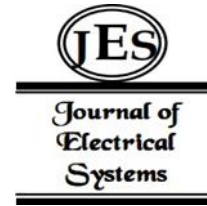


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# Investigations of Mechanical Properties and Maximum Load Capacities under Abuse Testing of Lithium Ion Battery



**Abstract:** - Lithium-ion batteries are crucial in driving the various technological applications' innovation. In this regard, it is important to ensure the safety and reliability of LIBs as a matter of public concern. This paper explores the mechanical properties and abuse testing's maximum load capacities, highlighting the testing's abusive conditions. The focus is to deepen a broader understanding of the extreme mechanical load and the battery behavior responses. Based on the extensive abusive testing procedures, drop, impact, crush or penetration, and thermal runaway tests, the mechanical responses and failure modes of LIBs at the cell, module, and pack levels were analyzed. This work, is based on the drop and impact test, using solidworks simulation to establish the abuse testing impacts on battery mechanical and electrical properties. The model for conducting the tests was the 18650 lithium ion cell battery, subjected to the front, side and rear impact at various heights and velocities with reference safety standard AIS 156 and AIS 048. Mechanical properties and maximum load capacities' correlation was described, illuminating the crucial failure mechanisms and feasible mitigation approaches. The derived insights from the abuse testing have a significance to the design, safety and reliability of the LIB-based energy storage systems to guide the future research and development in safer and robust battery use.

**Keywords:** Lithium-ion batteries, mechanical properties, abusive conditions, drop and impact test, failure modes.

## I. INTRODUCTION

Mechanical properties and maximum load capacities are at the forefront of lithium-ion battery LIB's under abusive conditions. LIB's are frequently mechanically abused during and in between accidents, drop, explosion and leaking during misuse, or battery manufacturing mishaps. Thus, examining how LIBs perform under abusive conditions may aid in safeguarding the safety of the users, belongings, and the environment.[1] This could further advise the appropriate safety activities to limit any danger linked with mechanical abuse. The structural soundness of the cells is lost due to mechanical abuse. [2] The overall performance is critical, and the battery can explode or become useless. Here we have considered 18650 cylindrical cell lithium ion battery. Figure 1 shows the structure of lithium ion battery cell. As can be seen in Fig. 2, the LIB cell is made up of a jellyroll, battery casing, short-circuit protection device, and winding nail. Jellyroll is the energy storage component, including anode with current collector, cathode with current collector, separator, and electrolyte. The anode, cathode and separator are all porous materials, whose microstructure is given in Fig. 2.

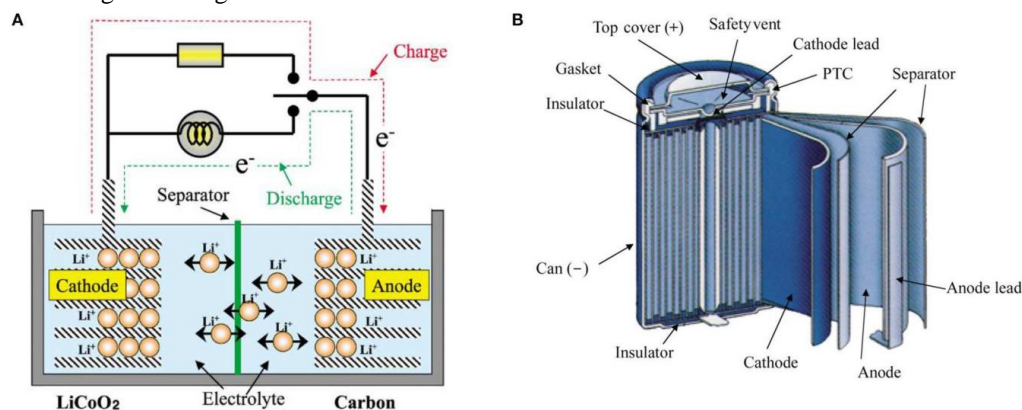


Figure 1: Structure of li-ion battery cell [2]

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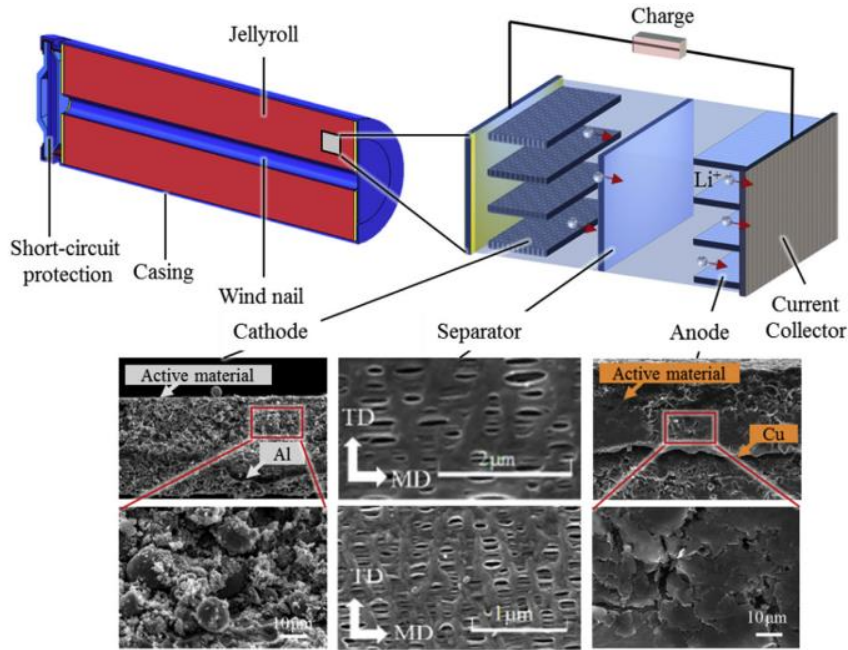
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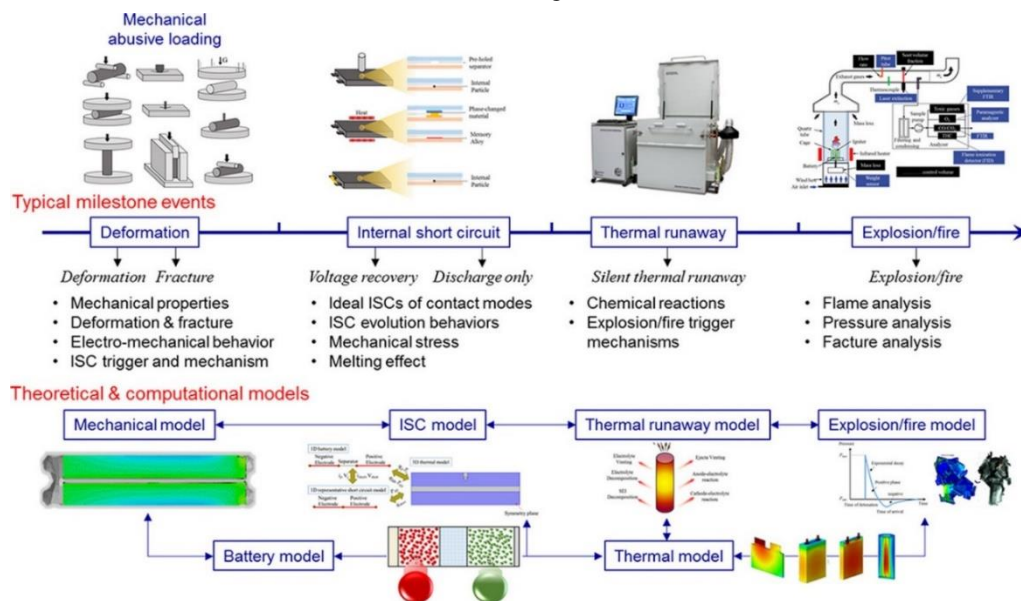
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**Figure 2: The structure and electrochemical characteristics of 18650 lithium-ion battery [1]**

A multi-faceted investigation into mechanical characteristics and maximum load capacity unveils the likelihood of developing approaches and escalating LIBs to adequately endure mechanical stresses during travel and installation. [3]Such factors are critical in attempting to address potential short/current pastes and separators that are often typical in batteries. This enhances the reliability of LIBs under abusive settings, furthering the value of systems reliant on battery and performance optimization.[4] Factually, understanding such mechanical behaviors may leverage the electrochemical performance of LIB's in such spots and adversely affect other factors, such as energy, as well as power output and cycle life. First, this might be potential with integration devices such as the present day electric automobile. Stringent regulatory kayak and standard centers have been particularly interested in battery reliability and safety. [5]A basic comprehension of the mechanical properties and maximum load capacities of lithium-ion batteries under abusive situations is the critical element in any compliance. Battery appropriate applications and clients, as well as local acceptance, are generated by regulatory expectations. Second, the mechanical behavior of LIBs continues outside this region of expertise, depending on the research. There get extra data when the underlying mechanisms that restrict research as well as further elements and design for the new batteries overlook the next section before understanding.



**Figure 3: Evolutionary process for LIB behavior upon mechanical abusive loading [1]**

The battery cell first deforms mechanically when mechanically abusive loading. A mechanical failure of separator or electrodes may cause a short circuit, the temperature will raise, produce gas, and increase the pressure.

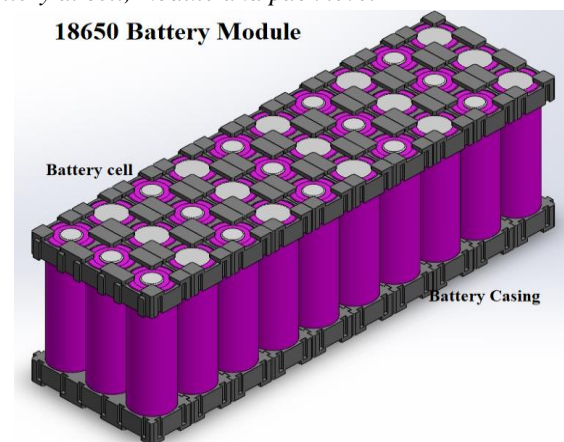
[6]Temperature rise becomes more sudden with the development of internal short circuit, which is termed thermal runaway. The thermal runaway becomes able of igniting a fire in severe conditions owing to high temperature. An example of the aforementioned process is illustrated in Fig. 3 in which a scenario formed four milestone stages, such as mechanical deformation, of internal short circuit, thermal runaway, and explosion/fire. [7]There are many paths for mechanical abuse to cause problems in lithium-ion batteries and the systems they power, which is why these abuse must be tested using standardized protocols. Mechanical abuse can serve as an ignition source for thermal runaway in lithium-ion batteries, leading to an uncontrollable temperature increase, electrolyte decomposition, and gas formation. The destruction of the cell can result in a fire and even an explosion, all of which are hazardous to persons, property, and the environment. [8]Mechanical harm, such as punctures or crushes, can induce an internal short circuit in lithium-ion batteries, leading to rapid discharge and localized heat generation. Short circuits have the potential to evolve into thermal runaway incidents, increasing the likelihood of fire and explosions. The mechanical properties of the cell components may be impaired due to mechanical abuse, resulting in electrolyte leakage. [9]Electrolyte leakage not only compromises battery performance but also increases the risk of chemical reaction, corrosion, and fire risks when released in the presence of air or other substances. Mechanical abuse may result in physical deformation or structural damage to the lithium-ion batteries' cells, modules, or modules. This interferes with the integrity of mechanical, electrical, and thermal contact between the cell elements, ultimately affecting overall system performance and safety. Mechanical abuse will release toxins such as electrolytes and electrode materials into the atmosphere. [10]It poses environmental risks due to pollution and necessitates costly cleaning and toxic waste disposal. Therefore, standardized testing protocols are vital to reducing these risks and increasing the safety and security of lithium-ion batteries. These protocols will allow the mechanical robustness and abuse endurance of lithium-ion batteries from different producers and end-uses to be efficiently tested. Test conditions and publishing protocols detail the specific mechanical abuse procedures, defined previously, like crush, penetration, and impacted tents, as well as key parameters, such as applied force, length of testing, and loading rates. Standardized test approaches describe the experimental procedures, instrumentation, and data collection methods required for consistent and repeatable mechanical abuse testing. [11]It help establish performance criteria and acceptance criteria goals provided desired levels of safety and reliability. As a result, LIBs must demonstrate they possess the requisite mechanical robustness and abuse tolerance capabilities. Standardized testing protocols are essential for achieving certification and compliance with industry standards, regulatory requirements, and safety certifications. [12]Specifically, LIB-based products must meet safety and performance expectations for conditions of routine and foreseeable abuse. Notably, standardized testing protocols offer a structured approach to reducing the risk of mechanical abuse of LIBs by Imposing penalties for prohibited acts and omissions. Consequently, adherence to the same testing protocols should boost confidence in LIB-based technologies and spur the development of safer and more reliable energy storage alternatives.

## II. MECHANICAL ASPECTS OF LITHIUM ION BATTERY

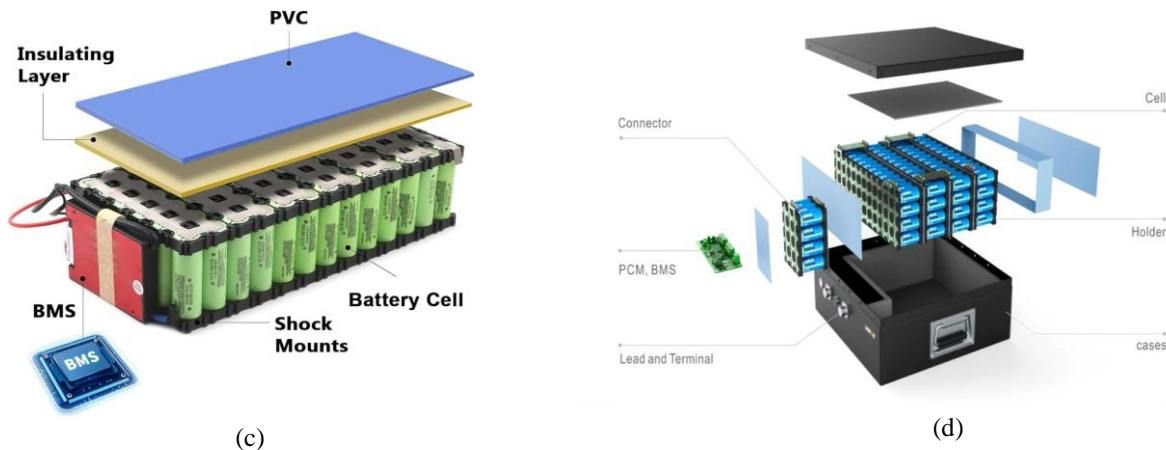
### A. Analysis of mechanical properties on lithium ion battery at cell, module and pack level



(a)



(b)



**Figure 4: construction of lithium ion battery. (a) Cell, (b) and (c) module, (d) pack level**

Figure 4 shows the constructive features of lithium ion battery at cell, module and pack level. Overall, the fundamental mechanical properties of lithium-ion batteries differ at cell, module, and pack levels, all of which are critical in determining the battery system's performance and reliability. The cell-level stiffness is the ability of the individual cell components to resist deformation or deflection under an applied mechanical load. [13] Specifically, it is primarily influenced by electrode thickness, separator properties, cell geometry, and corrosion resistance. High stiffness ensures the integrity of the cells and, thus, restricts excessive mechanical deformation during physical abuse. Cell strength is the ability of a cell to resist an external load, such as compression, tension, or torsion that cause it to rupture or may permanently deform it. The properties influencing strength are the mechanical properties of the electrode materials, the cell's electrolytes, and the cell mechanical packaging design. [14] High strength is essential to maintain the stability of the cells under abusive conditions. Deformation which defines the behavior or how the cell behaves when subjected to an external applied load. This includes bending, compression, and tension forces. The behavior of a cell under an external load helps in predicting the mode of failure and deciding on the best cell design to be used. Cells with low deformation tolerance should not be used in applications where mechanical stress is high such as automotive or aerospace systems. [15] The module's interfacial strength is the ability to stick individual cells together and what bonds cells to cell components, like the current collector, electrodes, and housing. Sufficient interfacial strength facilitates the required electrical continuity and mechanical stability and ensures heat dissipation inside the module. In addition to stiffness, deformation resistance also determines how well a module is capable of resisting various external mechanical loads without failure. Modules with a high deformation resistance are more likely to be able to absorb and dissipate mechanical stresses away from the cells and components, reducing the risk of localized cell damage. [16] At the pack level, the battery pack or assembly is capable of deforming slightly to absorb and dissipate external forces and stresses. From the aforementioned discussion, these fundamental mechanical properties must be fully considered when designing safer and more reliable lithium ion batteries. By maximizing strength, stiffness, and deformation, manufacturers will increase mechanical robustness of battery systems and hence buffer against the mechanical abuse, which is a threat to the performance of LIBs in long-term applications. [17] The mechanical properties of lithium-ion batteries are controlled by battery chemistry, electrode material, and production and assembly process. The following is a general overview of how these factors influence and relate to mechanical properties.

- *Electrolyte Composition:* The composition of the electrolyte has a significant impact on the mechanical properties of LIBs. Various types of electrolytes, including liquid, gel, and solid-state electrolytes, exhibit different mechanical properties. Solid-state electrolytes have higher mechanical stability than liquid electrolytes, thus posing a lower risk of electrolyte leakage and internal short circuits.
- *Separator Material:* The type of material used as a separator also influences the mechanical strength and deformation behavior of the LIB. Porous polymer separators are commonly used in LIBs as they are mechanically flexible, hard to puncture, and allows electrolyte transport while serving as a barrier to prevent short circuits.
- *Particle Size and Morphology:* The particle size and morphology of active electrode materials have an impact on the mechanical behavior of the LIB. Fine and uniform particle sizes allowing for dense packing and contact enhance the physical strength and chemical stability of electrodes.
- *Binder Selection:* Binders are important components of the electrode that dictate the adhesion between the active material and the current collector. The choice of binder affects the mechanical properties of the electrode;

mechanical strength, flexibility, cohesiveness, resistance to mechanical stress during cycling, and ideal performance under stress conditions.

- *Coating and Calendaring:* The choice of coating and calendaring process during the manufacturing of electrodes has an impact on the density, porosity, and mechanical strength of the electrodes. Good mechanical properties are achieved by adopting processes that increase packing density, eliminate voids, and achieve desirable particle-to-particle contact.
- *Cell assembly techniques:* different cell assembly methods such as winding, stacking, and pouch cell fabrication could also have a significant impact on LIBs’ mechanical properties. Proper cell assembly will ensure uniform electrode compression, uniform electrolyte distribution, and high mechanical robustness across the cell, reducing the possibility of internal short circuits or mechanical failure.
- *Encapsulation and packaging:* LIBs must be encapsulated and packaged to be more mechanically resistant to outer damage or mechanical hazards such as crush, pierce, or impact.

Integrating mechanical properties into the design and optimization of LIBs should be comprehensive and multifaceted. With the suitable selection of battery chemistry, electrode materials, and manufacturing processes, LIB manufacturers can use well-established materials and processes to ensure the mechanical robustness, safety, and reliability of lithium-ion battery systems. [18]

**B. Test Methodologies and Response on Mechanical Properties**

Well-established abuse testing protocols are necessary to assess the mechanical response of lithium-ion batteries under abusive conditions. Figure 5 indicates the Experimental setup and deformation of pouched (left) and bare (center) cells and Finite element models are shown in the (right) column, which can be performed on battery cell type to evaluate the response of battery testing on mechanical properties.

Test Type	Pouched Cells	Bare Cells	FE Models
(a) Through-Thickness Compression between Two Flat Plates			
(b) Hemispherical Punch Indentation			
(c) Three-Point Bending			
(d) In-Plane Unconfined Compression			
(e) In-Plane Confined Compression (only on bare cells)			

**Figure 5: Experimental setup and deformation of pouched (left) and bare (center) cells and Finite element models are shown in the (right) column. [2]**

Below are brief descriptions of some of the most commonly used abuse tests.

- *A crush test* involves evaluating the suitability of LIB cells, modules, and packs for mechanical robustness. The cell is put between two stiff plates or a hydraulic press, and a pre-set compressive load is gradually added until deformation or failure. Loading rate, maximum force, and time of the test are some of the critical test parameters that are considered. These evaluation factors are determined to provide a measure of deformation characteristics, structural integrity, and cell failure such as rupture and delamination.

- *Penetration test* assesses the ability of LIB cells or modules to resist penetration in sharp objects. A nail or a predetermined sharp object is pushed and the test is considered successful when the object penetrates the cell or when electrolytes are not spilled. Penetrator diameter and material, velocity, and angle of penetration are all expressions of the test parameters.
- *Thermal runaway test* LIB cells and cell modules are evaluated in a thermal runaway test, which is conducted to determine the circumstances under which a thermal out-of-control reaction is allowed to propagate. The initiation of an out-of-control reaction is promote by the provision of an external heating source, r overcharging the cells, or providing outside force. Heating rate, threshold temperature, temperature or gas generation curve are some of the expressions of temperature is monitored. Initiation of thermal runaway, propagation behavior, gas generation rate, and a product released are used to assess battery performance for safety and mitigation.
- *Vibration and shock test* Vibration and shock tests replicate the mechanical stresses faced by LIB cells during shipping, handling, or operation. Battery cells, modules, or packs undergo sinusoidal or random vibrations and mechanical shocks through a shaker and drop tester. Parameters for testing are vibration frequency, amplitude, duration, shock level, and waveform. Vibration and shock effects on cell/module structural integrity, electrical connectivity, and performance are examined through visual inspection, electrical tests, and postmortem studies. Abuse test conditions discovered some vital information regarding LIB mechanical behavior, failure mechanisms, and safety concerns. These abuse test conditions yielded vital information on LIB mechanical behavior, failure mechanisms, and safety concerns.[19]

C. *Effects of abuse testing on mechanical properties*

Figure 6 indicates The Process of Electric Vehicle Accidents Caused by Battery Failure where internal chemical reactions and a failure propagation driven by heat transfer will remain, which may cause the re-ignition problem that complicates the firefighting operations. Figure 7 shows Abuse Conditions Leading to Battery Failure in which the failure of lithium-ion batteries can occur with mechanical abuse, electrical abuse, and thermal abuse.

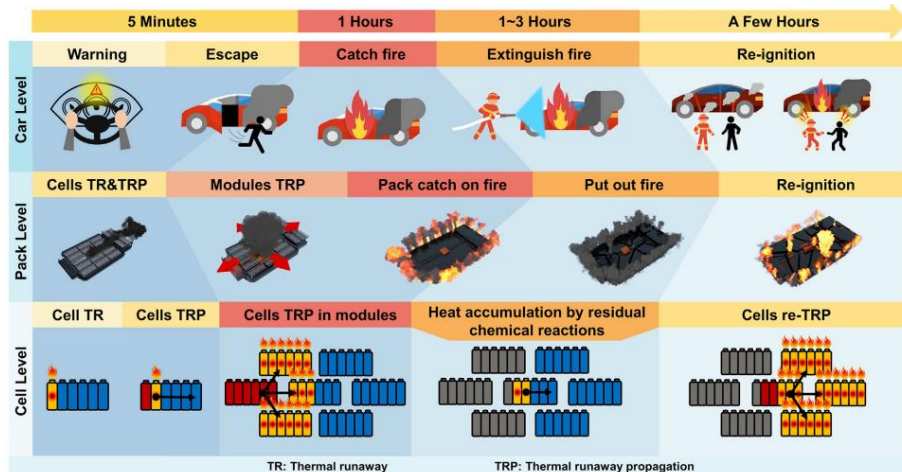


Figure 6: The Process of Electric Vehicle Accidents Caused by Battery Failure [3]

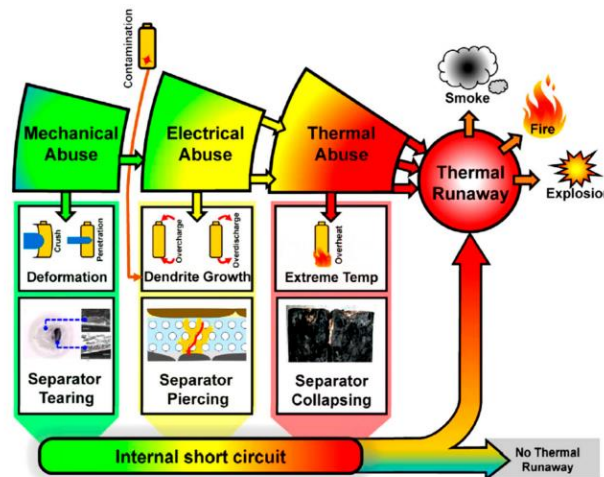


Figure 7: Abuse Conditions that Lead to Battery Failure [3, 4]

- **Deformation:** Compression, bending, or impact loading may cause deformation in LIB cells. Changes in the component after the tests are assessed through the force-displacement curves or visual inspection on the test samples. The degree of deformation and its patterns are the principal data VLSC serviced on the LIB's mechanical properties, stiffness, and ductility. Excess deformation would impair cell integrity, electrode-electrolyte contacts, and electrical connections, resulting in performance losses or catastrophic failure. Deformation knowledge might help to optimize LIB systems for mechanical integrity and safety.
- **Rupture:** Rupture of the LIB cells, modules, or packs occurs when the structure fails catastrophically under excessive mechanical loads, resulting in structural failure, leakage, or venting. Rupture events are detected through visual inspection, structural analysis, or force-displacement monitoring. The location, extent, and severity of rupture can indicate weak points, manufacturing defects, or material-related failure in the LIB. Rupture involves safety risks, including electrolyte leakage, thermal runaway, and fire. Therefore, analyzing rupture modes can identify critical failure mechanisms to enhance battery safety with design improvement or additional safety measures.
- **Thermal Runaway:** Thermal runaway of LIB cells refers to an uncontrolled exothermic reaction, leading to heat generation, temperature rise, gas generation, and possibly explosion. It can be detected through temperature monitoring, gas analysis, or visual observation of cell activity during abuse testing. The onset, propagation, and severity of thermal runaway can indicate battery safety and failure modes. Thermal runaway involves safety risks to users, property, or the environment. Therefore, anytime a LIB experience shows thermal runaway, the behavior is analyzed to determine the probable triggering factors, such as mechanical abuse, internal short circuit, or overcharging, and mitigation measures to prevent catastrophic thermal event.
- **Electrolyte Leakage and Gas Emission:** Mechanical abuse of the LIB cells, modules, or packs results in electrolyte leakage or gas emission from the components, indicating structural damage or internal short circuit. These responses can be based on visual inspection, gas sensors, or electrolyte sensors to determine leakage or gas composition or volume. Therefore, the response can indicate battery failure and involve safety hazards, such as chemical exposure, fire, or pollution. Therefore, anytime an LIB is smeared with electrolytes or gases, it is indicated, and the indices used in determining the response are analyzed to measure LIB response. The analysis of mechanical responses and failure modes observed during abuse testing presents valuable information on the behavior, safety, and reliability of lithium-ion batteries under such extreme conditions. By understanding these responses and failure mechanisms, researchers and manufacturers can design safer, more robust batteries and reduce the risks associated with mechanical abuse. The correlation between mechanical properties and maximum load capacities in abuse scenarios is crucial in understanding LIBs' behavior during the extreme conditions. Mechanical properties determine the ultimate load that a battery can withstand under different abuse scenarios.[20]

D. The relationship of mechanical properties to maximum loads

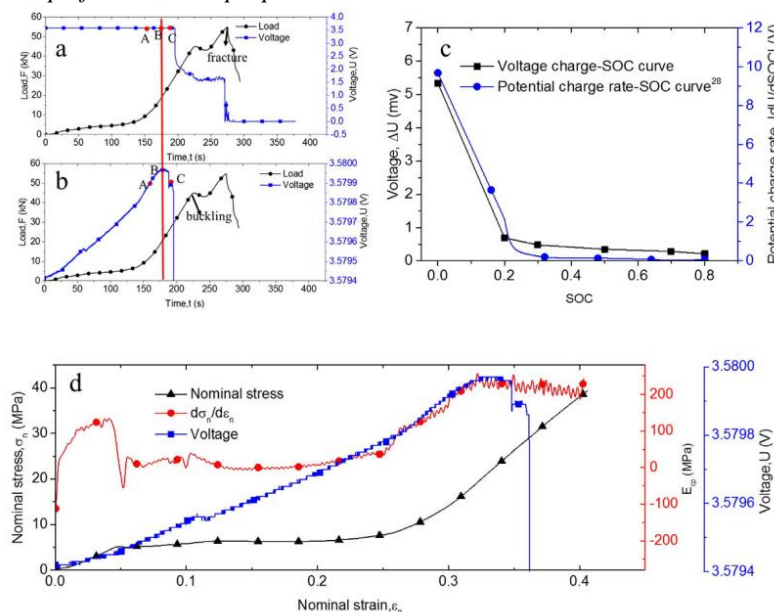
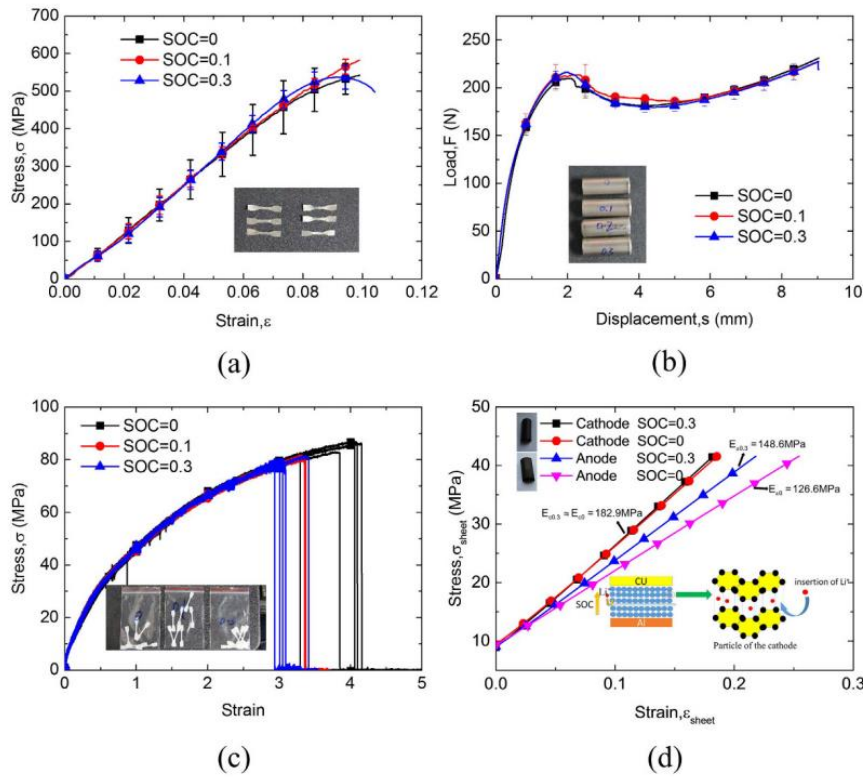


Figure 8: Effects of compression test on lithium ion battery [5]

Fig. 8(a, b) shows typical voltage-time and force-time curve in the compression test for 18650 LIB at SOC= 0.2; Fig. 8 (c) shows Voltage change–SOC curve maximum rising voltages in different SOC values during compression tests and potential charge rate–SOC curve; Fig. 8 (d) shows Illustration of nominal stress–strain, derivative nominal stress-strain, and voltage–strain curves in compression test for 18650 LIB at SOC= 0.2. During compression, the mechanical properties of stiffness, and strength are directly related to the mechanical abuse.



**Figure 9. Effects of tensile test on lithium ion battery cell [5]**

Figure 9 (a) Stress–strain curves for the tension tests of the skin under different SOC conditions, (b) Load–displacement curves for the compression tests of the skin under different SOC conditions, and (c) Stress–strain curves for the tension tests of the separator under different SOC conditions. Figure 9(d) Stress–strain curves for the compression of the cathode and anode under two different SOC conditions inequalities with schematic for the intercalation of  $\text{Li}^+$  where E denotes the bending modulus. The subscripts “a” and “c” denote anode and cathode, respectively, and numbers in subscripts are SOC values. A battery that has high levels of stiffness and strength can withstand a high level of compressive forces before deforming or failing. The LIB’s with good mechanical properties have high load levels during compression Penetration testing: mechanical properties affect the resistance of LIBs to penetration by sharp objects. A battery that is stiff, strong and deforms the least exhibits resistance to penetration. The LIBs with high mechanical properties have high abuse levels during penetration. A battery that does not deform during penetration through sharp objects is safe to handle and does not leak. While thermal runaway testing is primarily concerned with the thermal response of LIBs, mechanical properties are also evaluate in terms of their influence on the LIBs maximum load capacities during thermal abuse scenarios. Mechanical properties, such as stiffness, strength, and deformation characteristics, are directly related to the initiation and propagation of thermal runaway events. [21]LIBs with inferior mechanical properties can either face premature initiation of the thermal runaway or rapid propagation, resulting in reduced maximum load capacity. On the other hand, LIBs with consistently strong mechanical properties can withstand mechanical abuse without initiating the thermal runaway, which increases their maximum load capacities. [22]Overall the mechanical properties are directly proportional to LIBs maximum load capacities under abuse scenarios. The most hardened batteries with superior stiffness, strength, and deformation resistance properties have the highest maximum load capacities. [23]



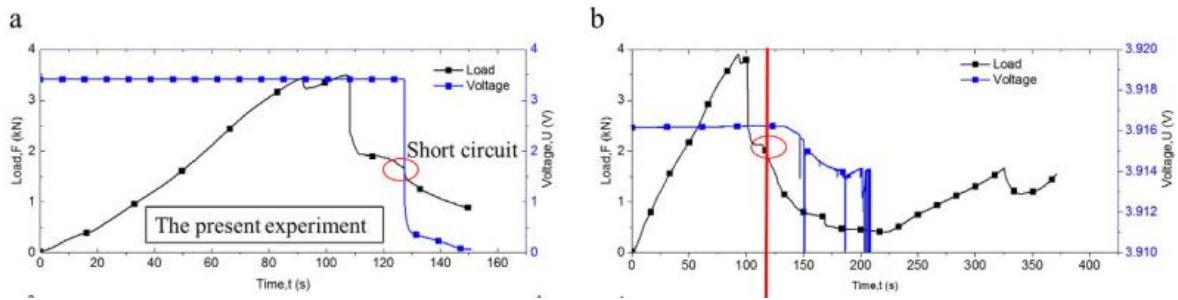


Figure 10: effects of bending test on lithium ion battery [5]

Figure 10 (a) shows Load and voltage-time curves for 18650 LIB under three-point bending tests with SOC= 0.1 whereas figure 10 (b) Load and voltage-time curve for 18650 LIB under three-point bending tests with SOC= 0.7. The relationship between mechanical properties and LIBs maximum load capacities is essential as it enables manufacturers to design high-strength batteries that can survive multiple abuse scenarios and still remain intact. Since abusive conditions can result in the failure of lithium-ion batteries, it is essential to consider some of the failure mechanisms that may occur due to effects on electrolytic solution. Electrolyte leakage is manifested by the presence of electrolytes outside the LIB cell or module enclosure, resulting from the loss of its physical integrity. Rupture of the cell case or cover, separator, and electrode layers can be caused by mechanical punctures, compression, or thermal expansion. Manufacturing defects, material degradation, and improper handling are possible causes. Chemical exposure, fire, and thermal runaway are all evident faults. [24] Furthermore, electrolyte leakage causes internal component corrosion, short circuits, and irreversible battery damage, resulting in power reduction or even catastrophic failure. Internal short circuits generally instigate safety issues. This may include fire, smoke, electrolyte leakage or escaping of other chemicals, thermal runaway, increase of pressure, and Capstone. Forming conductive bridges between battery electrodes inside the battery creates an internal short circuit. [25] Causes include electrode penetration, mechanical deformation, and separator damage during the manufacturing, assembly, and operation. Given these severe failure mechanisms under abusive conditions, awareness of the potential damages caused by electrode delamination, electrolyte leakage, and internal short circuits is critical to minimizing risks. Therefore, countermeasures developing and implementing to reduce the probabilities damage and chances to ensure the long turning performance of LIBs for various applications. [26]

### III. ADVANCEMENT IN BATTERY TECHNOLOGIES

It is crucial to develop and implement countermeasures to reduce the probabilities of damage and crash to ensure the long-term performance of LIBs for various applications. None of them will be complete without advanced strategies to improve the safety and reliability of lithium-ion batteries in the event of abuse.

#### A. Advanced materials:

- *Solid-state electrolytes*: Improved safety and stability compared to traditional liquid electrolytes due to their high mechanical strength, thermal stability, and Leach resistance and are not prone to leakage or combustion. This eliminates the risk of thermal runaway due to electrolyte and electrolyte-induced faller.
- *High-energy-density electrode materials*: Considered a need to more advanced electrode materials with higher energy densities and improved mechanical stability in the L 13 performance to reduce the risk of mechanical abuse incidence of one failure such as such lithium spark composite anodes and high-nickel cathodes materials are examples.
- *Self-healing polymers*: It may be required in battery a self-healing for energy coating or separator that is able to recover mechanical damage such as crack or the lamination in live active material allowing for repair reinstate original structural integrity without the user database.[27]

#### B. Structural design amendments:

- *Multilayered separator design*: Enhance the mechanical strength and puncture resistance of multi-layers separator design to improve the safety and reliability of lightweight battery by reducing damage in the separator-induced short-circuit and electrolyte.
- *Reinforced cell enclosures*: these are used with reinforced cell closure using impact materials likely include metallic or composite serving materials that would contain two cells and provide increased resistance to external mechanical abuse, reducing cell data for Malaysian rupture or penetration.

- *Flexible packaging materials*: Enables the fabrication of dual and deformable lightweight battery packs capable across multiple and mechanical stress. [28]
- C. *Active safety features*:
- *Pressure relief devices*: Delivers a pressure device such as a rupture disk or a vent system that is integrated into the closure to relieve conflict pressure build-up in live cell pack and energetic material production that would lead to catastrophic rupture of explosion.
  - *Thermal management systems*: Comprise of advanced thermal management systems operations Active heat sinks, case management materials, or active cooling system designs that are properly mitigate activity by eliminating or maintaining temperature safe level of teams.
  - *Battery Management Systems (BMS)*: BMSs that incorporate real-time monitoring, state-of-charge estimation, and cell balancing capabilities dramatically increase the safety and performance of LIBs. This is because they monitor abnormalities, reduce overcharging and overdischarging, and prevent thermal runaway. These new mitigation options benefit from recent advancements in materials science, engineering design, and electronics to considerably increase the safety, reliability, and performance of lithium-ion batteries under abusive use. By employing these techniques, battery producers and researchers can address safety concerns, meet regulatory requirements, and hasten the deployment of LIB-based technologies for a variety of applications. These include electric vehicles, renewable energy storage, and portable electronics. [29]

#### IV. SIMULATION AND EXPERIMENTATION

##### A. *Overview of Experimental test methodologies on li-ion battery cell*:

There are Mechanical behavior and safety performance of lithium-ion batteries under abusive conditions are extensively studied using various experimental setups, instrumentation, and data analysis techniques. Mechanical testing equipment includes specialized mechanical testing equipment, such as hydraulic presses, universal testing machines, drop towers, or pneumatic impactors. [25] These devices are used to apply controlled mechanical loads such as compression, tension, bending, or impact on LIB cells, modules, or packs. Environmental Chambers are used to maintain control over temperature, relative humidity, or atmospheric conditions during abuse testing. These chambers enable experiments to be carried out under controlled environmental conditions and facilitate exposure to real conditions. Physical safety measures, including blast shields, containment enclosures, and emergency shutdown systems, are utilized to minimize the risks associated with thermal runaway or mechanical failure during abuse testing. Force sensors, Load cells or force transducers are used to measure the applied force during compression, penetration, or impact experiments. [27] These sensors provide real-time force data, which is used to ensure proper loading conditions. Temperature sensors like Thermocouples or infrared cameras are used to measure changes in temperature within LIB cells or modules during thermal runaway testing. Sensing temperature changes helps identify when thermal events begin, monitor temperature rise rates, and gauge the severity of thermal runaway. Voltage and current sensors includes electrical measurements, such as voltage and current, are monitored during all tests to assess the electrical performance, as well as the possibility of internal short circuits or other electrical failures Experiments are filmed with high-speed cameras at high frame rates to allow for the visual analysis of deformation, rupture, or thermal events. High-speed video recording is critical in the visual analysis of failure mechanisms and dynamic behavior. Mechanical responses, such as stiffness, strength, or deformation behavior, may be determined through the analysis of force-displacement curves created using load cell data. [28] Temperature data from thermocouples or IR cameras are used during experiments to identify the initiation of thermal runaway; the propagation of thermal events; the maximum temperature that thermal runaway achieves. Failure mode analysis is used to identify the failure modes, studies rely on visual examination, microscopy, and post-test analysis. They may include mechanical deformation, rupture, delamination, electrolyte leakage, or electrode damage. Using Statistical analysis, such as regression analysis, analysis of variance, or reliability analysis, data are commonly analyzed and processed. Data variability and correlation between mechanical properties, conditions of abuse performance, and relevant battery performance metrics are determined. Overall, experimental setups, instrumentation, and data analysis techniques are critical in characterization, safety analysis, and failure mode determination in lithium-ion battery studies. These tools assist researchers in developing safer and more reliable energy storage systems. [29]

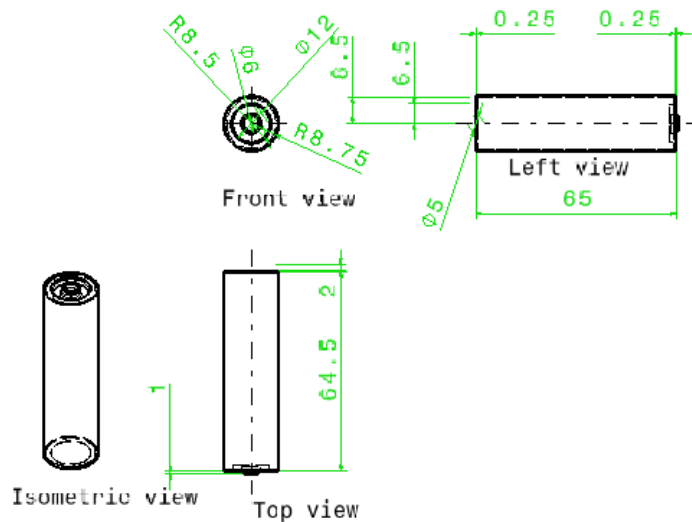
##### B. *Simulation study of Drop and Impact test on 18650 lithium ion battery cell*

###### *Material specification*

Table 1 indicates the mechanical material properties taken for CAD modeling of 18650 lithium ion cell and battery pack. Other material properties used for making case and terminals for battery cell. It also shows the parameters selected for drop and impact test in solidworks considering the AIS standard. Also Figure 11 shows, the dimension specifications for CAD modeling of 18650 lithium ion battery cell.

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

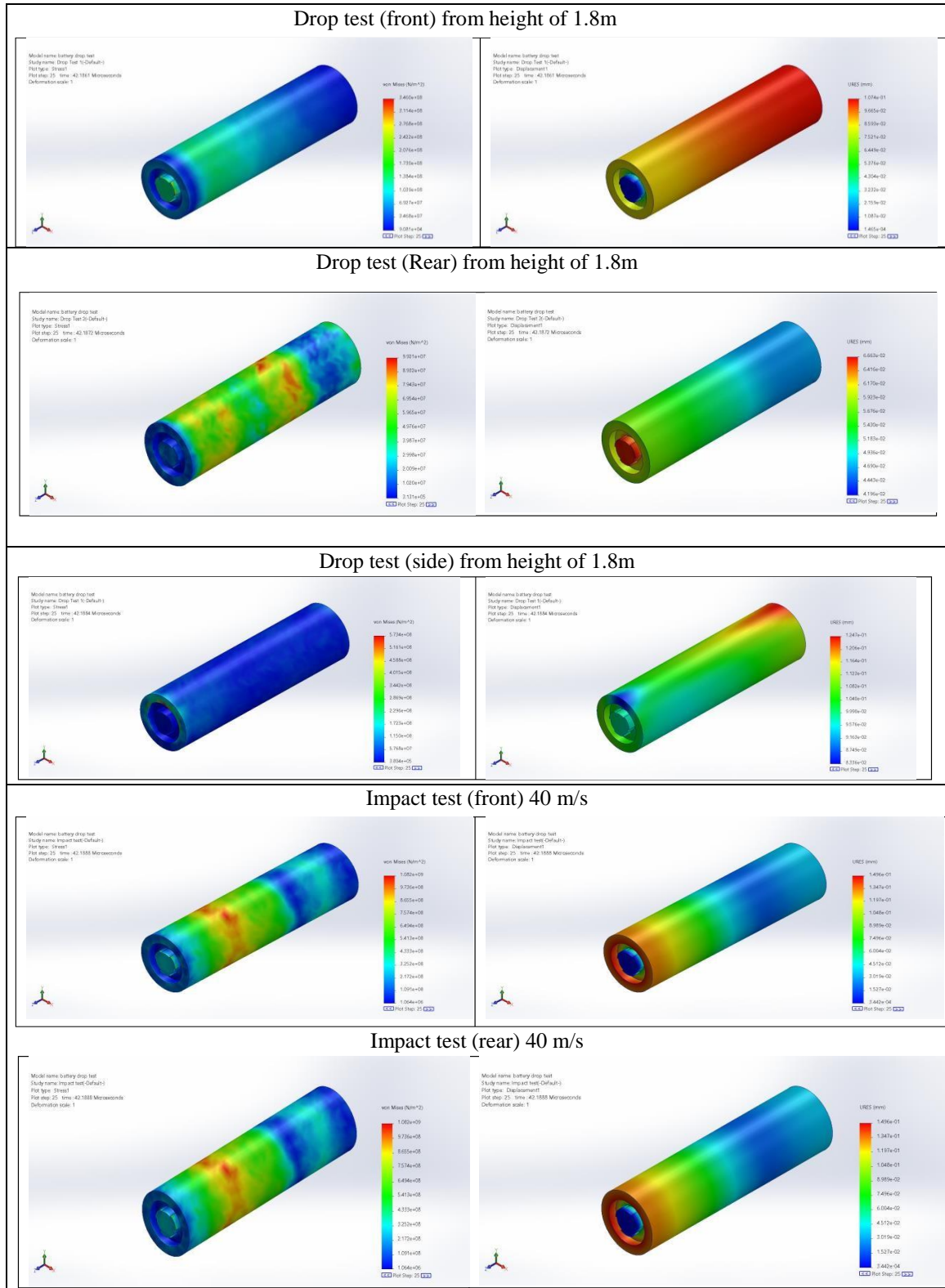
Sr. No.	Components	Specifications
1	Lithium cell	Mass:0.00865615kg, Volume:1.63324e-05m <sup>3</sup> , Density:530 kg/m <sup>3</sup> , Weight:0.0848303 N
2	Battery Case (aluminum)	Mass:0.00780363kg, Volume:1.01346e-06m <sup>3</sup> , Density:7,700 kg/m <sup>3</sup> , Weight:0.0764756 N
3	Battery caps(nickel)	Mass:0.000188594kg, Volume:2.21875e-08m <sup>3</sup> , Density:8,500 kg/m <sup>3</sup> , Weight:0.00184822 N
4	Drop height from lowest point	1,800 mm
5	Gravity	9.81 m/s <sup>2</sup>
6	Gravity Reference	Face<1>
7	Coefficient of friction	0.5
8	Target Stiffness	Rigid target
9	Critical Damping Ratio	0.3

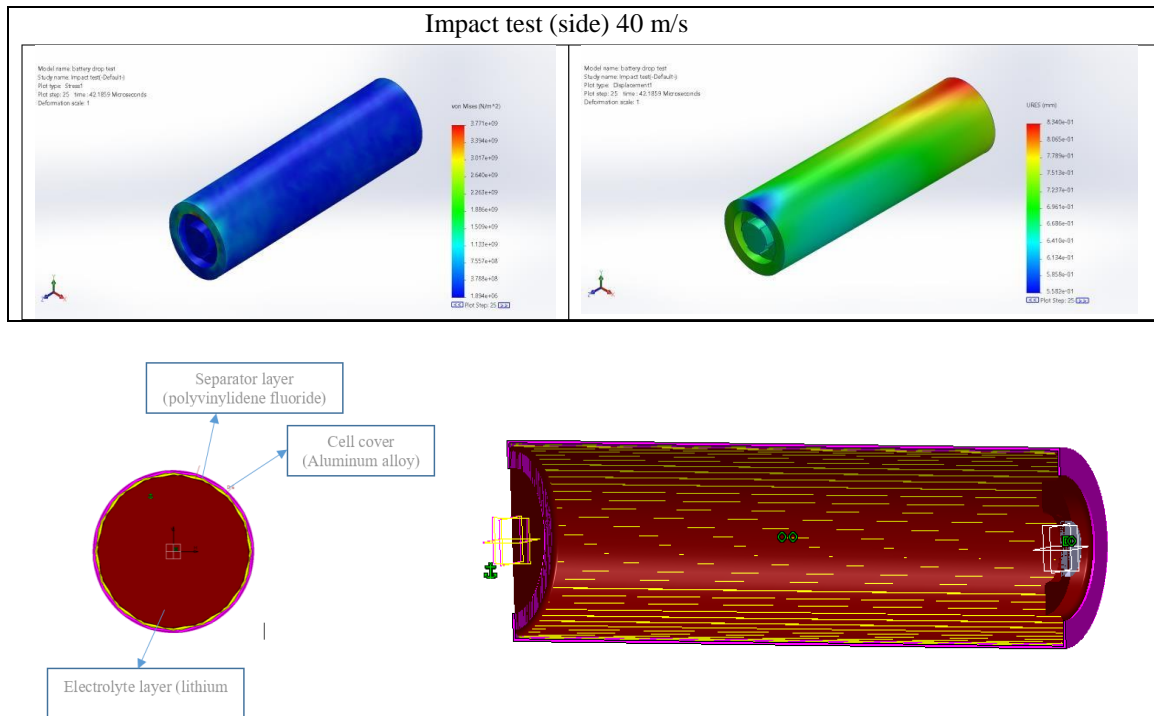


**Figure 11: CAD modeling specifications for lithium ion battery**

Table 2 indicates the simulation results for 18650 lithium ion battery cell for drop test and impact test for height of 1.8meters and velocity of 40m/s, indicating the severity and location of failures. Figure 12 shows the internal structural changes of lithium ion battery cell due to impact and drop test performed as per above specifications.

**Table 2: Simulation results of drop test for height of 1.8m in possible directions**





**Figure 12: battery drop and impact test layer variation at 1.4 meter height and 4m/s velocity from surface for front area**

### C. Implications for Battery Safety and Reliability:

The synthesized key findings derived from research studies on Lithium-Ion Battery abuse testing are instrumental in advancing battery safety, reliability, and performance. Indeed, by establishing critical failure messaging such as electrode delamination, electrolyte leakage, and internal shorting mechanisms under such conditions, researchers can pinpoint the root causes of battery failure. This understanding, in turn, points the way toward developing targeted mitigation strategies to counter these failure modes, thus enhancing battery safety. Additionally, the observed correlation between mechanical characteristics and the maximum load under different abuse conditions further highlights the need to optimize mechanical robustness in the design of LIBs. Specifically, increased stiffness, strength, and deformational resistance improve resistance to mechanical abuse, raising the threshold at which such abuse would result in failure and thus enhancing reliability. Furthermore, while a range of novel mitigation approaches based on advanced materials, such as solid-state electrolytes, high-energy-density electrodes, and self-healing polymers, appear promising, they have yet to demonstrate consistent results. These materials are specifically designed to offer mechanical stabilization, thermal resistance, and multiple safety features reducing the risk of failure under such conditions. [18] Similarly, structural modifications to the design, such as multilayered separators, stronger cell enclosures, and flexible packaging materials, have yet to be adopted in commercial production. These modifications would further reduce failure rates by providing additional protection against mechanical abuse, eliminating electrode delamination, and lowering the risk of thermal runaway. Finally, incorporating active safety systems, such as pressure release valves, thermal cutoffs, and complex battery management systems, substantially improves real-time monitoring and control over LIB operation under abusive conditions. Such systems allow for early detection of abnormalities, a rapid response to thermal runaway events, and prevent catastrophic failures, resulting in significantly improved battery safety. Ultimately, the synthesis of key findings from studies in the field of LIB abuse testing aids in the establishment of regulatory standards and industry norms regarding battery safety and reliability. [28] Adherence to these standards insures that LIB-based devices meet the minimum safety floor and inspires consumer confidence in their use across applications. Overall, the synthesized key findings of LIB abuse testing underline the importance of a multidisciplinary approach to battery design, integrating advances in materials science, engineering, and safety. Considering the emphasized failure mechanisms, optimizing mechanical characteristics, and developing novel mitigation approaches, researchers and manufacturers can enhance battery safety, reliability and, performance, facilitating the implementation of LIB-based technologies in various applications.

### D. Regulatory considerations, industry standards, and future research instructions

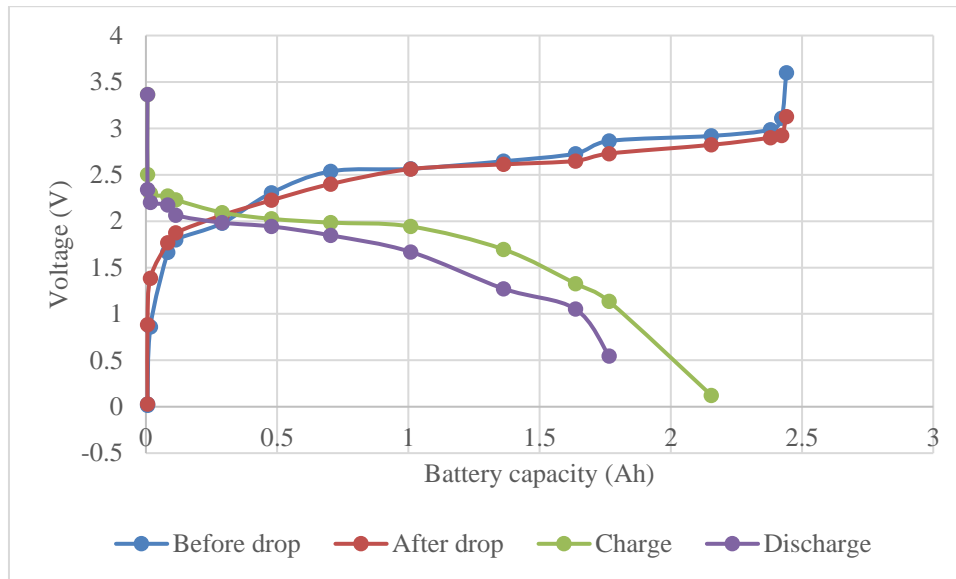
Regulatory considerations, industry standards, and future research directions are critical in advancing the field of lithium-ion battery abuse testing and ensuring the safety, reliability, and sustainability of LIB-based technologies. A majority of regulatory bodies enforce safety regulations with regard to the transportation, handling, and usage of LIBs. These regulations, including those from the U.S. Department of Transportation, the Federal Aviation Administration, and the International Civil Aviation Organization, typically lay down packaging, labeling, and testing requirements to minimize the risks of LIB abuse. Additionally, environmental and local authority bodies enforce environmental regulations that focus on hazardous materials and waste disposal during LIB manufacturing, recycling, and disposal.[20] Similarly, most regulatory bodies set product standards, such as UL 1642 for cell testing, UN 38.3 for transportation testing models, and others. In contrast, most environmental and local authority bodies and ASTM International develops voluntary consensus standards such as ASTM F2677 and ASTM D7777, contingent products testing and testing performance benchmarks, respectively. The International Electrotechnical Commission develops international standards, such as IEC 62133 and IEC 62660, for testing and evaluating LIBs across diverse applications. Research organizations also oversee future research directions that cut across identifying advanced materials such as solid-state electrolytes and nanomaterials and assessing the prevalence of incompatible materials with LIBs. Most of these approaches target enhancing the safety, energy efficiency, and reliability of LIBs for diverse applications. For example, more focus will feature enhanced safety and high-energy-density electrodes to stabilize LIB energy. Moreover, research efforts consider integrating artificially intelligent systems to manage the storage and retrieval of energy in LIBs. Standardization and future research will contribute significantly to enhancing the safety, reliability, and sustainability of LIB-based technologies.[27]

## V. RESULT AND DISCUSSION

The experiential test for single lithium ion 18650 cell is performed and results were taken about its mechanical and electrical parameters, before and after test as shown in figure 12. The drop impact test is vital in determining the structural integrity, safety and resilience of lithium-ion batteries in conditions similar to real-world events. Thus, the test is essential when utilized in the real-world applications such as electric vehicles, portable electronics and energy storage systems. Moreover, batteries are likely to receive mechanical shock during transportation, handling, or in case of accidents. Therefore, the drop and impact tests are required to ensure stability, reliability of lithium-ion batteries. Testing of batteries charged at controlled mechanical pressures enables researchers and engineers to discover failure modes, optimize system designs, and develop safe and robust energy storage solutions.

### A. Battery cell drop test.

Electrolyte leaking, smoking, fires, or battery explosions have not occurred following the drop test. A waterproof test was able to determine that the battery had lost its seal. From the visual inspection, some cracks and voids were seen at some positions in the shield portion of aluminum utilized in the production. Thus, there is a need to improve the battery cell in the external designs, for instance, in the rise of the mechanical capacity of the battery cell surface, progress workflow usage, battery sealing, and pre-comparison of battery electrical characteristics fall and strength & power. The result in Figure 13 during charging shows that the voltage stage is such that the curve does not change following the drop; it is roughly the same. Charge capacity and power attenuation are 0.97%. The terminal voltage of the battery is however overly higher following the collapse. In the first discharge curve, there was a great dispersion, and the voltages stage seems to have changed during withdrawal by a high level. The discharge capacity falls from 2.5Ah to 2.3Ah; the discharge has an energy fall from 9.2Wh to 9.1Wh thus; the two have been attenuated by 0.95% and 3.23%, successively.



**Figure 13: Lithium ion battery test and its effects on charging, before and after test**

#### B. Battery test effects after drop test:

Additionally, the charge and discharge test had to be conducted after the drop test and the test results indicate negligible variation of power and internal resistance w.r.to state of charge. There is no difference between the discharge power in the half power state before and after drop. Furthermore, a considerable variation in energy is seen during the cycle test of battery cell. There was no obvious effect of the battery voltage and discharge constant in this low battery state. The temperature rise of the battery pack has reduced compared with that before the crash, which is mainly due to poor sealing of the battery pack and the fact that the temperature of the battery pack rises to some extent. The relay will be disconnected if the battery management system performs a tamper protection test. The power battery cell will also not suffer shell explosion, smoke, fire, and other accidents. If the relay disconnects when the battery's maximum voltage exceeds 3.8V, it takes approximately 1.1s. The minimum battery voltage is less than 2.3V for about 0.7s. The battery management system relay was disconnected when the maximum temperature of the battery pack exceeds 60°C within 200ms. The battery did not cause gas, fire, or explosion. Own insulation is far more vital than the standard, and other abnormal conditions have no batteries. The fuse was fused in 15ms under full power condition for short circuit. A high-power relay can work normally. The battery pack is well protected. No batteries detecting exceptions. 1) When the anode position drop and impact test simulation results, the effects of failure on terminal end indicates failure due to internal short circuit and brake of battery terminal connections. Stress variation at the failure point can lead to the breaking of the separator layer. 2) The cathode position drop and impact test simulation results, the effects of failure on rear end indicates failure lead to the external short circuit. Stress variation at the failure point can lead to the breaking of the separator layer. To avoid this failure battery cells should always place vertically showing anode at top position. 3) The side position drop and impact test of lithium ion battery simulation, the failure due to failure lead to the external short circuit. Stress variation at the failure point can lead the breaking of the separator layer. Proper battery case should be designed to avoid directs impact on side surface of the battery.

## VI. CONCLUSION

In conclusion, the study of the mechanical properties and maximum load capacities of lithium-ion batteries when subjected to abuse testing cases has facilitated enhanced safety measures and improved reliability. Precisely, the above findings and implications underscored the following aspects, the mechanical properties and maximum load capacities of the LIBs cases abuse testing had a high correlation, indicating that the mechanical properties require further studies to improve quality and safety. The LIBs cases abuse were established encompassed numerous critical failure mechanisms. This assertion was supported by future studies on improvement and directions that proposed that more focus be on mechanical abuse analysis. Advanced materials and design are essential for the improvement of LIBs' abuse tolerance. Standard testing protocols facilitate a systematic approach to abuse assessment. In overall, it can be infer that the separator thickness has to improve with an optimal parameter to avoid contact between anode and cathode layer. The safety of battery cell is within the existing standards without leakage happened during test, without fire and explosion phenomenon. Comparative tests results revealed that

battery drops with battery pack has larger resistance, and less energy and capacity. But the discharge power between dropped battery and battery pack has no significant difference with that of before. But the battery management system played a protective role, and the fuse was also normal. Finally, future research may improve the methodology of testing, as well as developing innovative materials and safety strategies using emerging technologies.

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