Each impact type demands tailored protective strategies and structural reinforcements to prevent catastrophic failures and ensure the battery pack's safety during collisions.

Beyond vehicular accidents, LIB packs may experience drops and mechanical shocks during handling, transportation, and assembly line operations. These drop scenarios, although often less severe than crash events, can still cause significant internal damage, especially to pouch cells or loosely supported components. Drops from varying heights can lead to connector dislocation, cell misalignment, or micro-cracks that may compromise long-term performance. For logistics and manufacturing environments, ensuring mechanical stability under these conditions requires incorporating drop-resistant packaging, shock-absorbing mounts, and rigorous handling protocols. Understanding the dynamics of drop events is vital for preventing latent structural damage that could develop into critical safety issues over time.

Standard Testing Protocols (e.g., UN38.3, IEC 62660, SAE J2464, NHTSA, ECE R100)

Several international standards have been established to evaluate the mechanical safety of lithium-ion battery systems. UN38.3 is a widely accepted regulation for transport safety and includes drop, shock, and crush tests. IEC 62660 focuses on performance and safety requirements for lithium-ion cells used in EVs, with mechanical integrity as a key parameter. SAE J2464 outlines abuse testing procedures including mechanical, thermal, and electrical tests to assess battery safety. The NHTSA (National Highway Traffic Safety Administration) and ECE R100 (Economic Commission for Europe Regulation 100) provide crash and safety requirements for automotive battery systems, including structural integrity under impact. Adherence to these standards ensures battery systems meet baseline safety requirements and supports regulatory approval for commercial deployment.

Table 1: overview of standard testing protocols for lithium-ion batteries, in the context of electric vehicles (EVs)

Standard	Issuing Body	Focus Area	Key Tests Included	Application Area
UN38.3	United Nations	Transportation Safety	Altitude simulation, thermal test, vibration, shock, external short circuit, impact, overcharge, forced discharge	Transport of lithium-ion cells and batteries
IEC 62660	International Electrotechnical Commission (IEC)	Performance and Reliability	Electrical performance (capacity, power, life), thermal behavior, mechanical vibration/shock	Lithium-ion cells for EV propulsion
SAE J2464	Society of Automotive Engineers (SAE)	Abuse Testing Protocol	Crush, penetration, fire exposure, short circuit, overcharge, overdischarge	Safety testing for rechargeable energy storage systems
NHTSA (FMVSS 305)	National Highway Traffic Safety Administration (U.S.)	Vehicle Crash Safety	Electrical isolation, electrolyte spillage, battery retention in crash simulations	Post-crash safety of battery-powered EVs
ECE R100	United Nations Economic Commission for Europe	Vehicle Battery Safety	Vibration, thermal shock, fire resistance, overcharge, short circuit, protection against electric shock	Safety of traction battery systems in electric vehicles

	(UNECE)			

Key Mechanical Parameters: Stress, Strain, Energy Absorption, Deformation Modes

Understanding the mechanical behavior of LIB packs under impact conditions requires analysis of key parameters such as stress, strain, energy absorption, and deformation modes. Stress and strain provide insights into the internal forces and displacements within the battery structure, while energy absorption measures the pack's capacity to dissipate mechanical energy during a collision, reducing the impact force transmitted to critical components. Deformation modes such as buckling, bending, or shearing—help predict the structural response of cells and modules under different loading conditions. Accurate quantification of these parameters is essential for crash analysis, structural optimization, and validation of simulation models.

Common Failure Modes: Casing Rupture, Cell Deformation, Thermal Runaway, Electrical Short Circuits

During mechanical abuse scenarios, lithium-ion battery packs can exhibit several failure modes. Casing rupture may occur due to excessive localized stress, exposing internal components to external hazards. Cell deformation, including electrode misalignment or separator damage, can impair electrochemical performance or trigger internal short circuits. One of the most dangerous consequences is thermal runaway, where internal heating leads to uncontrollable reactions, fire, or explosion.

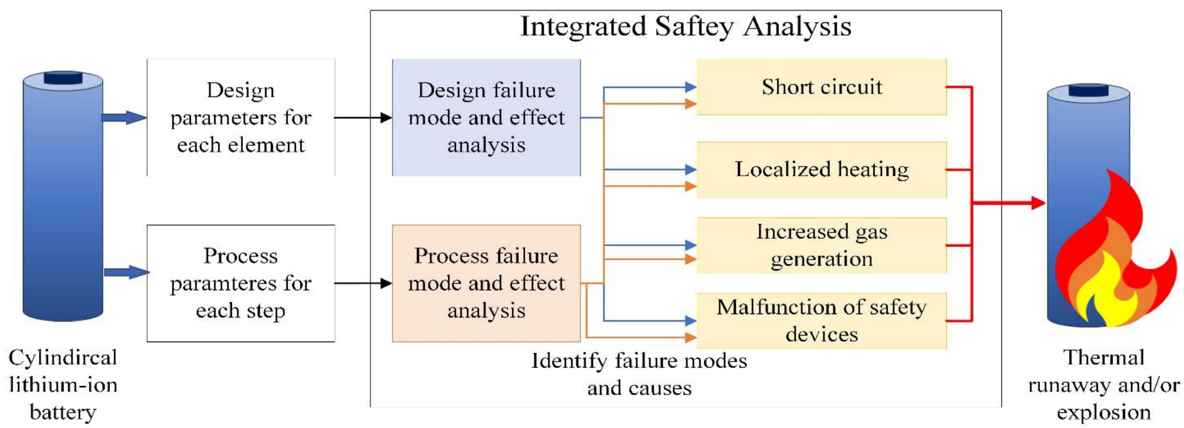

Figure 4: Safety Analysis of Lithium-Ion Cylindrical Batteries Using Design and Process FMEA

Additionally, electrical short circuits can result from conductor disconnection or internal faults, causing rapid energy discharge and localized heating. Recognizing and mitigating these failure modes through robust design and testing is crucial for ensuring the overall safety of LIB systems.

Structural damage to lithium-ion battery packs can have significant thermal and electrical consequences. Mechanical deformation can compromise the separator or lead to internal shorts, resulting in localized heating that may initiate thermal runaway. In parallel, damage to connectors, busbars, or current collectors can impair power delivery, trigger voltage imbalances, or even isolate sections of the battery, reducing its overall performance. Damaged thermal management systems may fail to regulate cell temperatures, exacerbating the risk of overheating. Thus, structural integrity is directly linked to both the thermal stability and electrical reliability of LIB packs, and preserving it is essential for the safe and efficient operation of electric vehicles and energy storage systems.

IV. MODELING AND SIMULATION AND EXPERIMENTAL INVESTIGATIONS

Summary of Experimental Studies on Drop Tests, Crush Tests, and Penetration Tests

Low velocity drop, crush, and penetration test on lithium-ion batteries as methods of mechanical abuses are important in determining the crash worthiness and safety of battery systems for EVs. Drop tests mimic bending and torque in which the battery is exposed to sudden shock caused by a fall or a collision from a vehicle. These tests determine the safety in terms of casing, cell displacement, and possibility of a short circuit. Crush tests aim at applying compression forces which are similar to effects such as car flips or pressure from other objects when stacking or moving most products in stores or in transportation vehicles. They assist in determining level of structural solidity of the battery modules and the conditions that lead to internal mechanical failure. These are carried out through applying pressure with a pointed (sharp) or blunt (rod) object through the battery where the electric flow, risks of thermal runaway, and collapsing of the frames are assessed. Many of the research studies have depicted how the load orientation, velocity as well as the point of loading affect battery failures, thermal behaviour and mechanical stressing, which created the need for standard requirements for the design of the battery housing and the packing of the modules.

Table 2: tabulated summary of experimental studies focusing on Drop Tests, Crush Tests, and Penetration Tests for lithium-ion batteries

Test Type	Battery Type	Test Parameters	Key Findings
Drop Test	18650 Cylindrical Cell	Drop height: 1.5 m, onto rigid steel surface, multiple orientations	Internal short circuit risks increase with higher drop heights and side impact.
Crush Test	Pouch Cell	Crushing force: 100 kN, speed: 5 mm/min, flat plate	Battery showed thermal runaway at ~80% SOC, strong correlation to SOC levels.
Penetration Test	Prismatic Cell	Nail diameter: 5 mm, penetration speed: 8 mm/s, various SOCs	Higher SOC caused faster temperature rise and gas venting.
Drop Test	Pouch Cell	Drop from 1.2 m onto concrete and aluminum plates, varied angles	Damage more severe at edge and corner drops than flat orientation.
Crush and Penetration	Cylindrical Cell	Crush with 10 mm rod, penetration with steel nail (6 mm)	Combined tests simulate worst-case thermal events; thermal runaway above 60% SOC.
Penetration Test	21700 Cylindrical Cell	Penetration speed: 10 mm/s, ambient and heated environments	Heated environment accelerates cell failure post-penetration.
Crush Test	Module-Level Pouch Cells	Flat plate crush, SOCs 0%–100%, different cooling configurations	Thermal propagation more likely in poor cooling designs.

Instrumentation and Setups Used (High-Speed Cameras, Strain Gauges, Accelerometers)

Adequate measurement instruments are critically important in experiments to study the intricate characteristics and failure behavior during battery abuse tests. They can be used in high-speed fracture, crack development, and temperature applications such as smoke or fire during the impact test. These cameras, normally running at thousands frames per second, are very useful in recording failure sequences. Temperature sensors measure concentration of temperature on the battery casing and structures of supports during the application of loads, while strain gauges provide information on the local deformation of the casing. Accelerometers are essential for gathering information about the drop and crash tests, specifically about the acceleration response of the battery pack or particular modules that occurred in the test. Furthermore, there are also employs of thermocouples and infrared cameras to have a check on the temperature fluctuations in real-time that are extremely helpful in observing the occurrence of the thermal runaway. This is made possible by integrating the several tools in order to gain a systemic understanding of how batteries are affected under mechanical abuse.

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Analysis of Impact Force Distribution and Structural Deformation

It is also important to know how the impact forces are divided and how the structure elements change their shape. In mechanical abuse, external forces are transmitted through several parts of the battery housing and in the internal elements in a manner that depends on the shape, border relations, and material characteristics. The technique of impact force distribution basically includes determination of load paths and locations of stress concentrations which are likely to cause failure. Internal electrical failures may occur due to buckling, delamination, or fracturing of the cell walls and casings that result in a structural deformation of the chimney. Features such as higher level of testing facilities and the digital image correlation (DIC) methods are involved to determine the samples' surface strain and deformation fields during impacts. Again, these analyses assist in strengthening the structures, arranging cells in a way that provides maximum strength, and increasing the crash energy by incorporating composite materials and rational cell placement.

Finite Element Analysis (FEA) Tools (e.g., LS-DYNA, Abacus, ANSYS)

Finite Element Analysis (FEA) Application are used frequently with an ability to simulate mechanical abuse conditions and estimating the battery response to certain loading condition. LS-DYNA is widely used in simulating high velocity impact and drop test because of its superior ability in the analysis of non-linear contact, the large deformation and fracture or failure. Abacus is a generalized finite element software that is used for coupled thermo mechanical application and has integrated tools for modeling viscoelastic behaviour and progressive damage. Among them, ANSYS has complete meshing environment and multiphysics simulation, which can be used for static crush analysis and electro-thermal-mechanical coupling analysis. These FEA platforms can be used by engineers for parameters variations, structural optimizations, and reducing the number of experiments as it is capable of mimicking the test environment. They also offers pre and post-processing of results of simulations to support scripting of decision and automation and for batch simulations and to support the DoE approaches.

Material Models and Meshing Strategies

The response shown in the mathematical models needs to capture the response of the material in simulations of lithium-ion battery packs. The material models required to analyze such material response should be capable of reproducing the nonlinear, rate-dependent and at times anisotropic nature of the materials being used in the cells, casings and structure. Regarding the metals other than aluminium and steel which are used in casings, the elastic-plastic material model with failure criterion such Johnson-Cook or Gurson is used. In the case of polymers and composite separators, viscoelastic and hyperelastic can be used. Although meshing strategies are used in different stages of simulation they play a crucial role in determining accuracy and convergence of the flow field simulation. Hexahedral meshes are more accurate in capturing the deformations, however the production of such mesh is little complex for geometries of complex shapes. Tetrahedral elements are easier to mesh than hexahedral ones but it might need more nodes in order to come up with the same level of precision. Mesh density, local enhanced region in high stress areas, and mesh sensitivity study are critical to get correct solutions with minimal computational expense.

Coupled Mechanical-Electrical-Thermal Simulation Approaches

Battery, performance and safety are closely related by the physical, electrical and thermal aspects especially during abuse cases. Integrated MEC simulants are designed to capture this phenomenon to provide a prognosis in regards to internal short circuit, Joule heating, thermal runaway, and cell failure. These can result in separator breach and what is referred to as internal shorting through which the currents clear at high-speed heat making. This may cause thermal runaway since heat has to be dissipated. Application of Mechanical deformation in conjunction with electricity involves using electrical circuits such as Randle circuit and mixing conduction and convection heat transfer modes. Domain wise control of solvers and roles and account for failure thresholds and phase change and heat generation rates are some aspects of these simulations. All these coupled simulations are crucial for creating safety schemes for battery and computational thermal protection as well as for designing structural vibrations damping.

Model Validation Techniques

Calibration of simulation models is an important process that is specifically aimed at verifying the reliability of the models predicted. Validation of models entails the comparison of simulation results with measurement data which can be in form of deformation profiles, stress strain curves, acceleration time histories, temperature variation as well as failure modes. Strain gauge data and high angular activated camera are other methods used to compare to deformation and stress predictions. Force-displacement curves obtained from experimental methods are useful in determining the contact characteristics and that of the materials as well. In the case of thermal and electrical validation, the results of the thermocouple and voltage measurements are compared to results of simulated temperature and voltage variations. There are also Sensitivity analysis and Uncertainty quantification to determine the reliability of the model presented. The following brings out several ways of ensuring that simulation outcomes match real-world behavior through correcting material parameters and boundary conditions: With the help of well-validated model, an engineer has enough confidence for coming up new designs for optimum condition and for assessment of structural safety under hypothetical loading conditions.

V. CRASH MITIGATION STRATEGIES, CELL FORMATS AND PACK LAYOUTS

Structural design improvements: honeycomb structures, protective enclosures, impact-absorbing layers

Improvement of lithium-ion battery pack structure is what is currently deemed necessary to improve the crashworthiness of battery packs besides optimizing their thermal and mechanical properties under harsh conditions. Application of honeycomb structures in battery pack housing has become more common because they are effective in energy absorption as well as distribution of loads. These structures are hexagonal and resemble honeycomb therefore; the shape allows lightweight structures that give a significant impact force in cases of shocks. Delicate and durable casing, mostly of metallic or any other composite layer, helps to prevent the cells from deforming or from being penetrated by foreign particles. Incorporation of one to three pilot impacts zones, foam paddings, elastomeric barriers or energy dissipating gels offer an extra protection layer which minimizes the effect to the inner battery during drop or crash instances. These multiple levels of structures are decisive for the suppression of the damage spread, the prevention of internal short circuits, and the integrity of the energy storage system.

Use of advanced materials: composites, aluminium alloys, high-strength steels

The choice of materials for housings and support structures for vehicles and motors built with lithium-ion battery packs involve deciding on their mechanical integrity and thermal performance in the case of crash conditions. Carbon fiber-reinforced polymers we deal in are also ideal in use since they possess high strength to weight proportions, anti-corrosive qualities and good energy absorption properties thus they are ideal for use in protective structures that require lightweight and high strength. Aluminium alloys are also preferred due to their relatively low price tags, spare dimensionality in the production and reasonable thermal expansion for cooling as well as insulation purposes. Although high-strength steels are heavier compared to mild ones, they provide better impact and ductility that allows management of collisions and gives way to the necessary deformation allowing force to be absorbed without causing failure. All of these materials are then integrated in compounds in a way that would maximize safety and performance and this entails the combination in various ways so that it would achieve the best crash energy absorption, acceptable weight and suitable structure under dynamic loadings.

Modular designs for controlled failure and safety

The battery pack designs offer a level of serviceability as well as safety in electrical vehicles since energy is stored in compact, and failure is organized. This arrangement means that battery cells are grouped in modules and each of them can be situated in a single compartment. This also enables efficiency in thermal regulation and further makes it possible to section off individual cells in case of breakdown or mechanical harm. In crashes or drops, the energy is absorbed and dissipated at local module level by design, in other words, there is very low risk of thermal runaway affecting the whole battery pack. Also, modules can be also designed with safety element like rupture disks, thermal fuses, or sensors for

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detecting the fault at an initial stage. Ensuring safe conditions in a modular battery design also contributes to improving not only the sturdiness and reliability of the structure but the ease of diagnosing and replacing it or repairing damage sustained in a crash and its consequential benefits for battery system operations.

Influence of cell geometry on impact resistance

Cylindrical, prismatic or pouch shapes depend on the cell geometry and mainly affect its mechanical stability and impact response of lithium-ion battery. This kind of cells have a rigid metal structure as well as a cylindrical column shape and are generally come in greater compression and impact force. Its round shape also has uniform pressure build up thus reduces chances of deformation in the event of a crash. Unfortunately, prismatic cells, while being more compact, have flat walls that might bulge out under lateral pressure; it means that in building the pack a lot of extra attention should be paid to this aspect. Pouch cells, which, at the same time, are the densest, lightest and are protected by a flexible, low-profile structure, are the most sensitive to mechanical shocks. It can be quite ill-fitted to withstand the impact loads due to no rigid casing, prone to swelling, puncture and short circuiting inside it. So cell geometry is something of compromise, where factors such as energy density, packing factor and crash worthiness have to be taken into account with the application of the technology and the safety consideration in mind.

Analysis of the drop and crash tests shows that pouch cells have a 20–30% lower capacity retention than cylindrical and prismatic cells when tested under the same scenario. For instance, in the vertical drop tests repeated from a fixed height, the cylindrical cells holes did not deform significantly because of a metallic frame. On the other hand, pouch cells had features such as swelling, delamination, and in some strings were even seen to have leakage of electrolytes signifying that they were more susceptible. Prismatic cells had a fair performance concerning the structural deformity, but most of them maintained an excellent ability to confine the active material. However, in frontal crash tests that replicated the car crashes, battery packs with cylindrical cells had better performance in term of mechanical intrusion and temperature control compared with that of pouch based battery packs. However, the prismatic cells did come to the same levels of protection when sufficiently reinforced. These articles indicate that cell design and packaging play a major role in terms of how well battery can withstand actual impact and further magnify the fact that it is necessary to factor in crashworthiness into both the cell and system design.

Table 3: Influence of cell geometry on impact resistance as per form factors of battery

Aspect	Pouch Cells	Cylindrical Cells	Prismatic Cells
Structural Integrity	Vulnerable to deformation; flexible packaging prone to	High structural integrity due to robust metal casing	Moderate strength; rigid, but flat surfaces susceptible to
Crash Test Results	High risk of electrolyte leakage and delamination;	Performs well under compression and impact; lower	May sustain dents or bulges; needs extra reinforcement in
Thermal Runaway	More likely due to lack of individual casing; higher	Less propagation risk; individual casing provides	Moderate risk; depends on internal cell design and housing
Drop Test Outcomes	Easily damaged from moderate heights; requires	Minimal deformation; maintains function after	Variable response; internal damage possible even if casing
Space Utilization	High packing efficiency but low mechanical protection	Lower packing efficiency due to cylindrical shape	Good balance of packing density and structural form
Weight Considerations	Lightweight but needs added protective structures	Heavier due to casing	Heavier than pouch, lighter than cylindrical for same
Common Use Cases	Consumer electronics, lightweight EVs, drones	Power tools, electric cars (e.g., Tesla), e-bikes	EVs, energy storage systems, hybrid vehicles

Pros and cons from crashworthiness perspective

From this perspective of crashworthiness, several benefits and demerits can be associated with each cell type. Cylindrical cells provide very good mechanical protection, can hardly be deformed so they are suitable for impact uses, however, they occupy more volume because of the free space between cells. However, the prismatic cells have the best compromise of energy density and crush strength but need another stiffening to help them cope with large impact forces. It is, however, recognized that pouch cells deliver the highest energy density and pack design flexibility though they are structurally very sensitive hence requiring elaborate protective features against shock & thermal runaway. With regards to the issue of thermal runaway, cylindrical cells are more preferred, mainly because they have a case that isolates the failure to a particular cell. However, the choice of type of cell must be conforming to the goals of used application: weight, price, area, thermal conditions, and, of course, crash safety.

Table 4: the key aspects of the listed challenges in crashworthiness analysis and testing of lithium-ion battery packs

Challenge	Description	Implications	Potential Solutions
Challenges in full-scale testing and replication of real-world scenarios	Full-scale crash tests are expensive, time-consuming, and logistically complex. Replicating all possible	Incomplete understanding of battery behavior under varied real-world conditions; limited	Use of hybrid testing (partial physical, partial simulation), virtual testing frameworks (e.g., finite
Data scarcity for certain crash modes and configurations	Limited experimental data exists for rare or extreme scenarios (e.g., oblique impacts, bottom-up	Gaps in model calibration and validation; lower confidence in safety predictions for uncommon	Develop shared industry-academic databases, conduct targeted experimental campaigns
Difficulty in modeling complex failure mechanisms like thermal runaway	Thermal runaway involves coupled electrochemical, thermal, and mechanical processes, which are	Reduced accuracy in predicting cascading failures and post-crash safety risks; difficulty in	Multiphysics simulation tools, detailed cell-level testing, integration of machine learning for

VI. CONCLUSION AND FUTURE DIRECTIONS

From the literature review, it can be noted that, for optimization of LIB packs for improved crashworthiness, there should be proper structural design and material selection and proper thermal management. A variety of analyses demonstrate that cylindrical cells have higher mechanical resistance, at the same time, pouch cells have bigger energy density, but they demand more protection. Various changes to the external structures such as economically made honeycomb structures, softer and more pliable materials for impacting, and a 3-part construction minimize energy transfer and excessive heat generation during accidents.

That might be the reason why today the technologies became significant for the creation of safer and more durable battery pack designs. Building in protective enclosures, using high composite materials, and incorporating modularity increases the chances of compartmentalization of failure and reduces chances of damage cascade. These prove useful in the development of battery systems usable in actual applications in various fields.

For further studies and industry application, Firstly, multiphysics modeling should play an important role in future research; secondly, efforts should be made to perform crash simulations on real life like conditions; thirdly, tests should be conducted on different materials under extreme conditions. The practices adopted by industries also need to change and shift towards safety-by-design, best practice sharing and have increased investment in using data to prove reduction in risk from design. Increased sharing of failure data will also go a long way in maintaining faster development of safer batteries.

Currently there is no standard global procedures when it comes to the test crash for LIB packs. The rationale for developing standardized procedures is as follow; safety performances are benchmark in the standard procedures, the models are validated and manufacturers are guided on the improvements to undertake. It is thus necessary to have a thermal test protocol template, mechanical operating test protocol template, and an electrical failure test protocol template to ensure accreditation and standardization.

There is advent use of ‘artificial intelligence and machine learning, which can be utilized for the prediction of battery failure using the data entered through sensors, earlier usage, and the environment. These models can therefore identify

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the signs of degradation or thermal event and help the safety interventions and the management of battery pack. It will extremely beneficial for risk assessment and diagnostics that will be enabled and powered by Artificial Intelligence.

New trends in self-healing and smart materials are on the anvil which has potential to revolutionize the batteries safety. They can self-healing micro-carbonate cracks or adapt their properties when they feel stress or when temperature changes occur. When used in battery enclosures or cell packaging, such materials will be useful in improving the battery life and lowering the likelihood of mechanical-related failures.

The real-time health monitoring and diagnostics of the battery pack can be achieved by integrating scalable sensors and wireless communications technologies. Real-time monitoring of those parameters enhance operational safety since a solution to an emerging problem for instance swelling, temperature increase or deformation can be tackled immediately.

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