

Investigations of Mechanical Testing and its Effects on Lithium Ion Battery and Battery Pack for Electric Vehicle Application

Sonali Sabale¹, Deepak Watvisave², Vishwajeet Gaike³, Ravikant Nanwatkar^{4,*}

Abstract

This research delves into the comprehensive study of mechanical testing methodologies and their consequential impact on the structural integrity, safety, and performance of Lithium-Ion batteries (Li-ion) and battery packs designed for electric vehicle (EV) applications. The investigation aims to enhance the understanding of mechanical stressors' influence on the reliability and safety of energy storage systems crucial for the sustainable advancement of electric mobility. The paper opens with mechanical testing protocols that have already been established on single Li-ion cells. Various tests, including compression, puncture, and impact resistance evaluations, are conducted to simulate real-world scenarios during manufacturing, transportation, and operational phases. Through these tests, the vulnerabilities and failure modes of individual cells are meticulously examined, shedding light on potential areas for improvement in cell design and manufacturing processes. Extending the investigation to encompass complete battery packs, the research establishes testing procedures to simulate dynamic conditions encountered during electric vehicle usage. Vibrations, accelerations, and thermal cycling are systematically applied to assess the overall structural integrity of the battery pack, including its components such as connectors and cooling systems. Ideally, one would like to determine possible weak- or failure-modes due to mechanical stress under Furthermore, the study endeavors to establish a correlation between mechanical stresses and the electrical and thermal performance of Li-ion batteries. Experimental data is analyzed to quantify the impact of mechanical testing on critical parameters such as capacity retention, internal resistance, and temperature regulation mechanisms. This holistic approach aims to provide insights into the interdependencies between mechanical stresses and the long-term performance and safety of Li-ion batteries in the context of electric vehicles. The anticipated outcomes of this research are expected to inform the development of advanced battery pack designs, manufacturing processes, and safety protocols for electric vehicles. By uncovering the intricate relationship between mechanical stressors and the performance of Li-ion batteries, the research aims to contribute to the continuous improvement of electric vehicle technologies, fostering their wider adoption and ensuring the durability and safety of energy storage systems in the evolving landscape of sustainable transportation.

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INTRODUCTION

The integration of lithium-ion batteries (Li-ion) in various applications, particularly in electric vehicles (EVs), has led to an increasing emphasis on understanding the mechanical behavior and durability of these energy storage systems. Mechanical testing plays a crucial role in

evaluating the structural integrity, safety, and overall performance of Li-ion batteries, offering insights into their response to external forces and potential failure modes. The increasing trend of electric vehicles automatically puts ensuring Li-ion battery reliability and safety in the forefront. This introduction aims at presenting first the role of mechanical testing and its impact on Li-ion batteries. Increasing Adoption of Lithium-Ion Batteries: Lithium-ion batteries are the most notable energy storage technology, and are now used in portable devices as well as electric vehicles [1,2]. These battery types have high energy density, lightweight, and are rechargeable, thus proving to be perfect for today's energy storage needs.

- *Importance of Mechanical Testing:* The mechanical reliability of Li-ion batteries is a critical aspect that influences their performance, safety, and overall lifespan. Mechanical testing involves subjecting the batteries to various stressors to simulate real-world conditions, enabling researchers and engineers to identify potential weaknesses and failure modes.
- *Real-World Stress Scenarios:* Li-ion batteries are exposed to diverse mechanical stresses during their lifecycle, including those arising from manufacturing processes, transportation, and operational usage. Understanding how these stressors impact the batteries is essential for designing robust energy storage systems that can withstand the dynamic environments in which they are deployed.
- *Key Mechanical Tests for Li-ion Batteries:* Mechanical tests include compression tests to simulate external pressure, puncture tests to assess resistance to penetration, and impact tests to evaluate the response to sudden forces. These tests are designed to replicate scenarios that Li-ion batteries may encounter, helping researchers to quantify their mechanical resilience.
- *Effects of Mechanical Stresses on Li-ion Batteries:* Mechanical stresses can lead to a range of effects on Li-ion batteries, including physical deformation, internal damage to cell components, and in extreme cases, thermal runaway. Understanding the consequences of these stresses is essential for mitigating risks and improving the safety and reliability of Li-ion battery systems.
- *Research Objectives:* The work focused on comprehensive investigation of the mechanical effects on lithium ion battery at pack and cell level. Through a combination of experimental analysis and theoretical modeling, the study seeks to quantify the impact of mechanical stresses on the structural, electrical, and thermal aspects of Li-ion batteries, ultimately contributing to the development of safer and more reliable energy storage solutions [3].

In summary, the exploration of mechanical testing and its effects on Li-ion batteries is imperative for advancing the reliability and safety of energy storage systems, especially in the context of their widespread use in electric vehicles and other critical applications. By unraveling the intricate relationship between mechanical stresses and battery performance, this research aims to contribute to the continuous improvement of Li-ion battery technologies.

Problem Definition

The integration of lithium-ion batteries (Li-ion) in various applications, particularly in electric vehicles (EVs), necessitates a thorough understanding of their mechanical behavior. While Li-ion batteries offer high energy density and efficiency, they are susceptible to mechanical stresses that may arise during manufacturing, transportation, and operational usage. The stresses significantly effects on mechanical reliability, reliability and durability considering the performance parameters. Therefore, the problem at hand involves comprehensively investigating the effects of mechanical tests on Li-ion batteries to identify potential failure modes, vulnerabilities, and areas for improvement in their design and manufacturing processes [4].

Objectives

- *Characterize Mechanical Vulnerabilities:* Conduct a series of mechanical tests, including compression, puncture, and impact tests, to systematically characterize the vulnerabilities and failure modes of Li-ion batteries. This involves identifying points of weakness in the battery structure and understanding how different stressors impact their physical integrity.

- *Quantify Mechanical Resilience:* Develop quantitative metrics to assess the mechanical resilience of Li-ion batteries. This includes defining parameters such as the critical force for deformation, penetration resistance, and impact resistance. The goal is to establish a baseline for evaluating the batteries' ability to withstand various mechanical stresses.
- *Correlate Mechanical Stresses with Electrical Performance:* Investigate the correlation between mechanical stresses and the electrical performance of Li-ion batteries. Assess how mechanical deformation or damage affects critical electrical parameters such as capacity retention, internal resistance, and voltage stability. This correlation is crucial for understanding the holistic impact of mechanical stresses on battery functionality.
- *Examine Thermal Consequences:* Explore the thermal consequences of mechanical stresses on Li-ion batteries. Investigate how deformation or damage induced by mechanical tests influences the batteries' thermal behavior, including heat generation, dissipation, and the risk of thermal runaway. Analysis of these thermal issues has significant effects on safety considerations of lithium ion batteries [5].
- *Optimize Battery Design and Manufacturing Processes:* Utilize insights gained from mechanical testing to propose optimizations in Li-ion battery design and manufacturing processes. This involves identifying potential modifications to enhance structural robustness, mitigate vulnerabilities, and improve overall mechanical resilience without compromising energy density and efficiency.
- *Enhance Safety Protocols:* Develop and recommend safety protocols based on the findings from mechanical testing. This includes guidelines for handling, transportation, and operational usage of Li-ion batteries to minimize the risks associated with mechanical stresses. The objective is to contribute to the establishment of best practices for ensuring the safety of Li-ion batteries in various applications.
- *Contribute to Industry Standards:* Align the research findings with existing industry standards or propose new standards for mechanical testing of Li-ion batteries. This objective aims to provide a benchmark for manufacturers, researchers, and regulatory bodies, facilitating a unified approach to assessing the mechanical resilience of Li-ion batteries.

By addressing these objectives, the research aims to advance the understanding of the mechanical behavior of Li-ion batteries and contribute to the development of safer, more reliable energy storage solutions, particularly in the context of their application in electric vehicles and other critical systems.

Methodology

The methodology for conducting mechanical tests on lithium-ion batteries involves a systematic approach to simulate and assess the batteries' response to various stressors. Below is a general outline of the methodology:

1. *Experimental set up:*
 - Identify the specific mechanical tests to be conducted, such as compression, puncture, and impact tests. Define the test parameters, including the applied force, deformation criteria, and testing environment conditions [6].
 - Select representative lithium-ion battery samples that mirror the characteristics of those used in the intended applications. Ensure the samples are in a fully charged state to replicate real-world conditions.
 - Instrument the battery samples with sensors for measuring critical parameters such as force, deformation, and temperature. Ensure that the instrumentation does not interfere with the mechanical tests.
2. *Apply controlled force*
 - Gradually and uniformly to the battery, measuring the force- deformation relationship. Monitor for any signs of deformation, bulging, or structural failure.
 - Conduct puncture tests using a sharp object or a dedicated puncture apparatus.

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- Apply controlled force to simulate puncture scenarios and observe the response of the battery. Monitor for structural damage, electrolyte leakage, or other signs of failure.
 - Perform impact tests using a drop tower or impact testing apparatus. Drop a standardized mass from a specified height onto the battery to simulate impact scenarios [7].
3. *Evaluate the battery's response*
 - Response to impact, observing for deformation, cracking, or other structural changes.
 - After each test, carefully inspect the battery samples for visible damage or structural changes. Analyze the recorded data from instrumentation, including force, deformation, and temperature measurements.
 - Correlate the mechanical test results with electrical performance metrics, such as capacity retention, internal resistance, and voltage stability.
 4. *Evaluate the impact of mechanical stresses*
 - The electrical functionality of the lithium-ion batteries.
 - Conduct thermal analysis during and after mechanical tests. Monitor temperature changes in the battery samples to assess the thermal consequences of mechanical stresses.
 - Look for signs of excessive heat generation or potential thermal runaway.
 5. *Optimization and Recommendations:*
 - Based on the results, propose optimizations in battery design, manufacturing processes, or safety features to enhance mechanical resilience.
 - Formulate recommendations for handling and operational guidelines to minimize the risks associated with mechanical stresses.
 - Document all test procedures, parameters, and results systematically. Finally the paper summarized with research findings, gained perceptions and scope for further research.

This methodology ensures a systematic and controlled approach to conducting mechanical tests on lithium-ion batteries, providing valuable insights into their mechanical resilience and aiding in the development of safer and more reliable energy storage systems [8].

LITERATURE SURVEY

Lithium-ion batteries (LIBs) are integral to electric vehicles (EVs), providing the energy needed for propulsion. However, their structural integrity and performance are often challenged by the harsh mechanical environments encountered during vehicle operation, transportation, and accidents. Mechanical testing is essential to evaluate how LIBs respond to these forces and to ensure they meet safety, reliability, and performance standards. For instance, vibrations from road surfaces can lead to fatigue over time, potentially causing internal damage or even cell failure. Similarly, impacts during collisions or mishandling can compromise the battery's structural integrity, increasing the risk of thermal runaway—a hazardous chain reaction leading to fire or explosion. By conducting rigorous mechanical testing, researchers can identify potential failure modes and improve designs to withstand these stresses, ensuring safer and more durable battery systems for EV applications. Additionally, mechanical testing contributes significantly to enhancing battery reliability and longevity. LIBs undergo repetitive mechanical stresses throughout their operational life, which can degrade their electrochemical performance. For example, deformation of battery components, such as electrodes and separators, can increase internal resistance or create short circuits, affecting energy output. Testing helps in optimizing material choices and cell designs to mitigate these issues, improving performance over time. It also plays a crucial role in meeting regulatory requirements and instilling consumer confidence by demonstrating a high level of safety and reliability [9].

Research on the mechanical testing of LIBs has primarily focused on three critical areas: vibration, compression, and shock testing. Vibration tests simulate the dynamic stresses experienced during

vehicle operation, such as those caused by rough road conditions or high-speed driving. These tests help in understanding how prolonged exposure to vibrations affects the structural and electrochemical integrity of LIBs. Studies have shown that vibrations can lead to micro-cracks in electrodes, loosening of connections, and even electrolyte leakage, all of which degrade battery performance. Compression testing, on the other hand, examines the battery's ability to withstand forces exerted during stacking, transportation, or accidents. Researchers have observed that excessive compressive loads can deform the internal components, leading to short circuits or capacity loss. Shock tests are used to evaluate the battery's resilience to sudden impacts, such as those occurring during vehicle collisions or drops. These tests are critical for identifying weak points in battery design and ensuring that the battery can safely absorb and dissipate impact energy without catastrophic failure. Together, these studies have provided valuable insights into the mechanical behavior of LIBs under various stress conditions, aiding in the development of safer and more robust battery systems [10,11].

While existing research has significantly advanced our understanding of the mechanical behavior of LIBs, several critical knowledge gaps remain. One major gap is the limited exploration of the combined effects of mechanical and thermal stresses on battery performance. In real-world applications, LIBs often face simultaneous mechanical loads and temperature variations, especially in EVs operating in extreme climates or during thermal runaway events. The interplay between these factors can exacerbate structural degradation and accelerate performance loss, yet this area remains underexplored in the current literature. Another gap is the lack of studies on the long-term effects of cyclic mechanical loads, which mimic the repetitive stresses LIBs endure throughout their operational life. These cyclic loads can lead to gradual fatigue and microstructural changes, impacting both the mechanical and electrochemical properties of the battery. Additionally, there is limited research on the mechanical testing of newer battery technologies, such as solid-state lithium-ion batteries, which may exhibit different failure modes compared to traditional LIBs. Addressing these gaps is crucial for developing a comprehensive understanding of LIB behavior under real-world conditions and for designing next-generation batteries that are both safer and more durable.

SIMULATION AND MODELING

Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a powerful computational tool used to simulate mechanical stresses and predict failure modes in lithium-ion batteries (LIBs). In the context of LIBs for electric vehicles (EVs), FEA helps model the complex interactions between various components, including electrodes, separators, and casings, under mechanical loads such as vibrations, shocks, and compression. By discretizing the battery structure into smaller elements, FEA enables detailed analysis of stress distribution, deformation patterns, and potential failure points. For instance, during vibration simulations, FEA can identify areas within the battery pack that experience stress concentrations, which may lead to material fatigue or cracks over time. Similarly, under compressive loads, the analysis can reveal how internal components, such as the separator, might buckle or tear, increasing the risk of thermal runaway. These insights are critical for improving battery designs to enhance durability and safety.

Validation

The accuracy of FEA models must be validated through experimental data to ensure their reliability. Validation involves comparing the predicted outcomes of the simulations—such as deformation magnitudes, stress levels, and failure locations—with actual results from mechanical testing. For example, if compression tests reveal specific points of structural failure, these should align with the stress peaks identified in the FEA simulations. Any discrepancies between the two can help refine the model, such as by incorporating more accurate material properties or boundary conditions. Validation not only strengthens the confidence in the simulation results but also enables

predictive modeling for scenarios that are challenging to replicate experimentally [12]. This synergy between FEA and experimental testing ensures a comprehensive understanding of the mechanical behavior of LIBs, guiding the development of safer and more robust batteries for EV applications (Table 1).

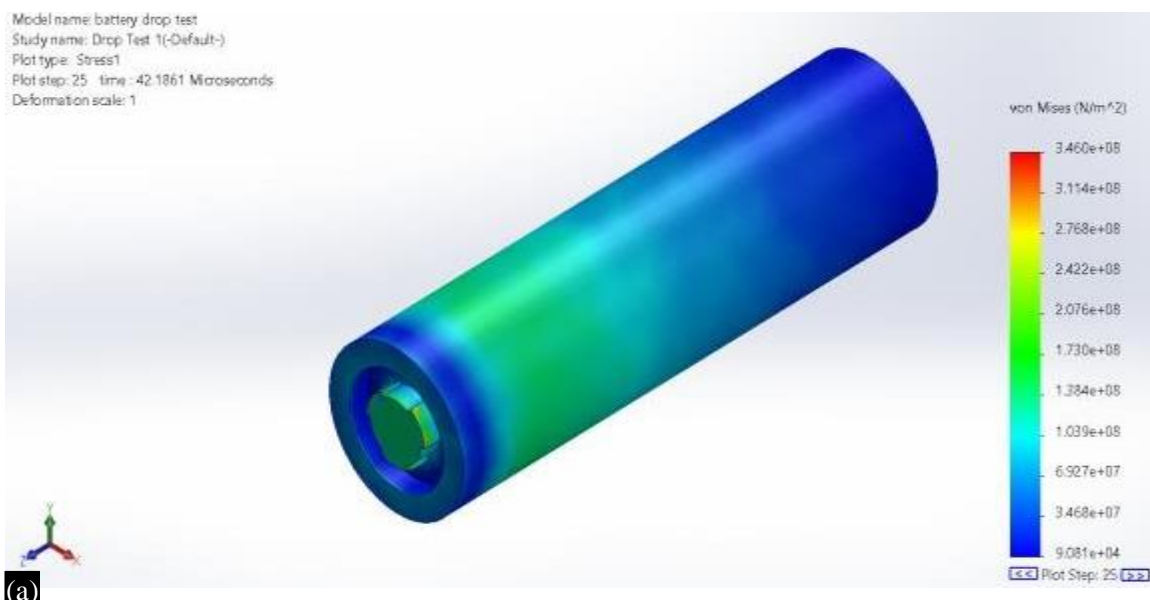
SolidWorks software is widely used for simulating drop and impact tests of lithium-ion batteries due to its robust design and analysis capabilities. By leveraging its built-in simulation tools, engineers can create detailed 3D models of batteries, including cells, modules, and packs, to assess their structural behavior under various drop and impact scenarios. The software allows for precise control of parameters such as drop height, impact angles, and material properties, enabling accurate prediction of stress distribution, deformation, and potential failure points. These simulations help identify weak areas and guide design improvements to enhance the durability and safety of lithium-ion batteries for electric vehicle applications, reducing the need for extensive physical testing (Figure 1).

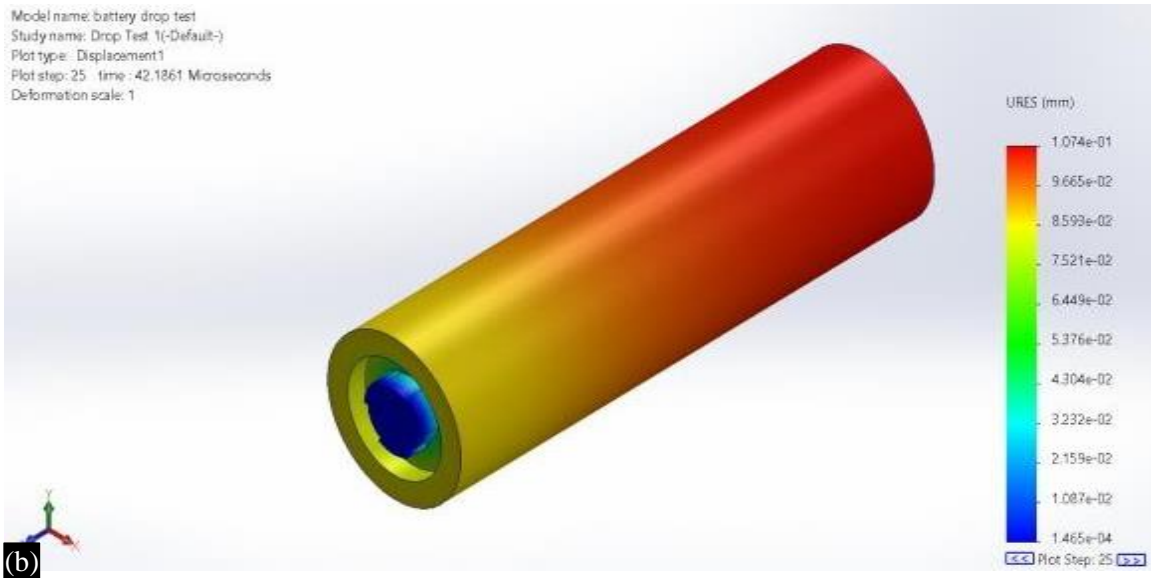
Material Specification

Table 1. Material properties of 18650 lithium ion battery cell [5].

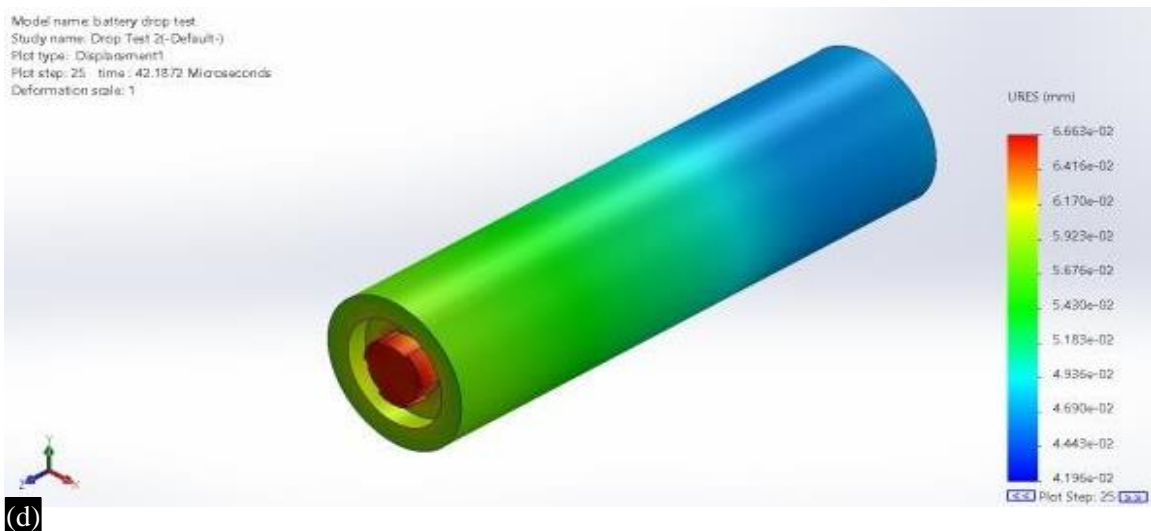
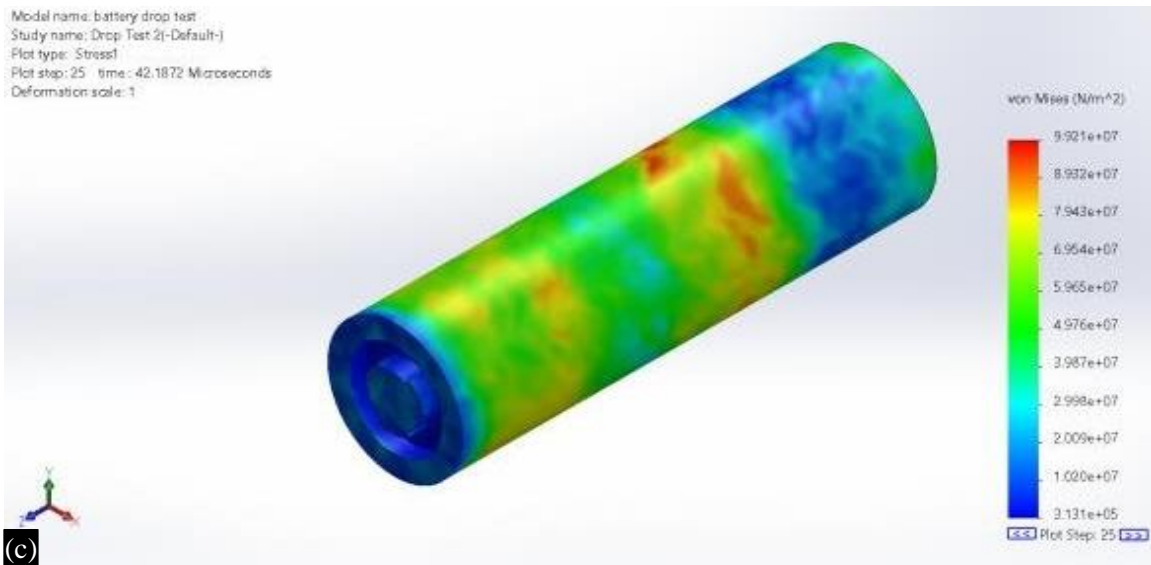
Lithium cell	Mass:0.00865615 kg, Volume:1.63324e-05 m ³ , Density:530 kg/m ³ , Weight:0.0848303 N
Battery Case (aluminum)	Mass:0.00780363 kg, Volume:1.01346e-06 m ³ , Density:7,700 kg/m ³ , Weight:0.0764756 N
Battery caps(nickel)	Mass:0.000188594 kg, Volume:2.21875e-08 m ³ , Density:8,500 kg/m ³ , Weight:0.00184822 N
Drop height from lowest point	1,800 mm
Gravity	9.81 m/s ²
Gravity Reference	Face<1>
Coefficient of friction	0.5
Target Stiffness	Rigid target
Critical Damping Ratio	0.3

Drop test (front) from height of 1.8m

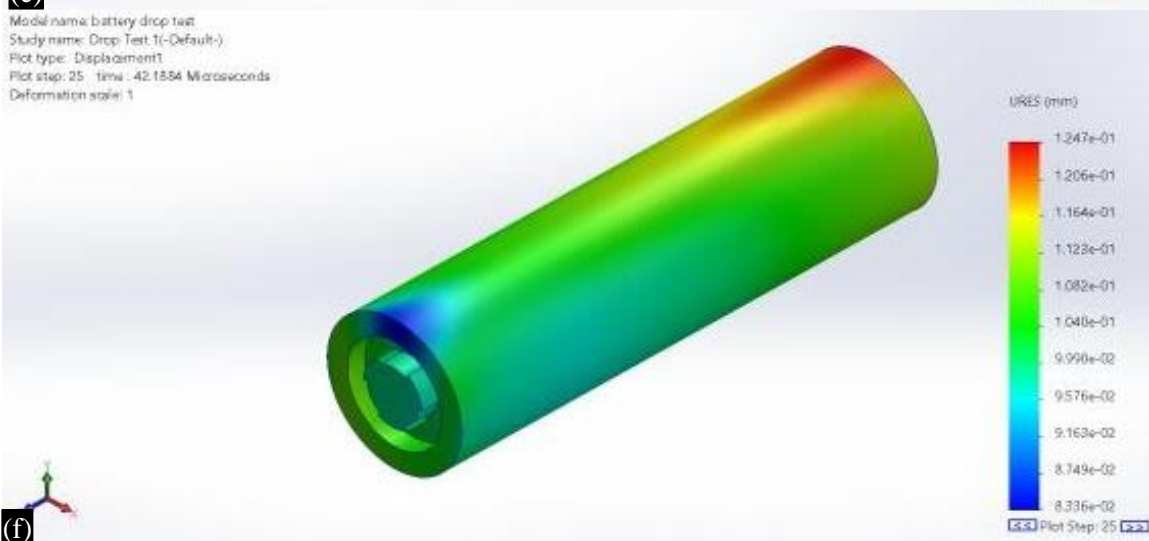
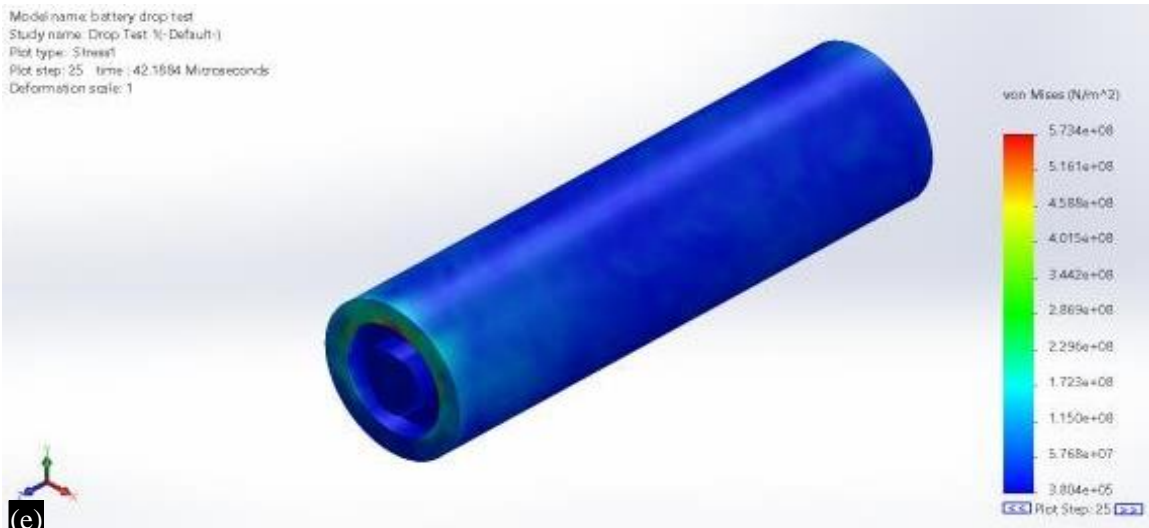




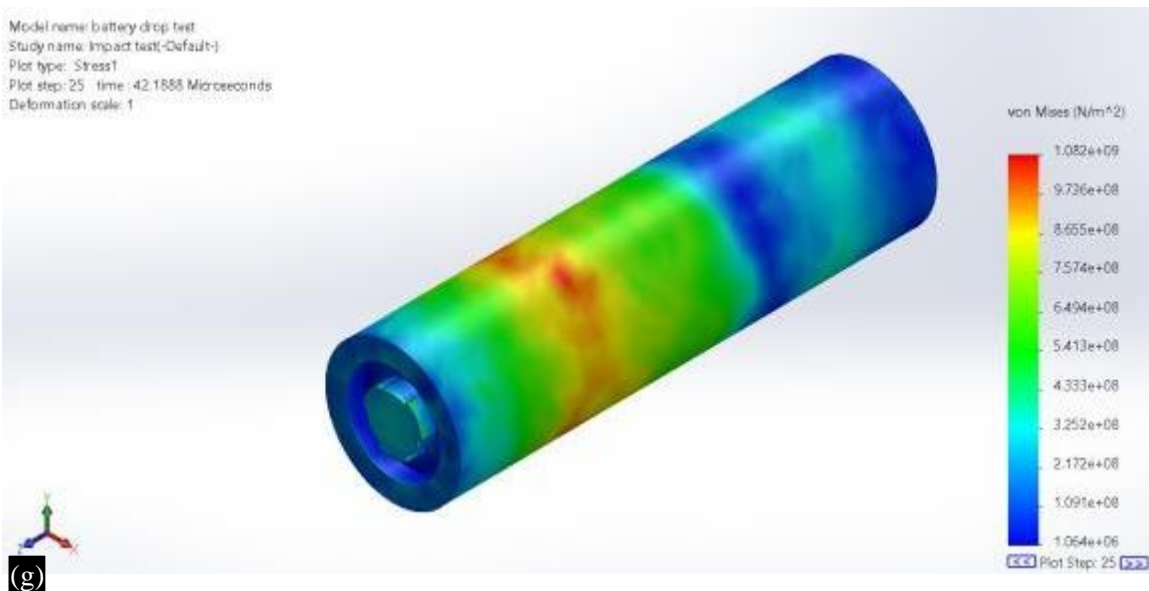
Drop test (Rear) from height of 1.8m



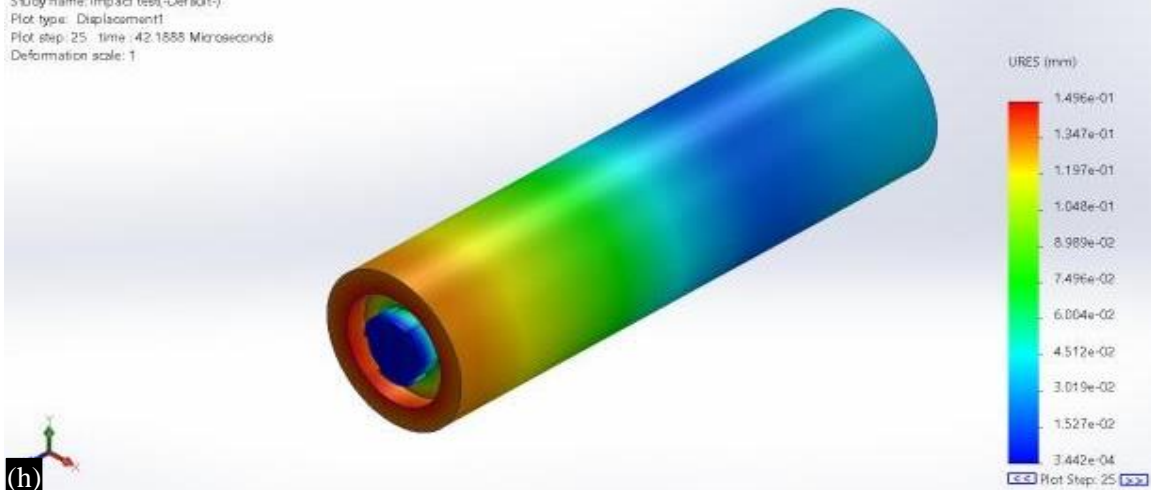
Drop test (side) from height of 1.8m



Impact test (front) 40 m/s



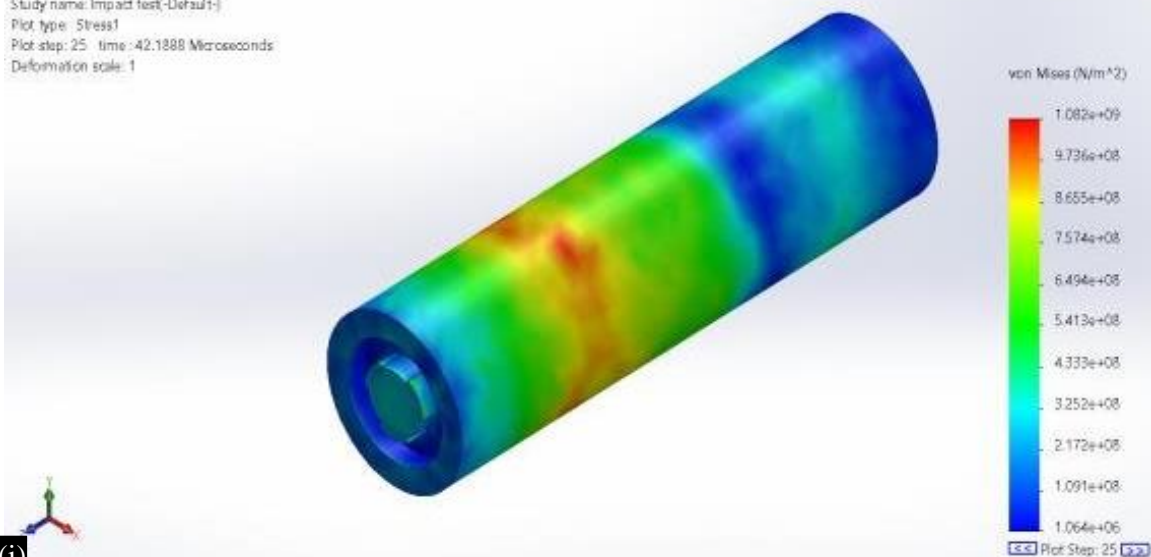
Model name: battery drop test
Study name: Impact test(-Default-)
Plot type: Displacement1
Plot step: 25 time: 42.1888 Microseconds
Deformation scale: 1



(h)

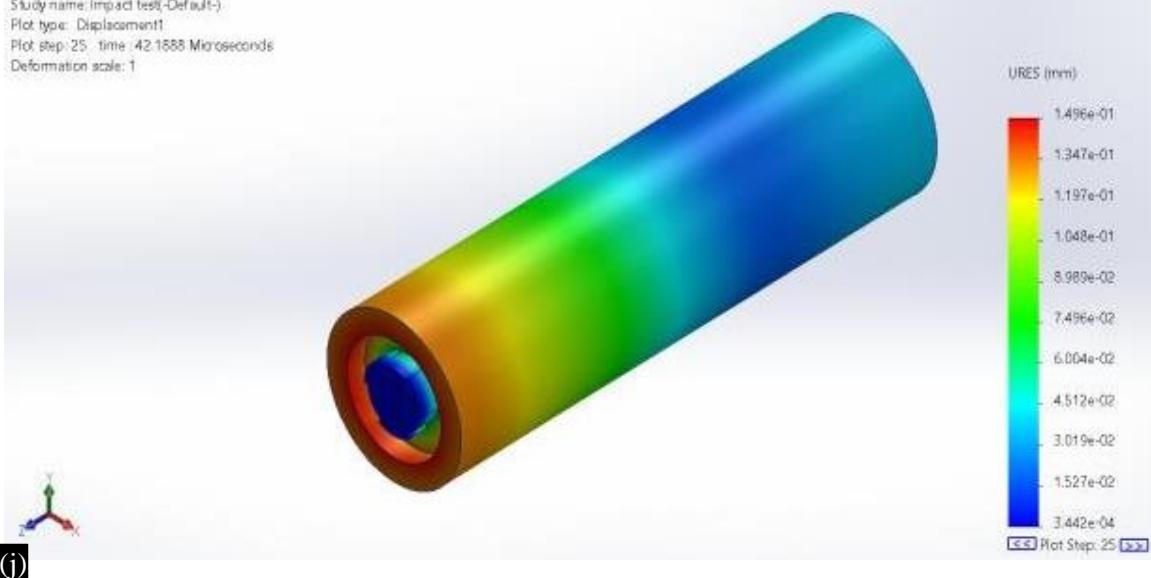
Impact test (rear) 40 m/s

Model name: battery drop test
Study name: Impact test(-Default-)
Plot type: Stress1
Plot step: 25 time: 42.1888 Microseconds
Deformation scale: 1



(i)

Model name: battery drop test
Study name: Impact test(-Default-)
Plot type: Displacement1
Plot step: 25 time: 42.1888 Microseconds
Deformation scale: 1



(i)

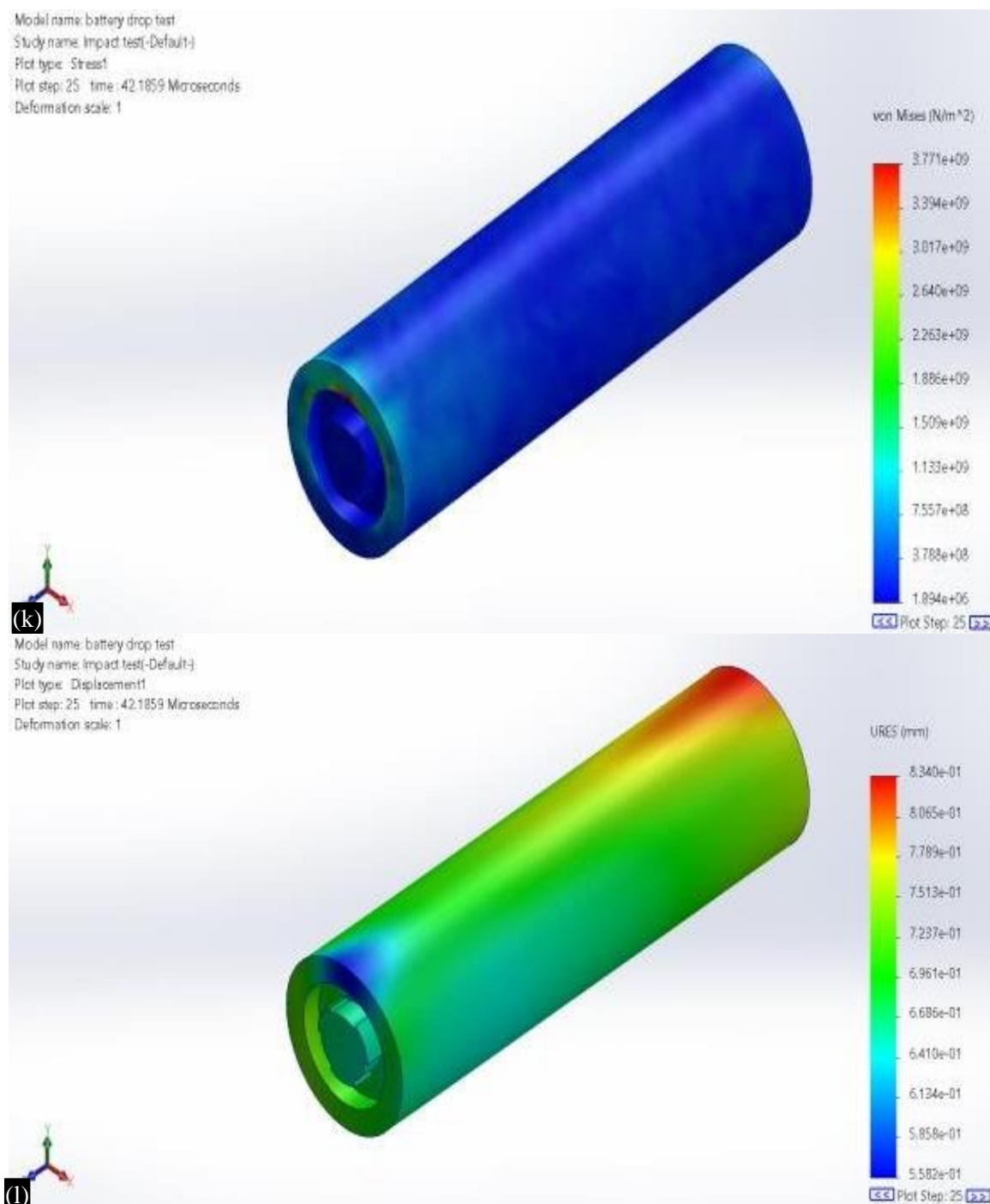
Impact test (side) at 40 m/s

Figure 1. Simulation results of drop test for height of 1.8m in possible directions.

RESULTS AND DISCUSSION

Drop and impact tests for lithium-ion batteries are significant as they provide critical insights into the batteries' structural integrity, safety, and resilience under conditions simulating real-world scenarios. These tests are particularly relevant in applications such as electric vehicles, portable electronic devices, and energy storage systems where batteries may be subjected to mechanical shocks during transportation, handling, or accidents (Table 2-Table 4). The significance of drop and impact tests for lithium-ion batteries can be understood through the following key points:

Table 2. Structural failures or damage modes at different levels (cell, module, pack).

Level	Damage Mode	Description	Consequences
Cell	Electrode Cracking	Cracking of electrodes due to mechanical stress, leading to loss of electrical conductivity.	Increased internal resistance, decreased efficiency, and potential for internal short circuits.
	Separator Tearing	Physical damage to the separator material that separates the positive and negative electrodes.	Risk of internal short circuits, thermal runaway, and reduced capacity retention.
	Localized Dents or Deformation	Dents or deformation of the outer casing due to impact or drop.	Risk of internal damage, including compression of internal components and potential electrolyte leakage.
Module	Warping of Housing	Bending or distortion of the module's outer casing under mechanical forces.	Reduced protection for internal cells, potential for casing rupture or failure under continued stress.
	Damage to Inter-cell Connections	Physical damage or loosening of the connections between cells in the module.	Loss of electrical continuity, imbalance in charge/discharge cycles, and reduced module performance.
	Shifting or Misalignment of Cells	Movement or misalignment of cells within the module due to impact forces.	Uneven stress distribution, potential for electrical contact issues or short circuits.
Pack	Buckling of Outer Casings	Structural deformation of the battery pack casing under severe impact or drop conditions.	Compromised mechanical integrity, possible leakage of electrolytes, and higher risk of thermal runaway.
	Connector and Busbar Failures	Damage or disconnection of electrical connectors or busbars within the battery pack.	Loss of power delivery, reduced performance, and potential safety hazards like short circuits.
	Damage to Mounting Points and Fixtures	Damage or deformation of mounting points or fixtures that hold the pack in place within the EV chassis.	Reduced stability of the pack, risk of pack movement, and potential for mechanical damage to cells.

Table 3. Impact on Electrical Performance of lithium ion battery and the correlation between mechanical stresses and changes in electrical parameters

Aspect	Mechanical Stress	Impact on Electrical Performance	Key Observations
Voltage	Compression/Impact	Increased internal resistance leading to voltage drop.	Voltage drop during or after mechanical stress due to damage to internal components or electrode misalignment.
	Vibration	Fluctuations in voltage due to intermittent contact or internal short circuits.	Sudden voltage dips observed during impact tests, especially in damaged cells or modules.
Capacity Retention	Shock/Drop Impact	Decreased capacity retention after mechanical stress, especially under repeated loading.	Significant reduction in capacity after repeated mechanical stresses due to internal damage or degradation.
	Repeated Cycling/Deformation	Reduced charge/discharge efficiency over time due to internal damage or structural changes.	Cells experiencing repeated mechanical deformation show faster degradation of capacity over cycles.
Thermal Runaway Risk	Severe Impact/Compression	Increased risk of thermal runaway due to separator damage or internal short circuits.	Impact or severe compression can cause separators to tear, triggering thermal runaway.
	Vibration/Repeated Stress	Thermal instability leading to heat buildup and potential thermal runaway.	Cells exposed to repeated mechanical stress show increased risk of heat generation, leading to thermal failure.
Internal Resistance	Impact/Shock Loading	Increase in internal resistance, leading to higher energy loss and reduced efficiency.	Mechanical stresses increase internal resistance, which reduces power output and overall efficiency.

Table 4. results across different LIB designs, materials, and configurations

Factor	Cylindrical Cells	Pouch Cells	Prismatic Cells	Modular Configurations	Integrated Pack Configurations
Mechanical Resilience	High resistance to external deformation; robust structure.	More prone to deformation and bulging under stress.	Moderate resilience; better control over shape but more vulnerable to mechanical forces.	Better damage containment and energy distribution due to modular design.	Prone to cascading failure if one component is damaged.
Impact Resistance	Good impact resistance due to cylindrical shape.	Lower impact resistance; more sensitive to puncture or compression.	Moderate impact resistance; tends to bend under high force.	Enhanced impact resistance; better ability to distribute forces.	Less impact-resistant; localized damage can affect the whole system.
Structural Failure Modes	Cracking of electrodes, casing dents, internal short circuits.	Pouch swelling, separator damage, internal short circuits.	Warping, loss of cell alignment, and internal short circuits.	Better distribution of stress, reducing failure risk; some cell alignment issues.	Risk of domino effect leading to multiple failures in the pack.
Electrical Performance	Stable voltage, consistent capacity retention under moderate stress.	Reduced voltage and capacity retention after deformation.	Decreased voltage stability and lower efficiency after deformation.	Maintains better overall performance due to redundancy; higher reliability.	Risk of complete power loss if pack components are damaged.
Thermal Runaway Risk	Low risk if outer casing is undamaged; may increase with internal damage.	Higher risk due to pouch swelling, internal shorts, and separator damage.	Moderate risk; deformation may lead to separator puncture and short circuits.	Lower thermal runaway risk compared to integrated packs due to individual cell protection.	Higher risk of thermal runaway if one cell failure leads to cascading effects.
Durability Over Time	High durability; cylindrical shape distributes stress well.	Lower durability; pouch cells degrade faster under mechanical stress.	Moderate durability; better structure but can suffer from bending.	Enhanced durability over time; modular design allows for easier replacement of faulty cells.	Reduced long-term durability; pack-wide degradation due to cumulative damage.
Design Complexity	Simple design but less flexible for integration.	Flexible design; easier to shape and integrate into various configurations.	Moderate complexity; well-suited for EV applications with a balance of performance and stability.	Complex design requiring more space and management but increases flexibility and damage tolerance.	High complexity, integrating multiple components, increasing overall failure risk.
Cost	Generally lower cost due to simpler design and manufacturing processes.	Higher cost due to complex manufacturing process and pouch materials.	Moderate cost; balances performance and manufacturing complexity.	Higher cost due to additional materials and design complexity.	High cost due to integration of various components and high-performance needs.

- *Safety evaluation:* Drop and impact tests considered in this work help to predict lithium ion battery safety issues. Mechanical stresses, such as those encountered during accidental drops or collisions, can potentially compromise the structural integrity of the battery and lead to safety hazards such as thermal runaway or leakage of electrolytes. These tests perform a vital role for design improvement by recognizing potential safety risks by modifying it [13].

- *Real-World Simulation:* Simulating drop and impact scenarios allows researchers and engineers to replicate real-world conditions that batteries may face during transportation, assembly, or usage. Understanding how batteries respond to these mechanical stresses helps in designing robust energy storage systems that can withstand the dynamic environments they are exposed to in various applications.
- *Quality Control in Manufacturing:* Drop and impact tests serve as quality control measures during the manufacturing process of lithium-ion batteries. By subjecting a representative sample of batteries to controlled mechanical stresses, manufacturers can ensure that the batteries meet certain safety and reliability standards. This helps identify manufacturing defects and inconsistencies that may affect the mechanical resilience of the batteries.
- *Impact on Battery Components:* These tests provide insights into the impact on individual components within the battery, such as the separator, electrodes, and casing. Understanding how these components respond to mechanical stresses helps in improving their design and material choices, ultimately contributing to enhanced battery performance and safety.
- *Regulatory Compliance:* Drop and impact tests are often mandated by regulatory bodies and standards organizations for the certification of lithium-ion batteries. Performance and completions of these tests insures whether the batteries match the standardization of safety, its regulation to promisingly adoption of standard testing protocols in industrial applications.
- *Design Optimization:* The results of drop and impact tests inform the design optimization of lithium-ion batteries. Engineers can identify weak points or vulnerabilities in the battery structure and make design improvements to enhance its mechanical resilience without compromising other performance metrics, such as energy density and efficiency.
- *Risk Mitigation in Electric Vehicles:* In electric vehicles, where safety is paramount, drop and impact tests are crucial for assessing the resilience of the battery pack. Understanding how the battery pack responds to impacts or collisions helps in designing effective safety features and structural reinforcements to minimize the risks associated with mechanical stresses [14-17].

By subjecting batteries to controlled mechanical stresses, researchers and engineers can identify potential failure modes, optimize designs, and contribute to the development of safer and more robust energy storage solutions considering safety and reliability of lithium ion batteries.

Mechanical testing of LIBs poses several challenges, including replicating real-world conditions accurately. The variability in testing parameters, such as load rates and environmental factors, makes standardization difficult. Additionally, the complexity of battery pack designs and materials complicates the identification of failure mechanisms. Testing large-scale packs is also resource-intensive, requiring advanced equipment and facilities.

The study has limitations, including a focus on specific battery chemistries and configurations, which may not be generalizable to all LIB technologies. The interplay between mechanical, thermal, and electrochemical factors was only partially explored, leaving room for further investigation. Lastly, long-term cyclic loading effects were not comprehensively studied, limiting insights into fatigue behavior over extended operational periods. Addressing these limitations can guide future research and improve the applicability of the findings.

CONCLUSIONS

1. During drop and impact testing of lithium-ion batteries, deformation patterns vary across the cell, module, and pack levels. At the cell level, localized dents and internal misalignments of electrodes are common, with potential tearing of separators leading to short circuits. Modules often experience warping of housings, shifting of stacked cells, and damage to inter-cell connections. At the pack level, structural buckling, deformation of outer casings, and failure of connectors and mounting points are observed. These patterns highlight critical areas for design reinforcement to enhance durability and safety under mechanical stresses.

2. Result of simulation tests for drop and impact conditions shows the considerable failure at terminal ends of lithium ion battery progressing to internal short circuit. This is due to braking of battery terminal connections because of variation inn stresses at those points of force action leading to braking of separator layer.
3. Simulation results of drop and impact test with cathode position shows effects of failure on rear end indicates failure lead to external short circuit as stress variation at failure point can lead to breaking of separator layer. To avoid this batteries placement should be always vertical i.e. at positive terminal as a base to avoid failures chances.
4. After considerable effects on front and rear end, the results of side impact shows the considerable effects on battery failures leading to external short circuit the reason of which is also the braking of separator layer between anode and cathode material of the battery. This shows proper battery case should be designed to avoid directs impact on side surface of the battery.
5. Overall it can be conclude that separator thickness needs to improve with optimized parameters in order to prevent contact between anode and cathode layer.

REFERENCES

1. Golriz Kermani a, Mohammad Mehdi et.al. in ELSEVIER research publication, “*Deformation of lithium-ion batteries under axial loading: Analytical model and Representative Volume Element*” 2021
2. Ran Tao, Zhibo Liang et.al. In Acta Mechanica Solida Sinica article published in 2021, “*Mechanical Analysis and Strength Checking of Current Collector Failure in the Winding Process of Lithium-Ion Batteries*”
3. Wenwei Wang, Yiding Li et.al. In Chinese Journal of Mechanical Engineering, “*Mass-Spring-Damping Theory Based Equivalent Mechanical Model for Cylindrical Lithium-ion Batteries under Mechanical Abuse*” 2020
4. Juner Zhu, Marco Miguel Koch, et. al. in Journal of The Electrochemical Society, 2020, “*Mechanical Deformation of Lithium-Ion Pouch Cells under In Plane Loads—Part I: Experimental Investigation*”.
5. Lian, Junhe; Koch, Marco et.al. In Journal of the Electrochemical Society, published in 2020 on, “*Mechanical Deformation of Lithium-Ion Pouch Cells under in-plane Loads—Part II: Computational Modeling*”
6. Faezeh Darbaniyan, Xin Yan et.al. In journal of Applied Mechanics published 2019, “*An Atomistic Perspective on the Effect of Strain Rate and Lithium Fraction on the Mechanical Behavior of Silicon Electrodes*”
7. Rong Xu, Yang Yang et.al. In ELSEVIER research publication, “*Heterogeneous damage in Li-ion batteries: Experimental analysis and theoretical modeling*” 2019
8. Sangwook Kim and Hsiao-Ying et.al. In CROSSMARK research article, “*Mechanical stresses at the cathode– electrolyte interface in lithium-ion batteries*” 2018.
9. Hansinee Sitinamaluwa, Jawahar Nerkar et.al. In Crossmark RCS advances journal, “*Deformation and failure mechanisms of electrochemically lithiated silicon thin films*” 2017.
10. Golriz Kermani and Elham Sahraei et.al. In MDPI energy article, “*Review: Characterization and Modeling of the Mechanical Properties of Lithium-Ion Batteries*” (2017)
11. Liang Tang, Jinjie Zhang et.al. In PLOS one research article, “*Homogenized modeling methodology for 18650 lithium-ion battery module under large deformation*” 2017.
12. Cheng Lin, Aihua Tang et.al. in Hindawi publication research article, “*Electrochemical and Mechanical Failure of Graphite-Based Anode Materials in Li-Ion Batteries for Electric Vehicles*” 2016.
13. Cheng Lin, Aihua Tang, et.al. In Nanomaterial and Nanotechnology research article, “*Analysis for Mechanical Failure of DISs with Graphite Anode in Lithium ion Batteries for Electric Vehicles*” (2016).
14. Sulin Zhang in NPJ Computational Materials journal, “*Chemomechanical modeling of lithiation-induced failure in high-volume-change electrode materials for lithium ion batteries*” 2016.

15. JunXu, Binghe Liu in nature scientific reports 2016, "*State of Charge Dependent Mechanical Integrity Behavior of 18650 Lithium-ion Batteries*"
16. Scott A. Roberts, Hector Mendoza et.al. In Journal of Electrochemical Energy Conversion and Storage 2016, "*Insights into Lithium-Ion Battery Degradation and Safety Mechanisms from Musicale Simulations Using Experimentally Reconstructed Microstructures*".
17. Sergiy Kalnaus, Yanli Wang et.al. In Oak Ridge National Laboratory, Oak Ridge, TN 37831–6164, USA in 2014 paperentitled, "*Mechanical behavior and failure mechanisms of Li-ion battery separators*".