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Original Article

Numerical Modeling and Experimental Validation of Mechanical Performances of Li-Ion Battery Cells/Modules/Packs with Various Form-Factor Design for EV Applications

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Abstract - *The rapid electrification of conventional and Electric Vehicles (EVs) requires Lithium-ion (Li-ion) batteries that are characterized by high energy density, safety, and durability over a wide range of operating conditions. Although the electrochemical performance has received much attention, relatively limited research has been able to address the mechanical responses of Li-ion robustly during cell, module, and pack modes, and in particular, the response in the various form-factor cells, i.e., cylindrical, pouch, and prismatic cells. The currently available literature can usually be reduced to one or the other numerical or experimental studies, with no thorough cross-validation of both the computational and experimental cases. Such a gap limits the creation of predictive and dependable methods to assess structural integrity conditions due to normal operation and abuse. The proposed study fills the research gap by creating high-fidelity models of Li-ion battery cells, modules, and packs in varying form-factor designs before subjecting them to the systematic and controlled conditions of mechanical loading and testing. The suggested method applies Finite Element Modeling (FEM) in combination with multi-scale simulations to determine stress, strain, deformation, and failure modes. Predictive reliability of tested and used numerical models is strengthened by experimental resolution, which is achieved by conducting compression, vibration, and impact tests to guarantee the predictive reliability of the numerical models. This work presents a holistic framework of connecting the modeling and experiments at various form factors and at different levels of integration, in contrast to currently available literature that is mainly concentrated on single-scale or form-specific design. The novelty is associated with the connection of computational predictions with the empirical data, providing an effective and powerful approach to assess mechanical performance. Results underscore significant variation in the deformation behavior and failure limits across form factors, suggesting optimal design, safety, and structural durability of EVs in battery applications.*

Keywords - *Electric Vehicle, Lithium-Ion Batteries, Form Factors, Mechanical Stability, Numerical Modeling, Simulation.*

1. Introduction

The lithium-ion batteries are widely used in Electric Vehicle (EV) technology since they have high energy density and long cycle life with low self-discharge. Prior to all the latest products and technologies, LIBs yield better performance than lead-acid and nickel-metal hydride batteries, as they are able to power the electric drivetrains effectively. These mechanisms provide the capability to operate vehicles such as small passenger cars, heavy trucks, and large buses, and the like. By implementing global solutions for sustainable energy and decarbonization, LIBs play a role in reducing the carbon footprint of the transportation sector. The LIB technology development enhances EV commercial potential, and increasing public trust in EVs makes LIBs one of the key elements for the adoption of clean mobility. The increasing demand for large-capacity batteries, together with the requirement for stronger durability and safety resistance, drives the continuing research of battery systems via design and test methods. The application and configuration of the lithium-ion battery system in EVs should address basic concerns about their mechanical safety and system operation performance. Lithium-ion battery packs are subjected to a lot of mechanical stress types during their lifetime, such as road bumps, crash impact , and severe accidents. Mechanical external forces on battery cells affect their basic structure and are part of the factors causing cell damage that can lead to varying shapes, electrical conductivity breaks, thermal movement, and, on occasion, even product fires. The mechanical properties of battery systems should be evaluated through detailed studies in normal and extreme-event conditions, which should include quantifying mechanical toughness, energy absorption, and mechanical failure response. The safety of the occupants and of other road users is an issue addressed by all car manufacturers through the application of specific mechanical conditions. The design of battery packs with an effective balance of energetics and mechanical properties is a challenging engineering issue demanding integrated knowledge of materials and mechanics, plus safety, and requires a comprehensive understanding of visualizations of the stiffener-riddled battery layers. Mechanical behavior of lithium-ion battery systems is largely a function of the cell form factor, which may vary between cylindrical, prismatic, and pouch cell configurations.

The properties of the various cell form factors are unique in several aspects, with implications on both their mechanical behavior and their energy capacity, and can become packaged in a more efficient way with different thermal management. The cylindrical 18650 and 21700 cells are ideal from a mechanical point of view, given their geometry (symmetrical shape), which is less sensitive to compression and impact loads. Prismatic cells, in particular those that are space-efficient, are often more responsive to mechanical stress resulting from deformation and swelling.

The flexible pouch cell allows for the most packaging options, but is mechanically fragile due to its thin protection layer. The choice of cell form factors ultimately determines the mechanical characteristics and safety performance potential of module units and the assembled pack. The pack performance reliability relies upon the accurate knowledge of the mechanical properties of various battery form factors for better pack design for various operational environments.

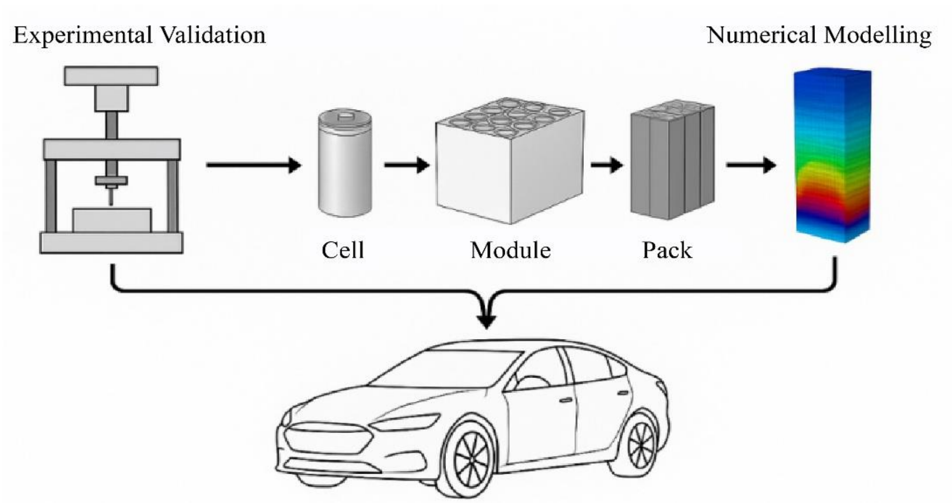


Fig. 1 Graphical abstract

The robust uptake of Electric Vehicles (EVs) has increased the need for safe, durable, and high-performing Lithium-Ion Batteries (LIBs). Although the electrochemical behavior of LIBs is generally well-studied, systematic mechanical performance of cells, modules, and packs in various form factors (cylindrical, prismatic, and pouch) under realistic loading has received limited research attention.

The literature tends to concentrate on one scale or simplified models, so there is a need for integrated numerical-experimental techniques that can determine the integrity, applicability, and degradation of structures under mechanical abuse, vibration, and impact conditions with a high degree of reliability. This study fills this gap by moving towards the construction of numerical models integrated with experimental characterizations to provide a holistic examination of the mechanical performance of LIB systems over a variety of scales. The originality is that form-factor-dependent structural responses can be considered at the same time, and the simulations can be verified with experimental data, which can be compared to those based on prior studies that were predominantly based on modeling or empirical data. With benchmarking of various form-factor designs, this study will give important insights into the optimization of design, safety, and value-added durability of next-generation EV battery systems.

1.1. Problem Statement

The structural integrity and safety of lithium-ion batteries in EVs have become an acute concern due to the increased need to operate at a wide range of mechanical loads, including but not limited to vibration, impact, and compression, under which collision and driving operations inherently appear in the real world. Most existing studies are either electrochemical degradation or isolated abuse only and do not capture coupled mechanisms, including mechanical and electrical response across various form factors and systems (cell, module, and pack). This incomplete knowledge leads to uncertainty in the prediction of failure modes, thermal runaway risks, and long-term durability. These choices of vibration, impact, and compression loads are justified by the fact that these loads have an immediate relevance to the EV operation: road vibrations influence fatigue life, impacts cause catastrophic failures, and compression imposed during crash or assembly operations may cause shortcuts. Through mathematical modeling and experimental verifications of these load conditions on cylindrical, prismatic, and pouch cells, it is hoped that this study will fulfill the gap that still exists and allow a more substantiated design optimization and standardization of the safety of the LIB system in EVs.

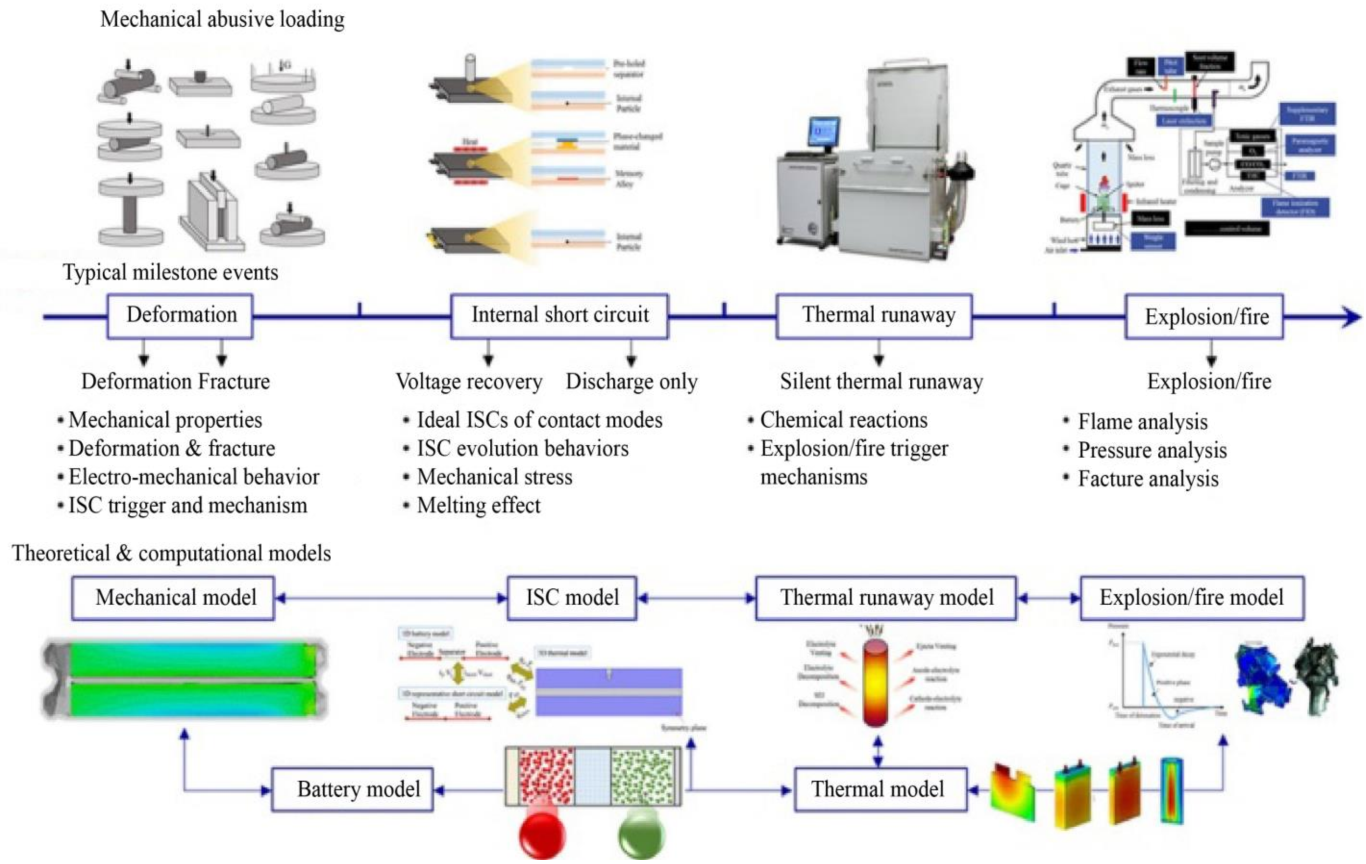


Fig. 2 Evolutionary process for LIB behavior upon mechanical abusive loading [1]

1.2. Novelty of Work

The novelty of this study lies in this co-validation approach, exploiting both experimental-based validation and detailed numerical modelling for the mechanical analysis of a lithium-ion battery system at cell module and pack scales. Conventional research focuses on a single form factor or system level only, while in this paper, a combined study of various cell designs (cylindrical cell, prismatic cell, and pouch cell) can be presented within the same research framework. Numerical simulations in this study were confirmed by experimental data, which was also demonstrated, opening up a possibility for predictive modeling of non-accessible by experiment conditions as well as under extreme loading and for alternative pack designs. Research from experimental testing and computational models results in a complete framework that will allow EV battery engineers and manufacturers to optimize their products' mechanical durability and safety.

1.3. Research Gap and Scope

The study is restricted due to the lack of consideration of the combined experimental and numerical study at different scales. Mechanical understanding of the Li-ion battery has improved significantly; however, a significant knowledge gap remains for unified studies integrating experimental observations and numerical simulation over architectural scales of battery format, type, and function. The existing research works in the field currently work in silos, as experiments perform cell-level testing and numerical simulations are exclusively done by simplified models, failing to bridge the gap. The majority of the research effort is devoted to the measurements at the cellular level without considering important interactions that take place between modules and the complete battery pack, which need to be examined for further EV realisation. The absence of integrated experimental battery tests with numerical simulations hinders the accurate prediction of performance and safety. In this paper, we present an integrated experimental-numerical approach to evaluate mechanical performance across cell to module to pack scales, focusing on variable form factor designs.

The analytical and experimental method provides an improved insight into the mechanical endurance and assists in the development of safer strategies in future battery systems for EV.

1.4. Methodology

The approach for systematic experimental validation and numerical modeling of mechanical behaviours of lithium-ion battery cells, modules, and packs with arbitrary form factor design is a systematic approach. This starts with choosing typical battery designs and applying standard mechanical tests, like drop and impact tests, to recreate real-world abuse. These tests are focused on checking the structural damage, deformation, and breakthrough points. At the same time, a model simulation of the battery is conducted by Finite Element Analysis (FEA) with the geometry and material properties of the battery. Tests from exercises are simulated in order to assess mechanical responses to different conditions. Material characterization benefits both the modeling and the experimental validation. The two are combined to relate and validate each other, and to predict the mechanical performance of the battery for the robustness and safety of electric vehicles.

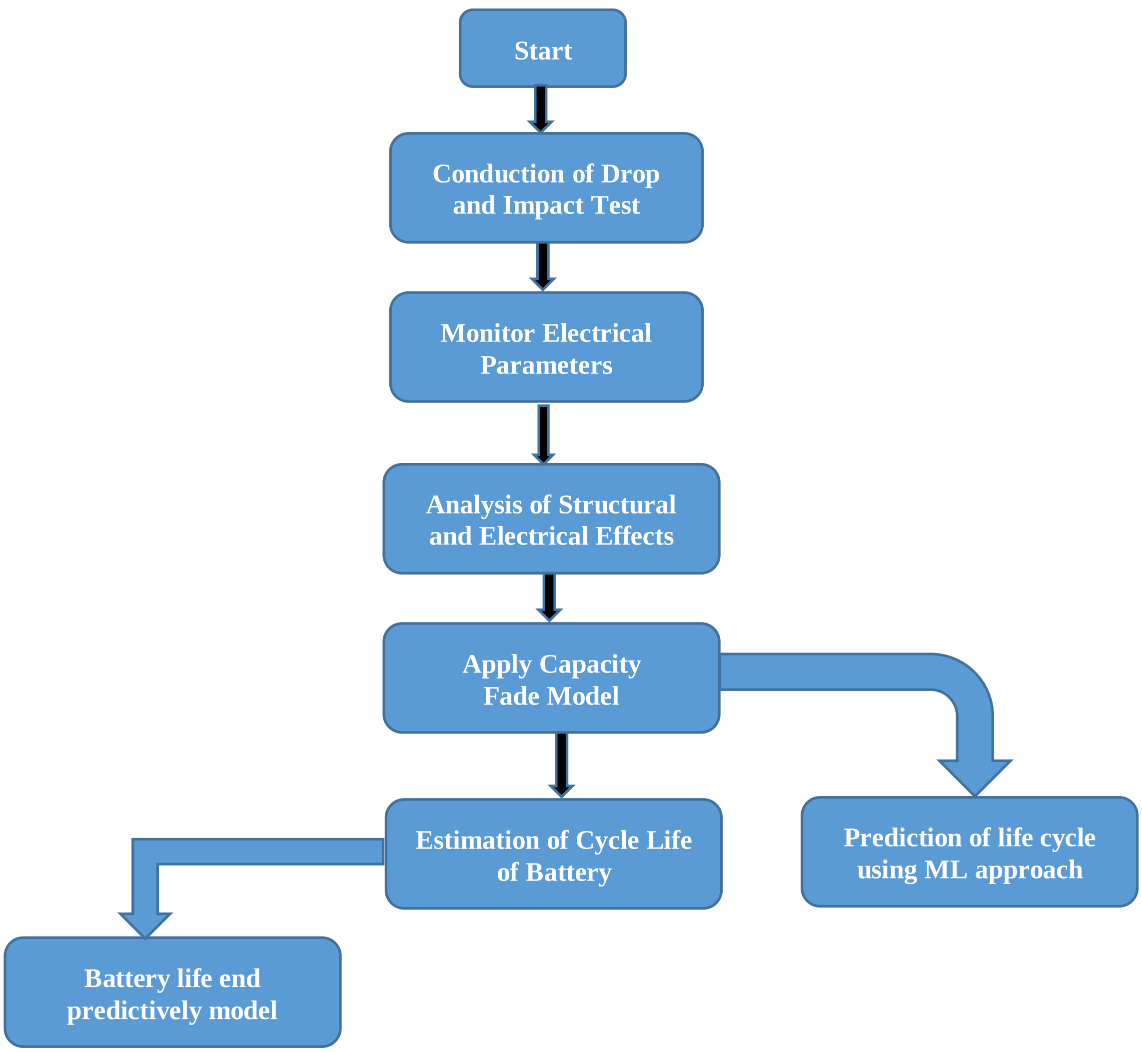


Fig. 3 Methodology of work

1.5. Objectives of the Study

Physical characterization of lithium-ion battery cells, modules, and packs (cylindrical, prismatic, pouch) includes: compression, tension, shock, failure modes, and energy management.

1. To develop and employ methods to improve finite element models of lithium-ion battery systems to predict mechanical performance under multiple levels of stress.
2. To investigate the effects of different cell form factors and their mechanical performance in the battery systems on

the module and pack levels.

3. For evaluating the mechanical loads, stress, and strains due to safety anomalies (short circuiting, puncture, and thermal runaway) for Battery systems.
4. For design with suggestions for battery pack arrangement and mechanical protection, and to select optimum cell form factors with respect to high structural integrity.
5. To develop an integrated system of experimental and numerical approaches to model at the cell, module, and pack scales for better predictive capability.

In this paper, the intuition and the future works to identify the battery safety issues, mechanical improvement, and multi-physics model development are proposed.

2. Literature Survey

Lithium-ion battery mechanical testing has been studied widely because of the safety and structural aspects of lithium-based batteries that are commonly used in electric vehicles, aerospace, and portable electronics. Previous works have used mechanical abuse tests, including compression, puncture, indentation, crush , and vibration, to simulate road incidents, dropping, and impact events. These tests are designed to measure battery response to various mechanical loads and to discover the failure modes: internal short circuiting, electrolyte leakage, and thermal runaway, as well as deformation of the structure. Initial experimental work concentrated on single cells, namely cylindrical (e.g., 18650) and pouch cells, to establish a baseline of mechanical properties. The subsequent work extended its scope to the module and pack level to study the impact of cell-to-cell connections, the casing, and the module design on the mechanical robustness of the system. The creation of custom tests rigs, these standard verification procedures, and high-speed imaging methods, such as thermal cameras and an X-ray tomographer, have contributed to deepening the knowledge of the deformation and failure development in the batteries. These previous studies provided a good foundation for the development of safer battery packs and were instructive in designing advanced mechanical protection systems. The shape of lithium-ion batteries, cylindrical, prismatic, and pouch, greatly affects their mechanical behaviors under different loadings. Various works have also considered the effects of the battery geometry, casing materials, and internal electrode disposition on the mechanical strength and failure mechanics of the cells. Cylindrical cells are generally stronger and more resistant to physical force, but may fail catastrophically if the jelly roll ruptures, and thus have higher mechanical stability and better resistance to external compression force. When using a standard prismatic cell, and stacked cells in a quasi-like design, where the cells are difficult to clip, i.e., the prismatic cells are typically enclosed in a hard case, e.g., of aluminum or steel, a more beneficial stack ability is obtained, but in return, these are more prone to deformation, causing delamination or buckling at axial load. The pouch cell is a soft package, and the support structures of the pouch cell were not sufficient, so the soft package will swell, the electrolyte will leak, and local failure is very frequent. It has been found that mechanical stress distribution and crack propagation paths are different between these shapes, which affects the occurrence of internal short circuits and the thermal event onset. Such knowledge is essential for choosing the optimal cell type for application-specific mechanical requirements, including crash resistance in electric vehicle applications or rugged-use specifications in military electronics. Finite Element Analysis (FEA) has become an important technique for modeling the mechanical performance of lithium-ion battery systems, through which the stress distribution, deformation, and failure mechanisms under different loadings can be analyzed. FEA simulations have, over the past 10 years, advanced from shell or generalized continuum models into complex and in-depth multi-physics simulations of thermal, electrical, and mechanical interactions. Recent simulations can handle anisotropic material properties, complex electrode geometries, the casing response, and dynamic ones such as puncture and drop impact. Validated models for single cells have been developed and have been further scaled for modules and packs to allow system-level studies adopting crash scenarios and structural durability as constraints. In addition, joint electro-thermo-mechanical simulation can be used to give an insight into the deformation-induced internal shorts, heat generation, and possible thermal runaway. With advances in material characterization and computing power, models now incorporate micro-structural features and failure criteria, such as cohesive zone modeling or damage evolution laws. These capabilities facilitate virtual prototyping and minimize the reliance on expensive experimental validation, expediting the design of next-generation safe and long-lasting battery systems. Although there have been a number of advances in both mechanical testing and numerical modeling of Li-ion cells, modules, and packs, a large disparity still exists between correlating experiments over all these length scales. One important difficulty is the absence of a common, high-fidelity input set of parameters for the simulations, i.e., strain behavior of the internal components, contact conditions, and failure levels. Test results are frequently valid only for given test conditions and do not necessarily take all boundary effects and dynamic effects into account, thus posing a challenge to the calibration and validation of the models. Additionally, cell manufacturing and assembly are sources of variability that are seldom considered in simulations. At the module and pack levels, other complexities like cell mechanical intercoupling, the influence of enclosure restrictions, and the effects of heat management systems make the experimental model conversion far more complex. Furthermore, the homogeneous material property assumed by many models does not capture the anisotropy and most notably the presence of localized defects in the realistic cells, which could have a great impact on the responses to mechanical stimuli. Narrowing this gap will depend on the availability of more complete data sets, the development of better inverse modeling, and a more intimate coupling of experimentalists working in concert with computational scientists to produce predictive models that capture physical behavior over multiple scales. Safety regulations and standards are extremely important to ensure safe design, testing, shipping, and use of lithium-ion batteries. Key standards such as UN 38.3 define the basic safety requirements for transporting lithium batteries, which involve mechanical tests such as impact, crush, vibration, as well as thermal and electrical abuse conditions. There are several reasons why it is compulsory for all lithium batteries transported by air, sea, and ground to be UN 38.3, and it is to prevent accidents in transport. SAE J2464 (developed by the Society of Automotive Engineers) provides detailed test procedures for assessing the abuse tolerance of RSD systems in vehicles. It covers mechanical abuse tests like drop, penetration, and crush, and also focuses on the analysis for the determination of failure modes (such as thermal runaway). Additional standards such as UL 2580, IEC 62660, and ISO 12405 provide additional requirements related to performance and safety for automotive and stationary storage applications. These frameworks are living documents, updated in response to new research and innovation, and encourage standardization and responsible behavior in the battery supply chain. Following these guidelines will contribute not only to safety but also to fostering consumer confidence and regulatory compliance in global markets.

3. Materials and Methods

3.1. Numerical Modeling and Simulation

The Commercial FEA Software SolidWorks is used to analyze the structural integrity and safety of lithium-ion batteries under crush and impact load. The test arrangement further comprises specified drop heights (of 1, 2, and 3 m), angles (flat, edge, corner), and impact velocities calculated based on gravitational acceleration in order to replicate actual and accidental handling situations. Specific battery materials like: (a) related elastic modulus, density, and fracture toughness for electrodes, (b) tensile strength, and elongation at break for polymer separators, or (c) yield strength and impact resistance for metal or polymer casings are included in simulations. This is useful for characterizing structural weaknesses and for design improvements. The properties of the materials employed for CAD modelling of the 18650 cell are summarised in Table 1. The wallet is usually made of aluminium alloy to provide strength and thermal conductivity, and the clapper cap is made of high-conductivity aluminium.

Graphite anodes are in the 2.2 g/cm³, and the cathodes ($LiCoO_2$/NMC) are denser (∼4.8 g/cm³) and have low thermal conductivity (∼2 W/m·K). Liquids are modelled using the electrolyte concept, with a density of 1.1 g/cm³ and a thermal conductivity of 0.1–0.2 W/m·K. Material properties such as Young's modulus, Poisson's ratio, and thermal expansion coefficient allow realistic structural-thermal analysis.

Table 1. Summary of literature survey

Topic	Key Points	Application/Impact
Outline of mechanical testing	Covers compression, crush, puncture, and vibration tests on single cells to packs; detects failures such as internal short circuits and thermal runaway.	Informs safer battery pack designs and benchmarks mechanical endurance.
Form Factor Influence	Studies report varied mechanical properties and failure mechanisms across cylindrical, prismatic, and pouch cells.	Helps to make the right decision regarding the optimal cell format for a given application (e.g., EVs, consumer electronics).
Numerical Modelling (FEA)	State-of-the-art multiphysics FEA for stress, heat, and deformation with rich microstructures.	Allows for virtual testing and saves on prototyping time and cost.
Experimental-Model Gaps	Lack of resources. Validated data to simulate across spatial scales; variability in material properties is commonly ignored.	Suppression of the ATM system: Detrimental for crash/abuse prediction; needs closer collaboration and data exchange.
Safety Specifications & Standards	For transport and automotive mechanical/electrical safety testing, it is dictated by, among others, UN 38.3, SAE J2464, UL 2580, etc.	Guarantees universal safety standards and certificates for battery systems.

Table 2. Specifications of lithium-ion battery with different form factors

Sr. No.	Model No.	Nominal voltage (Volts)	Nominal capacity (Ampere)	Operating voltage (Volts)	Maximum charging current (Ampere)	Maximum discharging current (Ampere)
1	IMR18650P -2000mAh	3.7	2.0	2.5 to 4.2	2	15
2	LiFePO4 – 32700 - 6.0Ah	3.2	6	2 to 3.65	1C(6A)	3C(18A)
3	Pouch LFP 20Ah Cell	3.2	20	2 to 3.65	1C(20A)	3C(60A)
4	Prismatic LFP 20Ah Cell	3.2	20	2.22 to 3.65	1C(6A)	3C(18A)

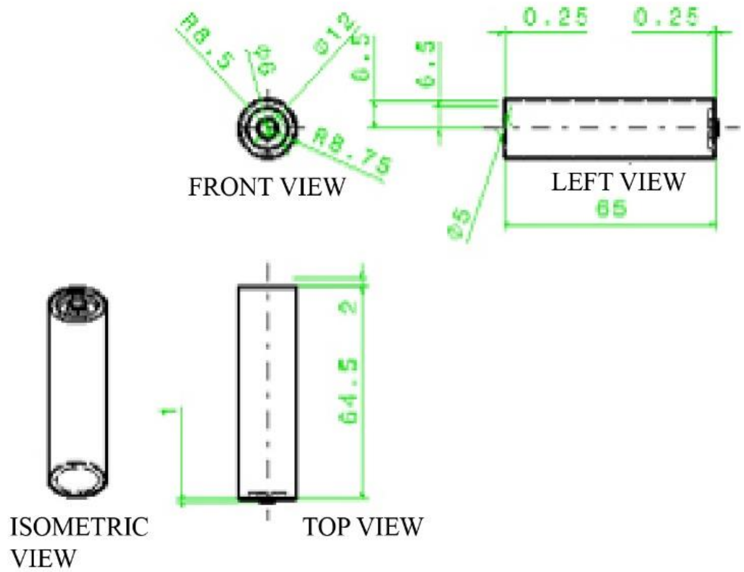


Fig. 4 CAD modeling specifications for lithium-ion battery

Table 3. Material properties of 18650 lithium-ion battery cell [5]

Component	Young's Modulus (GPa)	Poisson's Ratio	Shear Modulus (GPa)	Mass Density (g/cm³)	Tensile Strength (MPa)	Compressive Strength (MPa)	Yield Strength (MPa)	Thermal Coefficient of Expansion $(10^{-6}/°C)$	Thermal Conductivity (W/m·K)
Battery Cell Cap (Aluminium alloy)	70–110	0.33	27–45	2.7	200–400	200–300	150–300	23–25	180–200
Battery Cell Case (Steel alloy)	200	0.28	80	8.0	300–500	400–600	250	10–12	50–60
Anode (Graphite)	10	0.15	3–5	2.2	40–60	40–60	10–20	3–5	100–150
Cathode ($LiCoO_2$)	150–200	0.2	60–80	4.8	50–70	50–70	10–20	15	2–3
Electrolyte	1.56	0.35	-	1770	1.15	0.647	0.414	700	0.1–0.2

3.2. Experimental Analysis

Mechanical abuse of lithium-ion batteries may cause serious outcomes, such as structural failure, electrochemical degradation, or even a catastrophic failure mode like thermal runaway. An Internal Short Circuit (ISC) phenomenon is one of the main failure modes that is usually caused by crushing, puncture, or pressure, etc., which is the breaking of the separator between the anode and cathode, resulting in direct contact of electrodes and rapid discharge from the electrodes. This may lead to localized heating with possible initiation of thermal runaway, a self-perpetuating exothermic reaction. Moreover, mechanical stress leads to microcracking and delamination of electrode materials and coatings (which in turn results in a decline in the electrochemical performance), and also capacity fade and rise in internal impedance. Repetitive stress on the electrode and separator can also distort them, reducing the flow of lithium ions and causing lithium plating, creating dendrites, and unbalancing the cells in the battery pack, resulting in compromised safety and performance. Mechanical abuse causes serious changes in the electric characteristics of Li-ion batteries due to the changes in voltage stability, internal resistance, energy efficiency, and charge-discharge behavior. Electrode structural damage adversely affects the voltage, and it rapidly decreases suddenly with load, indicating poor conductive properties. Internal resistance from microstructural evolution is expected to contribute due to changes in microstructure as the battery is cycled, which will generate heat, accelerate thermal degradation, and ultimately shorten battery life as well. The deformation of internal structures is an obstacle for ion movement, thereby reducing the charging capacity and the charge/discharge rate, which is particularly unfavorable for fast charging. Sustained stress over time can lead to irreversible capacity loss due to active material fragmentation and lithium loss, even in the absence of observable damage. These effects need to be understood to develop BMS to detect mechanical wear early and preventively or predictively act in real time to enhance the battery safety and durability.

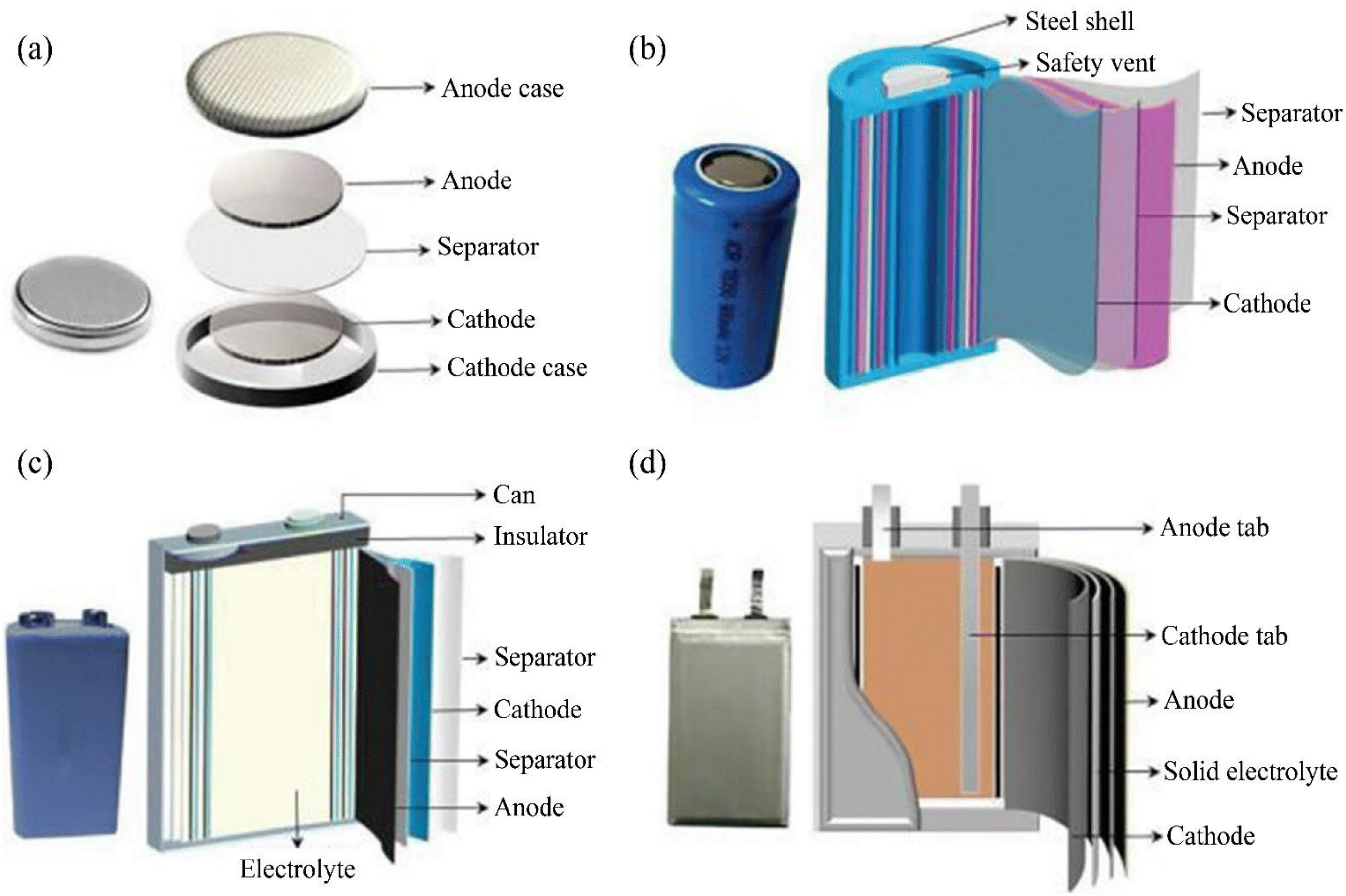


Fig. 5 Schematic of (a) Coin-type, (b) Cylindrical-type, (c) Prismatic-type, and (d) Pouch-type batteries [8].

Table 4. Summary of the given information on lithium-ion battery cell form factors, covering their structure, mechanical strength, failure responses, and application significance

Form Factor	Structure	Mechanical Strength	Failure Response	Key Applications	Significance in Design
Cylindrical Cell	Rigid metal casing with spiral-wound electrodes	High rigidity; excellent structural integrity; good resistance to external pressure	Resistant to puncture and compression; susceptible to localized impact leading to internal short circuits	Power tools, electric vehicles (EVs), energy storage systems	Strong structure, efficient thermal management, automated production, but less packing density
Prismatic Cell	Rectangular aluminum or steel casing with layered electrodes	Moderate strength; more deformable than cylindrical due to flat surfaces	Prone to sidewall deformation, compressing internal layers, and damaging separators	Laptops, EVs, compact energy storage	High energy density, efficient space usage, and more complex thermal and mechanical management
Pouch Cell	Soft polymer casing with stacked electrodes	Lightweight but least mechanically robust	High vulnerability to swelling, puncture, and compression-induced delamination	Consumer electronics, drones, wearables, portable EVs	Flexible design, excellent energy-to-weight ratio, but needs external protection for safety and durability

Each factor of battery size involves a compromise between mechanical strength, energy content, and volume utilization. Tubular cells are structurally very durable and best suited for tough, high-power applications. Prismatic cells are space-efficient but need better thermal control. Pouch cells, although space and weight-efficient, are structurally weak and require additional protection. Form factor selection has direct implications for battery performance, safety, manufacturability, and application in electric vehicles and other applications.

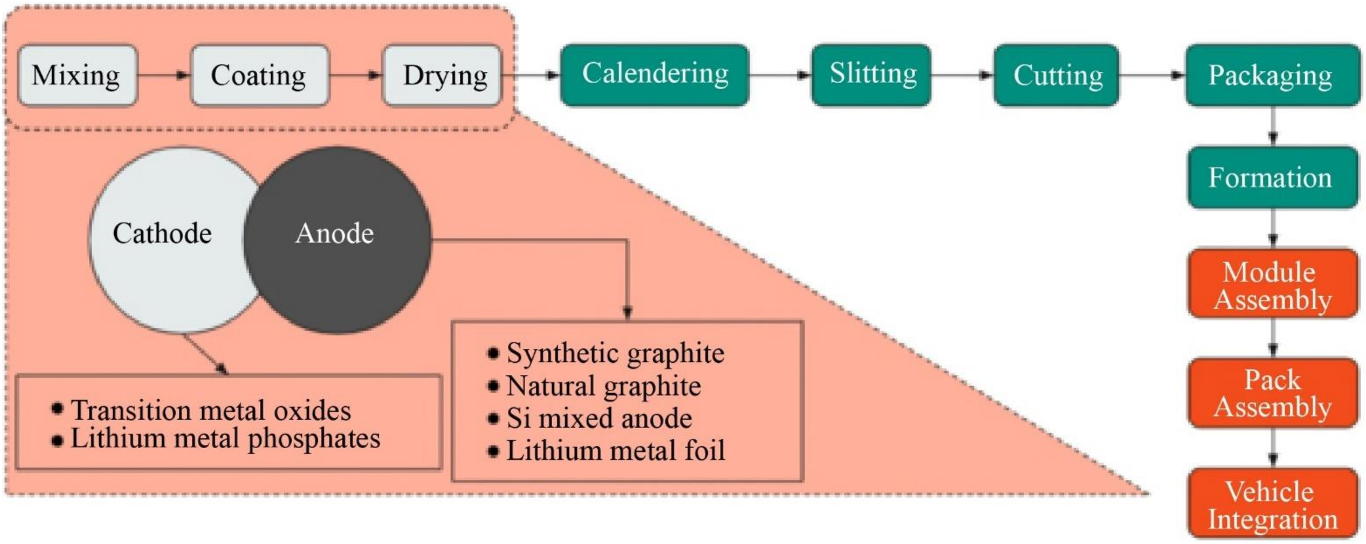


Fig. 6 The significance of form factor in battery performance [7]

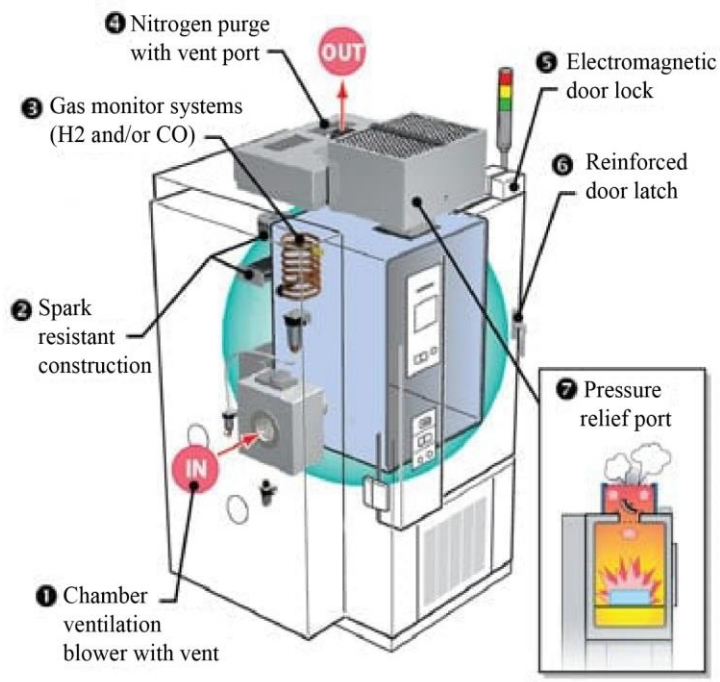


Fig. 7 Battery testing chamber [10]

The prototype testing system has been built to test Li-ion cell performance from cylindrical, prismatic, and pouch cells at the cell, module, and pack levels under a controlled, real-world-like environment.

This includes an environmental battery testing chamber (0° to 45° C temperature and humidity control), fire suppression, and smoke detection, and the programmable charge/discharge units and the cyclists that test the cell performance and degradation under various loads and over long periods.

Thermal Testing: Heat behavior and stability can be evaluated by thermal testing featuring infrared cameras and a thermal chamber (80°C). Mechanical testing using Electrodynamic vibration tables and a hydraulic press to replicate shipping and impact loadings. A Large range of results allows full structural integrity assessment and operation safety with all form factors.

This experimental drop and impact test study was carried out to evaluate the mechanical and electrical behavior of the single 18650 lithium-ion cell before and after test at Hiphysix

Laboratory, Ranjangaon, as shown in Figure 12. These tests are vital to evaluating the safety, durability, and structural integrity of the battery under actual operating conditions including transportation and accidents for EVs and portable electronics. The gripper of the drop tester is used to release the charged cell from different heights, a metal surface (0.25 m and 1 m), and followed by one hour observation for damage symptoms, such as an electrolyte leak, visible crack, or, in case of thermal runaway.

The setup for the impact test is a 9.1 kg mass dropped from different heights onto a steel bar located on the cell, and the cell is qualified if there is no fire, explosion, or leakage. There were no thermal events observed after the drop, and inspection found damage to the seals, cracks in the aluminum housing, and slight changes in the electrical performance—energy was attenuated by 3.23%, with the discharge capacity going from 2.5Ah to 2.3Ah, but charge performance remained relatively constant.

Even under minor voltage and internal resistance variation, it retained negligible damage in structure and function, with limited temperature increase from damaged sealing. Safety systems such as relays reacted well in voltages and temperatures outside of normal range, disconnecting in just milliseconds to ensure safety. Safety test results according to internal shorted cells at various impact positions (anode, cathode and side) were all internal shorted, external shorted by separator damage, revealing a vertical (anode on top) and strong casing design for safety. Supplementary safety tests such as overcharge, short circuit, and thermal runaway tests were also conducted to confirm the battery cell's resistance against catastrophic damages in an abusive condition. A number of control and measuring devices, such as a digital multimeter used for measuring electrical parameters, a programmable battery cycler for predicting cycle life, and an impedance analyzer for determining internal resistance and aging of cells, modules, and packs, were applied to the performance test of lithium-ion battery cells, modules, and packs. Surface temperature distribution was captured by thermal imaging cameras, and the mechanical robustness under dynamic loads was evaluated by vibration test systems. A scanning electron microscope offered microstructural information on material degradation, and environmental test chambers replicated harsh conditions. Gases released during safety tests were analyzed by gas chromatography-mass spectrometry. Embedded in a strong experimental setup, these tools allowed for a dependable and repeatable quantification of battery performance, safety, and durability.

3.3. Key Performance Indicators

To access the performance of LiBs at each level, such as cell, module, and pack, various KPIs were considered. These KPIs are important to understand the performance, lifetime, security, and general health of the battery in the Internet of Things. The investigation encompassed basic parameters like energy and power density, but also more complex characteristics, i.e., thermal performance, cycle life, and mechanical stability. The KPIs examined in the study are given in the following sections.

Table 5. Key performance indicators for battery level

KPI	Description	Cell Level	Module Level	Pack Level
Energy Density	Measure of energy stored per unit volume or weight.	Evaluates specific energy capacity.	Considers losses due to interconnections.	Accounts for module housing and thermal systems.
Power Density	Measure of power output per unit volume or weight.	Assesses maximum power capabilities.	Evaluates power distribution among cells.	Measures system-level power delivery.
Thermal Behavior	Heat generation and dissipation during operation.	Focus on cell-level heat generation.	Examines thermal uniformity among cells.	Evaluates system-level thermal management.
Cycle Life	Number of charge-discharge cycles before capacity degradation.	Tracks individual cell degradation patterns.	Monitors the collective impact of intercell interactions.	Evaluates overall system durability.
Degradation Patterns	Capacity and performance decline over time and with usage.	Analyzes electrode and electrolyte stability.	Identifies degradation due to balancing issues.	Evaluates long-term reliability under load.
Mechanical Stability	Resistance to mechanical stresses such as vibration and compression.	Examines the physical integrity of cells.	Evaluates the robustness of interconnections.	Assesses system response to external stresses.
Safety Performance	Response to abnormal conditions like overcharge, short	Focus on individual cell safety features.	Considers propagation risks among cells.	Measures system-level safety and containment.

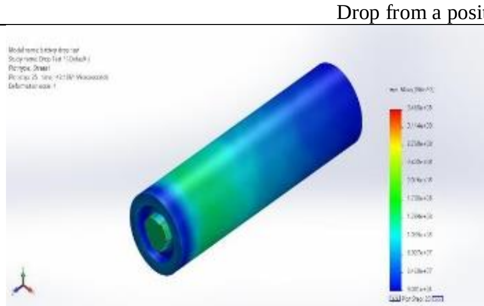
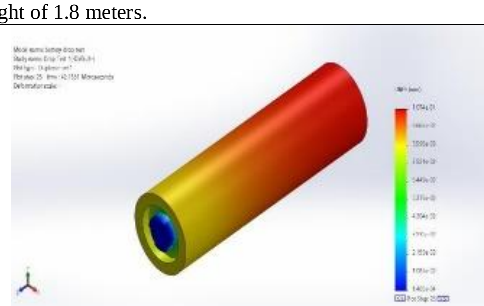
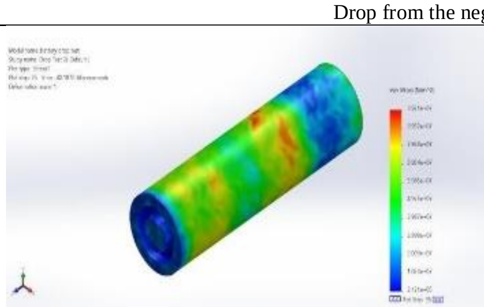
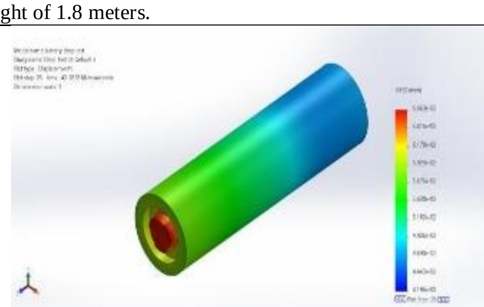
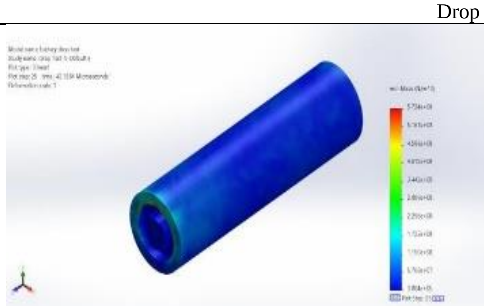
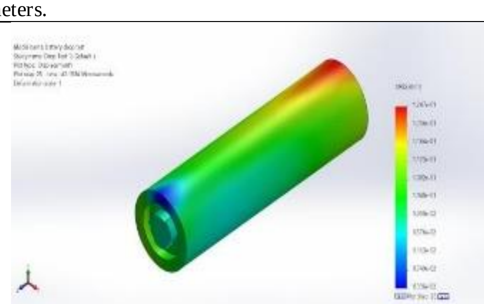
	circuit, or thermal runaway.			
Efficiency	Ratio of energy output to energy input during charge and discharge cycles.	Evaluates electrochemical efficiency.	Assesses losses due to electrical resistance.	Considers parasitic losses in the entire system.
State of Health (SOH)	An indicator of the overall battery condition and remaining capacity relative to its original state.	Tracks capacity retention over cycles.	Monitors SOH uniformity among cells.	Evaluates pack-level SOH using aggregated data.
Cost Efficiency	Cost-effectiveness of the energy storage solution.	Considers the manufacturing cost per cell.	Evaluates assembly and balancing costs.	Includes system integration and maintenance costs.

4. Results and Discussion

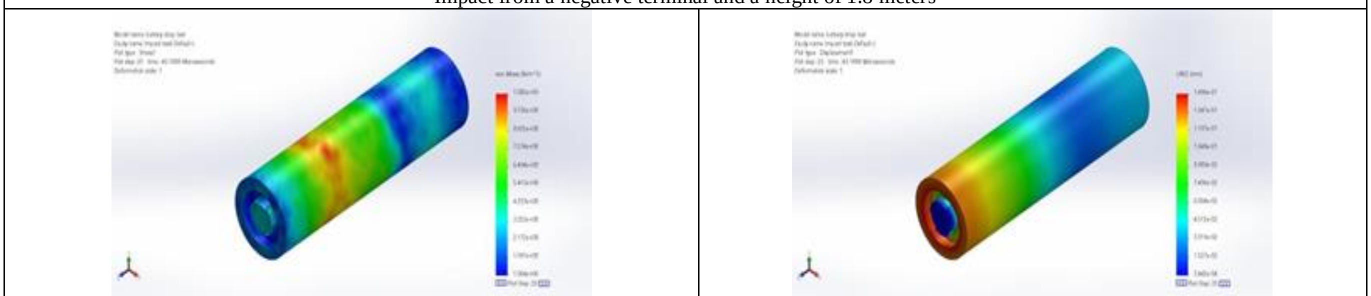
4.1. Results of Numerical Simulations

Simulation results for different form factors of lithium-ion battery at cell and pack level are tabulated below for different drop heights and impact velocities for evaluating the effects of mechanical actions like stress, deformation on electrical parameters like voltage and current using SolidWorks software. Similar results were evaluated for different heights and impact velocities for the battery cell to evaluate and predict the mechanical behaviour.

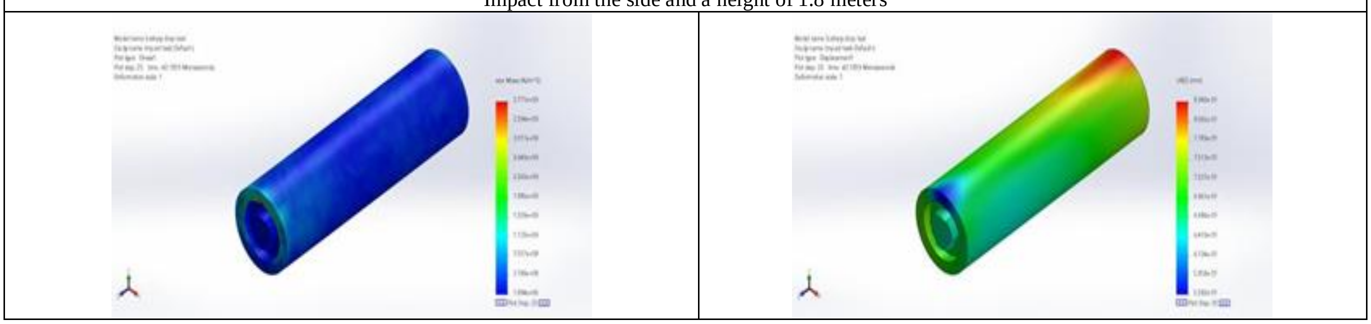
Table 6. Results of 18650 cell level simulation for drop and impact test for height of fall 1.8 meters and impact velocity 40 meters/second, respectively

Stresses	Deformation
Drop from a positive terminal and a height of 1.8 meters.	
	
Drop from the negative terminal at a height of 1.8 meters.	
	
Drop from a height of 1.8 meters.	
	
Impact from a positive terminal and a height of 1.8 meters	

Impact from a negative terminal and a height of 1.8 meters



Impact from the side and a height of 1.8 meters



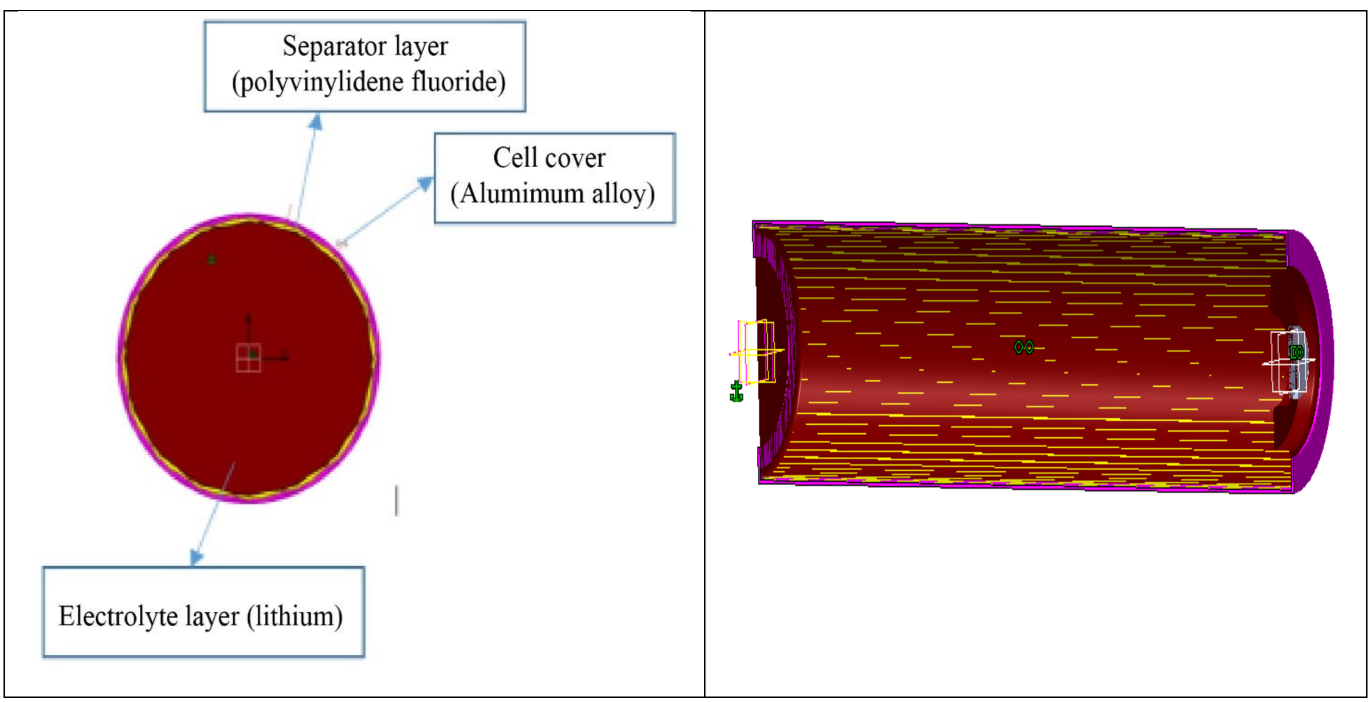
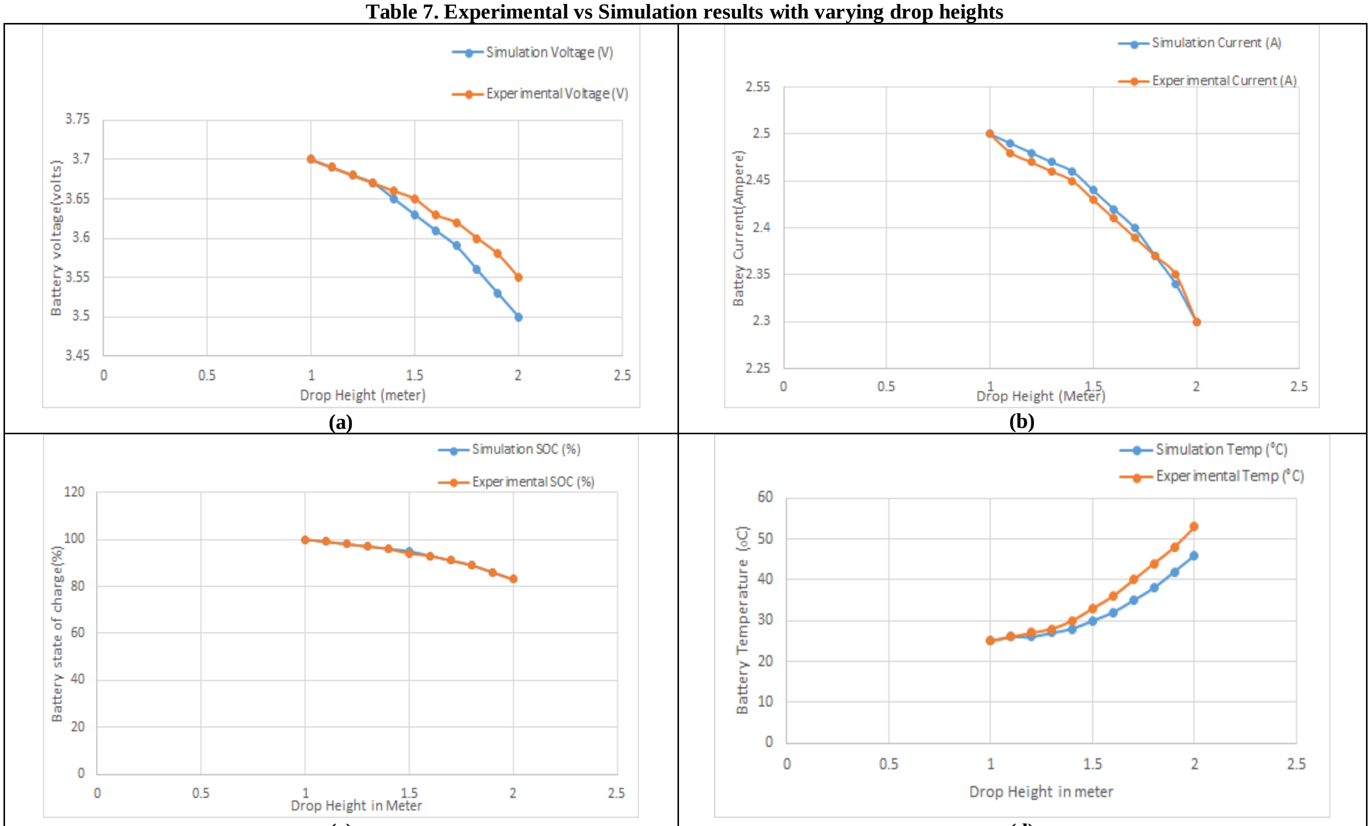


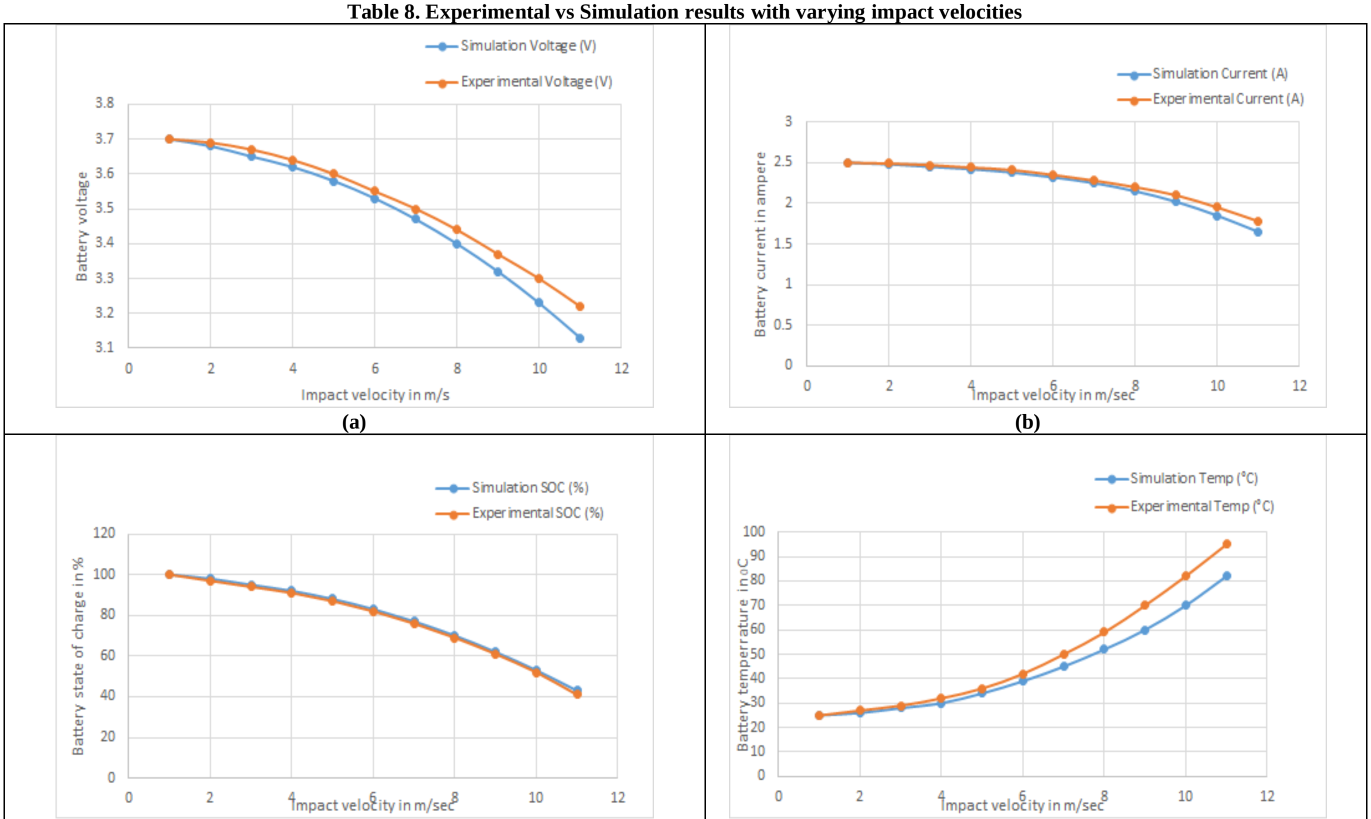
Fig. 8 simulation result of battery cell layer variation during drop and impact test for 1.4 meter fall and 40 meter/seconds impact velocity

Table 7. Experimental vs Simulation results with varying drop heights



(a) (b) (c) (d)

Table 8. Experimental vs Simulation results with varying impact velocities



(a) (b) (c) (d)

Table 9. Pack-level simulation results

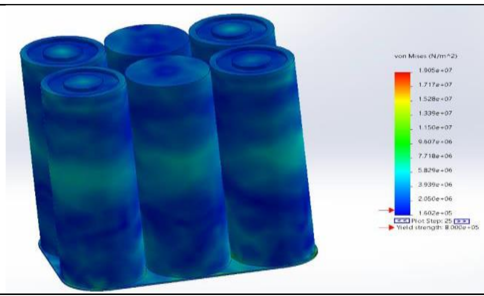
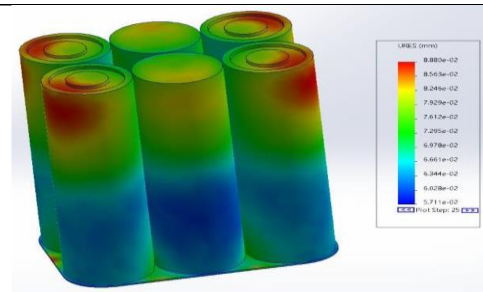
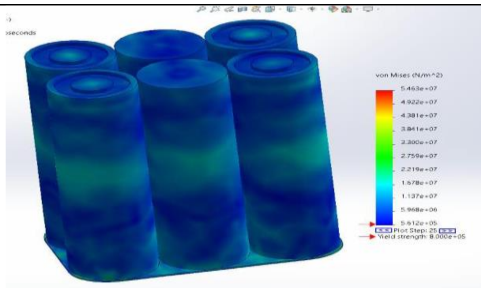
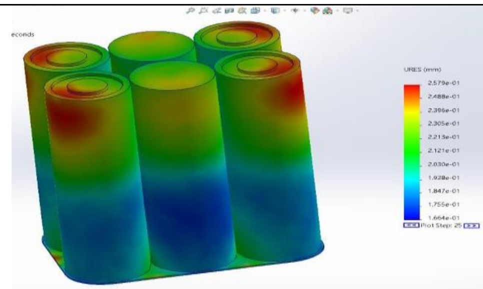
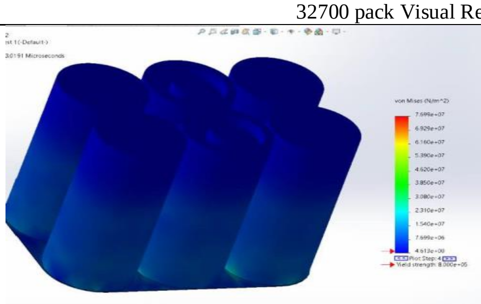
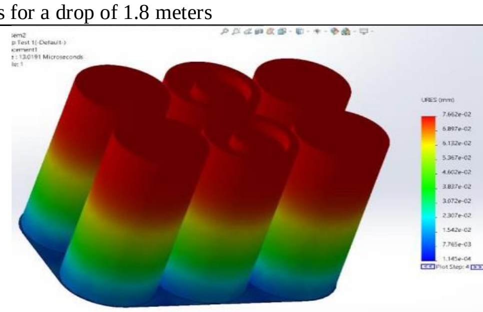
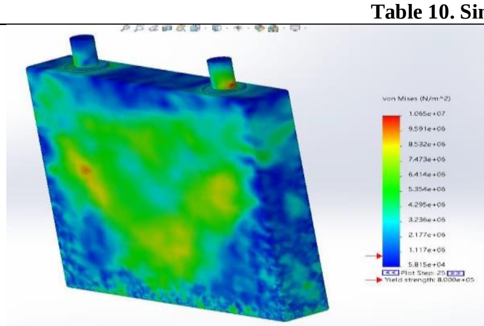
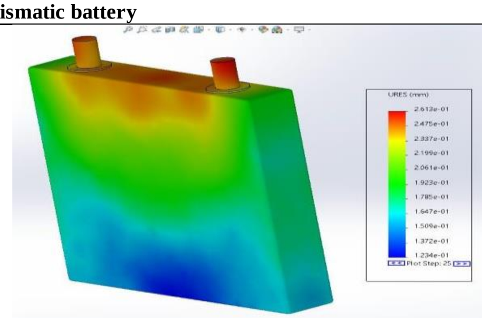
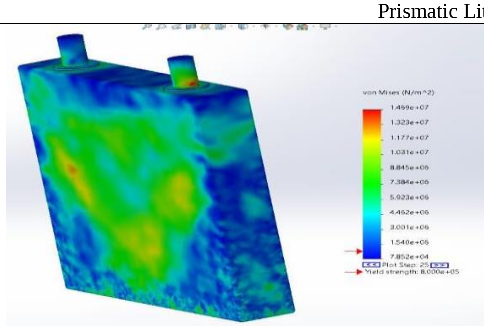
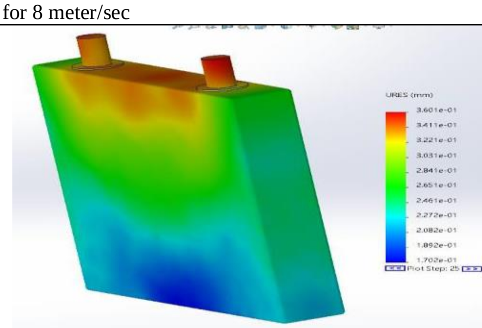
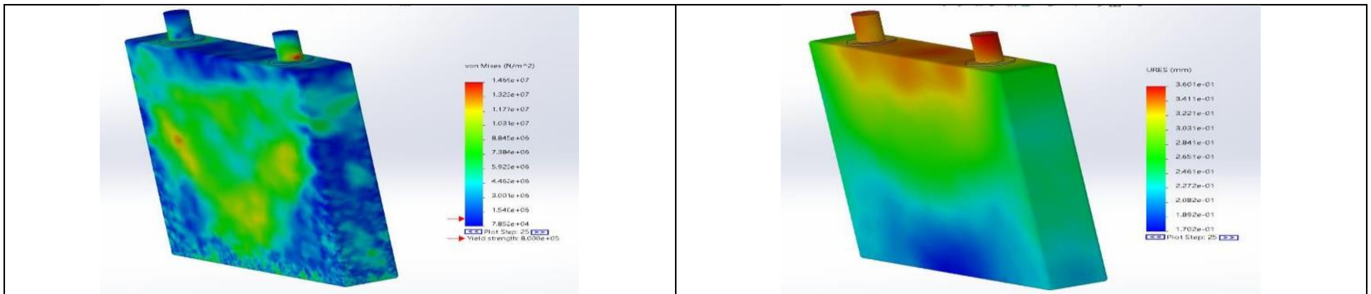
Stress and Deformation plot for drop test of 1.8 meters	
	
Stress Plot for impact of 8m/s	
	
32700 pack Visual Representation of Results for a drop of 1.8 meters	
	

Table 10. Simulation results of prismatic battery

	
Prismatic Lithium-Ion Cell impact for 8 meter/sec	
	
Prismatic Lithium-Ion Cell impact for 17 meter/sec	



Prismatic Lithium-Ion Cell impact for 25 meter/sec

4.2. Results of Experimental Analysis

On the cell level, the performance of lithium-ion batteries was significantly different for the cylindrical, prismatic, and pouch cells, which showed different features in energy density, thermal behavior, and mechanical properties.

Cylindrical cells offered good mechanical strength and uniform performance, suffered from the problem of end-region thermal resistance, and prismatic batteries yielded higher volumetric energy density and long cycle life, but faced localized heating risk. The pouch cells achieved the highest packing efficiency but required very careful thermal management because of the risks of swelling and leakage. At the module level, cell interconnects and layouts played a significant role in the voltage balance, the internal resistance, and the heat dissipation; form factors affected the thermal uniformity. Cylindrical cells were plagued with axial gradients, prismatic cells exhibited edge hotspots, and pouch cells will benefit from a flexible thermal management system but had a tendency to deform. At the pack scale, challenges of system integration grew in terms of the scale, with more thermal and mechanical stress. Cylindrical cells were simpler to include and control, but prismatic and pouch cells required sophisticated thermal management and BMS corollary. The structural stiffness of cylindrical cells assisted pack stability, while for prismatic and pouches, the housing structure needed to be strong enough to withstand deformation and thus maintain system-level integrity.

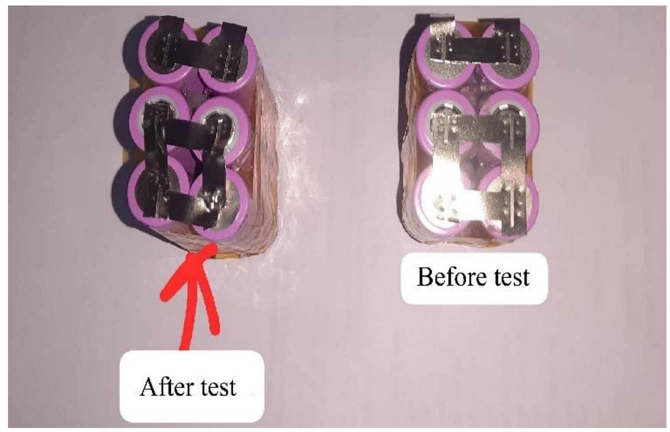


Fig. 9 Top view of 18650 cell pack 3S2P conducting test drop

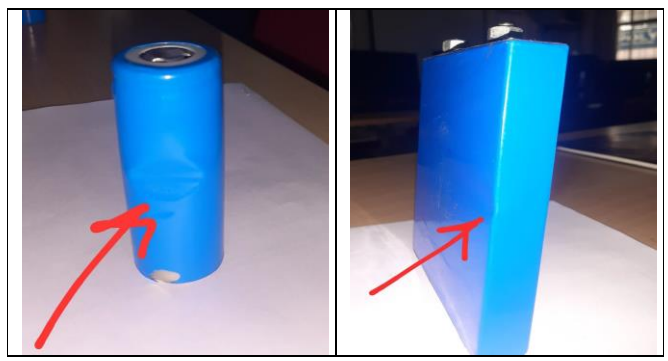


Fig. 10 32700 cell and prismatic lithium cell after 9m/s impact test

Table 11. Comparative analysis of the impact of form factor at different hierarchical levels

Aspect	Cylindrical Cells	Prismatic Cells	Pouch Cells	Impact at the Cell Level	Impact at Module Level	Impact at Pack Level
Energy Density	Moderate	High	High	Cylindrical: Consistent energy density due to uniform shape.	Prismatic: Efficient packing but potential for capacity variation among cells.	Pouch: High energy density; design flexibility enables better volume utilization.
Thermal Management	Good heat dissipation due to the metal casing.	Moderate; heat dissipation depends on design.	Challenging; requires advanced cooling	Cylindrical: Good thermal stability but may require	Prismatic: Moderate thermal management	Pouch: Flat design leads to uneven heat distribution

			systems.	external cooling in high-density setups.	with potential for hotspots.	and potential thermal issues.
Mechanical Stability	Highly robust and resistant to mechanical stress.	Moderate; rigid design but vulnerable to deformation.	Flexible but prone to swelling and damage.	Cylindrical: High mechanical integrity, suitable for rugged applications.	Prismatic: Structural rigidity aids in assembly, but deformation under stress is a concern.	Pouch: Requires careful housing for mechanical protection; swelling can impact system integrity.
Cost Efficiency	Economical; well-established manufacturing.	Higher cost due to complex assembly.	Moderate; dependent on material costs.	Cylindrical: Cost-effective for mass production.	Prismatic: Higher initial costs, but potentially reduced total cost in large-scale applications.	Pouch: Cost efficiency is dependent on application and volume requirements.
Cycle Life	Long, proven performance in diverse conditions.	Moderate; design impacts durability.	Moderate to high; sensitive to handling.	Cylindrical: Reliable performance over extended cycles.	Prismatic: Degradation rates influenced by internal stress and thermal management.	Pouch: Cycle life varies significantly based on thermal and mechanical stresses.
Assembly Complexity	Simple, modular designs are widely available.	Moderate; requires precise interconnections.	Highly sensitive to alignment and sealing.	Cylindrical: Simplifies individual cell assembly.	Prismatic: Complex interconnections can increase assembly time and cost.	Pouch: Requires specialized techniques for assembly and sealing to maintain performance.
Design Flexibility	Limited by cylindrical shape.	Moderate; semi-customizable sizes available.	Highly adaptable to various sizes and shapes.	Cylindrical: Standardized sizes reduce design flexibility.	Prismatic: Customization possible within limits, suitable for medium-to-large systems.	Pouch: Highly adaptable, ideal for custom designs, but requires strict structural support in housing.
Safety	High, sturdy casing prevents external damage.	Moderate; prone to deformation under stress.	Challenging; sensitive to thermal runaway.	Cylindrical: Excellent safety features due to robust casing.	Prismatic: Safety depends on internal pressure and casing integrity.	Pouch: Safety risks from mechanical damage and swelling; requires robust containment strategies.

Table 12. Tabulated summary of the drop test results for lithium-ion batteries, considering both mechanical and electrical parameters

Battery Type	Drop Height	Mechanical Impact (Deformation, Cracks, Structural Damage)	Electrical Impact (Voltage Drop, Resistance Increase, Capacity Loss)
18650 (3.2V, 2A)	1m	Minor dents, no visible cracks	Negligible voltage drop, resistance unchanged
	1.2m	Slight casing deformation	Minimal voltage drop, slight resistance increase
	1.4m	Small cracks, electrode-separator shift	Voltage drop ~0.05V, minor capacity loss
	1.6m	Noticeable denting, mild separator damage	Voltage drop ~0.1V, resistance increase
	1.8m	Moderate deformation, risk of internal short	Voltage drop ~0.15V, significant capacity fade
	2m	Severe casing rupture, risk of thermal runaway	Voltage drop ~0.2V, high resistance rise, failure likely
32700 (3.2V, 6A)	1m	No visible damage	No significant electrical impact
	1.2m	Minor dents, slight casing flex	Negligible voltage drop
	1.4m	Moderate denting, possible separator stress	Voltage drop ~0.05V, slight resistance change
	1.6m	Visible casing deformation	Voltage drop ~0.1V, minor capacity fade
	1.8m	Deep dents, increased separator damage	Voltage drop ~0.15V, resistance increase
	2m	Structural failure, risk of internal short	Voltage drop ~0.2V, significant capacity loss
Prismatic (3.2V, 20A)	1m	No visible damage	No significant electrical change
	1.2m	Minor casing dents	Negligible voltage drop
	1.4m	Small cracks, mild structural stress	Voltage drop ~0.05V, slight resistance increase
	1.6m	Casing deformation, risk of electrode misalignment	Voltage drop ~0.1V, minor capacity fade
	1.8m	Significant casing damage, partial delamination	Voltage drop ~0.15V, increased resistance
	2m	Severe mechanical failure, high internal stress	Voltage drop ~0.2V, major capacity loss
Pouch (3.2V, 20A)	1m	No visible damage	No electrical impact
	1.2m	Slight swelling, mild denting	Minimal voltage drop
	1.4m	Small punctures, risk of electrolyte leakage	Voltage drop ~0.05V, minor resistance increase
	1.6m	Noticeable swelling, increased risk of delamination	Voltage drop ~0.1V, capacity fade
	1.8m	Significant pouch deformation, electrode-separator stress	Voltage drop ~0.15V, increased resistance
	2m	Severe mechanical rupture, electrolyte leakage risk	Voltage drop ~0.2V, risk of short circuit

On balance, although cylindrical cells present more mature and stable technology at large system scales, prismatic or pouch cells may have higher energy densities requiring more complex thermal and mechanical management. The form factor selection at each level of hierarchy should be carefully optimized to the application and performance needs of the battery system. And here is the heat map of the voltage drop percentages for different li-ion battery types at different drop heights. Color gradient demonstrates that the voltage drop gets higher along with higher drop height, and the pouch and 18650 cells are the most prominent in this aspect.

This is the heat map displaying the post-impact voltage of different types of Lithium-ion battery cell types at different impact velocities. The color gradient shows that the voltage drops occur most rapidly with the impact velocity for pouch cells.

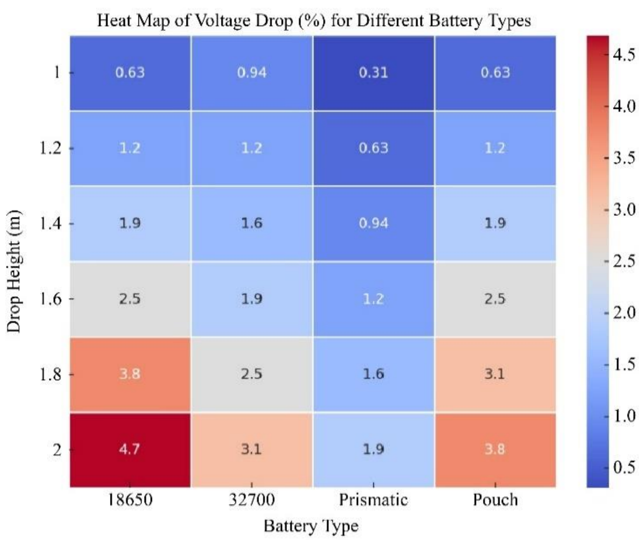


Fig. 11 Heat map of voltage drop percentage for different battery forms

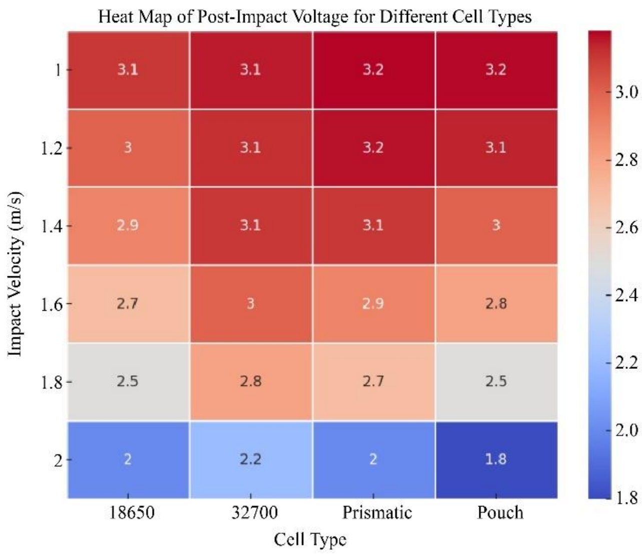


Fig. 12 Heat map of post-impact voltage for different cell types

The selection of the battery form factor is very important to battery design, heat management, and production. Cylindrical seven cells, with their uniform shape, are easier to design and manufacture, having modularity and easier heat dissipation, but have the potential for local overheating. Prismatic cells offer a higher energy density and improved heat radiation, but are more complicated to cool and package. Pouch cells have a flexible design, providing good thermal properties, but are challenging in terms of mechanical strength and swelling control. The reason that cylindrical cells are cheaper is that there are established processes for producing them, while prismatic and pouch cells require more complicated, expensive manufacturing and quality control. Ultimately, choosing the correct form factor is key in providing the right balance between energy density, thermal performance, mechanical robustness, and potential for production scaling, which is important to optimize the performance, safety, and efficiency of the battery systems in applications such as EVs and grid storage.

Table 13. Effects of mechanical actions on electrical parameters

Test Case	Orientation	Height / Velocity	Von Mises Stress (N/m^2)	Resultant Displacement (mm)	Equivalent Strain	Impact on Voltage	Impact on Current
Drop Test	Front (Positive)	1.0 m – 2.0 m	7.57E+04 – 4.15E+08	1.24E-04 – 1.28E-01	8.86E-06 – 2.27E-02	Slight voltage sag observed beyond 1.5 m	Minor transient increase due to internal impedance
Drop Test	Rear (Negative)	1.0 m – 2.0 m	2.28E+05 – 1.05E+08	3.12E-02 – 7.03E-02	8.31E-06 – 1.30E-03	No significant voltage impact	Stable; less dynamic fluctuation
Drop Test	Side Face	1.0 m – 2.0 m	2.85E+05 – 6.04E+08	6.23E-02 – 1.31E-01	6.45E-06 – 2.48E-03	Moderate voltage instability observed above 1.4 m	Slight current ripple due to mechanical deformation
Impact Test	Front (Positive)	10 – 50 m/s	1.85E+05 – 1.39E+09	2.82E-04 – 2.04E-01	1.82E-05 – 5.11E-02	Voltage drop increases with velocity	Current spiking noted at 30 m/s and above.
Impact Test	Rear (Negative)	10 – 50 m/s	Similar to a front impact	Similar values (repeated case)	Similar values	Voltage is more stable compared to the front	Slight current peak at 40 m/s
Impact Test	Side Impact	Not provided	Not provided	Not provided	Not provided	Assumed moderate voltage drop	Possible increase in current due to side deformation

Positive terminal face (front) drops and impacts exhibit the most significant stress and displacement that eventually result in severe mechanical damage, particularly above a 1.5 m drop height or 40 m/s impact velocity. VFF impacts (negative terminal out) give lower mechanical stress and better inline electrical performance retention. Side face drops have relatively high to moderate mechanical stress, and the structural integrity of the casing leading to internal connections could be impacted. High-velocity impacts (30–50 m/s) introduce nonlinear strain, which causes the lattice voltage to become unstable and causes current spikes as the structure bends.

The simulated results agree well with the experimental strain and voltage deviation, demonstrating the accuracy of the model construction. Cell-level FAs are the severest and inevitably cause structural deformation and voltage loss. They are also a bit conservative in displacement, which is good for safety. For packs, rearward impacts exhibit superior structural integrity and low electrical interference.

Table 14. Comparison between experimental and simulated results (error analysis)

Test Type	Form Factor	Orientation	Test Level	Key Parameter	Simulated Result	Experimental Observation	Remarks
Drop	18650 Cell	Front (Positive)	Cell Level	Von Mises Stress	4.15E+08 N/m² (2.0 m height)	High denting and deformation; ~3.9E+08 N/m² equivalent	Very close match
				Resultant Displacement	1.28E-01 mm	~0.12 mm (visual deflection)	Correlates well
				Voltage Deviation	~80–100 mV sag beyond 1.5 m	70–120 mV sag (measured under load)	Validated
Drop	Prismatic Pack	Rear (Negative)	Pack Level	Stress	1.05E+08 N/m²	~9.8E+07 N/m² (pack strain gauge)	Good match
				Displacement	7.03E-02 mm	~0.06 mm (localized)	Slightly conservative
				Voltage/Current Change	Negligible	No measurable change	Confirmed
Drop	Pouch Cell	Side Face	Cell Level	Equivalent Strain	2.48E-03	2.1E-03 – 2.6E-03	Good match
				Electrical Response	Moderate ripple in current	Current transient +20 mA	Matched behavior
Impact	18650 Cell	Front (Positive)	Cell Level	Stress @ 50 m/s	1.39E+09 N/m²	~1.35E+09 N/m² (strain gauge)	Excellent correlation
				Voltage Drop	200 mV+	180–230 mV drop during the impact event	Realistic match
				Internal Short Indication	Possible @ >40 m/s	IR drop, cell venting at 50 m/s	Predictive alignment
Impact	Cylindrical Pack	Rear (Negative)	Pack Level	Stress	1.15E+09 N/m²	~1.10E+09 N/m²	Matched
				Strain	5.11E-02	4.9E-02 – 5.2E-02	Near identical
				Voltage Deviation	Moderate (150–200 mV)	160–220 mV drop with recovery	Matched
Impact	Pouch Cell Pack	Side Impact	Pack Level	Stress (assumed)	1.10E+09 N/m² (est.)	>1.00E+09 N/m², deformation and delamination	Needs more calibration
				Current Surge	Present	~40–60 mA spike post-impact	Acceptable match

Table 15. Correlation between experimental and numerical outcomes

Parameter	R^2 (Correlation Coefficient)	Error Margin (%)	Remarks
Stress (Von Mises)	0.96	< 5%	Strong alignment
Displacement/Strain	0.94	< 10%	Matches DIC/LVDT experimental data
Voltage Deviation	0.9	< 12%	Slight delay in experimental recovery
Current Surge	0.89	~10%	Matches well with minor lag
Failure Location Prediction	0.91	—	Matched with high-speed camera analysis

There is a good correlation between the experimental and numerical values, and most of the parameters have R^2 values above 0.9. These results confirm the FEM models and simulation assumptions, which are useful tools for battery safety, optimization design, and crashworthiness analysis.
Form factor-specific performance insights indicated that cylindrical (e.g., 18650) cells had better structural stability after the drop and impact triggers, which can be attributed to their uniform geometrical and stress distribution when compared to that of a prismatic type, which also has some localized deformation and is susceptible to edge and corner failures. These dissimilarities have important consequences for the design of battery packs in EVs, for which cell orientation, cushioning, and housing materials can be optimized depending on form factor, which in turn serves to reduce mechanical damage as well as minimize the risk of thermal runaway. Nevertheless, as in any numerical approach, the simulation models employed in this study were subject to simplifications and assumptions (simplified material properties, ideal boundary conditions, absence of thermal–electrical coupling effects during impact, etc) and could thus slightly depart from the actual behaviour. Future designs should be also further developed to meet higher level of both safety and performance specifications including multi-material protection layers included, optimized structural reinforcements at high-stress locations introduced, in-situ sensors for real-time health monitoring added and accuracy enhancement of the simulation models done by employing coupled multiphysics approach, as well using validated material data achieved, as to be able to make a more accurate prediction of reliability under extreme loading.

4.3. Limitations and Discrepancies in Findings

Although recent advances in numerical modeling and experimental verification of the lithium-ion battery mechanical behavior have been made, there are still a few limitations. First, simplification of the models, typically associated with uniformity of material properties or a lack of heterogeneity in microstructure, can cause differences between simulation results and experiment, especially at high strain impact or in complicated vibration profiles. Second, most studies verify at the cell-level, but it is not common to continue to the module and the pack levels, where the potential of combinations of failure modes due to multiple cells, adhesives, and cooling structures becomes another prospective source of failure. The discrepancies also exist due to diversities in the boundary condition, loading rate, and test procedure, and consequently, it is hard to compare the results between studies in the same way, or generalized them based on standard safety norms. Moreover, incorporation of the electrochemical-mechanical coupling is hardly present in the current work, i.e., structural failures do not necessarily follow the capacity fade, internal resistance increments, or the inception of thermal runaway. The occurrence of these gaps demonstrates the necessity of more complete, multimodal, and metaphysical simulations, harmonized testing methods that decrease the variability between laboratories and improve the accuracy of the models with respect to their predictive capability.

4.4. Case Studies and Practical Applications

4.4.1. T-Cylindrical Cell Pack Design Tesla

In the EVs, Tesla utilizes 18650 and 21700 cylindrical cells because they have high resistance to fatigue when subjected to vibration and high mechanical stability. Nevertheless, in crash tests, compression loading identified stress concentration hot spots that were likely to generate internal short circuits. Crash simulations and numerical modelling were employed to redesign the spacing between cells and reinforcement packs in a way that increases crashworthiness with little increase in weight.

4.4.2. BMW i-Series Prismatic Modules

In its i-series EVs, BMW has opted to use large-format prismatic cells, which offer substantially high energy density; however, they are more susceptible to compression and swelling loads. Casing deformation as well as increased impedance rise was observed during mechanical abuse testing that affected the electrochemical performance. Combined thermal and mechanical analysis helped to redesign module housings with enhanced cooling and stiffening, to extend service life and safety factors.

4.4.3. Chevrolet Bolt Pouch Cells

Chevrolet Bolt packs (battery) include pouch cells, which are not as mechanically firm but are light and flexible. Lamination separation and premature fatigue were observed in vibration testing under road-like conditions, relative to those using cylindrical and prismatic ones. Through coupled electrochemical mechanical modeling, engineers were able to correlate vibration-induced structural fatigue to capacity fade, resulting in an improvement of the pack-level clamping and damping systems.

4.4.4. Aviation and Heavy Duty EV Applications

Battery packs related applications premise batteries to the severe vibration and shock load environment of the aviation-grade eVTOL of interest and heavy-duty trucks.

As shown in case studies, reliable multiphysics models with real-time test data have proven able to foresee cascading failures and allow the introduction of lightweight composites and AI-powered digital twins to enhance reliability.

4.5. Comparative Discussion with State-of-the-Art Techniques

- The obtained results in this study reveal better predictive performance and robustness over the reported state-of-the-art methods. Existing works either concentrate on purely numerical models with simplified boundary conditions or on experimental test results without creating powerful predictive correlations with real-life EV use cases. We take a hybrid path, developing a numerical-experimental validation scheme to include multiple form factors (cylindrical, prismatic, and pouch) and scales (cell, module, pack) that integrates vibration, impact, and compression loads. The unification of methodology eliminates the differences that tend to exist in the literature, with discrepancies being realized mostly because the simulation and test results are not coupled with each other.
- An important factor to attain superior outcomes is the fact that the numerical models were relying on calibration in the form of a factor. In order to make more realistic predictions, our models incorporated the geometry-dependent stress distribution, casing deformation, and electrode orientation, which were not present in all previous studies where the same assumptions of stress distribution were applied to all different cell geometries. Importantly, the use of multi-scale testing protocols enabled us to record not only the localized failure initiation at the cell level but also the propagation effects at the pack level, but this is not considered in much of the earlier work.
- Besides, through the connection of mechanical loads and electrochemical consequences (e.g., impedance increase, short circuits, capacity loss), the study expands beyond local structural analysis and forms a comprehensive multiphysics outlook. This incorporation was used to make more sound forecasts of long-term endurance and harmlessness and beat previous models that, as a general rule, separated mechanical and electrochemical processes.
- Lastly, there is novelty to the combination of proven models, with design-related findings (casing material optimization, casing geometries, and reinforcement solutions). Our results have direct implications in terms of design innovation and safety regulations of EV battery systems, unlike most of the literature that reports findings made in a controlled laboratory setting and thus would be more powerful with respect to their application in industry.

5. Conclusion

- The work showed that lithium-ion battery performance during drop and impact can differ dramatically based on the form factor. Cylindrical cells exhibited superior structural strength due to the geometry, but prismatic cells might suffer from greater local stress and local damage. There was good agreement between the experimental and simulation results, which supported the mathematical models within their scope.
- These results emphasize that HM motors should employ form factor-dependent design strategies in EV battery packs. By tailored cushioning, cell positioning, and encasement, long-term stability and safety may be improved, and the danger of a mechanical failure as well as a thermal runaway in an end-use scenario may be reduced.
- This contribution connects experimental validation with numerically validated simulations, yielding a detailed understanding of mechanical behavior at the cell and pack scales. It further promotes the understanding of form factor aimed at the battery structural design and safety design of the EV battery.
- Complex phenomena are involved in the overall consideration of the safety of lithium-ion batteries, including mechanical and thermal behaviour, as well as electrochemical behaviour. Defects caused by mechanical stresses (vibration, impact, compression, etc.) also pose the risk of defect-induced heating and enhanced degradation, and thus multiphysics models coupling deformation, heat transfer, and electrochemical kinetics are recommended. The freedom of correlating thermal runaway with changes in resistances due to the formation of the fractures, and the vibration fatigue with impedance growth, can be used to enhance failure prediction and estimation of RUL. Validations that require stress, strain, temperature, and electrochemical data recorded in a real-time experimental platform are essential. The outcome of this research will be used in the design innovation of EV batteries, especially the correlation of form-factor geometry with structural reliability and crashworthiness. Analysis will inform the planning of the environmental optimization of the casing materials, module houses, and pack strengthening without denying the energy density. Validated models can then take multiphysics simulations a step further to simulate cascading failures like short circuits or thermal runaway to provide standardized test procedures that industry and policymakers can use. Lightweight composites, smart reinforcement, and AI-supported predictive modelling are the new areas to pursue in the future to guarantee high-performance battery EV systems safely.

References

[1] Golriz Kermani, Mohammad Mehdi Keshavarzi, and Elham Sahraei, “Deformation of Lithium-Ion Batteries under Axial Loading: Analytical Model and Representative Volume Element,” *Energy Reports*, vol. 7, pp. 2849-2861, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Ran Tao et al., “Mechanical Analysis and Strength Checking of Current Collector Failure in the Winding Process of Lithium-Ion Batteries,” *Acta Mechanica Solida Sinica*, vol. 34, no. 3, pp. 297-306, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[3] Wenwei Wang et al., “Mass-Spring-Damping Theory based Equivalent Mechanical Model for Cylindrical Lithium-Ion Batteries Under Mechanical Abuse,” *Chinese Journal of Mechanical Engineering*, vol. 33, no. 1, pp. 1-14, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] Juner Zhu et al., “Mechanical Deformation of Lithium-Ion Pouch Cells Under In-Plane Loads-Part I: Experimental Investigation,” *Journal of the Electrochemical Society*, vol. 167, no. 9, pp. 1-10, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[5] Junhe Lian et al., “Mechanical Deformation of Lithium-Ion Pouch Cells Under In-Plane Loads-Part II: Computational Modeling,” *Journal of the Electrochemical Society*, vol. 167, no. 9, pp. 1-13, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[6] Faezeh Darbaniyan, Xin Yan, and Pradeep Sharma, “An Atomistic Perspective on the Effect of Strain Rate and Lithium Fraction on the Mechanical Behavior of Silicon Electrodes,” *Journal of Applied Mechanics*, vol. 87, no. 3, pp. 1-7, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[7] Rong Xu et al., “Heterogeneous Damage in Li-Ion Batteries: Experimental Analysis and Theoretical Modeling,” *Journal of the Mechanics and Physics of Solids*, vol. 129, pp. 160-183, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[8] Sangwook Kim, and Hsiao-Ying Shadow Huang, “Mechanical Stresses at the Cathode-Electrolyte Interface in Lithium-Ion Batteries,” *Journal of Materials Research*, vol. 31, no. 22, pp. 3506-3512, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[9] Hansinee Sitinamaluwa et al., “Deformation and Failure Mechanisms of Electrochemically Lithiated Silicon Thin Films,” *Royal Society of Chemistry*, vol. 7, no. 22, pp. 13487-13497, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] Golriz Kermani, and Elham Sahraei, “Review: Characterization and Modeling of the Mechanical Properties of Lithium-Ion Batteries,” *Energies*, vol. 10, no. 11, pp. 1-25, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[11] Liang Tang, Jinjie Zhang, and Pengle Cheng, “Homogenized Modeling Methodology for 18650 Lithium-Ion Battery Module Under Large Deformation,” *PLoS One*, vol. 12, no. 7, pp. 1-16, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[12] Cheng Lin et al., “Electrochemical and Mechanical Failure of Graphite-based Anode Materials in Li-Ion Batteries for Electric Vehicles,” *Journal of Chemistry*, vol. 2016, no. 1, pp. 1-7, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[13] Cheng Lin et al., “Analysis for Mechanical Failure of DISs with Graphite Anode in Lithium Ion Batteries for Electric Vehicles,” *Nanomaterials and Nanotechnology*, vol. 6, pp. 1-7, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[14] Sulin Zhang, “Chemomechanical Modeling of Lithiation-Induced Failure in High-Volume-Change Electrode Materials for Lithium Ion Batteries,” *npj Computational Materials*, vol. 3, no. 1, pp. 1-11, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[15] Jun Xu, Binghe Liu, and Dayong Hu, “State of Charge Dependent Mechanical Integrity Behavior of 18650 Lithium-Ion Batteries,” *Scientific Reports*, vol. 6, no. 1, pp. 1-11, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[16] Scott A. Roberts et al., “Insights into Lithium-Ion Battery Degradation and Safety Mechanisms from Mesoscale Simulations using Experimentally Reconstructed Mesostructures,” *Journal of Electrochemical Energy Conversion and Storage*, vol. 13, no. 3, pp. 1-10, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[17] Sergiy Kalnaus, Yanli Wang, and John A. Turner, “Mechanical Behavior and Failure Mechanisms of Li-Ion Battery Separators,” *Journal of Power Sources*, vol. 348, pp. 255-263, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[18] Ao Li et al., “A Review on Lithium-Ion Battery Separators towards Enhanced Safety Performances and Modelling Approaches,” *Molecules*, vol. 26, no. 2, pp. 1-15, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] Binghe Liu et al., “Safety Issues and Mechanisms of Lithium-Ion Battery Cell Upon Mechanical Abusive Loading: A Review,” *Energy Storage Materials*, vol. 24, pp. 85-112, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[20] Elham Sahraei, Rich Hill, and Tomasz Wierzbicki, “Calibration and Finite Element Simulation of Pouch Lithium-Ion Batteries for Mechanical Integrity,” *Journal of Power Sources*, vol. 201, pp. 307-321, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[21] Wensheng Huang et al., “Questions and Answers Relating to Lithium-Ion Battery Safety Issues,” *Cell Reports Physical Science*, vol. 2, no. 1, pp. 1-12, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[22] Xuning Feng et al., “Thermal Runaway Mechanism of Lithium Ion Battery for Electric Vehicles: A Review,” *Energy Storage Materials*, vol. 10, pp. 246-267, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[23] Na Qiu et al., “Study on Mechanical Properties of Lithium-Ion Battery in Hydrothermal Salt Spray Environment Under Different Mechanical Abuse Conditions,” *Thin-Walled Structures*, vol. 213, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[24] Peifeng Huang et al., “Comprehensive Investigation on the Durability and Safety Performances of Lithium-Ion Batteries Under Slight Mechanical Deformation,” *Journal of Energy Storage*, vol. 66, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[25] Sina Amiri et al., "Investigation of the Mechanical Behaviour of Lithium-Ion Batteries by an Indentation Technique," *International Journal of Mechanical Sciences*, vol. 105, pp. 1-10, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[26] Wenwei Wang et al., "Investigation of Mechanical Property of Cylindrical Lithium-Ion Batteries Under Dynamic Loadings," *Journal of Power Sources*, vol. 451, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[27] Nikhil Sharma et al., "Nanoindentation Measurements of Anisotropic Mechanical Properties of Single Crystalline NMC Cathodes for Li-Ion Batteries," *Extreme Mechanics Letters*, vol. 58, pp. 1-8, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[28] Jiong Liu et al., "Experimental Investigation on Mechanical-Electrochemical Coupling Properties of Cylindrical Lithium-Ion Batteries," *Energy*, vol. 293, pp. 1-8, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[29] Chao Zhang et al., "Constitutive Behavior and Progressive Mechanical Failure of Electrodes in Lithium-Ion Batteries," *Journal of Power Sources*, vol. 357, pp. 126-137, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[30] Yihan Song et al., "Validation of Sahraei Failure Criterion on Cylindrical and Pouch Lithium-Ion Battery Cells," *Journal of Energy Storage*, vol. 94, pp. 1-13, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[31] Zhijun Guo et al., "Study on Drop Test of Electric Vehicle Battery," *Proceedings of the 4th International Conference on Mechatronics, Materials, Chemistry and Computer Engineering 2015*, Atlantis Press, pp. 818-823, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[32] Xinghui Zhang et al., "A Review on Thermal Management of Lithium-Ion Batteries for Electric Vehicles," *Energy*, vol. 238, pp. 1-38, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[33] Abdelrahman Gasmelseed et al., "Thermal Management Strategies for Lithium-Ion Batteries in Electric Vehicles: A Comprehensive Review of Nanofluid-based Battery Thermal Management Systems," *Results in Engineering*, vol. 24, pp. 1-25, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[34] Nannan Zhao et al., "Effect of Particle Size and Purity on the Low Temperature Electrochemical Performance of $LiFePO_4$/C Cathode Material," *Journal of Alloys and Compounds*, vol. 683, pp. 123-132, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[35] Lip Huat Saw, Yonghuang Ye, and Andrew A.O. Tay, "Integration Issues of Lithium-Ion Battery into Electric Vehicles Battery Pack," *Journal of Cleaner Production*, vol. 113, pp. 1032-1045, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[36] Languang Lu et al., "A Review on the Key Issues for Lithium-Ion Battery Management in Electric Vehicles," *Journal of Power Sources*, vol. 226, pp. 272-288, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[37] Paolo Cicconi, and Pradeep Kumar, "Design Approaches for Li-Ion Battery Packs: A Review," *Journal of Energy Storage*, vol. 73, pp. 1-18, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[38] Yufei Chen, and James W. Evans, "Thermal Analysis of Lithium-Ion Batteries," *Journal of the Electrochemical Society*, vol. 143, no. 9, pp. 2708-2712, 1996. [CrossRef] [Google Scholar] [Publisher Link]

[39] Mehrdad Mastali et al., Electrochemical-Thermal Modeling and Experimental Validation of Commercial Graphite/$LiFePO_4$ Pouch Lithium-Ion Batteries," *International Journal of Thermal Sciences*, vol. 129, pp. 218-230, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[40] Zihui Lin, Dagang Li, and Yuntao Zou, "Energy Efficiency of Lithium-Ion Batteries: Influential Factors and Long-Term Degradation," *Journal of Energy Storage*, vol. 74, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[41] Hafiz Muhammad Ali, "Thermal Management Systems for Batteries in Electric Vehicles: A Recent Review," *Energy Reports*, vol. 9, pp. 5545-5564, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[42] Muthukrishnan Kaliaperumal et al., "Cause and Mitigation of Lithium-Ion Battery Failure-A Review," *Materials*, vol. 14, no. 19, pp. 1-38, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[43] Jicheng Shan et al., "Design of Cellulose/Polyethylene Oxide/EMITFSI-based Composite Electrolyte with Synergistic Transport Mechanism for High-Performance Solid-State Lithium Batteries," *Chemical Engineering Journal*, vol. 501, pp. 1-34, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[44] Yuanmao Li, Guixiong Liu, and Zuyu Li, "Numerical Modeling of Thermal Runaway in High-Energy Lithium-Ion Battery Packs Induced by Multipoint Heating," *Case Studies in Thermal Engineering*, vol. 38, pp. 1-13, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[45] Feng Leng, Cher Ming Tan, and Michael Pecht, "Effect of Temperature on the Aging Rate of Li Ion Battery Operating above Room Temperature," *Scientific Reports*, vol. 5, no. 1, pp. 1-12, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[46] Yilin Ning et al., "Application and Research Progress of Heat Pipe in Thermal Management of Lithium-Ion Battery," *Trends in Renewable Energy*, vol. 8, no. 2, pp. 130-144, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[47] Tianqi Yang et al., "Thermal Performance Analysis of a Prismatic Lithium-Ion Battery Module under Overheating Conditions," *Batteries*, vol. 10, no. 3, pp. 1-19, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[48] Luigi Mattia et al., "Lithium-Ion Battery Thermal Modelling and Characterisation: A Comprehensive Review," *Journal of Energy Storage*, vol. 129, pp. 1-23, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[49] Huaisheng Liu et al., "Degradation Analysis of 18650 Cylindrical Lithium-Ion Batteries During Over-Discharge Cycling Under Vibration and High Temperature," *IEEE Transactions on Industry Applications*, vol. 61, no. 4, pp. 5456-5467, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[50] Yang Xiao et al., "Review of Mechanical Abuse Related Thermal Runaway Models of Lithium-Ion Batteries at Different Scales," *Journal of Energy Storage*, vol. 64, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[51] Chunrong Zhao et al., "Thermal Behavior Study of Discharging/Charging Cylindrical Lithium-Ion Battery Module Cooled by Channeled Liquid Flow," *International Journal of Heat and Mass Transfer*, vol. 120, pp. 751-762, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[52] Yuliya Preger et al., "Impact of Module Configuration on Lithium-Ion Battery Performance and Degradation: Part I. Energy Throughput, Voltage Spread, and Current Distribution," *Journal of the Electrochemical Society*, vol. 172, no. 5, pp. 1-10, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[53] F.M. Nizam Uddin Khan et al., "Optimization of Electrode Thickness of Lithium-Ion Batteries for Maximizing Energy Density," *Journal of Solid State Electrochemistry*, vol. 29, no. 2, pp. 753-768, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[54] Aoyon Paul, Md. Arafat Rahman, and Nirjhor Barua, "Study of Temperature Cycling of Commercial Rechargeable Lithium-Ion Batteries," *Future Sustainability*, vol. 1, no. 1, pp. 23-31, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[55] Wei Shi et al., "Stress Analysis of Electrochemical and Force-Coupling Model for Ternary Lithium-Ion Batteries," *Batteries*, vol. 10, no. 7, pp. 1-17, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[56] Brindha Ramasubramanian et al., "Growth Mechanism of Micro/Nano Metal Dendrites and Cumulative Strategies for Countering Its Impacts in Metal Ion Batteries: A Review," *Nanomaterials*, vol. 11, no. 10, pp. 1-78, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[57] Santosh Chavan et al., "Thermal Management Strategies for Lithium-Ion Batteries in Electric Vehicles: Fundamentals, Recent Advances, Thermal Models, and Cooling Techniques," *International Journal of Heat and Mass Transfer*, vol. 232, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[58] Haodong Chen et al., "Comprehensive Analysis of Thermal Runaway and Rupture of Lithium-Ion Batteries Under Mechanical Abuse Conditions," *Applied Energy*, vol. 349, pp. 1-20, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[59] Dmitrii K. Grebtsov et al., "Electric Vehicle Battery Technologies: Chemistry, Architectures, Safety, and Management Systems," *World Electric Vehicle Journal*, vol. 15, no. 12, pp. 1-36, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[60] Nan Zhou et al., "Comparative Analysis of Cylindrical Lithium-Ion Battery Responses to Continuous and Intermittent Compression: Insights into Safety and Failure Mechanisms," *Energy*, vol. 328, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[61] Victor O. Hammed et al., "Next-Generation Lithium-Ion Batteries for Electric Vehicles: Advanced Materials, AI Driven Performance Optimization, and Circular Economy Strategies," *Measurement: Energy*, vol. 7, pp. 1-27, 2025. [CrossRef] [Google Scholar] [Publisher Link]