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Original Article

Simulation and Experimental Analysis of Drop and Impact Tests on Lithium-Ion Battery Cells to Evaluate the Mechanical Effects on Electrical Parameters for Enhanced Battery Life

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Abstract *- The widespread use of Lithium-ion batteries in present energy storage systems faces critical challenges regarding their real-world mechanical durability, which strongly affects electric vehicles and portable electronic applications. A laboratory evaluation examines the mechanical consequences of drop and impact testing that affect lithium-ion battery cells' electrical performance variables and battery lifespan. The research utilized two methods that synchronized finite element simulations with experimental testing of drops and impacts under multiple operational conditions. Impact tests and mechanical stresses demonstrate direct relationships with electrical parameter shifts, which consist of elevated internal resistance and capacity failures coupled with unstable voltage outputs. Lithium-ion cells demonstrate extreme vulnerability to mechanical forces, presenting safety issues, durability challenges, and performance instability effects. This research delivers important findings about battery system engineering that help designers create stronger cell construction methods combined with protective encasement improvements to reach enhanced reliability and safety standards. This research makes important advancements in energy storage science by studying unexamined relationships between mechanical forces and electrical responses in lithium-ion batteries.*

Keywords *- Lithium-ion batteries, Drop test, Impact test, Mechanical forces, Electrical performance, Finite element analysis, Reliability and safety standards.*

1. Introduction

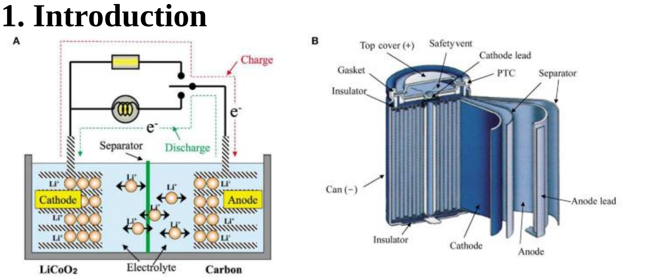


Fig. 1 Structure of li-ion battery cell [2]

Lithium-ion batteries support modern energy storage systems and equip various applications, including consumer electronics, Electric Vehicles (EVs), renewable energy integration, and grid storage. Their widespread usage benefits from a peculiar blend of high energy density, lightweight, long cycle life, and low self-discharge rates as opposed to among the various battery chemistries. This performance makes them a necessity in enabling the sustainable energy transition. With their compact and reliable energy solutions, lithium-ion batteries power a myriad of electronic devices, including smartphones, laptops, and wearable technology. The manufacture and sale of electric vehicles have further fed demand for LIBs because of their need for high power output and fast charging capabilities to satisfy the requirements of the automotive industry. The modular scalability of LIBs also allows their deployment for renewable energy systems, such as solar and wind, through the efficient buffering and dispatch of energy to deal with intermittent sources. The importance of LIBs continues beyond mere convenience and efficiency, addressing major global environmental challenges. By acting as an alternative to fossil fuel-based energy systems, LIBs help minimize greenhouse gas emissions, thus combating climate change. Further strides in lithium-ion battery technology, including solid-state supported designs and a nascent recycling process, are a few diverse attempts at enhancing sustainability by reducing the environmental burden of raw materials extraction and disposal upon end-of-life. As global energy demand rises, the need for lithium-ion batteries for smart grids and decentralized energy systems becomes increasingly critical. They promote energy storage at different scales, providing load balancing, peak shaving, and backup power, which are vital functions in stabilizing and creating resilient grids. The aforementioned adaptable features are responsible for the importance of lithium-ion batteries in modern-day energy systems, whereby the quest for reliable, clean, and effective energy storage continues to grow. Lithium-ion batteries have become an essential fragment of current energy structures, encouraging innovation and sustainability in various industries. Their continued development and optimization will further enhance their performance, safety, and affordability and solidify the bricks on which future energy solutions will be built.

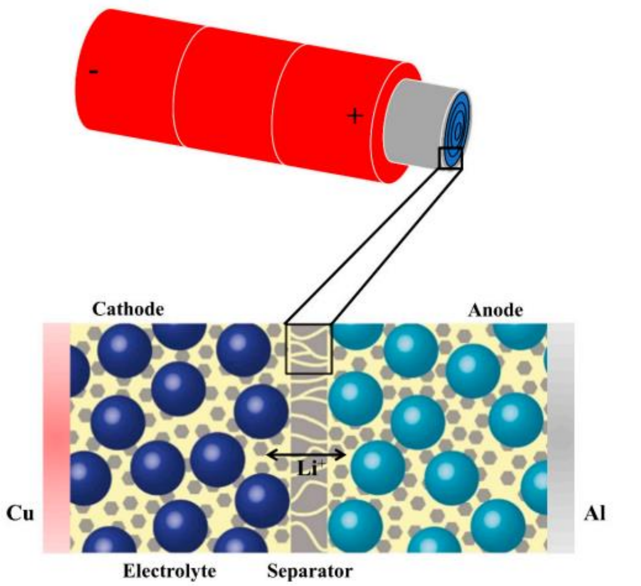


Fig. 2 Schematic image of a separator in a cylindrical Li-ion battery cell and a zoomed-in cross-section of the layered structure [1]

Lithium-Ion Batteries (LIBs) are one of the best available energy storage systems; however, mechanical effects during handling, transportation, and use greatly compromise their structural and functional integrity. Both the safety and performance of LIBs are severely challenged by such impacts, manifested as drops, collisions, and vibrations. Lithium-ion cells' compactness and layered structure consisting of thin electrodes, separators, and electrolyte-filled compartments make them weak against mechanical stress. Even minor deviations in form may result in internal damage, such as misalignment of electrodes, puncturing of separators, and leaking of electrolytes, which would subsequently deteriorate the electric properties of the cell and, in extreme cases, may lead to thermal runaway and fire hazards. One such major challenge is the unpredictable nature of mechanical impact in real-life scenarios. One of the major types of discharge damage could be a result of mechanical impacts, such as those sustained during transportation handling, by jolting and/or dropping from a significant height. Their confinement in EVs means they are pressured to endure shining combinations of sustained vibration and bumps, which can result in gradual wear and tear on the battery. Such mechanical stress makes short circuits, increases impedance, and leads to capacity fade, thus shortening the battery's lifetime. Consumer products often accidentally fall, which may result in a crush by the casing or damages caused inside the cell, damaging safety and effectiveness.

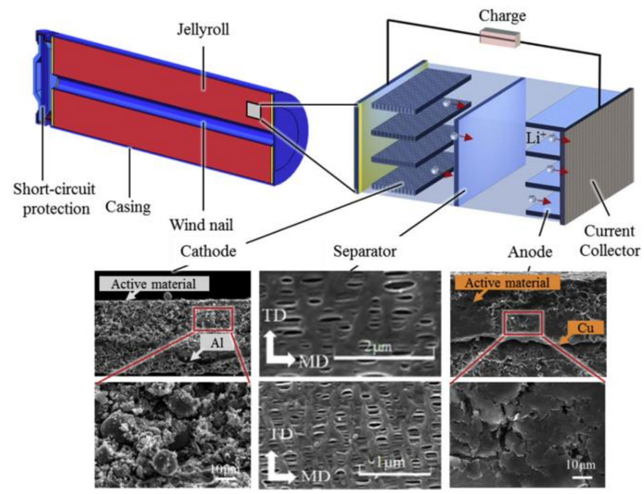


Fig. 3 The structure and electrochemical characteristics of 18650 lithium-ion battery [1]

Also, the ramifications of mechanical impacts on lithium-ion batteries aren't visible immediately. The latent damage may not be detected until it culminates in reduced performance or catastrophic failure under certain conditions of use. This hidden degradation is a heavy burden in battery diagnosis and quality assurance. Developing robust testing protocols simulating real-world mechanical impacts and predicting their effects on battery behavior is extremely important to alleviate these risks. Another challenge comes with the stopping between making batteries compact and lightweight and making them strong enough to deal with harsh conditions. Thin casings and lightweight materials allow better energy density and portability but are often not very mechanically strong. This creates a space for innovative materials and designs that are in balance between durability and performance. A multi-faceted approach to tackle these challenges would require advanced material development, better battery management systems to detect and mitigate damage, and better packing specifications. Such knowledge about the mechanisms of action of mechanical impacts towards the electrochemical and structural integrity of lithium-ion batteries is paramount to forming safer, more resilient energy storage systems. This will not only enhance the reliability and safety of LIBs across applications but will also create faith in their utilization concerning critical and high-stakes environments such as electric vehicles and renewable energy storage.

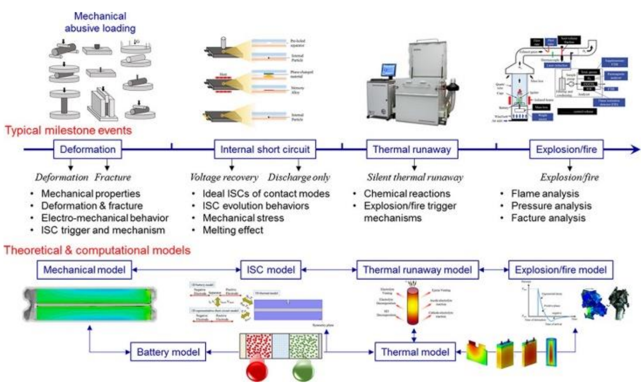


Fig. 4 Evolutionary process for LIB behavior upon mechanical abusive loading [1]

The drop and impact tests on lithium-ion battery cells provide invaluable information regarding their mechanical strength, safety, and working performance under all kinds of conditions. However, these tests are occasionally necessary because lithium-ion batteries are used in many portable electronics, electric vehicles, and stationary energy storage systems. Contained in this subject of research, the drop and impact tests take center stage during manufacturing, handling, transportation, and on-site use, and the battery has to endure mechanical stress to a great extent for these actions not to lose their functionality and operational safety. The tests help the researcher gain insight into which force of impact will actually compromise the cell's function and safety. The importance of such studies lies, first, in ensuring safety for high-end applications. Mechanical impacts may induce the occurrence of internal short-circuits in separating membranes or electrodes, possibly leading to thermal runaway, wherein an uncontrollable reaction and energy release occurs, ultimately resulting in a fire and/or explosion. All these understanding force design efforts very much towards ever safer designs or safer mechanisms, offering hope in down-scoping the background of enormous public tragedies within consumer electronics and EVs/industrial applications. In addition, drop and impact tests provide valuable information on the relationship between mechanical stresses and the electrical parameters of cell batteries, such as capacity retention, internal resistance, and voltage stability. This tests an understanding of how mechanical damage convalesces performance degradation over time, such as how repeated impacts create microcracks in electrode materials or current collector disconnections, affecting efficiency and cycle life. This knowledge is crucial for manufacturers wishing to manufacture long-lived and reliable batteries.

The above drop and impact tests are critical in the optimization of battery packaging and assembly. Lightweight and compact designs are desired by these industries for purposes such as EVs and consumer electronics; however, all of these come at some expense of reduced mechanical protection. Engineers can analyze results and design boxes around more resilient structures, materials that absorb shocks, and internal structures that provide better durability without significantly growing the weight or size of construction. In addition, regulatory bodies and industry standards frequently require extensive mechanical testing of lithium-ion batteries to gain certification for safety and reliability in specific applications. Drop and Impact tests are part of the mechanism of this certification to verify compliance with safety guidelines and boost consumers' confidence. Overall, the study of drop and impact tests on lithium-ion battery cells is highly pertinent for the improvement of their safety, reliability, and performance; this furthers a field of battery technology, informs improvements in design, and ensures compliance with safety standards among these goals so that it allows the lithium-ion batteries to be used reliably over diverse applications, even in demanding applications. Few studies explore both numerical simulations and experimental evaluations of impact tests and drop tests for analyzing mechanical effects on battery electrical properties despite extensive research about lithium-ion battery structural thermal behavior under mechanical stress.

A critical knowledge gap exists due to the insufficient development of robust frameworks that link physical deforming forces with declining electrical battery performance. The manufacturing process combines transportation routines and end-user utilization to expose lithium-ion battery cells to drop and impact forces. Mechanical stresses result in cell structure damage that disrupts electrical safety and performance. A thorough examination of mechanical stress relationships and their effects on electrical parameters, along with strategies for prolonged battery lifecycles, is still poorly understood. This study aims to bridge this research gap by performing detailed simulations along with experimental drop and impact tests to investigate mechanical and electrical impact factors that enhance battery reliability and lifetime.

1.1. Problem Statement

The Lithium-Ion Battery (LIB) is a preferred choice for applications within the realms of electric cars, portable electronics, and renewable energy storage because of its high energy density and long cycle life. However, those batteries are also prone to mechanical abuse, such as dropping or impacting, leading to performance degradation, safety hazards, and reduced lifecycle. Mechanical deformation resulting from these events can affect the battery cell's internal structure and modify key electrical parameters such as capacity, resistance, and voltage. Although such interactions are vital, far less has been done to understand how mechanical impacts correlate with electrical behavior changes. Thus, a lack of such data obstructs robust designs and the development of protection systems for lithium-ion batteries.

1.2. Scope of Work

The scope of the study includes simulation and experimental analysis of drop and impact tests carried out on lithium-ion battery cells for the assessment of mechanical effects on their electrical parameters, which include:

- Developing a Finite Element Model (FEM) for simulating drop and impact as well as prediction of stress and strain distribution due to impact inside cell structure during impact.
- Systematic drop and impact tests on lithium-ion cells with controlled conditions and Taking electrical measurements such as internal resistance, voltage, and capacity before and after the tests.
- Considering the relationship between mechanical state and changes in electrical performance and establishing cutoff thresholds for the mechanical impact could forceatively develop battery performance.
- Proposals for improved design of cell structures and protective casings and Guidelines for internal workings to limit damage incurred by mechanical abuse.

1.3. Novelty of Work

The main contribution of this research integrates simulation methods alongside experimental techniques to completely analyze the mechanical effects of drop and impact testing procedures on lithium-ion battery cells. This study differs from traditional mechanical damage investigations by showing how mechanical stress affects electrical characteristics, specifically capacity maintenance, resistance, and voltage stability.

The investigation employs sophisticated simulation platforms with real laboratory tests to expand knowledge about how multiple impact conditions affect battery operational quality and durability. Through this combination of modeling and experimental techniques, the research develops fundamental knowledge and design recommendations to create more stable energy storage solutions that improve safety and maximum operational lifespan. The main novelty in the research include:

- Integration of computer-aided simulations with experimental test methodologies to provide insights into mechanical effects arising on lithium-ion cells due to mishaps.
- Assessment of the key electrical parameters critical for performance and safety beyond a mere singular focus on structural damage due to mechanical impacts.
- Provision of actionable design and operational insights that will enable increasing mechanical abuse tolerance of the batteries.
- Employing various heights and angles of drop and different materials of surfaces to establish a wealth of scenarios from real life.
- Based on the outcomes, recommendations are made on design changes and preventive measures that can be applied to electric vehicles and consumer electronics.

1.4. Objectives

The study's principal objective is to clarify the effects of mechanical stress arising from drop and impact events on the electrical performance and longevity of lithium-ion battery cells. This is being attempted in this study via the characterization of the mechanical and electrochemical interaction occurring within the battery under stress; the specific objectives of this investigation are:

- *Determine the Effect of Mechanical Stress on Electrical Parameters:*
  1) Investigate how mechanical deformations produced by drop and impact events affect other critical electrical properties, such as capacity retention, internal resistance, voltage stability, and energy efficiency.
  2) Quantify the amount of performance degradation resulting from mechanical stress so that a clear understanding can be made of its implications toward battery reliability.
- *Determine the Mechanisms of Failure:*
  1) Study the structural changes and patterns of damage undergone by battery cells individually subjected to mechanical impact, i.e., separator piercing, electrode cracking, and electrolyte leakage.
  2) Establish a correlation between the mechanisms of failure and the change in electrical behavior to determine the cause of degradation.
- *Establish Simulations and Experimental Procedures to Validate Models:*
  1) Create a robust finite element analysis (FEA) model that would be able to simulate mechanical stress scenarios and predict how they would impact the battery performance.
  2) Validate the simulation results via experimental drop and impact tests.
- *Determine the Threshold of Mechanical Stress:*
  1) Define safe operating limits of mechanical impact allowable in battery cells without significant performance loss before safety is compromised.
  2) Propose guidelines for the industry to improve the handling, packaging, and design of batteries.

2. Literature Survey

Besides, most investigations revolved around how mechanical abuse (e.g., drop, impact, compression, and penetration) detriments the structural and electrochemical performance of LIBs. They are cantered to assess mechanical damage failure mechanisms, safety hazards, and potential ways to enhance the lifespan and reliability of battery systems. Additionally, a significant ongoing area of research involves finite element modeling to investigate the effect of mechanical stress on various cells in abuse scenarios. Generally, we can use finite element modeling to better understand mechanical loading effects on cell components (e.g., electrodes, separators, and electrolyte layers). They modelled drop-impacting events to predict stress and strain distributions to identify areas prone to physical failure. These models have also been used for the design optimization of cells, electrode geometry, and casing materials to enhance mechanical resilience. Experimental investigations complement simulations that replicate real-world damage scenarios. Drop tests extensively evaluate how impact energy affects cell deformation and electrical performance. For instance, controlled drop experiments have illustrated how impact severity leads to internal short circuits, capacity fade, and thermal runaway risks. The compressing and penetrating tests have highlighted the threshold at which cells pass into catastrophic failure, thereby explaining how structural deformation interplays with safety. Advanced diagnostic techniques, such as X-ray Computed Tomography (CT) and Scanning Electron Microscopy (SEM), have been adapted after the test to find internal damage and material degradation. Recent investigations have delved into dynamic vibration and shock testing, with a specific emphasis on its implications for the automotive and aerospace sectors. These studies assess the long-term impacts of mechanical vibrations during operation, as such vibrations can lead to fatigue in battery pack assemblies and threaten electrical connections. Additionally, certain research efforts have explored the relationship between mechanical stress and electrochemical reactions, revealing that repeated mechanical loading can accelerate both dendrite growth and capacity degradation. Although significant strides have been made in this field, there remain gaps in comprehending how mechanical disturbances influence key electrical parameters like resistance, voltage stability, and energy efficiency.

Furthermore, many studies concentrate solely on isolated abuse scenarios instead of addressing the various combinations of events that batteries are likely to face in practical applications. An integrated approach that merges advanced simulations with experimental methods and electrochemical diagnostics is essential to bridge these knowledge gaps. This developing body of research plays a vital role in improving lithium-ion batteries' safety, performance, and longevity across multiple applications. The cells of lithium-ion batteries (LIBs) are extremely prone to mechanical stresses, often resulting in different modes of failure that end up compromising the battery's performance, safety, and longevity. Such failure modes are generally categorized into structural, thermal, and electrochemical failures that usually occur after some mechanical impacts, compression, vibration, or perforation. Mechanically induced stresses can induce deformations in the electrodes, therefore generating interfacial delaminations between active material and current collectors, which diminishes the effective surface area available for electron transfers. As a result, this will lead to heightened internal resistance and, hence, reduced capacity. Also, in other cases, high levels of deformation could give rise to the rupture of the porous separator; this is a critical component that inhibits the anode and cathode from touching each other. Separator rupture often brings internal short circuits that lead to thermal runaway fires or explosions. From a thermal viewpoint, localized mechanical damage creates uneven heat generation during operation, especially when there is an increase in internal resistance due to electrode deformation. Elevated temperatures exacerbate side reactions, such as electrolyte decomposition, which threaten further battery performance degradation. In severe conditions, if the heat generated by the reactions exceeds the most reasonable thermal stability limit of the materials, this situation ignites fires or explosions. These modes of failure electrochemical failures are very important. Microcracks, thus formed due to mechanical stresses, expose fresh surfaces of the electrode material to the electrolyte and promote undesired side reactions. This further leads to the massive formation of Solid-Electrolyte Interphase (SEI) layers and, in some cases, the formation of lithium dendrites. These force reductions of cell capacity and coulombic efficiency to occur with time, while dendrites tremendously increase the chance of internal short circuits. Also, it makes the components of the cell fragile through repeated mechanical cycling, and here again, the whole system, via mechanical activation, gradually degrades and ultimately fails.

Real-life scenarios, such as drop impacts in electric vehicles and portable electronics, will trigger combined mechanical stresses, thereby intensifying any of these failure modes. Scenarios from real life, including drops or impacts on electric vehicles and portable electronics, combine multiple mechanical stressors, thereby exacerbating these failure modes. Studies have also shown that mechanical abuse can cause deformation of the battery casing, reducing the ability to effectively contain thermal and chemical hazards. While some of these risks have been mitigated by advanced designs and protections, a thorough understanding of these failure modes is now requisite to designing safer and more robust lithium-ion batteries. Right now, a lot has been diagnosed in understanding the macroscopic mechanical behavior of Lithium-Ion Cell Battery Development (LIBs). Yet, the integration of simulation and experimental validation needs improvement to achieve a comprehensive overview of the performance of LIB under mechanical stress. One major gap is identified as the absence of standardized protocols that ensure the simulation models are close to real life.

Fine Element Modeling (FEM) is now very widely used for simulating drop, impact, and vibration scenarios; however, validation against experimental results over similar conditions has not been performed in many studies. The differences in properties amongst materials, manufacturing inconsistencies, and the effects of environmental factors such as temperature or humidity remain poorly accounted for in simulations, leading to a mismatch with experimental outputs. Another critical gap lies in the capacity of simultaneous multi-physical interactions simulated in a battery under mechanical load. While FEM models excel in determining stress and strain distributions, coupling electrochemical and thermal effects of this occurred simultaneously through mechanical abuse is often not employed. Experimental studies provide insight concerning these coupled behaviours but lack the means to pulse-call any one variable nor move through a diverse impact scenario. This disconnect hinders establishing one unifying framework to close the mechanical deformation electrochemical and thermal performance correlations. In addition, the whole lot of simulated models could not be refined because of the unavailability of high-resolution experimental data. Many advanced diagnostic tools, such as X-ray computed tomography and scanning electron microscopy, provide more detail on internal damage mechanisms, but so far, their usage is very limited owing to cost and accessibility. In the absence of such data, simulations tend to rely on guesses about the behaviours of materials and thresholds of failure that might not even closely mimic real-life performance. There is also a very strong tendency in current research to focus on isolated failure modes, such as mechanical or thermal effects, without regard to their interplay in dynamic and multi-impact scenarios. For example, in drop tests performed in experiments, repeated impacts or vibration effects are often ignored.

In simulations, gradual microstructural damage over time usually has no effect. This gap hinders a holistic understanding of mechanical abuse's development and interaction with other degradation mechanisms like dendrite formation or capacity fade. Lastly, an apparent gap exists between the research establishment and practical design improvements. Even with knowledge based on simulations and experiments identifying weak points in battery cells, adopting these insights into effective design practices improving cell geometry, material compositions, or casings never gets enough focus. Bridging the gap requires greater collaboration among researchers, engineers, and manufacturers to frame experimental and modelling approaches to satisfy industrial needs. The mending of these lapses, seeking to respect interaction among such models with advanced diagnostic tools and inter-and intra-program collaboration, will greatly boost the predictive efficiency and relevant application of the integrated simulation-experimental frameworks for safety and performance optimization in lithium-ion batteries.

3. Methodology

3.1. Simulation Approach

Finite Element Analyses (FEA), done through SolidWorks, are expressing various items to conduct drop and impact tests on lithium-ion batteries, where a detailed setup is done to get their structural integrity and safety during mechanical stress. Drop height, angles, and impact velocity are defined in detail for the tests to describe realistic handling or accidental conditions. Drop heights may vary in the range of 1 to 3 meters, while drop angles may include flat drops, edge drops, and corner drops to mimic different contact orientations. The impact velocity, which should be realistic dynamic loading, is then determined from the expression of drop height under gravitational acceleration. The working of critical battery materials is integrated for a realistic demonstration of simulations. Electrodes, with their respective elastic moduli, density, and fracture toughness, were determined to analyze their behavior under deformation.

The separators, generally made from polymer materials, are then assigned tensile strength and elongation at break to check short-circuit potential. The casing, in the case of metallic or polymeric ones, is assigned yield strength, ductility, and impact resistance for checking the housing against inner components. This detailed methodology assists in the identification of weak spots that can help target design improvement and ensure standard conformance.

3.1. Simulation Study of Drop and Impact Test on 18650 Lithium Ion Battery Cell

3.1.1. Material Specification

Table 1 shows the material properties for CAD modeling of lithium-ion battery cells. Normally, a lithium-ion cell is prepared for engineering with a pertinent CAD model to analyze its effective performance via simulations in SolidWorks. To work on analysis and simulations, proper material specifications for the case of the battery cell have to be defined to recreate realistic analysis in practice.

The materials used for the battery-casing are aluminum alloys or steel, which ensure their enormous strength, are lightweight and have good thermal conductivity. The cell cap would normally be of high-conductivity aluminum to enhance thermal performance.

Properties include a density of about 2.2 g/cm³ for anodes, which are modelled using properties of graphite with moderate thermal conductivity. Cathodes, usually built up of $LiCoO_2$ or NMC, are denser (4.8 g/cm³) with low thermal conductivity (2 W/m•K). The electrolyte, while approximating a liquid material, possesses a rather low density (1.1 g/cm³).

The thermal conductivity (0.1-0.2 W/m•K) enables one to carry out thermal simulations. Careful assignment of many other mechanical properties of the cell, such as Young's modulus, Poisson's ratio, and coefficients of thermal expansion, allows one to accurately estimate structural and thermal performance.

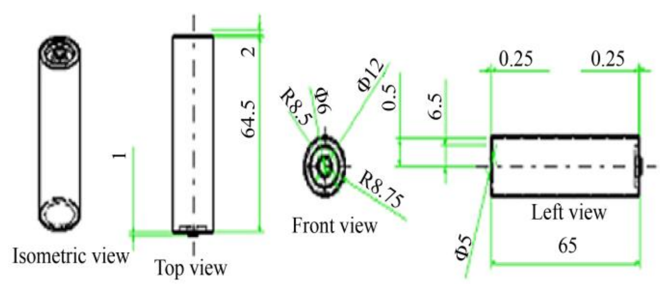


Fig. 5 CAD modeling specifications for lithium-ion battery

Table 1. 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

Fig. 6 CAD model of 18650 li-ion battery cell

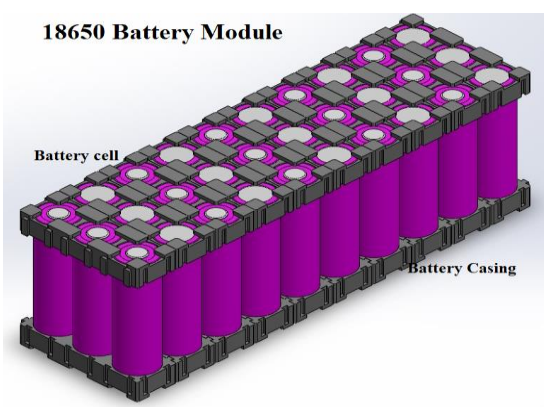


Fig. 7 CAD model of 18650 li-ion battery pack

3.2. Experimental Approach

The test starts with a lithium-ion battery cell of 3.7 volts and 2.5 amperes, with the initial environmental temperature of 20 ± 5^0C and relative humidity less than 70% following UN 38.3:2019 for impact and HPLI03/Test-Bat/WI-80 standard and IEC 62133-2:2017 standard. For the drop test, each fully charged battery cell is dropped three times from different heights from 1.2 meter and 1.5 meters on a flat concrete floor or metal floor, with acceptance criteria of no fire and no explosions. Similarly, the impact test is carried out with the same environmental conditions. During the impact test, the cell is kept on a flat, smooth surface. A 15.8 mm ± 0.1mm diameter, at least 6cm long, or the longest dimension of the cell, whichever is greater, type 316 stainless steel bar, is to be placed across the center of the sample. A 9.1kg ± 0.1kg mass is to be dropped from different heights (for sample 01:65cm, for sample 02:70cm, for sample 03:75cm) at the intersection of the bar and sample in a controlled manner using a near frictionless vertical sliding track or channel with minimum drag on the falling mass. The test sample is to be impacted with its longitudinal axis parallel to a flat surface and perpendicular to the longitudinal axis of the 15.88 mm ± 0.1 mm diameter curved surface lying across the center of the sample. Each sample is to be subjected to only a single impact.

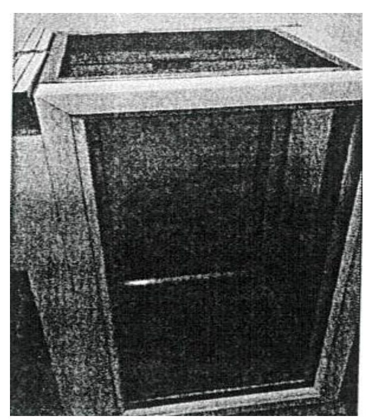


Fig. 8 Sample image of drop test

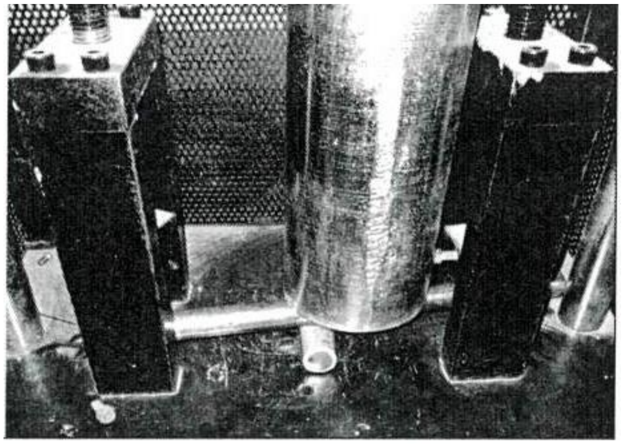
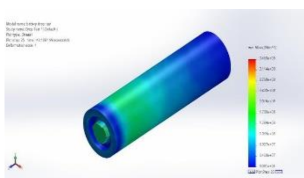
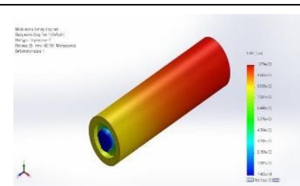
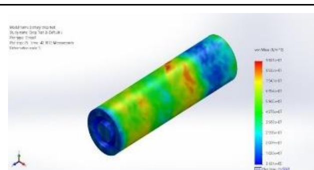
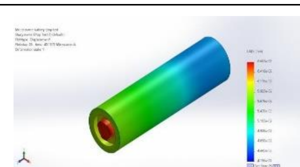
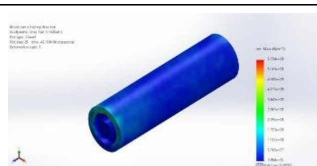
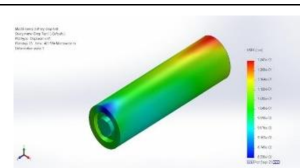
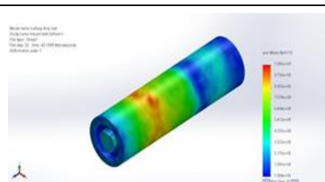
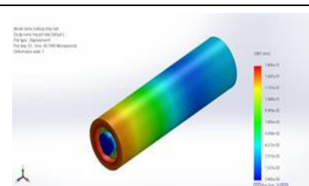


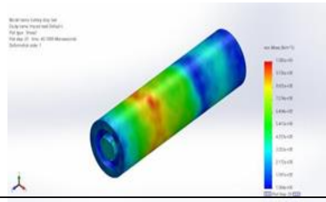
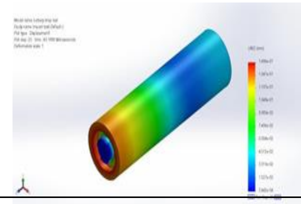
Fig. 9 Sample image for impact test

4. Results and Discussion

Table 2 shows the simulation results for the 18650 lithium-ion battery cell during drop testing and impact testing at a drop height of 1.8 meters and an impact velocity of 40 m/s, respectively, indicating the extent of damage and location of points of failure. Figure 6 depicts the deformational alterations in the internal structure of a lithium-ion battery cell as a result of the above-specified impact and drop tests. Simulation studies of drop and impact tests carried out in SolidWorks on a CAD model of 18650 lithium-ion battery cells provide necessary information regarding structural and thermal stability under mechanical stress. These studies show deformations, distribution of stresses, and heat spots, which will help identify various failure modes, such as casing rupture, internal short circuits, or electrolyte leakage. Results outline design weaknesses, encouraging engineers to reconsider materials, geometries, and means of protection. During the experimental test, no fire or explosion had occurred. The results are depicted below for further evaluation.

Table 2. Results of simulation for drop and impact test for the height of fall 1.8 meters and impact velocity 40 meter/second, respectively

Stresses	Deformation
Drop from positive terminal and height of 1.8 meters.	
	
Drop from negative terminal and height of 1.8 meters.	
	
Drop from the side and height of 1.8 meters.	
	
Impact from positive terminal and height of 1.8 meter	
	
Impact from negative terminal and height of 1.8 meter	

Impact from side and height of 1.8 meter

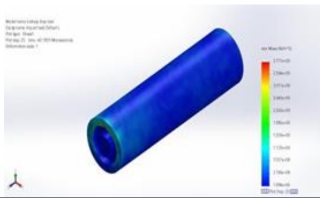
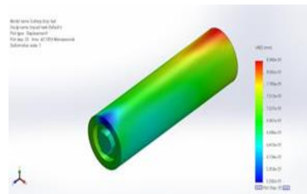
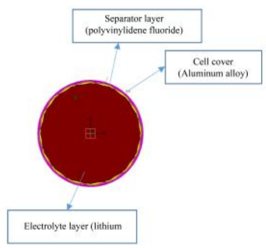
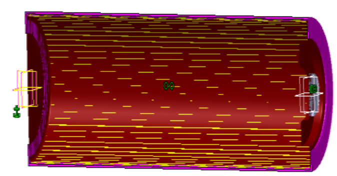



Fig. 10 Simulation result of battery cell layer variation during drop and impact test for 1.4-meter fall and 40 meter/seconds impact velocity





Similar results were evaluated for different heights and impact velocities for battery cells to evaluate and predict mechanical behaviour. The results are tabulated below,

Table 3. Drop test results with varying heights for the front area

Height of drop (meter)	Von mises stress (N/m^2)		Resultant Displacement (mm)		Equivalent Strain	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	7.57E+04	2.91E+08	1.24E-04	9.08E-02	8.86E-06	1.61E-02
1.1	7.93E+04	3.06E+08	1.30E-04	9.52E-02	9.28E-06	1.69E-02
1.2	8.29E+04	3.20E+08	1.41E-04	9.95E-02	9.64E-06	1.76E-02
1.3	8.68E+04	3.35E+08	1.42E-04	1.04E-01	1.01E-05	1.84E-02
1.4	9.08E+04	3.46E+08	1.47E-04	1.07E-01	1.04E-05	1.91E-02
1.5	9.49E+04	3.59E+08	1.57E-04	1.11E-01	1.07E-05	1.97E-02
1.6	9.77E+04	3.71E+08	1.61E-04	1.15E-01	1.11E-05	2.03E-02
1.7	1.01E+05	3.83E+08	1.68E-04	1.18E-01	1.15E-05	2.10E-02
1.8	1.03E+05	3.94E+08	1.70E-04	1.22E-01	1.19E-05	2.16E-02
1.9	1.07E+05	4.05E+08	1.75E-04	1.25E-01	1.23E-05	2.22E-02
2	1.09E+05	4.15E+08	1.79E-04	1.28E-01	1.24E-05	2.27E-02

Table 4. Drop test results with varying heights for the rear area

Height of drop (meter)	Von mises stress (N/m^2)		Resultant Displacement (mm)		Equivalent Strain	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	2.28E+05	7.43E+07	3.12E-02	4.96E-02	8.31E-06	9.13E-04
1.2	2.51E+05	8.12E+07	3.42E-02	5.44E-02	9.05E-06	1.00E-03
1.4	2.72E+05	8.79E+07	3.70E-02	5.88E-02	9.41E-06	1.08E-03
1.6	3.01E+05	9.39E+07	3.96E-02	6.28E-02	1.02E-05	1.16E-03
1.8	3.13E+05	9.92E+07	4.20E-02	6.66E-02	1.06E-05	1.23E-03
2	3.41E+05	1.05E+08	4.43E-02	7.03E-02	1.15E-05	1.30E-03

Table 5. Drop test results with varying heights for side area

Height of drop (meter)	Von mises stress (N/m^2)		Resultant Displacement (mm)		Equivalent Strain	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	2.85E+05	4.26E+08	6.23E-02	9.27E-02	6.45E-06	1.72E-03
1.2	3.12E+05	4.69E+08	6.81E-02	1.02E-01	8.35E-06	1.92E-03
1.4	3.37E+05	5.06E+08	7.35E-02	1.10E-01	8.69E-06	2.07E-03
1.6	3.59E+05	5.41E+08	7.86E-02	1.18E-01	9.52E-06	2.22E-03
1.8	3.80E+05	5.73E+08	8.34E-02	1.25E-01	9.76E-06	2.35E-03
2	4.00E+05	6.04E+08	8.79E-02	1.31E-01	9.91E-06	2.48E-03

Table 6. Impact test results with varying heights for the front area

Velocity of impact	Von mises stress (N/m^2)		Resultant Displacement (mm)		Equivalent Strain	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
10	1.85E+05	6.45E+08	2.82E-04	2.04E-01	1.82E-05	3.64E-02
20	3.44E+05	9.52E+08	3.09E-04	2.62E-01	3.82E-05	5.11E-02
30	7.89E+05	8.43E+08	1.35E-04	2.13E-01	9.86E-05	4.57E-02
40	1.06E+06	1.08E+09	3.44E-04	1.50E-01	7.29E-05	3.39E-02
50	1.67E+06	1.39E+09	3.48E-04	1.00E-01	5.88E-05	1.61E-02

Table 7. Impact test results with varying heights for rear area

Velocity of impact (m/s)	Von mises stress (N/m^2)		Resultant Displacement (mm)		Equivalent Strain	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
10	1.85E+05	6.45E+08	2.82E-04	2.04E-01	1.82E-05	3.64E-02
20	3.44E+05	9.52E+08	3.09E-04	2.62E-01	3.82E-05	5.11E-02
30	7.89E+05	8.43E+08	1.35E-04	2.13E-01	9.86E-05	4.57E-02
40	1.06E+06	1.08E+09	3.44E-04	1.50E-01	7.29E-05	3.39E-02
50	1.67E+06	1.39E+09	3.48E-04	1.00E-01	5.88E-05	1.61E-02

Table 8. Impact test results with varying heights for side area

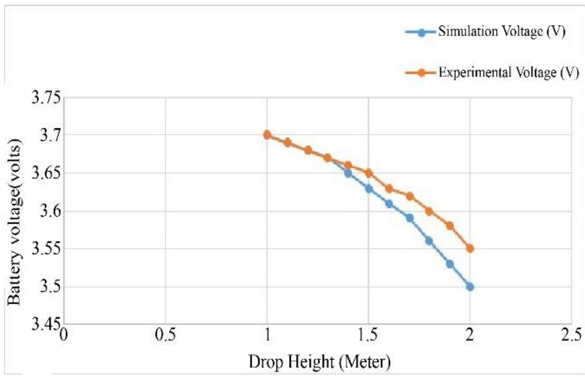
Velocity of impact (m/s)	Von mises stress (N/m^2)		Resultant Displacement (mm)		Equivalent Strain	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
10	6.28E+05	9.62E+08	1.40E-01	2.10E-01	1.71E-05	3.96E-03
20	1.12E+06	1.91E+09	2.80E-01	4.19E-01	2.58E-05	9.00E+00
30	1.45E+06	2.85E+09	4.19E-01	6.27E-01	2.92E-05	1.20E-02
40	1.894E+06	3.771E+09	5.582E-01	8.340E-01	3.705E-05	1.596E-02
50	2.236e+06	4.679e+09	6.968e-01	1.040e+00	5.613e-05	1.997e-02

Table 9. Specification of experimental testing (Drop test) of lithium-ion battery at cell level

height	Visible damage	leakage	Thermal runaway
1 meter	X	X	X
1.2 meter	X	X	X
1.5 meter	X	X	X

Fig. 11 Lithium-ion battery cell of specification 3.7Volt, 2.5Amp taken for experimentation before test conduction

Table 10. Experimental vs simulation results with varying drop heights



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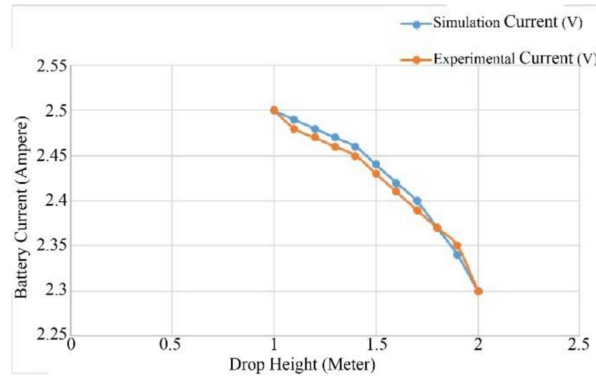

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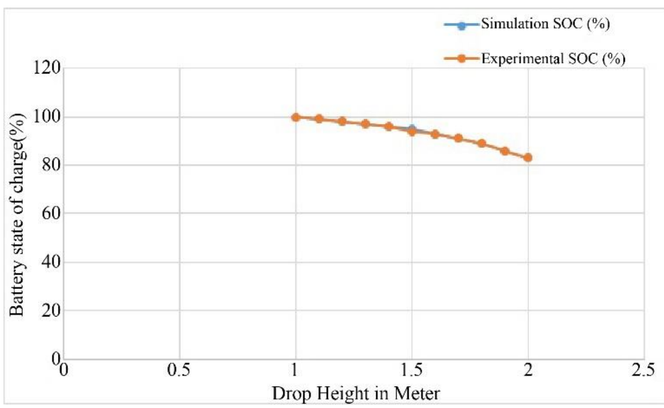

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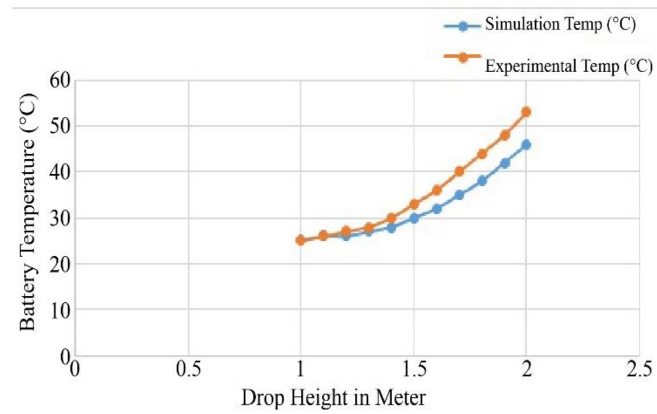
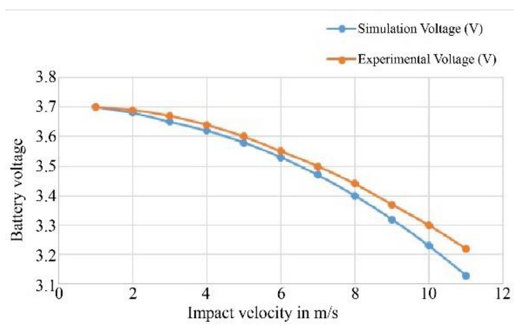


(d)

Table 10. Experimental vs simulation results with varying impact velocities



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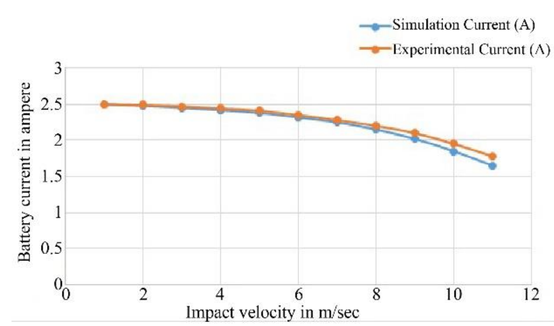

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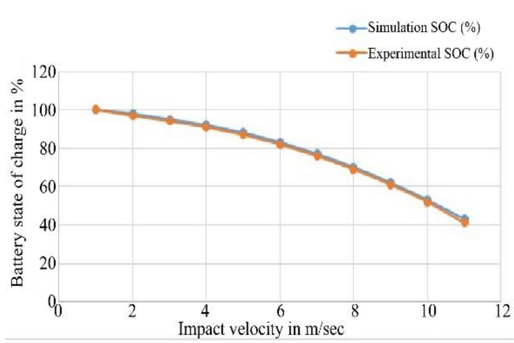

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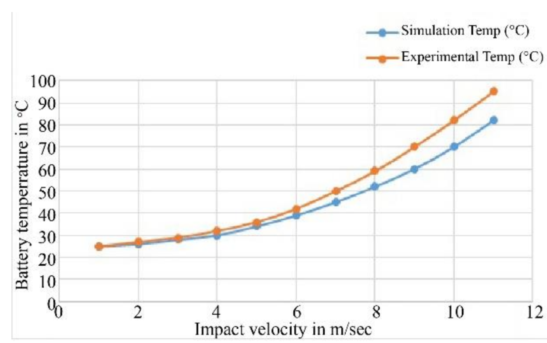

(d)

Table 11. Specification of experimental testing (Impact test) of lithium-ion battery at cell level

Impact Height	Visible damage	leakage	Thermal runaway	Voltage after
65 cm	✓	X	X	1.8 v
70cm	✓	✓	X	0.2 v
75cm	✓	✓	✓	0.5 v

Fig. 12 Lithium-ion battery cell after drop and impact test

The data has proposed the analogy between the electrical and mechanical behavior of drop and impact testing of battery cells, as tabulated below,

Table 12. Relation of Mechanical tests on and Electrical parameters of Lithium-Ion Batteries

Mechanical Tests	Objective	Impact on Battery	Electrical Parameters Affected
Compression Test	Evaluate the battery's resistance to compressive forces.	Distortion of cell structure, probable internal short circuits.	Capability deprivation, internal resistance, voltage drop.
Vibration Test	Evaluate battery performance under vibration conditions typical of vehicle environments.	Releasing of connections mechanical damage to electrodes and separators.	Impedance increase, current fluctuations, potential capacity loss.
Shock Test	Simulate high-impact forces like crashes or drops.	Internal damage, electrode fractures, separator punctures.	Voltage drops, charge-discharge efficiency reduction, safety risks.
Drop Test	Evaluate the battery's durability when dropped from a certain height.	Cell casing deformation, internal component damage.	Irregular voltage output, increase in self-discharge rate.
Thermal Cycling with Mechanical Stress	Combine temperature variations with mechanical stresses to test thermal and structural limits.	Thermal expansion-contraction damage, separator shrinkage, electrolyte leakage.	Capacity fades, reduced cycle life, over-voltage or under-voltage behavior.
Penetration Test	Evaluate resistance to sharp objects penetrating the cell.	Internal short circuits, potential thermal runaway.	Voltage collapse, potential catastrophic failure.
Tensile/Shear Test	Evaluate the strength of tabs, connections, or housing materials.	Discontinuation of tabs, casing failure.	Increase in contact resistance voltage abnormalities.

Table 13. Relation of Electrical tests on and Mechanical parameters of Lithium-Ion Batteries

Electrical Tests	Objective	Impact on Battery	Mechanical Properties Affected
Capacity Test	Quantity is the total charge the battery can store.	Decrease in capacity due to internal short circuits or electrode degradation.	Compression resistance structural integrity of electrodes.
Internal Resistance Test	Evaluate resistance within the battery.	High resistance can indicate electrode damage or separator failure.	Deformation under compression or vibration-induced defects.
Cycle Life Test	Evaluate the number of charge-discharge cycles the battery can sustain.	Capacity fades over time, structural fatigue of electrodes.	Mechanical stability of electrode layers and separators.

Impedance Spectroscopy	Depict the battery's impedance across frequencies.	Variations in impedance due to separator degradation or electrode delamination.	Elasticity and adhesion properties of materials.
Short-Circuit Test	Regulate battery safety under short-circuit conditions.	High current discharge leads to heating and structural damage.	Separator and electrode thermal and mechanical stability.
Thermal Runaway Test	Simulate extreme conditions to assess safety margins.	Abandoned heat generation causes mechanical deformation or rupture.	Casing integrity, separator melting point.

5. Conclusion and Future Scope

The simulation results show intricate details about stress and strain patterns across the battery cell, specifying regions experiencing high mechanical loads and deformation. Critical failure points- such as the edges of electrodes, separator layers, and tab connections- are pointed out as components susceptible to structural damage under mechanical stress.

The experimental findings provide adequate support to these observations by comparing the electrical parameters before and after testing and evident variations in capacity, internal resistance, and voltage stability values due to deformation. Physical changes within the cell analysis further corroborate the effects of mechanical impacts on battery performance, such as depreciation in efficiency and a corresponding rise in safety risk.

A strong agreement between simulation and experimental data corroborates simulation models, supporting their predictive ability to evaluate mechanical impacts. These insights shed light on the mechanical-stress-induced degradation mechanisms, such as electrode delamination and separator damage, forming the basis for optimizing battery design for increased durability in practical applications.

The comparative tests showed that battery drops with battery packs have higher resistance and less energy and capacity. However, the difference between the dropped battery and battery pack for the discharge power generally agreed with that of the before tests.

These were, however, protected by the battery management system, and the fuse was normal. Future research may expand on it by developing a methodology for testing and developing new materials and safety strategies through emerging technology.

The simulation shows the distribution of stress and deformation in the battery cell, highlighting points of maximal mechanical loads and deformation; such critical failure points include electrode edges, separator layers, and tab connections, which provide insight into areas most susceptible to mechanical damage under operational or test conditions. These are critical data for optimizing cell design and structural integrity.

- The interplay between mechanical and electrical stresses helps design batteries with more safety features, such as strong casing, improved separators, and thermal management systems.
- Combined tests give a realistic assessment of battery reliability in real-world conditions where mechanical and electrical stresses often occur simultaneously.
- Test results will inform the future improvement of battery materials and designs, leading to longer-lived and safer batteries.
- Some studies found that some levels of mechanical loading-to-wit, as well as a couple of different critical levels of strain or energies resulting from dynamic impacts, could lead to structural damage like separation of electrodes and fracture of separators. These levels will depend on the design and materials of the batteries and are critical in defining safe operating limits. Knowledge of these values assists in avoiding situations leading to internal short circuits and even capacity loss.
- Moreover, mechanical stresses lead to internal structural failure, likely including micro-cracking in electrodes and separator failure, which create higher internal resistance and reduced effective capacity. These deformations disrupt ion flow and electron transfer, which in turn can lead to a measurable decrease in voltage stability, life cycle, and energy efficiency.
- Better designs include structural reinforcement of separator materials and battery casings, the addition of shock-absorbing layers that distribute impact energy, optimization of electrode configurations, and the inclusion of flexible or elastic materials to reduce the effect of mechanical stress on internal structures.
- Such technical advancements help to better understand the failure mechanisms, hence safer battery design and longer life cycles, consequently converting into fewer incidents related to battery failures in electric vehicles and reliable operation in mechanical stress-oriented environments for portable electronics and energy storage tools.
- It should feature the trunk firm packaging solutions, providing cushioning and protection during transportation. With the implementation of real-time monitoring systems that can sense mechanical stresses and different kinds of standard protocol testing for impact resistance, risk reduction during transport and handling

will be attained. In this study are enhanced understanding of how mechanical stress, such as drops and impacts, correlates with the performance and safety of lithium-ion batteries. Combining simulation and experimental approaches conveys elaborate insights into structural damage mechanisms and their correlation with electrical parameter degradation. The findings will contribute toward optimizing the design, durability, and safety of batteries for applications in electric vehicles and portable electronics.

- In conclusion, future works would thus investigate the interaction of thermal and electrical stress on lithium-ion batteries, including thermal runaway under mechanical deformation and changes in electrical performance during coupled mechanical-thermal abuse. Investigating stress conditions such as high-current discharges occurring during mechanical impacts or temperature-induced material fatigue would provide an integrated understanding of real-world degradation mechanisms to inform advanced battery safety protocols.

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