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A Review on Mechanical Behavior of Lithium Ion Batteries for Electric Vehicles

Sonali Sabale[1,*], Deepak Watvisave[2], Vishwajit Gaike[3], Ravikant Nanwatkar[4],
Pravin Nitnaware[5], Aparna Bagde[6]

Abstract

The current automobile industries are much dependent on conventional petroleum fuels like petrol, diesel, etc. which are creating many environmental issues due to combustion reactions and generation of carbon dioxide. This continuous use of conventional fuels leads to either increasing the price of it and vanishing of its resources in future. Considering this, pure battery-based electric vehicle or electric vehicle with hybrid combination of battery and any other energy storage sources can be used for automobile field. Batteries can be powered with electricity produced by renewable energy sources such as wind, solar, and others that are being wasted by human beings for many decades. Hybridization can lead to shortening the harmful effects of petroleum fuels. There are different types of batteries that are available for automobiles, including lithium ion, lead acid, nickel bromide, etc. which are used as per the specification considering efficiency parameters. These batteries are having significant advantages of storage of tremendous amount of energy in small units replacing the use of engine and zero or negligible combustion reaction. With many advantages, these batteries have some drawbacks like thermal runaway, overcharging, sensitivity to variation in temperature and most important cost and disposal. The major cause of these drawbacks depends on the mechanical properties of the battery. Mechanical deformation of the battery leads to failure of separator and current collector which gives rise to initiation of electrode contact creating many thermal issues in battery cell or packs. The current work focuses on review of causes and effects of generation of mechanical deformation in battery and modes to reduce it by significant way in considering less or negligible effect on efficiency parameters. Four different sources of mechanical stress exerted on a battery implemented in a structure are examined in this study, namely, structural, thermal, fabrication, and kinetics.

Keywords: Electric vehicles, battery, thermal runaway, mechanical deformation

***Author for Correspondence**
Sonali Sabale
E-mail: ravikant.nanwatkar@sinhgad.edu

[1,4]Research Scholer, Department of Mechanical Engineering, STES's Sinhgad College of Engineering, SPPU, Pune, India
[2]Research Guide, Department of Mechanical Engineering, MKSSS's Cummin's College of Engineering, SPPU, Pune, India
[3]Assistant Professor, MBA [HR & OB], Bharati Vidyapeeth, Pune, Maharashtra, India, Pune
[5]Department of Mechanical Engineering, D Y Patil College of Engineering Akurdi Pune, SPPU, Pune, India
[6]Department of Computer Engineering, JSPM NTC, Narhe, Pune, SPPU, Pune, India

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INTRODUCTION

Lithium-ion batteries (LIBs) are at the forefront of powering electric vehicles (EVs), largely due to their high energy density, long cycle life, and ability to deliver efficient power in a lightweight form. LIBs consist of two primary components: a cathode (positive electrode) and an anode (negative electrode), with a lithium salt electrolyte enabling ion movement between them during charging and discharging cycles. This movement of lithium ions creates a flow of electrons, providing the electrical power needed to drive an EV's motor. One of the key reasons LIBs have become the preferred technology for EVs is their ability to store more energy per unit of weight compared to other types of batteries, offering a higher energy density. This is essential for EVs, as it allows them to achieve longer driving ranges on a single charge, addressing one of the primary concerns of consumers considering the switch to electric transportation. Additionally, LIBs are more efficient in energy conversion, which enhances the vehicle's overall performance and reduces energy losses. As EVs continue to grow in popularity, LIB technology has evolved to address limitations such as charging times, battery longevity, and cost, driving advancements in electric vehicle development.

LIBs offer significant advantages over traditional battery technologies, such as lead-acid and nickel-metal hydride (NiMH), making them the ideal choice for EVs (Figure 1). One of the most important advantages is their higher energy density, which allows EVs to store more energy in less space and weight. This leads to a greater driving range per charge, which is essential for making EVs more practical for daily use and long-distance travel. Additionally, LIBs have a lower self-discharge rate, meaning they retain their charge longer when not in use, which is beneficial for ensuring the battery remains ready for use when the vehicle is needed. Another significant advantage is their longer cycle life, as LIBs can endure more charge and discharge cycles before experiencing a noticeable reduction in capacity, making them more cost-effective over the long term. In contrast, older technologies like lead-acid batteries experience much quicker degradation, requiring more frequent replacements. Furthermore, LIBs are capable of fast charging, which reduces the downtime for vehicles, allowing EVs to be recharged more quickly compared to other battery technologies. These advantages position LIBs as the leading choice for EVs, offering improved range, performance, and longevity compared to other energy storage options.

The mechanical behavior of LIBs is crucial in ensuring their durability, performance, and safety in EVs. During their use, LIBs experience a range of mechanical stresses, such as vibrations, shocks, and thermal expansion, which can have significant effects on their internal structure and overall functionality. For instance, during driving, EVs generate vibrations from road surfaces, and mechanical forces such as impacts and bending can cause internal damage to the battery's electrodes or separators, potentially leading to reduced battery life or catastrophic failure. Additionally, the changes in temperature due to charging and discharging cycles cause the battery components to expand and contract, creating mechanical stresses that can lead to material fatigue or failure over time. These mechanical factors can cause electrode delamination, separator punctures, and electrolyte leakage, all of which degrade the performance of the battery. Therefore, understanding and optimizing the mechanical behavior of LIBs—through the use of advanced materials, robust packaging designs, and rigorous testing—are essential to ensuring the long-term durability and efficiency of EV batteries. Mechanical stress testing, such as vibration, compression, and impact testing, plays a critical role in simulating the real-world conditions that batteries will face, allowing manufacturers to improve battery pack designs and enhance the overall safety and reliability of electric vehicles. Ensuring that LIBs can withstand mechanical stresses without compromising their performance is essential for maintaining high energy efficiency, reducing safety risks, and extending the operational lifespan of EVs.

Problem Statement

The performance, safety, and longevity of LIBs in EVs are highly influenced by their mechanical behavior. Mechanical stresses such as vibrations, thermal expansion, and external impacts during vehicle operation can cause damage to the internal components of LIBs, leading to degradation of performance, reduced lifespan, and potential safety risks such as thermal runaway or short-circuiting. While significant advancements have been made in improving the energy density and efficiency of LIBs, the understanding of their mechanical behavior under real-world conditions remains limited. Thus, there is a need for a comprehensive review of the mechanical behavior of LIBs in EVs to address these issues and ensure their durability, performance, and safety under various operating conditions.

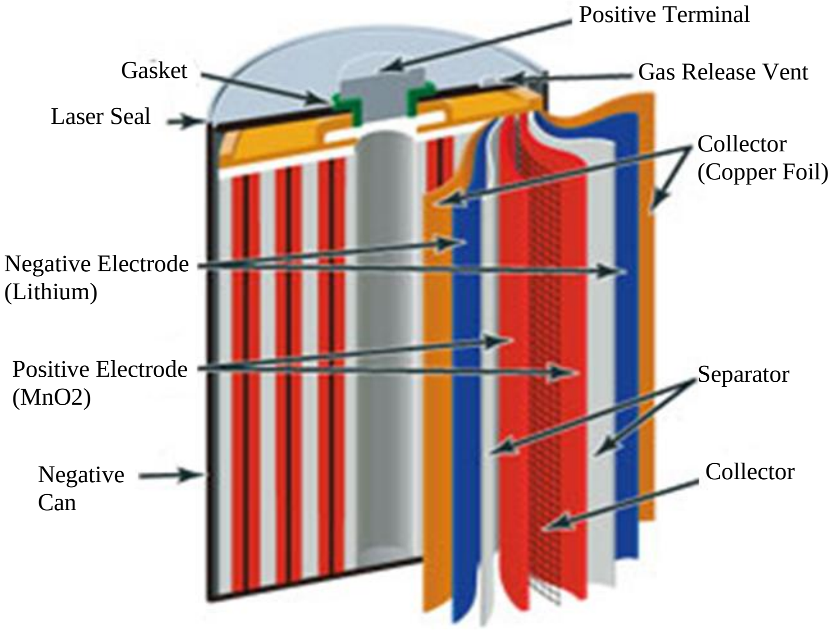

Figure 1. Structure of lithium-ion battery.

Objective

The primary objective of this research paper is to provide a thorough review of the mechanical behavior of LIBs used in EVs, focusing on the key mechanical challenges and their impact on battery performance and safety. The paper aims to:

1. Examine the effects of mechanical stresses such as vibrations, shocks, and temperature fluctuations on the structural integrity of LIBs.
2. Review the impact of mechanical failures like electrode cracking, separator damage, and electrolyte leakage on the performance and safety of EV batteries.
3. Identify and analyze the testing methods used to evaluate the mechanical behavior of LIBs.
4. Explore advancements in materials and design solutions that enhance the mechanical resilience of LIBs in EVs.
5. Provide recommendations for future research directions to address existing challenges in the mechanical behavior of LIBs for EV applications.

Scope and Novelty of Work

The scope of this research paper encompasses a detailed review of the mechanical behavior of LIBs used in EVs, including both experimental and theoretical aspects. The paper will cover:

1. A discussion of the key mechanical properties of LIBs, such as stress, strain, fatigue, and deformation, and how these properties impact battery performance.
2. A review of the factors affecting the mechanical behavior of LIBs, such as temperature, vibrations, shock loads, and charging/discharging cycles.
3. The evaluation of various mechanical testing techniques, including their applicability to LIBs in EVs.
4. An exploration of design strategies and material innovations that mitigate mechanical failure and enhance the durability of LIBs.

The novelty of this work lies in its comprehensive approach to understanding the interaction between mechanical behavior and electrochemical performance, providing an integrated perspective that can guide the design of more durable and reliable battery systems for EVs. The paper will also highlight gaps in current research and suggest innovative approaches for future work in improving the mechanical integrity of LIBs.

Methodology

To write this research paper, the following methodology was adopted:

Literature Review

An extensive review of existing research articles, journals, and conference papers related to the mechanical behavior of LIBs was conducted. This included studies on mechanical testing methods, failure modes, and advancements in battery design for enhanced mechanical performance.

Data Collection

Relevant data on mechanical behavior, including stress-strain responses, thermal expansion characteristics, vibration resistance, and fatigue behavior, was gathered from published research and experimental studies.

Categorization and Analysis

The collected data were categorized based on factors affecting mechanical performance, such as external forces (vibrations, shocks), environmental conditions (temperature fluctuations), and internal factors (charging/discharging cycles). The impact of each factor on battery life and safety was analyzed.

Comparison of Testing Methods

A comparative analysis of various mechanical testing techniques used for LIBs was performed to assess their strengths, weaknesses, and relevance to real-world EV applications.

Design and Material Considerations

The review also covers recent advancements in material science and battery pack design strategies that aim to improve the mechanical robustness of LIBs, including the use of advanced composite materials and enhanced structural designs.

Synthesis and Recommendations

Based on the analysis, the paper synthesizes key findings and provides recommendations for future research directions. This includes identifying knowledge gaps, proposing new areas of investigation, and suggesting potential improvements in battery technology to enhance mechanical resilience in EV applications.

LITERATURE SURVEY

A summary of the literature survey is presented in Table 1 [1–10]. The mechanical behavior of LIBs is crucial for their performance, safety, and longevity in EVs. LIBs, like other materials, experience stress, strain, deformation, and fatigue under various loading conditions. Stress refers to the internal forces that resist external mechanical forces, while strain is the resulting deformation caused by stress. Deformation occurs when the battery materials stretch, compress, or bend under external forces, which may lead to irreversible changes in shape. Fatigue is the process of material deterioration that happens when a material is subjected to repeated cycles of stress and strain, often leading to the initiation of cracks or other structural failures. Understanding these mechanical properties is essential, as they directly influence the performance and lifespan of LIBs. For instance, high mechanical stresses can cause the electrodes to crack or degrade, which in turn reduces the battery's ability to hold charge. Deformation of structural materials can lead to poor alignment of the internal components, compromising the electrical and thermal management of the battery. Fatigue damage in LIBs may result in reduced cycle life and the gradual decline in battery capacity.

Mechanical behavior plays a significant role in determining key performance parameters of LIBs, including energy density, cycle life, and thermal stability. Energy density is the amount of energy stored per unit of mass or volume. Mechanical deformations, such as swelling or cracking, can cause the electrodes to misalign, thereby reducing the available area for energy storage and lowering the energy density. Mechanical stresses also influence cycle life, as repeated strain during charge-discharge cycles can lead to material fatigue and damage, causing a loss of capacity over time. Thermal stability is another critical performance factor, as excessive mechanical deformation can lead to the release of heat and increase the likelihood of thermal runaway or short-circuiting. Thus, a stable mechanical environment is essential to maintaining high energy density, long cycle life, and safe thermal management.

Mechanical stress can have a significant impact on the key materials in LIBs, including the electrodes, electrolyte, and separator. The electrodes are typically made from materials such as graphite (anode) and lithium cobalt oxide or lithium iron phosphate (cathode), which are susceptible to cracking or delamination under stress. When these cracks form, they reduce the effective surface area available for lithium-ion exchange, thereby diminishing battery efficiency. The electrolyte, which facilitates ion movement between the electrodes, may leak or degrade under mechanical strain, reducing the ionic conductivity and overall battery performance. The separator, a porous membrane that prevents short-circuiting between the electrodes, may puncture or shrink due to excessive stress or temperature fluctuations, potentially leading to short circuits or even fires. Therefore, understanding the mechanical stresses that affect these materials is vital for designing more robust and safer LIBs.

MECHANICAL TESTING METHODS

Various experimental techniques are used to assess the mechanical behavior of LIBs, ensuring that they can withstand real-world operational conditions. Common methods include compression, tension, and bending tests. Compression tests involve applying compressive forces to evaluate how the battery materials deform under load. Tension tests, on the other hand, stretch the battery materials to observe their resistance to tensile forces. Bending tests are conducted to simulate the bending forces that may be applied to batteries during usage, such as from vibrations or mechanical impacts in a vehicle. These basic tests help identify the mechanical limits of LIBs and provide crucial data on their structural integrity under different stress conditions. In addition to traditional testing methods, advanced techniques like nanoindentation, X-ray tomography, and strain gauges offer more detailed insights into the mechanical behavior of LIBs. Nanoindentation measures the hardness and elastic properties of battery materials at a microscopic level, providing valuable information about how materials will respond to small-scale forces. X-ray tomography enables the visualization of the internal structure of LIBs, allowing researchers to detect internal defects, cracks, or deformation without disassembling the battery. Strain gauges are used to measure the strain and deformation of materials in real-time, giving accurate measurements of how the battery components respond to mechanical loading. Each of these testing methodologies has its advantages and limitations. While basic tests such as compression and tension are useful for evaluating overall material behavior under standard loading conditions, advanced techniques like nanoindentation and X-ray tomography provide more in-depth, localized insights into battery integrity. In the context of EVs, a combination of these methods is typically used to assess the mechanical robustness of LIBs under the unique conditions they face, such as vibrations, thermal fluctuations, and external impacts (Table 2).

Factors Affecting Mechanical Behavior

Temperature fluctuations can significantly affect the mechanical properties of LIBs. High temperatures can cause expansion of materials, potentially leading to deformation, swelling, or stress-induced failure. Conversely, low temperatures can cause contraction and brittleness, increasing the risk of cracking or material fatigue. These temperature-induced mechanical changes can result in decreased performance, reduced energy density, and shortened cycle life. During the charging and discharging processes, LIBs undergo repeated volume changes due to the movement of lithium ions between the electrodes. These volume changes can induce mechanical stress, leading to structural deformation or fatigue over time. Repeated cycles can also cause electrode cracking, delamination, and other forms of material degradation, ultimately impacting the battery's overall lifespan and performance.

Table 1. Summary of literature survey.

Name of Author(s), Publisher and Year of Publication	Title of Paper	Methodology / Findings	Scope of Further Work
Golriz Kermani, Mohammad Mehdi Keshavarzi, et al., Elsevier Publication, 2021 [1]	Deformation of lithium-ion batteries under axial loading: analytical model and representative volume element	Parameters controlling the in-plane deformation of cells	The proposed method is applicable only to flat sections of pouch and prismatic cells and cannot be applied to cylindrical cells with wounded jellyrolls. Also, the post-buckling response of cells cannot be predicted by this approach.
Ran Tao, Zhibo Liang et al., Acta Mechanica Solida Sinica, Elsevier Publication, 2021 [2]	Mechanical analysis and strength checking of current collector failure in the winding process of lithium-ion batteries (LIBs)	Work stems from the difficulty and obstacles in the winding process of actual production of LIBs.	Other experimental crash test can be worked with same methodology.
Wenwei Wang, Yiding Li, et al., Springer Open Journal, 2020 [3]	Mass-spring-damping theory based equivalent mechanical model for cylindrical lithium-ion batteries under mechanical abuse	An equivalent mechanical model with the equivalent physical meaning of mass-spring-damping is proposed for cylindrical LIBs	The model can be used in safety warning devices based on mechanical penetration.
Juner Zhu, Marco Miguel Koch et.al., Journal of the Electrochemical Society, 2020 [4]	Mechanical deformation of lithium-ion pouch cells under in-plane loads—part I: experimental investigation	The mechanical deformation of a large-format lithium-ion pouch cell under in-plane loads is investigated via compression of fully constrained cells, in-plane compression of cells sandwiched by foams, and in-plane indentation by a round punch.	More research is needed to get better understandings of several other battery and loading parameters.
Lian, Junhe; Koch, Marco et al., Journal of the Electrochemical Society, 2020 [5]	Mechanical deformation of lithium-ion pouch cells under in-plane loads-part II	The study aims to provide a modeling approach for the in-plane compression on lithium-ion pouch batteries in a fully confined case with a flat punch.	The imperfections in the homogenized model, limited effects on the formations of buckles, Finer mesh could lead to a reduction of the force response.
Faezeh Darbaniyan, Xin Yan, Journal of Applied Mechanics, 2019 [6]	An atomistic perspective on the effect of strain rate and lithium fraction on the mechanical behaviour of silicon electrodes	The mechanisms underlying the plasticity behavior of Si-anode as a function of lithiation	Methodology can be applied with different tests and battery set up.
Rong Xua, Yang Yang et al., Elsevier Journal of the Mechanics and Physics of Solids, 2019 [7]	Heterogeneous damage in Li-ion batteries: Experimental analysis and theoretical modelling	The heterogeneous electrochemistry and mechanics in a composite electrode of commercial batteries using synchrotron X-ray tomography analysis and microstructure resolved computational modeling.	Methodology can be applied with different tests and battery set up.
Sangwook Kim and Hsiao-Ying, et al., Journal of Materials Research, 2016 [8]	Mechanical stresses at the cathode–electrolyte interface in lithium-ion batteries	Multiphysics finite element models to understand fluid–structure interactions in a half-cell battery system. Effects of C-rate, particle sizes, lithiation, and phase	The methods and findings could also be broadly applicable to other battery technologies, such as sodium-ion, magnesium-ion, and potassium-ion.

		transformation of the cathode at the interface	
Hansinee Sitinamaluwa, Jawahar Nerkar, et al., RSC Advances, 2017 [9]	Deformation and failure mechanisms of electrochemically lithiated silicon thin films	Deformation and failure mechanisms of electrochemically lithiated a-Si thin films using nanoindentation and molecular dynamics simulation techniques.	The methods and findings can be used for other testing and battery combinations.
Liang Tang, Jinjie Zhang, et al., PLoS One journal 2017 [11]	Homogenized modelling methodology for 18650 lithium-ion battery module under large deformation	A general method to establish a computational homogenized model for the cylindrical battery module is proposed.	The homogenized modeling method is widely applicable for different packing modes
Cheng Lin, Aihua Tang, et al. Hindawi Publishing Corporation, Journal of Chemistry, 2017 [12]	Electrochemical and mechanical failure of graphite-based anode materials in Li-ion batteries for electric vehicles	Worked on single particle model (SPM) based on kinetics of electrochemical reactions. Then the Li-ion concentration and evolution of diffusion induced stresses within the SPM under galvanostatic operating conditions were analyzed by utilizing a mathematical method.	Further work can be done on cathode part of battery.
Sulin Zhang, NPJ Computational Material journal, 2017 [13]	Chemomechanical modelling of lithiation-induced failure in high-volume-change electrode materials for lithium ion batteries	Worked on progress in continuum-level computational modeling of the degradation mechanisms of high-capacity anode materials for LIBs using silicon (Si) as an example.	Focused studies are still critically needed to understand and control these interfacial processes to enhance the overall performance of the electrode materials for LIBs.
Jun Xu, Binghe Liu et al., Nature Scientific Reports, 2016 [14]	State of charge dependent mechanical integrity behavior of 18650 lithium-ion batteries	The electrochemical failure behaviors of LIBs with various states of charge (SOCs) under both compression and bending loadings, underpinned by the short circuit phenomenon.	Used to understand the mechanical integrity behavior at working condition and also provides basic experimental results to guide crash-safety single battery and battery pack design and monitoring.
Scott A. Roberts, Hector Mendoza, et al. Journal of Electrochemical Energy Conversion and Storage, 2016 [15]	Insights into lithium-ion battery degradation and safety mechanisms from mesoscale simulations using experimentally reconstructed microstructures	Computational approach for modeling electrochemical, mechanical, and thermal phenomena of lithium-ion batteries at the mesoscale.	Further work can be modified with advanced numerical methods.

Impact of Mechanical Loads (Vibrations, Shocks) from the Vehicle Environment on Battery Cells

Mechanical loads such as vibrations, shocks, and impacts are inherent in the vehicle environment. These loads can induce mechanical stresses that lead to internal damage in LIBs, including cracking, separator puncture, or short-circuiting. The design of battery packs and modules must account for these external forces to ensure that the battery remains intact and functional under real-world driving conditions. As LIBs age, they undergo several degradation mechanisms that impact their mechanical and electrochemical performance. These include electrode cracking, electrolyte leakage, and separator puncture, all of which can result in reduced capacity, poor performance, and safety concerns. Understanding these degradation processes and their relationship to mechanical stresses is essential for developing more durable and reliable LIBs [10].

Table 2. A comparison of various testing methodologies and their applicability to lithium-ion batteries (lIBs) in electric vehicles (EVs).

Testing Methodology	Description	Applicability to LIBs in EVs	Advantages	Limitations
Compression test	Application of compressive forces to assess deformation and stress.	Useful for simulating forces from external pressure, such as during crashes or impacts in EVs.	Simulates real-world conditions like mechanical impacts.	May not capture localized damage or small-scale stress.
Tension test	Stretching the battery material to observe tensile strength and elongation.	Helps assess how materials, especially electrodes LIB, respond to forces that stretch them.	Provides data on material elongation and breaking points.	Limited applicability to LIBs under normal EV operating conditions.
Bending test	Applying bending forces to assess flexibility and structural integrity.	Simulates mechanical stress from vibrations or bending during driving.	Evaluates flexibility and resistance to bending.	May not be as relevant for batteries with rigid structures.
Nanoindentation	Measures hardness and stiffness of materials at micro/nanoscale.	Useful for evaluating electrode materials, separator films, and electrolyte layers.	Provides precise data on hardness and stiffness.	Only measures small-scale mechanical properties, not full battery response.
X-ray tomography	Uses X-ray imaging to visualize internal structures and defects.	Detects cracks, deformations, and internal damage without disassembling the battery.	Non-destructive, detailed visualization of internal structure.	Limited to 2D or 3D imaging; may not reveal all types of failures.
Strain gauges	Measures strain and deformation in real time during mechanical testing.	Tracks deformation under actual mechanical loads, such as vibrations or impacts.	Provides real-time, localized strain data.	May require extensive setup and calibration for complex battery designs.
Dynamic vibration testing	Subjecting the battery to vibration or shock tests to assess resilience.	Simulates real-world conditions in EVs, such as road vibrations and handling shocks.	Good for understanding battery behavior in dynamic environments.	May not represent all real-world loading conditions or mechanical stresses.
Fatigue testing	Repeated loading and unloading to assess the effects of cyclic stress.	Helps predict long-term performance and the potential for mechanical failure due to repetitive cycling.	Provides insight into battery degradation over time.	Time-consuming and may not reflect all EV operating conditions.
Drop test	Simulates impacts from drops or accidents by subjecting the battery to a fall.	Tests battery resilience against external impacts, such as accidents or harsh handling.	Simulates high-impact events that may occur in EVs.	Does not account for prolonged or low-level stresses.

Mechanical Behavior at Cell, Module, and Pack Levels

The mechanical behavior of LIBs differs at the cell, module, and pack levels due to the varying structural and design requirements at each level. At the cell level, individual battery units are subjected to localized mechanical stresses, while at the module and pack levels, these stresses are distributed across multiple cells and managed through packaging and structural components. The design of modules and packs must ensure that cells are securely held in place, minimizing movement and the risk of mechanical damage (Table 3).

Table 3. Differences in mechanical behavior at the cell, module, and pack levels.

Aspect	Cell Level	Module Level	Pack Level
Mechanical stress	Primarily influenced by internal electrode swelling, shrinkage, and deformation.	Stresses arise from interactions between cells and module casing, as well as thermal expansion.	Mechanical stresses result from external impacts, vibrations, and pressure on the entire pack.
Deformation behavior	Cells may experience internal deformation, such as electrode distortion due to charge/discharge cycles.	Modules face deformation from the alignment and compression of multiple cells.	Packs experience significant deformation from external mechanical forces (e.g., vehicle collisions, vibrations).
Structural integrity	Individual cells are more prone to internal damage (e.g., electrode cracking) due to localized mechanical stress.	The module structure helps absorb some mechanical stresses, but inter-cell contacts may lead to failures.	The pack's structural integrity is influenced by the overall casing, cooling system, and battery housing, making it more resistant to external impacts.
Impact of temperature	Temperature variations can directly affect the cell's internal mechanical behavior, especially during cycling.	Modules distribute heat but may still face temperature-induced stresses on the interconnections between cells.	Temperature management is critical at the pack level, as thermal expansion or contraction can cause mechanical failure across the entire system.
Vibration response	Cells may experience localized vibrations and mechanical stresses during electric vehicle (EV) movement.	Modules mitigate vibrations between cells but still face risks from the overall battery system’s vibrations.	Packs endure the highest level of vibrations and external mechanical impacts due to vehicle motion, handling, and external forces.
Packaging and support	Minimal packaging, usually a pouch or cylindrical case, which provides some structural support but limited impact resistance.	Modules use more robust casings or frames to protect individual cells and ensure consistent pressure and alignment.	Battery packs have rigid structural housing and often include shock-absorbing materials, cooling plates, and support systems for better protection.
Mechanical failures	Cells are vulnerable to mechanical failures such as cracking, electrolyte leakage, and separator puncture due to localized stress.	Modules may experience failures due to internal cell damage or inadequate alignment and cooling, leading to mechanical failure.	Packs can experience failure in the form of external impacts, structural collapse, or damage to the battery management system (BMS).
Load distribution	Cells experience localized load distribution based on internal material properties.	Modules distribute the mechanical load across multiple cells, reducing individual stress.	At the pack level, load distribution is managed by the overall design and support structures to minimize stress concentrations.
Cooling system influence	Cells have limited direct cooling and are affected by localized heating.	Modules may incorporate cooling systems, but their effectiveness depends on the cell arrangement and module design.	Packs often feature dedicated cooling systems (e.g., liquid cooling, air cooling) that reduce thermal stress on the cells and modules, enhancing overall mechanical stability.

The Role of Packaging Materials and Structural Design

The packaging materials and structural design of battery packs play a critical role in preventing mechanical failure. High-strength materials, such as aluminum or composite materials, are often used to protect the cells from external mechanical forces. Additionally, proper spacing and shock-absorbing materials are essential for minimizing the risk of damage caused by vibrations or impacts.

Battery cooling systems are essential for maintaining the thermal stability of LIBs, but they also have mechanical implications. Cooling systems often involve the use of heat sinks, thermal interfaces, and cooling plates that must withstand thermal expansion and contraction without compromising the integrity of the battery pack.

Structural Integrity and Safety Concerns

Mechanical failure in LIBs can result in significant safety hazards, including thermal runaway, short-circuiting, and fires. If a battery is damaged due to mechanical stress, it may cause internal short circuits, which can lead to overheating and thermal runaway. Therefore, ensuring the structural integrity of LIBs is essential for EV safety. External mechanical forces, such as accidents, road debris, or harsh driving conditions, can cause severe damage to the battery pack, resulting in safety risks. Battery housing designs must be optimized to protect against these external forces, ensuring that the cells remain intact and functioning properly. The design of battery housings plays a key role in ensuring mechanical resilience and safety. Advanced materials and structural reinforcements can help protect against external mechanical stresses, reducing the likelihood of battery failure due to impacts or vibrations.

Material Innovations and Their Impact on Mechanical Performance

Recent research has focused on developing new materials that can improve the mechanical performance of LIBs. Carbon composites, for example, can enhance the strength and flexibility of electrodes, making them less prone to cracking under stress. Flexible electrodes and solid-state electrolytes also hold promise for improving the mechanical resilience of batteries. Solid-state batteries, which replace the liquid electrolyte with a solid material, are less susceptible to mechanical failure due to their inherent stability. Lithium-sulfur batteries, with their high energy density, also offer potential for improving both the electrochemical and mechanical performance of batteries.

Modeling and Simulation of Mechanical Behavior

Numerical simulations, such as finite element analysis (FEA) and computational mechanics, are used to model the mechanical behavior of LIBs under various loading conditions. These simulations can predict how a battery will behave under different stresses, helping to design more robust and reliable systems. To improve the overall prediction of battery performance, mechanical models are integrated with electrochemical models. This integration allows researchers to simulate the combined effects of mechanical stresses and electrochemical processes, providing a more accurate representation of how LIBs perform in real-world applications (Table 4).

Exploitation of structural batteries requires advanced analysis and simulation of mechanics and electrochemistry due to their interdisciplinary nature. For example, when structural batteries are in operations, they may be subject to various external loadings, which may affect electrochemical functions of batteries depending on applications. Four different sources of mechanical stresses exerted on a battery were examined in this study: structural, thermal, fabrication and kinetics. Manufacturing loads are applied while battery electrodes are compressed to achieve desired volume fraction to improve their volumetric properties as well as conductivities. Heat generated by exothermic reactions and electrical resistance in batteries produces repetitive thermal expansion and contraction of the materials. Kinetic loads are due to chemical reactions in the battery. Lithium ion insertion into and extractions out of lattices of the active materials during charging or discharging causes the lattices to experience repetitive volume changes. There have been theoretical and experimental efforts to identify failure mechanisms due to these mechanical loadings in battery active materials. A series of studies showed that compression of carbonaceous electrode materials during manufacturing not only improves their performances, but also can damage the materials, resulting conductivity decrease. Mathematical models suggested that stresses induced during lithium ion insertion and extraction can be larger than the strength of the active materials. A numerical study revealed how particle size and aspect ratio affect stresses induced by intercalation in a $LiMn_2O_4$ particle. Strains in battery electrodes at macro-scale and micro-fractures in active material particles have been empirically found. Despite the numerous efforts to understand the mechanical stresses in batteries, there has been little attention paid to various sources of loadings applied to batteries, other than intercalation-induced stresses. This is probably because batteries in conventional applications are not intended to bear any structural load and assumed to be kept in a stress-free environment. However, even batteries in conventional applications are subject to compressive loadings during fabrication. Evaluating possible sources of loads and designing batteries is thus important. Overarching objectives are to determine how materials architecture, electrochemistry, and charge/discharge processes influence load transfer within and outside the cell.

CASE STUDY

Experiment Setup and Mechanical Tests

Both carbon fiber ends extruding out of the battery were fixed in wooden blocks with epoxy for mechanical test grip. Then the battery was loaded in the universal material tester along with the potentiostat BioLogic instrument (Figure 2).

Since a carbon fiber tow contains 2000 filaments, all the filaments could not be aligned so that they can be evenly strained by the equal amount. Instead, the fibers were strained until the applied load reached a certain value, say 50 N, then the point where most fibers were engaged with the tension was found from the load-elongation curve. Then the engagement point was recorded, and the cross head of the material tester was returned to the starting point. When we applied different values of strains, this engagement point was used as a pre-strain so that the actual elongation was the sum of the pre-strain and the strain we set as an experiment level. Electrochemical tests were done while 0%, 0.15%, and 0.3% of strain were applied to the battery. Two basic electrochemical techniques were used in this study: galvanostatic cycling (GC) and cyclic voltammetry (CV). In GC, changes in potential of a battery are measured while it is charged/discharged with a constantly imposed current. Using this technique, the actual capacity of a battery can be obtained by the product of the imposed current and the elapsed time. In CV, potential of a battery is controlled. Following triangular function with respect to time, and the resulting current is measured. It is known that current peaks appear in both cathodic and anodic scan direction when an electrochemically reversible system is considered.

Table 4. Material and causes of mechanical deformation on battery parts.

Component	Material	Mechanical Behavior
Coating	Powders of graphite/active particles and binders.	Pressure dependence
Separator	Porous polymer (with/without ceramic coating).	Orthotropic, elasto-viscoplasticity, temperature dependent
Shell casing or pouch	Steel or aluminum sheet	Strain hardening, ductile fracture

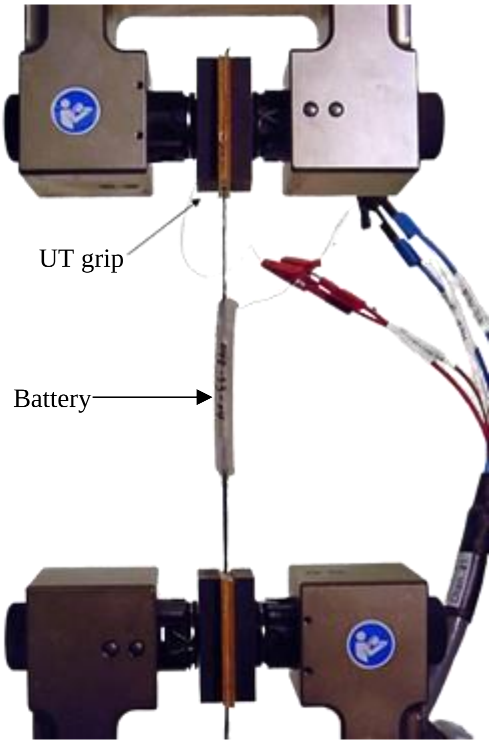

Figure 2. Tensile test set up for mechanical test of lithium-ion battery.

Fabricated batteries were galvanostatically cycled once with a current, C/30 or 0.184 mA between 0.01 and 1.5 V for a formation cycle. A formation cycle is first few cycles during which organic electrolytes decompose and solid-electrolyte interphase forms. Since charges consumed during this process are irreversible, this cycle should precede any measurement of interest. Cyclic voltammetry (CV) was then employed to obtain diffusion coefficients of lithium ions in carbon fibers with voltage scan rate from 0.1 to 3.2 mV/s between 0.01 and 1.5 V. Since fibers have a circular cross section, the diffusion equation was formulated in a cylindrical coordinate system as (Figures 3 and 4),

$$\frac{\partial C}{\partial t} = D\left[\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\left(\frac{\partial C}{\partial r}\right),\right]$$

where C is the concentration, r is the radius of a single filament, and t is the time. The boundary condition that the net flux of diffusing species at the electrode surface is equal to zero can be expressed as

$$D_O\left(\frac{\partial C_O(r,t)}{\partial r}\right)_a + D_R\left(\frac{\partial C_R(r,t)}{\partial r}\right)_a = 0$$

where Ds are the diffusion coefficients of oxidizing and reducing species, and a is the radius of fiber. In CV, the electric potential E can be expressed with the initial potential E_i and voltage scan rate v as

$$E = E_i + vt.$$

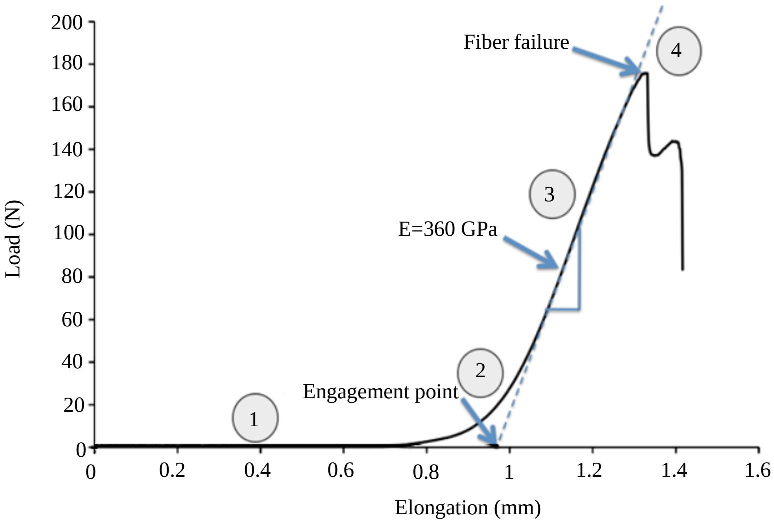

Figure 3. Load-elongation curve of battery under uniaxial tension.

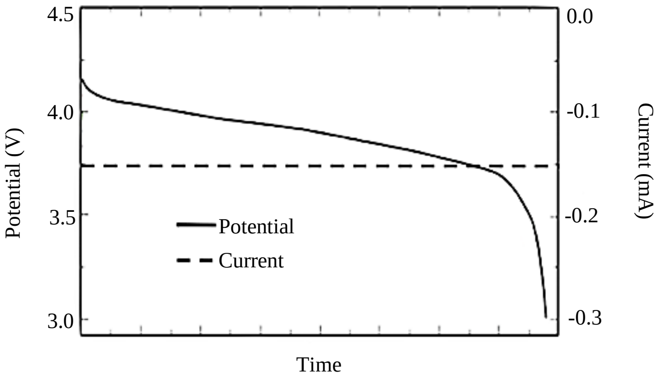

Figure 4. Change in potential is measured while battery is discharged with a constantly imposed current in galvanostatic cycling.

Nernst equation combined with Equation 3 gives,

$$E_i + vt = E^0 + \frac{RT}{nF} log \left[\frac{f_O C_O}{f_R C_R}\right],$$

$$or \frac{C_O}{C_R} = \frac{f_R}{f_O} exp \left[\frac{nF}{RT}(E_i - E^0)\right] exp \left[\frac{nF}{RT} vt\right],$$

where R is the universal gas constant, T is the absolute temperature, n is the charge transfer number, and F is the Faraday constant (Figures 5 and 6). Nicholson solved these equations by a finite difference method. From the following relationship between current and concentration gradient,

$$i = nFAD \left(\frac{\partial C}{\partial r}\right)_a$$

The current can be expressed as

$$i = \pm 1.475 \frac{n^{3/2} F^{3/2}}{R^{1/2} T^{1/2}} A D^{1/2} C^0 v^{1/2} \psi$$

Where the electrode surface area and values of is are available from the references.

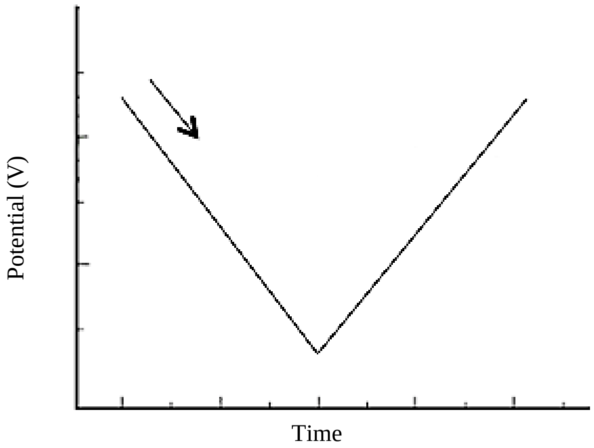

Figure 5. In cyclic voltammetry, potential is controlled as a triangular function with various potential scan rates.

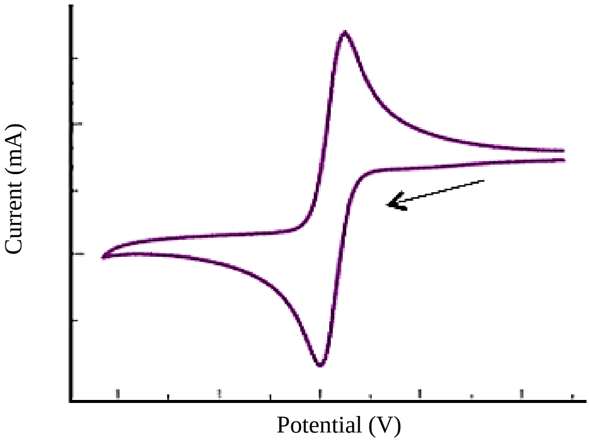

Figure 6. Resulting current in a reversible system shows peaks in both scan directions.

As the fibers were stretched, the load stayed close to zero up to a certain point, here about 0.7 mm, where most fibers were straightened and started to be actually loaded, and then the load rapidly increased as more filaments were engaged in tension at about 0.90 mm. The tensile modulus of this sample was 360 GPa, which is about 38% of the actual value, and the ultimate elongation was 0.3%, which is also smaller than the value provided by the manufacturer, indicating the applied load was not evenly distributed among filaments. Figure 7 show galvanostatic discharge/charge curves with a C/30 current. The initial voltage of a fresh battery was around 3.3 V and it dropped rapidly as the battery was discharged. The discharge curve became gentle from 1.8 V down to 0.4 V implying electrolyte DEC and EC decomposition. Then the discharge curve plateaued at a few different potentials, referred as staging phenomena due to lithium ion intercalation into graphite. The first expulsion and charge measurements were 186 mAh/g and 162 mAh/g, correspondingly. These values resemble 43% to 50% of hypothetical volume of graphite, 372 mAh/g. Limited graphite contents or degree of graphitization of the fiber are thought to be the major cause of the battery having lower utilization. It is well known that the capacity of carbon-based electrode is largely dependent on the graphitization degree. Another reason of having lower utilization may be sought from the battery configuration. For the purpose of the experiment, compression between two electrodes could not be applied which is common procedure in conventional batteries. Finite distance between the two electrodes may cause the battery to have lower capacity owing to excessive concentration polarization. Cyclic voltammetry with various scan rates ranging from 0.1 to 1.6 mV/s were conducted and the results of a control sample are shown in Figure 8. As the applied voltage scan rate increased, peak currents increased from 0.8945 to 1.613 mA and the position of anodic peak also shifted from 0.3706 to 0.6708 V. At very low potential scan rate, it is known that distinct peaks corresponding to different stages described with galvanostatic charge-discharge appear in voltammogram, but they merge into one peak as scan rate increases. From Equation 1, the peak current is the function of the diffusion coefficient and the square roots of potential scan rates. When the peak current is plotted against the square roots of the potential scan rates, the proportionality of these two values can be used to obtain a diffusion coefficient. From the result shown in Figure 3, the diffusion coefficient of lithium ions in the control carbon fibers was 3.1×10^{-6} cm^2/s using Equation 2. Figure 4 presents a cyclic voltammogram with the fixed scan rate 0.1 mV/s and 0, 0.15, and 0.30% of strains. The peak current increased from 0.5191 to 0.5583 to 0.6661 mA as the practical strain improved. Changes in peak position shifting from 0.3509 to 0.3596 to 0.3526 V were not as significant as the peak current changes with respect to scan rate variances. For a reversible system, increase of potential scan rates induces increase of peak currents while keeping the distance between cathodic and anodic peak positions constant. However, in a quasi-reversible system as in this study, potential scan rate affects both peak current and peak positions. Given that the potential scan rate and peak position remained constant, we can deduce that the peak currents were increased by altered kinetic parameters, especially diffusivity. In Figure 4, the peak currents from cyclic voltammogram of a sample under different tensions are plotted against the square roots of potential scan rates, and interpolated with linear functions. The slopes of these regression lines vary from 0.35 to 0.61 mA/(mV/s)$^{1/2}$ and diffusion coefficients corresponding to these slopes can be obtained in the range, 8.06×10^{-7} to 2.4×10^{-6} cm^2/s. Though the slopes in Figure 5 and in other samples changed with respect to the applied strains, they did not seem to have a statistically meaningful trend among various samples as shown in Figure 6. The diffusion coefficients obtained from the experiments were in the same order with those Takami et al. reported using Electrochemical Impedance Spectroscopy (EIS), but 3 to 4 orders of magnitude larger compared to other studies measuring diffusivity of carbon fibers with various techniques. Takami and co-workers explained that the high diffusivity of lithium ions in carbon fibers was attributed to the radial texture of filament microstructure. In literature, however, diffusivity of lithium ions in graphite is not in good agreement and various depending on physical and chemical characteristics of materials and electrochemical techniques used for the diffusivity measurement. The reason that the diffusivity differs in strained carbon fibers may be the distortion of microstructures. Imanish et al. studied how the microstructure of a carbon fiber affects the capacity and cyclability. They explained the dependence of battery functions on crystallite structure as the difference in susceptibility to structural failure and lithium ion accessibility. Shioya and Takaku reported reorientations of crystallites in carbon fibers under tension using X-ray diffraction. Therefore, the modification of dissemination path due to inflexible rotation of crystallites under tension might be an important cause of the change in diffusivities. Another possible cause came from the uncertainty of the tensile test. As seen in Figure 7, when fibers were stretched, individual fibers were subject to different strains from each other due to technical difficulty of alignment of multiple fibers. Consequently, the diffusion coefficient of tested battery was the averaged results obtained with differently strained fibers, in which the strain was an important control parameter. When strains were applied to a structural battery, and the battery was charged/discharged, the battery experienced change in stresses. As seen in Figure 8, the load measured with the materials tester decreased from 55 down to 44 N during discharging and recovered the initial loading at the completion of one full electrochemical cycle. The pattern of the measured load was precisely consistent with that of charges, and the magnitude of change in load during cycling was also directly proportional to the amount of charge, implying the number of lithium ions inserted into graphite was a key factor. Previous experimental work using X-ray and computational work showed that graphite lattices expand as lithium ions intercalate into graphite and agreed that the change in spacing between lattices was less than 10%. Thus, we can deduce that the measured load change up to 20% originated not only from the elongated lattices, but also more likely from other factors in the carbon fiber due to lithium intercalation. In carbon fibers, the graphite lattices are aligned along fiber direction. In other words, the axis of graphite is perpendicular to the fiber to have higher stiffness and strength although all the graphite lattices are not perfectly aligned within a fiber. This fact strengthens the postulation that the changes in the measured load shown in Figure 9 are more likely intrinsic. Considering design of structural batteries or battery-implemented applications, the findings in this experimental study may be used as a criterion. Since the intrinsic property of an active material significantly changes during battery operation, one cannot adopt materials properties reported for uses in typical structural applications. Instead, significantly conservative design criteria should be applied. Changes in battery functions, though they were not as significant as structural aspects from this study, should also be carefully considered. As the final thought on the experiment, differently from porous materials, tensions applied to the fibers may not cause the fibers to contract laterally as a whole so that individual filaments can better contact to each other. This is because there is no structural connection between individual fibers. Even though the contact between fibers may slightly differ from relaxed fibers to strained ones, the electronic conduction in carbon fibers mainly occur along the longitudinal direction due to high anisotropy of graphite. This reasoning made the assumption feasible that we alter the actual material differently from previous work using porous materials (Figures 7–14).

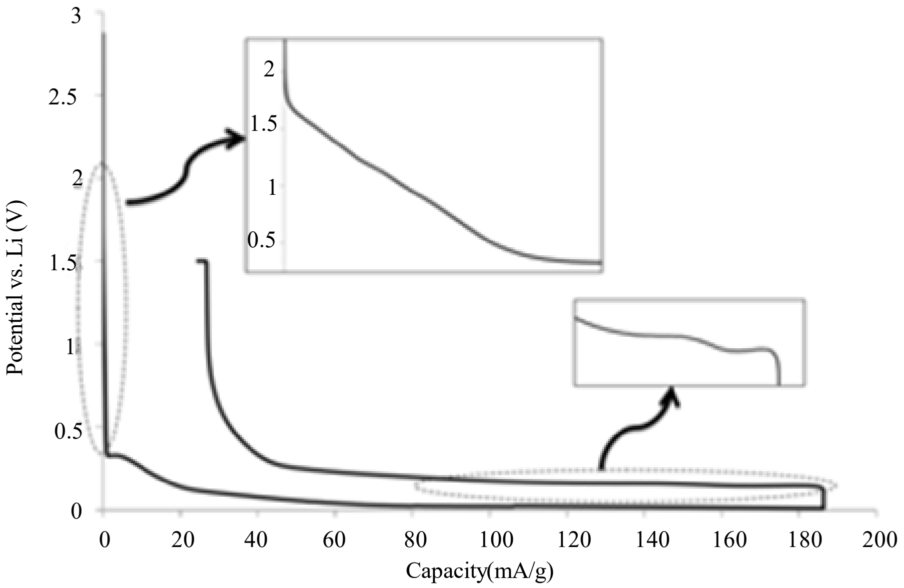

Figure 7. Galvanostatic discharge/charge curve, (top inset) showing gentle curve due to electrolyte decomposition, (bottom inset) voltage plateau due to staging effects.

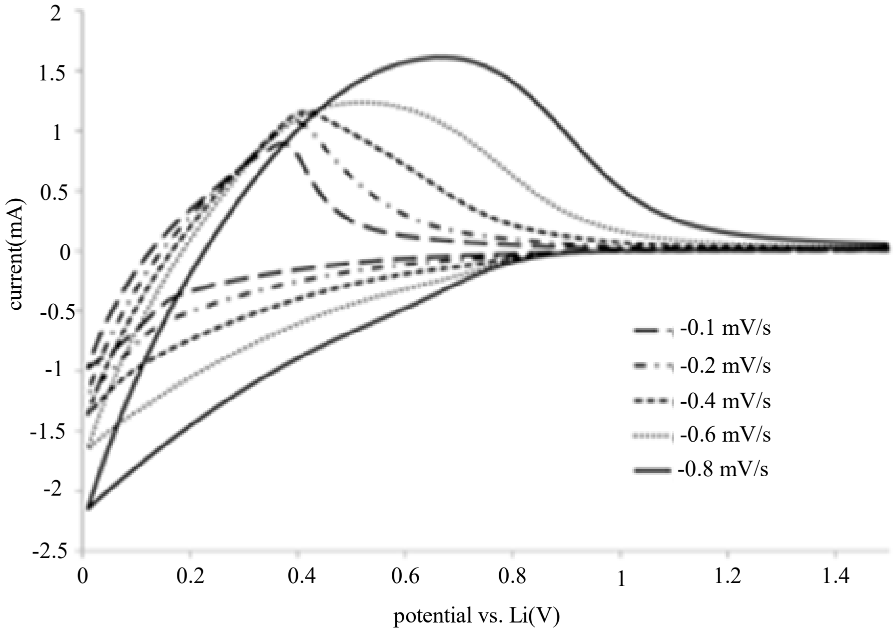

Figure 8. Cyclic voltammogram with potential scan rates between 0.1 and 1.6 mV/s in a control sample.

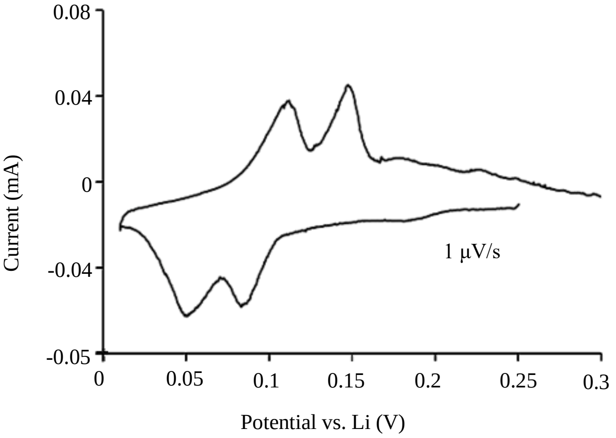

Figure 9. Distinct current peaks appear when graphite is cycled with very low potential scan rate (1 μV/s).

Summarization of Case Study

In this study, we studied the effects of mechanical stresses on electrochemical performance of batteries. A carbon fiber–lithium battery was fabricated for coupled mechanical-electrochemical experiments. The diffusion coefficients of lithium ions in carbon fiber were measured using CV and the load applied to the fiber was monitored while the carbon fiber (working electrode) was stretched with a material tester. The diffusivity obtained from experiments under strains of 0% to 0.3% varied from 8.06×10^{-7} to 2.4×10^{-6} cm^2/s within the same sample. The change in lithium ion diffusivity may be caused by alteration of diffusion path due to microstructure changes during tension tests, but did not result a statistically meaningful trend. Load measured during electrochemical cycling strongly depended on the amount of lithium ions intercalated into graphite. Considering findings from previous work and arrangement of graphite lattices, the changes in measured loadings may be caused by materials property change rather than expansion of the material. It is recommended that this possibility of material property change should be considered when designing a structural battery. To better understand the underlying mechanism in the change of diffusivity under external mechanical stresses, characterization of the carbon fiber microstructure would be required. Observation of lattice parameter and orientation change of the carbon fiber using X-ray during tension tests may clarify the direct cause of change in diffusivity. One of the difficulties in this study was to make filaments evenly align with the loading so that every single filament is under the same strain. We can resolve this problem by testing a single filament instead of a tow of fibers. However, designing a battery that can be used in this type of coupled experiments is not trivial, considering grabbing a brittle fiber for tension tests and sealing the battery while allowing motion for material tests.

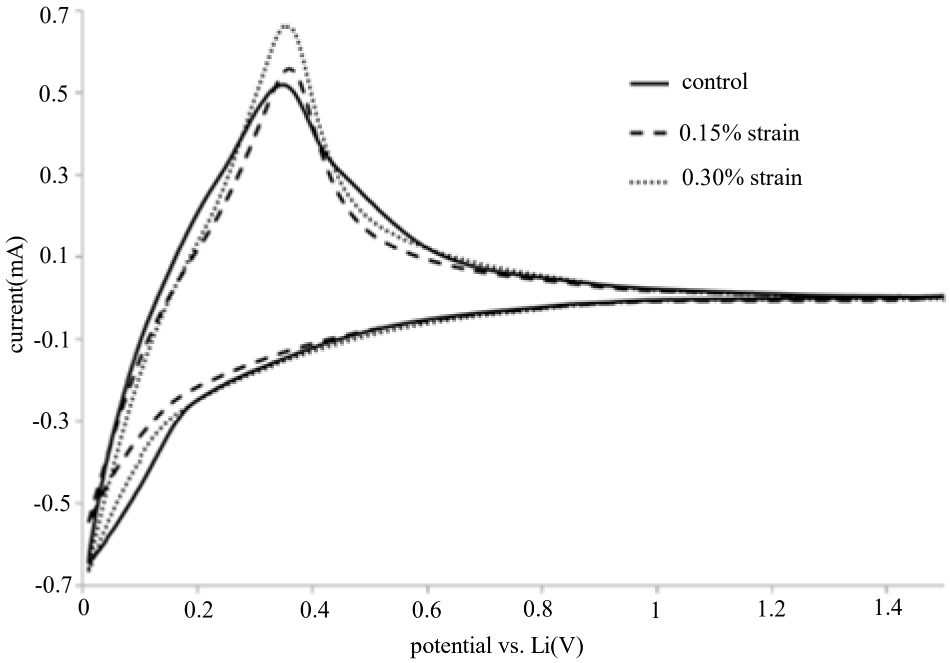

Figure 10. Cyclic voltammogram with various strains.

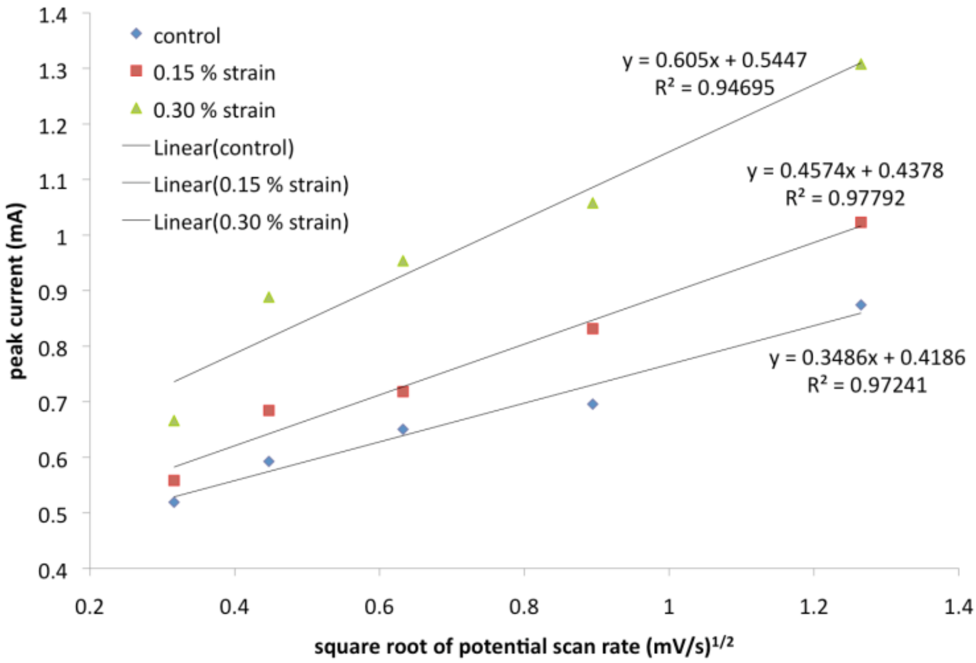

Figure 11. Peak current versus square root of potential scan rate. Regression lines are added to see changes in the relationship with respect to the applied loadings.

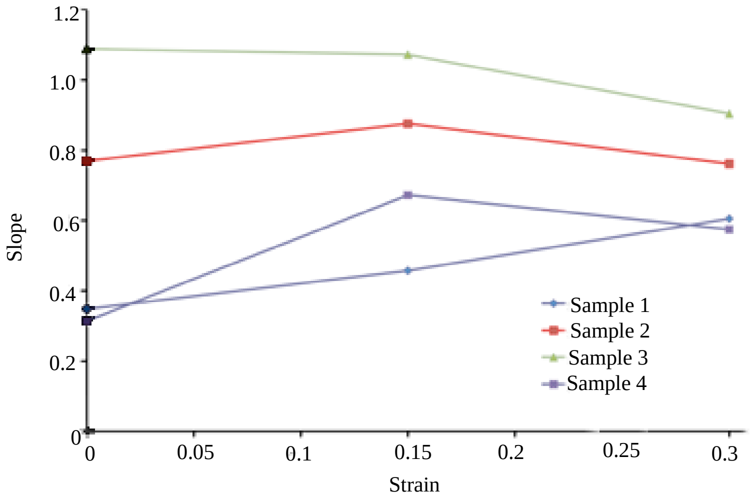

Figure 12. Slopes are plotted against strain. Slopes vary, but not in a significant pattern.

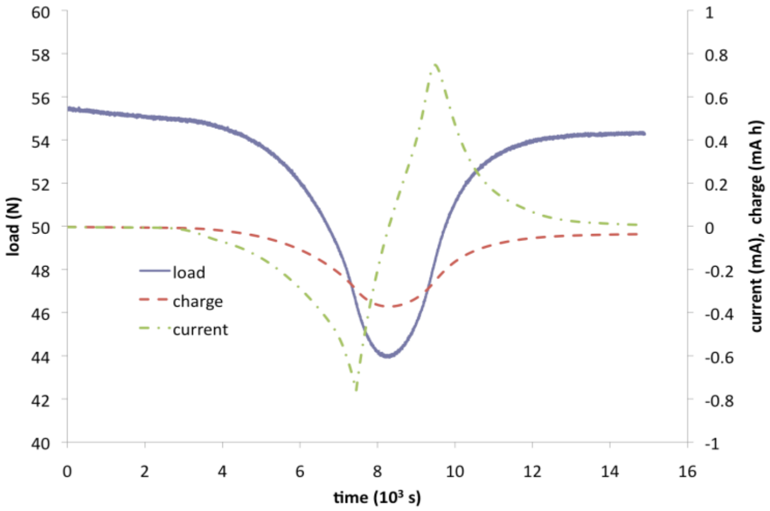

Figure 13. Measured load changes as lithium ions intercalate into graphite as shown with the charge and current curves.

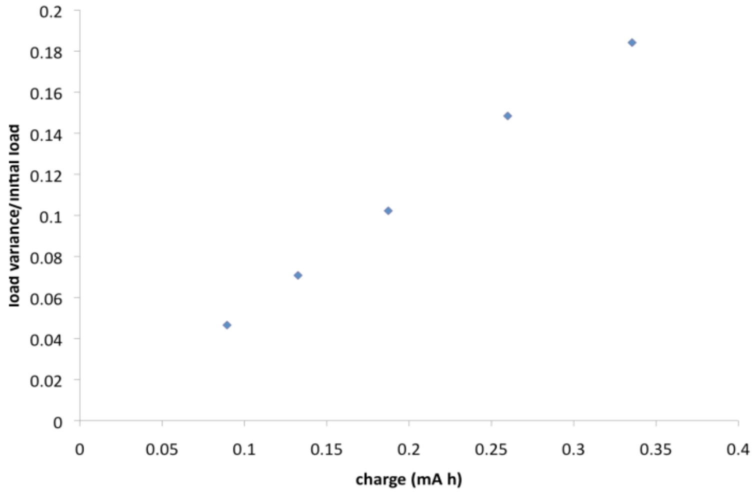

Figure 14. Change in measured loads is directly proportional to the amount of lithium ions inserted into graphite.

CONCLUSION AND FUTURE SCOPE

The mechanical behavior of LIBs, such as stress, strain, and deformation, directly impacts their performance, cycle life, and thermal stability. The relationship between mechanical behavior and battery efficiency is crucial in EV applications, where external forces, temperature variations, and vibration stresses can affect battery integrity. Continued research is essential to improve the mechanical integrity and safety of EV batteries. Understanding how mechanical stress influences battery materials at various scales can help mitigate failure risks and enhance the longevity and reliability of LIBs in EVs. Integrating mechanical behavior studies into the design and development of EV batteries is critical for advancing battery technology. By focusing on improving the mechanical robustness of LIBs, we can ensure safer, more durable, and efficient EV batteries, contributing to the growth of the EV market and sustainability efforts.

Four different sources of mechanical stresses exerted on a battery implemented in a structure were examined in this study: structural, thermal, fabrication and kinetics.

- Compression of conventional particulate electrode material would produce stresses as high as 2 GPa and thermal expansion of batteries embedded in a structure had stress of 100 MPa. Considering strength of typical oxide materials, these values may cause mechanical failure in electrode particles.
- On the other hand, stresses due to structural loadings and intercalation kinetics were relatively low, ranging from 0.2 to 45 MPa. Reinforcement materials in composite structures function as load bearing component when structural loading was applied, but as rigid constraint, leading to critical stresses when thermal loading was considered.
- Also, in a structural battery, the stresses exerted to the structure can be altered as large as 20% of the initially applied value during charge/discharge cycles of the battery.
- Thus, when designing structural battery applications, one need to consider the trade-offs in functions of reinforcement in composites as well as the influence of electrochemistry to the structural stability.
- Stresses induced by structural loadings were relatively low compared to other sources of stresses. This is likely because structural batteries are mostly light duty applications and they adopt composite structures.
- Thermal expansion in Power Fiber produced significant stresses. The thermal stresses may cause material failure, resulting in failure as power storage. This relatively high stress was also caused by layered structure.
- Differently from the structural loading case, reinforcement materials with higher elastic modulus functioned as rigid confinement. Thus, when designing structural batteries, not only beneficial features of composites such as lightweight and high strength, but also their adverse effects as stress sources when combined with thermal expansion should be carefully considered.
- The stresses during fabrication are considered as a critical source which causes mechanical failure of particles. However, compression process during fabrication can be avoided if electrodes are made as thin films as in Power Fiber using various deposition techniques.

Future Trends and Research Directions

- Emerging technologies focus on improving the mechanical robustness of LIBs. Materials like carbon composites, flexible electrodes, and solid-state electrolytes are being developed to enhance the structural integrity and overall durability of LIBs. These innovations aim to reduce the risk of mechanical failure, such as cracking or deformation, thereby extending battery life and improving safety.
- Artificial intelligence (AI) and machine learning (ML) are playing an increasingly important role in optimizing battery design. These technologies can simulate mechanical behavior under various stress conditions, predict potential failures, and optimize the materials and structural components of LIBs. AI and ML algorithms are also being used to automate the design process, making it more efficient and reducing time-to-market for improved battery technologies.

- Further research is needed to develop advanced mechanical testing methods that can simulate real-world conditions, such as repeated vibrations, thermal cycling, and shock impacts. Additionally, more focus is required on multi-scale modeling to understand the behavior of LIBs at the cell, module, and pack levels. Research should also investigate aging and degradation mechanisms, particularly how they affect the mechanical performance of batteries over time.

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